

Small-scale modelling of stiffened raft and cavity raft designs

by

Dirk Maartens Bester

DOCTOR OF ENGINEERING

in the

Department of Civil Engineering

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

TSHWANE UNIVERSITY OF TECHNOLOGY

Supervisor: Prof. E. Theron

Co-supervisor: Dr P.R. Stott

Co-supervisor: Prof. J. Snyman

December 2024

DECLARATION

I hereby declare that this thesis submitted for the degree Doctor Technologiae, at the Tshwane University of Technology, is my original work and has not previously been submitted to any other institution of higher education. I further declare that all the sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references.

A handwritten signature in black ink, appearing to read 'Dirk Maartens Bester', is written over a light gray rectangular background.

Dirk Maartens Bester

ABSTRACT

Since 1994, the South African Government has attempted to provide affordable, sustainable, subsidized housing for its most economically disadvantaged citizens. This commitment has translated into significant financial investments in constructing and repairing subsidized housing for the socioeconomically challenged population of South Africa. Government-subsidized housing (GSH) units constructed on active clay soils have experienced substantial foundation failures. It is estimated that the Department of Human Settlement has spent approximately R2 billion on the repair of GSH in the 2008 and 2009 financial years. This issue, as highlighted by Diop *et al.* (2011), is particularly prominent within the Karoo Supergroup, which stands as South Africa's most widespread stratigraphic unit. The primary challenge of low-cost housing structures is their vulnerability to damage caused by expansive clay soils. This vulnerability arises from their lightweight construction, which makes them susceptible to lifting when clay soils expand due to moisture absorption. To address this, raft foundations are employed for the construction of GSH on expansive clays. Current design methodologies for raft foundations rely primarily on assumptions regarding the shape of the centre dome, which forms due to moisture movement beneath the foundation. However, this assumption is often inaccurate, particularly when dealing with clay soils. Previous research pertaining to moisture movement and foundation performance (Miller *et al.*, 1995 and Fityus *et al.*, 2004) was typically conducted using a foundation without a superstructure or sheets covering the ground to simulate the footprint of a foundation, which does not align with the actual conditions. Instrumentation installed under a GSH in the Free State revealed substantial disparities between assumed and observed moisture movement beneath a raft foundation (Bester, Stott and Theron, 2016).

This study critically evaluates existing raft foundation design methods and compares it with a novel approach employing cavity foundations through small-scale modelling techniques. Instrumentation was installed to monitor moisture movement and differential heave. The findings revealed discrepancies between assumed and observed values, highlighting the inadequacy of current design methods in predicting soil behaviour.

The study recommends incorporating building orientation, increasing rigidity in foundation beams, or implementing alternative designs that facilitate moisture escape. These findings emphasize the need for a more robust design approach, which can significantly enhance the reliability of foundations on expansive clays.

Keywords: Government subsidy house, raft foundation, clay soils, moisture movement, edge penetration distance, cavity raft foundation.

ACKNOWLEDGEMENTS

I wish to express my heartfelt gratitude to several individuals and organisations whose support and guidance have been instrumental in the completion of this doctoral thesis:

- I. I sincerely appreciate the Tshwane University of Technology (TUT) and the Department of Civil Engineering at TUT for their unwavering support throughout this research endeavour.
- II. My deepest gratitude goes to Professor E. Theron, Senior Lecturer at the Department of Civil Engineering at the Central University of Technology. Her exceptional support, expertise, and encouragement have played a pivotal role in shaping my research project and academic journey. Her guidance and continuous motivation has significantly contributed to my growth as a researcher, and I consider myself fortunate to have had her as my mentor.
- III. I also want to acknowledge and thank my co-supervisor, Dr P.R. Stott, for his consistent support, encouragement, and invaluable guidance throughout this research project. His insightful feedback and constructive criticism has been paramount in refining my research methodology and findings. His patience and dedication has been a constant source of motivation, and I am privileged to have had him as my co-supervisor.
- IV. Additionally, I would like to express my appreciation to my co-supervisor, Professor Snyman from Tshwane University of Technology. His expertise and support has been indispensable in shaping my research project, and his

commitment to the field of Civil Engineering has been a source of inspiration.

I am thankful for his insights, guidance, and committed support throughout this endeavour.

V. I would like to acknowledge the invaluable support received from various funding agencies, notably Tshwane University of Technology and the National Research Foundation.

VI. I owe a special debt of gratitude to my family and friends for their unwavering encouragement, support, and understanding, which has been a constant source of strength throughout this journey. I extend heartfelt thanks to Anri for her belief in me and her support, to Japie for all his help and encouragement, and to my parents for their nonstop support.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION	1
1.1. An overview of the research	1
1.2. Problem statement	8
1.3. Research aim	10
1.4. Objectives of the study	11
1.5. Data collection	11
1.6. Analysis of raw data	12
1.7. Modelling	13
1.8. Results and discussions	14
1.9. Inferences	14
1.10. Research design and methodology of the study	14
1.11. Limitations	15
1.12. Chapter scheme	16
CHAPTER 2: LITERATURE REVIEW	17
2.1. Introduction	17
2.2. Introduction to soils	17
2.2.1. Expansive clay soils in South Africa	18
2.2.2. Geology and mineralogy of problematic clay soils in South Africa	19
2.3. Water movement in soils	23

2.3.1.	Saturated soils.....	24
2.3.2.	Unsaturated soils.....	24
2.3.3.	Active zone	27
2.3.4.	Soil suction	28
2.3.5.	Concepts of suction	31
2.3.6.	State of stress.....	31
2.3.7.	Volume change behaviour of unsaturated fine-grained soils	33
2.3.8.	Volume change behaviour: effective stress approach	33
2.3.9.	Volume change behaviour: two independent stress variables approach	34
2.3.10.	Numerical modelling of swell behaviour in clay	35
2.3.11.	Extended theory of porous media.....	36
2.5.	Construction of GSH in South Africa	37
2.6.	Review of raft foundation methods and design for active clay conditions.	39
2.6.1.	Raft foundations designs for active clay soils	41
2.6.2.	Edge heave and centre doming on expansive clay soils	43
2.6.3.	Factors affecting moisture changes underneath foundations	44
2.6.4.	Raft foundation methodologies, design and past research	45
2.6.5.	Field studies on foundation moisture patterns	51
2.6.6.	Ventilated foundations	52

CHAPTER 3: SCALE MODEL DEVELOPMENT AND INSTRUMENTATION FOR SM FOUNDATIONS	57
3.1. Introduction.....	57
3.2. Scaling laws.....	57
3.2.1. Scaling on shallow foundations	58
3.2.2. Scale selection of the models	60
3.3. Expansive clay selection and CLSM probe instrumentation	61
3.3.1. Soil sample collection	61
3.3.3. Soil property testing to determine soil properties in South Africa.....	61
3.3.4. Heave determination methods used in South Africa	64
3.3.5. Expansive clay used properties	66
3.3.6. Field moisture measurement methods	69
3.3.7. The installation of CLSM probes.....	71
3.3.8. Calibration of CLSM probes	73
3.3.8.1. Gravimetric moisture content.....	73
3.3.8.2. Bulk density	74
3.3.8.3. Volumetric moisture content	74
3.4. Construction of the climate room	75
3.4.1. Suns orientation to the earth	75
3.4.2. The implementation of artificial sunlight in the laboratory	77
3.4.3. The electrical components of artificial sunlight inside the laboratory	79
3.4.3.1. Arduino	79

3.4.3.2.	Relay switches.....	81
3.4.3.3.	The electrical wiring of artificial sunlight inside the laboratory	81
3.4.4.	The coding of artificial sunlight inside the laboratory	85
3.4.5.	The simulation of rainfall.....	86
3.5.	Construction of scale model foundations and monitoring	87
3.5.1.	3D printing	88
3.5.2.	Manufacturing of scale bricks	90
3.5.3.	The construction of the SM raft and cavity raft foundations.....	92
3.6.	Instrumentation monitoring of SM raft and cavity raft foundations	94
3.6.1.	Laser displacement sensors	94
3.6.2.	Concrete strain in shallow foundations	100
3.6.2.1.	Factors affecting concrete strain in foundations	100
3.6.2.2	Concrete strain measurements.....	100
3.6.2.3.	Strain measurement on the SM foundations	101
3.7.	Research data management and analysis	104
3.7.1.	Data analytics using 3DField	104
3.7.2.	Data analytics using contouring techniques	104
3.7.3.	Data capture collection & storage.....	106
3.7.4.	Data analysis	107
CHAPTER 4: RESULTS, DISCUSSION, AND RECOMMENDATIONS		110
4.1.	Introduction.....	110

4.2.	Botshabelo GSH raft foundation analysis from 2014	110
4.3.	SM cavity raft foundation analysis	115
4.3.1.	Moisture movement analysis	115
4.3.2.	Differential movement analysis.....	120
4.3.3.	Edge penetration analysis of the SM raft foundation	128
4.3.4.	Strain analysis of the SM raft foundation	135
4.3.5.	Summary of the SM raft foundation	137
4.4.	Comparison between the Botshabelo GSH raft foundation and the SM raft foundation simulation in the laboratory.....	138
4.5.	The SM cavity raft foundation analysis	142
4.5.1.	Moisture movement analysis underneath the SM cavity raft foundation...	142
4.5.2.	Differential movement analysis of the SM cavity raft foundation.....	146
4.5.3.	Edge penetration analysis of the SM cavity raft foundation	152
4.5.4.	Strain analysis of the SM cavity raft foundation	155
4.5.5.	Summary of the SM cavity raft foundation	157
4.6.	Summary: comparison between the SM raft and SM cavity raft foundation	158
CHAPTER 5: DESIGN RECOMMENDATIONS		159
5.1.	Current raft foundation design approaches and limitations based on the findings of the study.....	159
5.2.	Design recommendations based on the study findings	161
5.2.1.	Design recommendations for raft foundations	161

5.2.2.	Design recommendations for cavity or ventilated raft foundations.....	165
CHAPTER 6: CONCLUSION AND RECOMMENDATIONS.....		168
6.1.	Conclusion.....	168
6.2.	Limitations and shortcomings of the study.....	168
6.3.	Important findings of the study.....	169
6.4.	Recommendations.....	171
6.6.	Summary	173
CHAPTER 7: REFERENCES		174

LIST OF TABLES

Table 1.1: Common problems related to expansive soil movement (Devkota, <i>et al.</i> , 2022)	5
Table 2.1: GSH by province (Mashwama, <i>et al.</i> , 2018).....	37
Table 2.2: Foundation design, building procedures, and precautionary measures for single-story residential structures founded on expansive soil horizons (NHBRC, 1999)	40
Table 3.1: Scaling factors (Vorster, 2016).....	59
Table 3.2: Foundation indicator laboratory results	68
Table 3.3: Vertical orientation of the sun.....	77
Table 3.4: Arduino mapping for the program developed.....	84
Table 3.5: PETG and PLA properties	88

LIST OF FIGURES

Figure 1.1: Distribution of expansive clays in South Africa (Paige-Green & Turner, 2008).....	3
Figure 1.2: CLSM moisture probes layout of the scaled-down model of a GSH (dimensions are in meters).....	8
Figure 1.3: 3D layout of CLSM moisture probes beneath a typical GSH foundation	8
Figure 1.5: Research design diagram.....	15
Figure 2.1: Regional distribution map of swelling clay occurrences in South Africa (Diop, <i>et al.</i> , 2011). 20	
Figure 2.2: Schematic diagram of non-swelling clay (a) and (b) swelling clay (Grim, 1962).	22
Figure 2.3: Progression of wetting in unsaturated soil, with the wetting depth represented as the depth to the bottom of the transition zone (Nelson & Miller, 1997)	26
Figure 2.4: Water content curves in an active zone under structure and bare conditions (Nelson & Miller, 1997).....	28
Figure 2.5: Soil water and matric suction at three different stages of water content (Nelson, <i>et al.</i> , 2015)	29
Figure 2.6: Pseudo-semipermeable membrane effect causing osmotic suction in clay (Nelson, <i>et al.</i> , 2015).....	30
Figure 2.7: Curves of effective stress parameter or “factor” χ against the degree of saturation S_r for various soils (Jennings and Burland, 1962) redrawn for clarity...	34

Figure 2.10: Schematic representation of the expansive soil as a five-phase porous medium: microstructure and volume fractions in the representative volume element (RVE) (Nitsch et al, 2023).....	36
Figure 2.12: Photo of an L-shaped GSH in Botshabelo, Free State	38
Figure 2.13: Photo of a square-shaped GSH in Thaba Nchu, Free State.....	39
Figure 2.14: Photo of an H-shaped duplex GSH in Ashbury, Bloemfontein.....	39
Figure 2.15: A slabs centre lift and edge lift on expansive soils on the left, and the damage caused by expansive soils on the right (Tabassum & Bulut, 2023).....	44
Figure 2.16: Centre doming under an impermeable cover (Pidgeon, 1987).....	49
Figure 2.17: Typical layout of foundation beams for a stiffened raft foundation (Pidgeon, 1987).....	50
Figure 2.18: Unloaded mould with a shape defined by the mound exponent, m (Pidgeon, 1987).....	51
Figure 2.19: Unloaded mound with a flat top and parabolic or cubic shape edges (Pidgeon, 1987).....	51
Figure 2.20: Honeycomb design on expansive soil (CHEN, 1988).	54
Figure 2.21: Geoplast modulo system (Geoplast, 2020).	54
Figure 2.22: VoidForm's SureVoid system (VoidForm, n.d).	55
Figure 2.23: Typical wafflemat system cross-section (Pacific Housing Systems, 2023).	56
Figure 3.1: Soil-separate-size limits according to various systems (Das, 2007)	63
Figure 3.2: Van der Merwe's chart for heave prediction (Van der Merwe, 1964)..	65
Figure 3.3: Soil swelling potential using the Atterberg limits of Plasticity Index and plasticity ratio (Savage, 2007)	66

Figure 3.4: Moist black stiff clay.....	69
Figure 3.5: CLSM probes layout inside the laboratory.....	72
Figure 3.6: CLSM probes installation.....	72
Figure 3.7: The apparent path of the sun in the sky during different seasons in South Africa (CSIR, 2004)	76
Figure 3.8: Artificial sun layout.....	78
Figure 3.9: Lights layout photograph	78
Figure 3.10: Photograph of the circuit of heater lights	82
Figure 3.11: Circuit diagram of the heater lights	83
Figure 3.12: Program interface	86
Figure 3.13: Sprinklers layout for simulating rainfall	87
Figure 3.14: Bracket designs for OptoNCDT lasers on the steel frame	90
Figure 3.15: 3D-printed moulds for manufacturing bricks scaled one to six	91
Figure 3.16: The manufacturing of scale one to six bricks.....	92
Figure 3.17: The construction of the SM house	93
Figure 3.18: Completed SM house	94
Figure 3.19: Wiring of OptoNCDT lasers	96
Figure 3.20: Four-channel receiver of the laser optical displacement sensors	97
Figure 3.21: Screenshot of the SensorTool software homepage.....	98
Figure 3.22: Screenshot of the data collection page in SensorTool software	98
Figure 3.23: Steel frame layout for OptoNCDT lasers for measuring movement..	99
Figure 3.24: Strain gauge layout on SM raft foundation	102
Figure 3.25: Strain gauge layout on SM cavity raft foundation	103
Figure 3.26: Strain gauge with strain meter	103

Figure 4.1: Botshabelo GSH raft foundation moisture content maximum and minimum values from east to west at various depths	113
Figure 4.2: Botshabelo GSH raft foundation MC% maximum and minimum values from north to south at various depths	114
Figure 4.3: Year 2 – December: 3D moisture content (MC%) heat map of the SM raft foundation, orientation from the southwest corner.	116
Figure 4.4: CLSM probes at 200 mm underneath the SM raft foundation	117
Figure 4.5: CLSM probes at 300 mm underneath the SM raft foundation	118
Figure 4.6: CLSM probes at 400 mm underneath the SM raft foundation	119
Figure 4.7: SM raft foundation movement in mm from A1 to A6	121
Figure 4.8: The south-facing side of the expansive clay soil.....	122
Figure 4.9: SM raft foundation movement in mm from B1 to B6	123
Figure 4.10: The north-facing side of the expansive clay soil	124
Figure 4.11: SM raft foundation movement in mm from C1 to C6.....	126
Figure 4.12: SM raft foundation movement in mm from D1 to D6.....	127
Figure 4.13: Year 2 – December: 3D movement heat map of the SM raft foundation, orientation from the Southwest corner.....	128
Figure 4.14: SM raft foundation movement in (mm) from east to west (A5, A6, C6, C5 & D4).....	129
Figure 4.15: SM raft foundation movement in (mm) from east to west (B3, B4, B6, D6 & D2).....	130
Figure 4.16: SM raft foundation movement in (mm) from south to north (C1, C3, C5, D6 & D5).....	131
Figure 4.17: SM raft foundation movement in (mm) from south to north (C2, C4, C6, B6 & B5)	133

Figure 4.18: SM raft foundation movement in (mm) from south to north (A2, A4, A6, B4 & B2).....	134
Figure 4.19: SM raft foundation strain from A: X-X to J: Y-Y	137
Figure 4.20: Botshabelo GSH 2014 moisture content at depth 150mm of (a) January, (b) May, (c) August and (d) December	140
Figure 4.21: SM raft foundation year one moisture content of (a) January, (b) May, (c) August and (d) December	140
Figure 4.22: SM raft foundation differential movement in (mm) for (a) January, (b) May, (c) August and (d) December	141
Figure 4.23: Year 2 – December: 3D moisture content (MC%) heat map of the SM cavity raft foundation, orientation from the Southwest corner.....	143
Figure 4.24: CLSM probes at 200mm underneath the SM cavity raft foundation	144
Figure 4.25: CLSM probes at 300mm underneath the SM cavity raft foundation	145
Figure 4.26: CLSM probes at 400mm underneath the SM cavity raft foundation	146
Figure 4.27: SM cavity raft foundation movement in mm from A1 to A6.....	148
Figure 4.28: SM cavity raft foundation movement in mm from B1 to B6.....	149
Figure 4.29: SM cavity raft foundation movement in mm from C1 to C6	150
Figure 4.30: SM cavity raft foundation movement in mm from D1 to D6	151
Figure 4.31: Year 2 – December: 3D movement heat map of the SM cavity raft foundation, orientation from the Southwest corner.....	152
Figure 4.32: SM cavity raft foundation movement (in mm) from south to north (C2, C4, C6, B6 & B5).....	153
Figure 4.33: SM cavity raft foundation movement (in mm from south to north (C2, C4, C6, B6 & B5).....	155
Figure 4.34: SM cavity raft foundation strain from A to T.....	157

Figure 5.1: Edge penetration distance	160
Figure 5.2: Raft foundation orientation of the sun, pod design and location of the REC.....	163
Figure 5.3: Fixed end and loading conditions example.....	164
Figure 5.4: The proposed cavity raft foundation beam layouts.	166
Figure 5.5: Cavity raft foundation slab	166

LIST OF APPENDICES

APPENDIX A: The variation in moisture content of the Botshabelo GSH raft foundation throughout 2014.....	191
APPENDIX B: The variation in moisture content underneath the GSH in Botshabelo, Free State using 3DField modelling.....	200
APPENDIX C: The variation in moisture of the SM raft foundation due to simulated seasonal changes using 3DField modelling.....	213
APPENDIX D: The variation in moisture of the SM cavity raft foundation due to simulated seasonal changes using 3DField modelling.....	220
APPENDIX E: The movement of the SM raft foundation due to simulated seasonal changes using 3DField modelling.....	227
APPENDIX F: The movement of the SM cavity raft foundation due to simulated seasonal changes using 3DField modelling.....	234
APPENDIX G: Heat Maps of Raft and Cavity Raft Foundations.	241
APPENDIX H: Simplified strain data for the SM raft foundation.....	258
APPENDIX I: Simplified strain data for SM cavity raft foundation.....	263
APPENDIX J: Orientation of the sun in Botshabelo.....	269
APPENDIX K: Drawings of the SM raft and cavity raft foundation	272
APPENDIX L: C# coding for the artificial sun inside the laboratory.....	275

LIST OF ABBREVIATIONS

af	Pore air
BBM	Barcelona Basic Model
β	Scaling factor
CEC	Cation Exchange Capacity
C#	C sharp coding
CLSM	Continuous Logging Soil Moisture
DFM	Design for Manufacturing
e	Edge moisture variation distance or edge penetration distance
F_{sy}^a	Interaction body force between solids and air phase in the y-direction
f^*	Interaction function between contractile skin and soil structure
GSH	Government Subsidy House
IDE	Integrated Development Environment
L	Length
LDS	Laser Displacement Sensors
LED	Local Economic Development
LL	Liquid Limit
M	Model
m	Metres
mm	Millimetres
n_a	Porosity with respect to the air phase
n_c	Porosity with respect to the contractile skin
NCL	Normal Consolidation Line

NWM	Neutron Water Metres
OptoNCDT	Optical Non-Contact Displacement Transducer
P	Prototype
PETG	Polyethylene Terephthalate Glycol
PI	Plasticity Index
PL	Plastic Limit
PLA	Polylactic Acid
PTI	Post-Tensioning Institute
R	Plasticity Ratio
RVE	Representative Volume Element
SL	Shrinkage Limit
SM	Scale Model
S_r	Degree of saturation
s_t	Total suction
s	Matric suction
TOF	Time-of-Flight
TPM	Theory of Porous Media
U_a	Pore-air pressure
UNO	One in Italian
U_w	Pore-water pressure
V	Volts
w_f	Free pore water
w_r	Residual water
w_s	Swelling water (immobile, bound to clay particles)
X	Soil parameter related to degree of saturation

Y_m	Maximum Differential Heave
Z	Depth of the soil layer
σ	Total stress
σ'	Effective stress
π	Osmotic suction
$\mu\text{m/m}$	Micrometres per metre

CHAPTER 1: INTRODUCTION

1.1. An overview of the research

Expansive clay soils present a substantial challenge in housing construction in South Africa. The presence of expansive clay is widespread across the country, influenced by geological factors, soil type, local climate, and landforms. The regions most affected by expansive clay soils include the Free State, Highveld and Gauteng (Diop *et al.*, 2011). Expansive clay soils are known for causing building foundation instability due to their ability to swell with moisture and shrink upon drying. This is mainly driven by smectite clays like montmorillonite, which results in significant structural risks. Effective engineering is essential to counter these effects and preserve the integrity of structures built on expansive clay soils (Rogers, *et al.*, 2004). As a result, the financial burden of addressing challenges related to expansive clay soils in the housing sector is considerable.

Expansive clay soils are known for their ability to shrink and swell, causing damage to various types of structures (Paige-Green & Turner, 2008). Figure 1.1 illustrates the distribution of expansive clay soils throughout the country. These soils pose a significant risk, especially to lightweight structures like Government Subsidy Houses (GSH) that are prevalent across South Africa. The damage caused by these soils can often exceed the damage from natural disasters, leading to extensive financial losses (Badenhorst, 2017). Failures in the construction of GSH due to expansive clay soils have resulted in damage to the superstructure. Between 1980 and 2000, an estimated R1 billion was spent on repairing or rebuilding housing structures on expansive clay soils in South Africa (Williams, *et al.*, 1985). In the 2008 and 2009 financial years, the Department of Human Settlement allocated R18 billion for new

GSH construction, with a significant amount earmarked for addressing soil-related issues, predominantly expansive soils. At least R2 billion was allocated to address these concerns (Diop, *et al.*, 2011). This figure is based on adopting a conservative approach, as suggested by Williams and Pellissier (1991), for estimating the funds required to manage issues related to expansive clay soils and the additional costs for design and precautionary measures to be implemented in residential buildings. Williams and Pellissier (1991) estimated that almost R1 billion would be spent on such measures, considering that half of the annual construction investment, approximately R6.43 billion in 1990, was dedicated to residential buildings, and 15% of this amount would be needed to address all soil-related challenges (Williams & Pellissier, 1991). This underscores the need for significant financial backing to address the problems associated with expansive soils in residential construction projects. The National Department of Housing, now referred to as Human Settlements, spent a minimum of R18 billion to deliver 239,533 low-cost housing units in the 2008 and 2009 financial year, assuming a unit cost of R77,868. Utilizing a conservative approach such as that of Williams and Pellissier (1991), it can be implied that at least R2 billion could have been spent mitigating problem soil hazards, with expansive soils constituting the bulk of these challenges in South Africa (Diop, *et al.*, 2011).

According to a report by the Council for Scientific and Industrial Research (CSIR) in South Africa, the direct cost of expansive clay soil-related damage to housing in the country is estimated to range between R1 billion and R1.5 billion per year. The cost encompasses the expenses incurred in repairing damage to foundations, walls, roofs, and other structural elements of buildings affected by heave and soil

settlement (CSIR, n.d.). In 2019, *Business Day* reported that the South African Government had spent R 3.1 billion over the preceding five years on rectifying poorly constructed, low-cost GSH houses. The Eastern Cape accounted for the highest expenditure at R2.1 billion, allocated to the rebuilding and repair of 14,732 houses with structural defects, while the Free State spent R284.6 million to address structural issues in an undisclosed number of houses (Zuzile, 2019).

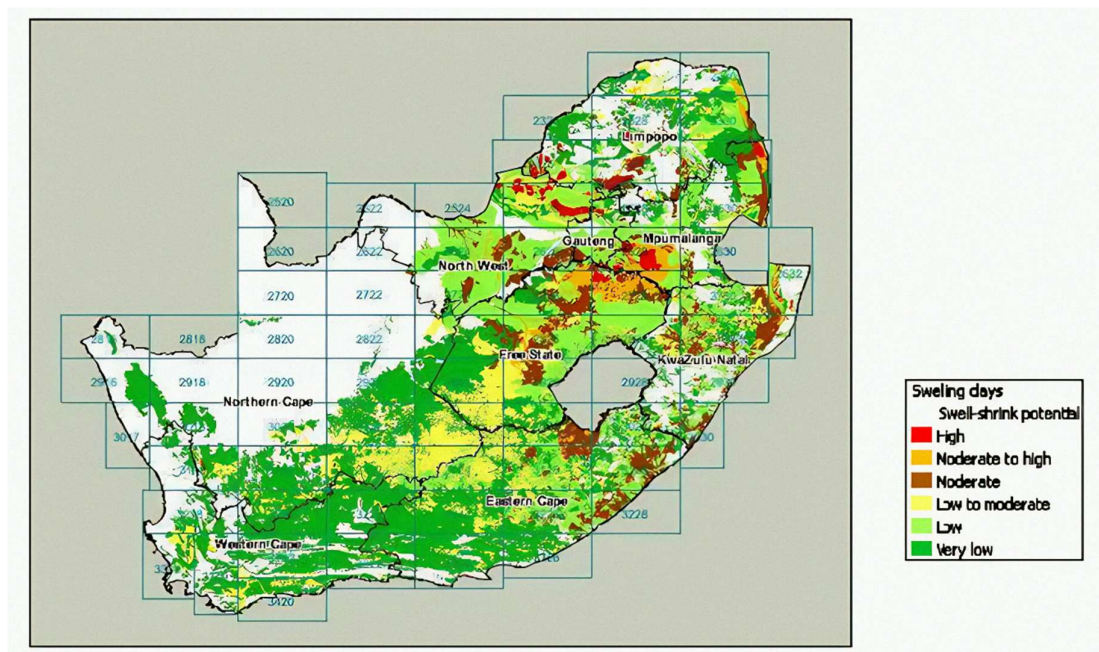


Figure 1.1: Distribution of expansive clays in South Africa (Paige-Green & Turner, 2008)

Despite concerted efforts by the South African Government and the Department of Human Settlement since 1994 to expand housing availability, particularly for the impoverished, the GSH program has encountered numerous setbacks (Bester, *et al.* 2016). These issues primarily originate from substandard construction practices (Stott, *et al.*, 2023). The economic fallout from the failures of the GSH is significant, going beyond just the costs of construction and repairs. These issues contribute to broader economic strains by fostering social instability and deepening poverty

cycles (Bradlow, *et al.*, 2011). Residents of the GSH often lack the financial means to repair and maintain structures that fall short of the expected performance criteria (Motlhabane, 2015). These challenges highlight the need for an overhaul of the RDP framework to ensure that it fulfils its goals of providing durable and affordable housing.

A significant knowledge gap exists regarding the interaction between expansive soils and raft foundations, which results in widespread structural damage. The construction of raft foundations for GSH has gained popularity in areas affected by expansive clay soils (Bester, *et al.*, 2017). The primary goal of using raft foundations on active clay soils is to minimise the differential movements of the structure caused by changes in the volume of the underlying soils, ensuring that the structure can endure these movements without excessive cracking. A critical factor to consider when assessing the performance of raft foundations is the migration of moisture beneath the foundation, leading to heave and uplifting of the structure. Numerous failures indicate that raft foundations are unable to withstand the differential movements occurring under them. This notion is reinforced by the observation of GSH constructed on “stock design” raft foundations. These “stock designs” prove insufficient to cope with the degree of differential movement resulting from heaving clays, particularly in conditions worse than moderate heave (Bester, *et al.*, 2016).

Expansive clays present a noticeable problem for lightweight buildings and shallow foundations. The sheer weight of heavier structures, such as high-rise buildings, provides the necessary counterforce against swelling clay pressures (Devkota, *et al.*, 2022). In contrast, lightweight structures and buildings can be uplifted by the

pressure exerted by swelling clay, which can reach up to 250 kPa, whereas GSH structures may experience uplift pressure as low as 12 kPa. Seasonal variations in moisture content beneath structures can lead to shrink-swell movements, resulting in various types of damage to buildings. During dry seasons, the moisture content at the edges of the building foundation may be significantly lower than at the centre, leading to central heaving, which can result in structural damage such as wall cracks. In contrast, during rainy seasons, when water accumulates beneath the edges of the foundation, the soil has a higher moisture content, leading to soil expansion and potential differential heaving, which can exacerbate foundation instability and structural damage (Tabassum & Bulut, 2023). Table 1-1 provides a summary of problems associated with expansive soil movement.

Table 1.1: Common problems related to expansive soil movement (Devkota, *et al.*, 2022)

Phenomenon	Soil reaction	Result
Heaving/ Shrink-swell	Ground movement	Building failure Buried pipe failure Road failure
Cracking	Increases permeability	Contamination of underlying groundwater through the easy movement of contaminants. Distortion of structures founded on slopes,
Slope instability	Slope movement	Road disconnection or interruption of water supply distribution networks.

The design of raft foundations is often based on assumptions regarding the dome shape that moisture movement will create in the expansive soil beneath the foundation. The assumptions are frequently derived from heave and differential

movement measurements made on foundation models without superstructures (Pidgeon, 1987; Pidgeon and Pellissier, 1987; de Bruijn, 1973; Strydom and Pellissier, 1991) or models using foundation simulations with sheet covers (Miller *et al.*, 1995; Fityus *et al.*, 2004). However, these models do not account for two crucial factors: the impact of the building on the temperature conditions under the raft foundation and the influence of the building on solar energy reaching the soil surrounding the slab (Bester *et al.*, 2016, 2017). Both factors can significantly affect moisture movement under the foundation.

The current accepted methods within building codes for foundation design on expansive clay soils have considerable limitations. They rely on the assumption of overlapping slabs for raft foundation design, which cannot accommodate various loading conditions and soil foundation models (Butut & Lytton, 2002). It is suggested that further research is conducted with residential house slabs and foundations, involving the measurement of moisture, temperature, and displacement sensors over an entire weather cycle to develop models that accurately capture the actual movement of the slab compared to model predictions (Tabassum & Bulut, 2023).

This study had three main objectives. First, to assess existing raft design processes; second, to develop a new cavity raft foundation design; and third, to compare the performance of these designs. The raft foundation design for this study was based on the layout, dimensions, and conditions of the Botshabelo study conducted by Bester *et al.* (2016, 2017). The Botshabelo GSH is located in section K, a part of the Mangaung Metropolitan area, approximately 45 kilometres east of Bloemfontein. Botshabelo witnesses the construction of numerous

government subsidy houses annually. The area is part of the Beaufort Group, which often comprises of dolerite intrusions, forming expansive clay conditions (Rutherford, *et al.*, 2015). Various equipment and tools were utilised in this study to assess the performance of foundation designs at different scales accurately. In particular, a foundation scale model (SM) was used to simulate real-world conditions under controlled experimental settings. Tools employed include continuous logging soil moisture (CLSM) probes, laser displacement sensors, and strain gauges.

The CLSM probe assesses moisture variation beneath different foundation scale model types, providing insights into the model's response to changing soil conditions. Meanwhile, laser displacement sensors are used to measure the vertical movement of the foundations in these scale models, and strain gauges capture any deformation or stress experienced by the model foundations. Figures 1.2 and 1.3 illustrate the layout of the CLSM probes applied in the study.



Figure 1.2: CLSM moisture probes layout of the scaled-down model of a GSH (dimensions are in meters)

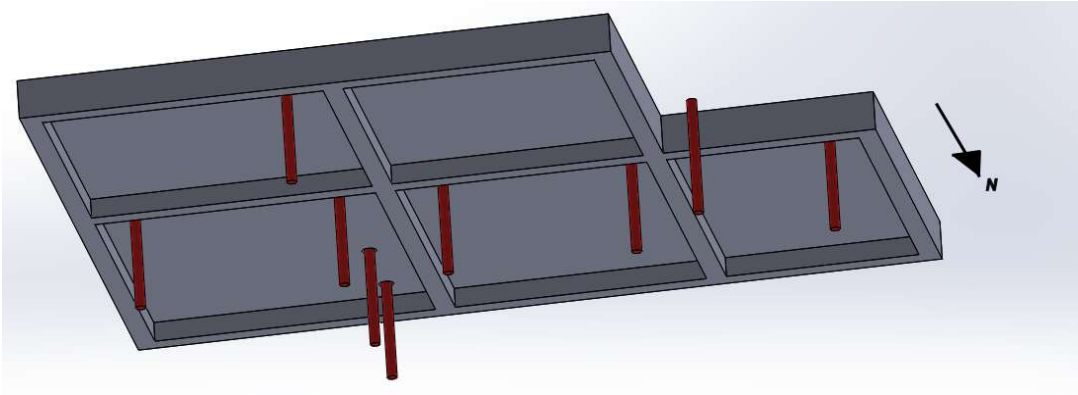


Figure 1.3: 3D layout of CLSM moisture probes beneath a typical GSH foundation

1.2. Problem statement

Expansive clays present the most prevalent soil problem in South Africa, causing millions of Rand in building damage due to heaving (Williams, *et al.*, 1985). The challenge posed by expansive clay is well-acknowledged by Geotechnical Engineers and Engineering Geologists across the country (Williams, *et al.*, 1985). Expansive clay soils pose a significant risk to lightweight structures, especially GSHs. The cyclic variation in soil moisture content is the primary cause of heave in expansive clay soils. Literature describes two prominent heave patterns: centre doming and edge heave. The occurrence of these patterns is influenced by factors including the type of building foundation, environmental conditions, and the time elapsed since construction (Duncan, 1992).

This study challenges the assumptions made by previous researchers, who relied on heave patterns observed in simulated foundations—typically flexible or rigid models—and sheet covers to estimate the extent of moisture movement from the

foundation's edge to its interior (Pidgeon, 1987; Fityus *et al.*, 2004; Miller *et al.*, 1995; Pidgeon and Pellissier, 1987). These prior studies often informed raft foundation designs by suggesting an edge penetration distance based on observed dome shapes, locations, and sizes. However, this study's findings indicate that moisture movement is more complex, influenced significantly by seasonal factors like sunlight exposure and runoff, particularly on the northern side, where the soil moisture content varies more noticeably. This nuanced view raises questions about the reliability of previous estimates for edge penetration distance, as soil beneath most parts of the foundation remains nearly fully expanded, with seasonal shifts primarily affecting the upper layers (Bester, et al., 2017). While this study also utilises simulated foundations, it diverges by employing a more dynamic approach that accounts for variable seasonal effects and environmental influences, such as surface exposure to sunlight. Unlike previous studies that relied on static assumptions, this approach provides a more realistic understanding of moisture movement, especially in seasonal variations, offering insights into foundation behaviour under more naturally fluctuating conditions.

The design and construction of raft foundations on expansive clay soils presents challenges, requiring a deep understanding of the soil's unsaturated soil behaviour, shrink-swell characteristics, moisture movement through the soil, foundation response, and soil-foundation-structure interactions. The direct contact between the raft foundation slab and the soil promotes moisture accumulation, as the moisture cannot escape or evaporate, leading to subsequent heave. As a result, raft foundations have inherent disadvantages, with the foundation slab resting directly on the soil, allowing moisture build-up and resulting in heave. Geoplast, an Italian

company, recognised these limitations and sought to successfully mitigate moisture accumulation through their Modulo system product (Geoplast, 2020). The South African Housing Department however adheres to a policy that promotes local economic development and job creation (LED, 2023). As a result, the department exclusively employs local materials and companies for GSH projects, which effectively excludes Geoplast from these initiatives. Furthermore, the costs of Geoplast products are often prohibitively high for implementation in low-cost housing projects in South Africa.

1.3. Research aim

The aim of the study is to provide an enhanced understanding of moisture movement beneath raft foundations and to develop design recommendations for both raft and cavity raft foundations on expansive clay soils, to mitigate moisture concentration and differential structural movement, ultimately reducing construction costs. The study used scaling laws and generated models based on small-scale modelling (SM) results. It endeavoured to establish a sustainable foundation design suitable for GSH's that enhances the living conditions of disadvantaged individuals in South Africa. The specific design addresses the challenges posed by expansive clay soils, ensuring durable structures on such grounds. Given the potential for expansive clay soils to heave, comprehending moisture movement beneath the foundation is paramount in risk mitigation. The findings from this study offer insights for designers encountering similar challenges in regions with expansive clay soil problems, contributing to the understanding of construction on expansive clay soils. The study focused on advancing sustainable housing solutions with the aim of addressing the associated challenges.

1.4. Objectives of the study

This study encompasses key components for understanding moisture movement beneath foundations and developing design procedures for raft and cavity raft foundations on expansive clay soils. The activities undertaken in this study include:

- I. Exploring current raft foundation designs on active clay soils through a literature review to evaluate the effectiveness and limitations of existing designs, which inform the design process and highlight areas for improvement.
- II. Designing and constructing a climate room to model and simulate raft and cavity raft foundations. This controlled environment replicates soil conditions, including simulated sunlight exposure.
- III. Measuring differential movements, moisture content beneath SM foundations, and strain on SM foundations. This process involved constructing SM models of both raft and cavity raft foundations and taking daily measurements to comprehensively understand moisture movement.
- IV. Recommending new design procedures for raft and cavity raft foundations on expansive clay soils based on insights gained from SM modelling results.
- V. Developing design recommendations to support sustainable housing solutions, particularly for low-income communities in regions rich in expansive clay soils.

1.5. Data collection

A variety of sensors, including moisture probes, laser displacement sensors, strain gauges, and data loggers, were used for data collection. The sensors measured

soil moisture content and foundation deformation which resulted from soil movement. The data collected was recorded using a data logger and analysed with Design for Manufacturing (DFM) Probe utility software.

Moisture probes were positioned at various depths within the soil, while laser sensors and strain gauges were installed on the foundation. All sensors were calibrated before data collection to ensure accurate readings. Daily data collection was conducted to track the differential movement and strain of the models, while moisture probe data was collected monthly. Data was documented in Microsoft Excel and Probe utility software.

1.6. Analysis of raw data

The raw data underwent a comprehensive quality check to ensure accuracy and completeness. This process involved crosschecking and transferring data into Excel sheets for analysis. The data was subsequently analysed and presented through graphical representation, displaying moisture readings over time to reveal seasonal variations at each measurement point. Graphs and tables were employed to depict moisture variation at different depths, as well as the differential movements and strain readings of the SM raft and cavity raft foundation. Once the data had been cleaned and verified, graphical output was utilised for analysis. The information obtained was instrumental in generating graphical models using 3DField software, enabling a detailed visualisation of moisture patterns and differential movement within the foundation. This approach facilitated informed decisions by providing a clear understanding of the soil-structure interaction and identifying potential

solutions to mitigate foundation movement and improve design strategies for expansive clay soils.

1.7. Modelling

The software program 3DField was applied to visualise and analyse geotechnical data, including data on soil moisture and foundation differential movement. This tool was considered adequate due to its ability to generate two or three-dimensional visualizations of the data, allowing for a broad understanding of spatial relationships and patterns within the moisture movement or differential movement behaviour of the foundation types. Its capability to interpolate datasets enables detailed analysis and interpretation, making it particularly relevant for this study, where accurate visualization and data analysis is essential for understanding the complexities of the foundations performance. 3DField has also previously been used in the Botshabelo study (Bester, *et al.*, 2016). 3DField facilitates accessibility to and rapid comprehension of data and information. The software employs a colour scale to represent moisture or movement patterns, with varying colours indicating different moisture content or movement levels.

The information generated by 3DField models can be valuable in the development of design guidelines for raft and cavity raft foundations. By analysing moisture data within the soil and understanding the factors influencing foundation heave, engineers can create more effective foundation designs capable of withstanding the effects of expansive clay soils. The use of software such as 3DField represents a significant opportunity within the field of foundation engineering and has the potential to drive advancements in design practices.

1.8. Results and discussions

Chapters 4 and 5 of the thesis delves into a comprehensive discussion of the results and detailed data modelling. In these chapters, data is scrutinised, and analyses or modelling is conducted. The modelling techniques identify patterns and trends in the data and assess the assumptions and research questions posed in the study. In conjunction with Appendices A to H, chapters 4 and 5 constitute critical components of the research presented in the thesis.

1.9. Inferences

Inferences were drawn regarding expansive clay soils, which present a challenge in Civil Engineering in South Africa due to their propensity to swell and heave, resulting in differential movement within the foundation of buildings. They are characterised by a high clay mineral content that swells and shrinks with changes in moisture levels, inducing alterations in volume that exert substantial stresses on structures built upon them. Based on the analysis conducted in this study, appropriate design procedures were recommended for Geotechnical Engineering in the design and construction of foundations on expansive clay soils. The procedures primarily address controlling moisture variations beneath the foundation, a critical element in the design of raft and cavity raft foundations.

1.10. Research design and methodology of the study

The study followed a systematic and structured research approach, as depicted in Figure 1.4. The figure outlines the methodology employed to investigate the characteristics of SM foundations. The methodology adopted in this study was

organised and executed in a stepwise manner, facilitating an examination of factors influencing moisture variation beneath foundations. The investigative process commenced with the identification of the research problem and the formulation of specific research objectives, followed by data collection, analysis, and modelling.

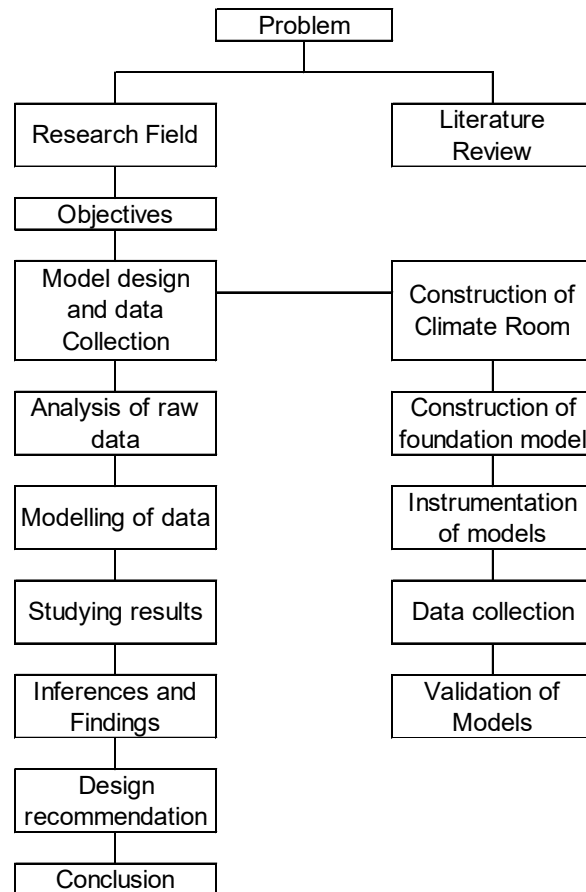


Figure 1.4: Research design diagram

1.11. Limitations

The study's limitations are discussed in the conclusion to provide a well-balanced view of the research findings and to identify areas warranting further investigation. The limitations highlight the need for additional research to validate the study's findings and to provide an enhanced comprehension of soil moisture variation

beneath foundations. The study acknowledges the limitations and considers their potential impact on the results.

1.12. Chapter scheme

The chapter scheme of the research project is structured as follows:

- I. **Chapter 1:** Introduction, problem statement, objectives, aim, scope of the study, research design, inferences and strategies.
- II. **Chapter 2:** Literature review. This chapter explores problematic soils, heaving and expansive clays, raft foundation design, factors influencing water variation beneath foundations, foundation design procedures, scaling laws testing procedures, the orientation of the sun to the earth, and the integration of laser displacement sensors, Arduino, and relay switches.
- III. **Chapter 3:** Laboratory test methods, results, and construction of the climate room. The chapter covers the calibration of moisture probes and the data collection process in this study.
- IV. **Chapter 4:** Data findings, discussions, and design recommendations.
- V. **Chapter 5:** Design recommendations based on the study findings.
- VI. **Chapter 6:** Findings, discussion, recommendations, and conclusion.
- VII. **Chapter 7:** References.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The literature review offers an overview of the challenges associated with expansive clay soils, the types of foundations employed, and the scaling laws and hardware and software applications utilized throughout the study. In reviewing existing literature on this subject, current foundation designs on clay soils were identified, and insights were provided.

2.2. Introduction to soils

Soil is a product of the weathering process in rocks during the geological rock cycle, resulting in a loose and unconsolidated accumulation of mineral particles. Weathering may occur as physical (parent rock broken, shaped and sorted by heat, wind, water, etc) or chemical (leachate from plant materials or groundwater solutes). Coarser soil fractions (gravel, sand, silt) are products of physical weathering, while clay fractions result from chemical reactions. Clay consists of materials with particle sizes under two microns and a family of minerals with similar chemical compositions and crystal structural characteristics, such as phyllosilicates. Common clays include kaolinite, montmorillonite-smectite, illite, chlorite, or combinations of these minerals (Velde, 1995). Clay minerals are significantly influenced by their affinity for water, with certain types of swelling and contracting based on hydration and dehydration. Hydration and dehydration can cause a 100% change in the thickness of a single clay particle, and variations in moisture impact the soil's suction stress state variable (Vanapalli & Fredlund, 2000). Unsaturated expansive soils exhibit a suction range from zero kPa (saturated) to

10,000 kPa (dry), affecting their volume change, flow, and shear strength behaviour (Diop, *et al.*, 2011).

The physical properties and behaviour of soil are examined in soil mechanics, which is then applied to address practical issues within Geotechnical Engineering (Knappett & Craig, 2012). Soil serves as an essential structural support for building foundations and construction materials in numerous construction projects. As a result, it is crucial to investigate soil properties and characteristics. Soil mechanics, the science of studying soils for their physical properties and behaviour under various conditions, plays a critical role in real-life problem-solving (Das & Sobhan, 2018).

2.2.1. Expansive clay soils in South Africa

Expansive clay soils are responsible for more damage to buildings than all other natural hazards combined (Nelson & Miller, 1997). Expansive clay soils are the most prevalent problematic soils in Southern Africa (Netterburg, 2019). Building foundations in South Africa are under strain due to the widespread presence of expansive clay soils throughout the country (Pellissier & Williams, 1991). The diverse geology, climatic conditions, and land use in South Africa have given rise to multiple challenges when constructing foundations on clay soils (Diop, *et al.*, 2011). Expansive clay soils exhibit a high shrink-swell potential due to the presence of expanding clay minerals. During wet seasons, the increased moisture content in clay soils causes expansion, while subsequent dry seasons induce soil shrinkage, resulting in foundation movements and cracking. The movement of clay soils can lead to structural damage to buildings (Douglas & Noy, 2010). Furthermore, the

variability of soils affects their behaviour, so making accurate predictions and mitigating potential damages is crucial for engineers (Badenhorst, 2017).

The formation of problematic soils in South Africa is heavily influenced by climate. South Africa faces unique challenges with various climates, including arid and semi-arid regions and wetlands. Arid and semi-arid regions are particularly susceptible to developing problematic soils due to soil dryness. This dryness causes the soil to shrink, leading to foundation settlement and the creation of collapsible and expansive soils (Byrne & Berry, 2008).

The soils present a significant challenge for engineers designing foundations for lightweight structures. Moisture fluctuations can cause them to expand and contract, resulting in substantial structural strain and cracking. Unfortunately, predicting the extent of the soil movement is complex, and even minor volume changes can result in severe damage (Rogers, *et al.*, 1985). Generally, crack repairs are unsuccessful due to the repetitive nature of stress variations. The primary issue with expansive clays is that the magnitude of soil movement is often unpredictable. Structural damage to buildings and houses can occur with as little as a 2% to 3% expansion and contraction of soil volume (Diop, *et al.*, 2011). Expansive soils are frequently found in the Gauteng, Free State, and Mpumalanga provinces of South Africa (Aneke, *et al.*, 2019).

2.2.2. Geology and mineralogy of problematic clay soils in South Africa

The distinctive geological properties of clay soils raise significant concerns for construction activities in South Africa. The soil's characteristics and behaviours give

rise to various engineering and environmental management challenges. Expansive clay soils affect many regions in South Africa, such as the Little Karoo, the extreme Northern Cape, the northern part of the Limpopo Province, and the eastern areas of the Mpumalanga Province. The regions most affected by expansive soils include the Free State gold fields, North West Province, Pretoria, Witwatersrand and Vereeniging (Diop, *et al.*, 2011). According to the National Home Builders Registration Council of South Africa (NHBC), unique design requirements are necessary if expansive soils are present (NHBC, 1999). South Africa's geological composition plays a crucial role in forming problematic soils, with its diverse range of sedimentary and igneous rocks. Sedimentary rocks with a high clay content are prone to collapsible soils, while igneous rocks with a high mineral content are susceptible to expansive soils (Diop, *et al.*, 2011). Figure 2.1 illustrates the regional distribution of swelling clay occurrences in South Africa.

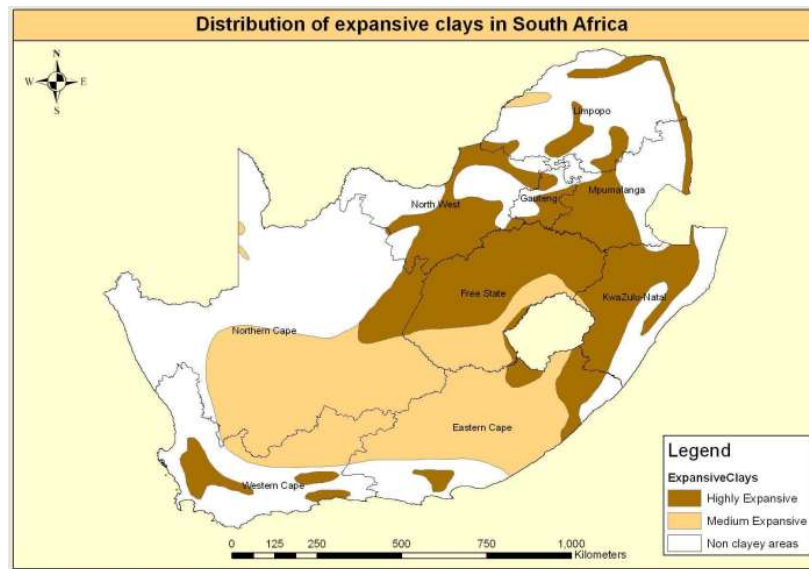


Figure 2.1: Regional distribution map of swelling clay occurrences in South Africa (Diop, *et al.*, 2011).

Problematic clay soils in South Africa primarily originate from the weathering of various rock types, including granite, basalt, dolerite, and shale. These rocks contain feldspar, quartz, mica, and clay minerals, which undergo physical and chemical weathering processes, resulting in clay minerals such as smectite, illite, and kaolinite (Diop, *et al.*, 2011). The clay minerals found in these soils are responsible for their distinct characteristics, including high plasticity, low permeability, and high sensitivity to changes in moisture content (Velde & Barrè, 2010). Clay minerals are complex aluminium silicates, typically less than two microns in size, composed of two fundamental units: silica tetrahedra and aluminium octahedra. In these clays, silica tetrahedra combine to form thin tetrahedral sheets, while aluminium octahedra join to form octahedral sheets (Diop, *et al.*, 2011). Clay crystals are made up of aluminium and silicon sheets held together by intra-molecular forces, as shown in Figure 2.2. Blue and purple circles represent the silica sheet, while green and red indicate the alumina sheet. Kaolin (Figure 2.2.a) has a 1:1 layering with alternating silica and alumina layers. Montmorillonite (Figure 2.2.b) has a 2:1 layering with alumina sandwiched between silica layers. A key feature for swelling is the space between each 2:1 unit, where exchangeable cations allow weakly bonded water molecules to attach to the silica sheets. This bonding, although weak, is much stronger than typical geotechnical cohesion. The addition (swelling) and loss (shrinkage) of these water molecules control clay's volumetric behaviour, while additional, more freely moving water molecules are dispersed throughout the soil fabric (Grim, 1962).

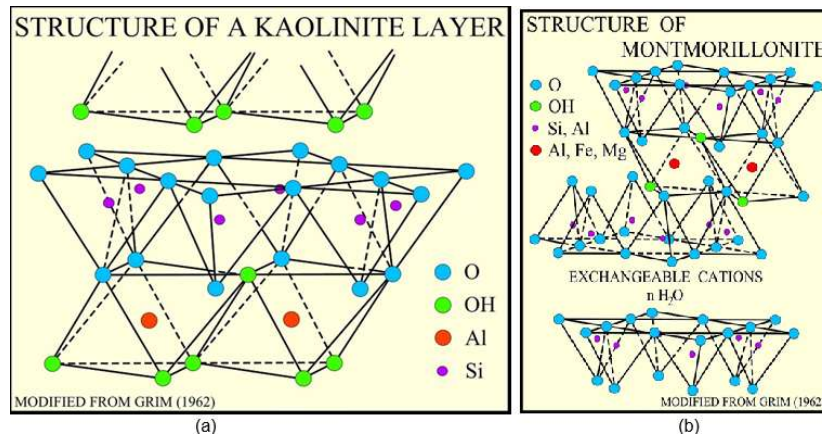


Figure 2.2: Schematic diagram of non-swelling clay (a) and (b) swelling clay (Grim, 1962).

Smectites, a group of clay minerals, possess a unique structure with one octahedral sheet nestled between two tetrahedral sheets, which creates a nearly neutral charge distribution within the clay. This allows clay crystals to attract and hold cations surrounded by water molecules within their crystalline layers, a property known as adsorption (Diop, *et al.*, 2011). Among the smectites, montmorillonite is particularly notable for its ability to absorb significant amounts of water molecules between its crystalline sheets, resulting in a high swelling potential that can increase the bulk volume of soil and reduce its strength. During dry periods, as moisture evaporates, the water trapped between clay sheets is released, causing the soil volume to shrink and often forming surface voids or cracks, which are visible indicators of expansive clay soils (Das, 2007; Diop *et al.*, 2011).

In South Africa, expansive clay soils, such as montmorillonite, pose challenges due to mineralogical, textural, and organic factors, which give rise to distinct physical and chemical properties, including high plasticity, swelling potential, and low permeability. These properties make expansive clay soils problematic for construction, leading to issues such as cracking, shrinkage, swelling, differential

settlement, and structural damage. The high plasticity of such soils, reflected in their high cation exchange capacity, is associated with an increased risk of heave, affecting foundation stability and making structures more susceptible to failure (Byrne & Berry, 2008; Stott, 2017; Williams, 1991).

The most common clay minerals found in soils and sediments include kaolinite, montmorillonite, and illite, each with unique characteristics that impact their behaviour and applications. Kaolinite, a 1:1 clay mineral with a layered structure of silicate tetrahedral and aluminium octahedral sheets, is often found in soils formed from the weathering of feldspar-rich rocks and is characterized by low plasticity, high thermal stability, and low cation exchange capacity (Das, 2007; Hazen et al., 2013; Nguyen et al., 2018). Montmorillonite, a 2:1 clay mineral with two tetrahedral silicate sheets and one aluminium octahedral sheet, typically results from volcanic ash weathering and is known for its high cation exchange capacity, swelling potential, and plasticity (Das, 2007). Illite, commonly found in soils derived from mica-rich rocks, exhibits high plasticity, low cation exchange capacity, and high potassium content, adding another dimension to the engineering considerations for soils containing these minerals (Yotsuji et al., 2021; Hazen et al., 2013).

2.3. Water movement in soils

In soils, water movement is a complex process influenced by various factors, including soil structure, texture, and moisture content (Hillel, 2003). The moisture in soil plays a significant role in governing water movement (Pons, *et al.*, 2000).

2.3.1. Saturated soils

Water moves primarily through inter-particle pores in saturated soils, driven by a high to low potential hydraulic gradient. This movement is influenced by the soil's hydraulic conductivity, which depends on factors like soil texture, structure, and porosity. Laboratory methods such as constant head and falling head techniques are typically used to determine saturated hydraulic conductivity (Hillel, 1982). Understanding water flow in saturated soils is essential in foundation engineering, where controlling seepage and ensuring dry conditions in pits, trenches, and dewatering systems is vital. Geotechnical engineers focus on water flow resistance, measured as hydraulic conductivity or permeability coefficient (Whitlow, 2001).

Saturated soils, fully filled with water and lacking air-filled pore spaces, exhibit key physical properties: porosity, bulk density, and hydraulic conductivity. Porosity affects water-holding capacity, while bulk density, influenced by porosity and composition, measures soil mass per unit volume. Hydraulic conductivity quantifies the rate of water movement through soil, impacted by soil structure and texture (Brady & Weil, 2016). Understanding these properties is critical for managing saturated soils in geotechnical applications (Knappett & Craig, 2012).

2.3.2. Unsaturated soils

In arid and semi-arid regions, soil near the ground surface is commonly unsaturated. Engineering processes such as compacting, excavating, and remoulding in constructing earth dams, highways and embankments often produce unsaturated soils, which pose challenges within traditional saturated soil mechanics. An unsaturated soil contains three phases: solids, water, and air, with a negative pore-

water pressure relative to the pore-air pressure (Fredlund and Rahardjo, 1993). Water movement in unsaturated soils occurs in both liquid and vapour phases, with lower hydraulic conductivity than in saturated soils due to air-filled pores that restrict flow. This movement is best understood through the soil water retention curve, which depicts the relationship between soil water content and potential energy, influenced by soil texture, structure, and pore size (Di Maio, *et al.*, 2015).

Moisture fluctuations in unsaturated soils cause volume changes, leading to shrinkage or swelling that may damage infrastructure, such as cracks in roads and buildings. This behaviour, controlled by soil suction, is crucial for predicting unsaturated soil performance in foundation design and often requires drainage solutions to manage moisture (Fredlund & Rahardjo, 1993). Construction in arid climates introduces water through impermeable surfaces like foundations and roadways, which limit evaporation. Additional water may come from broken pipes or leaks, with moisture distribution affected by infiltration rate, site conditions, and soil properties (Lu & Likos, 2004).

Expansive soils with low hydraulic conductivity and high suction can reach near full saturation under certain conditions, while non-expansive soils expand at lower saturation levels. Both soil types experience fluctuating saturation due to rainfall, evaporation, and initial moisture, so full saturation is not consistently achieved in expansive soils (Jones & Jefferson, 2012). In clay soils with low permeability, the wetting front may extend gradually over greater distances compared to sandy soils (Nelson & Miller, 1997). Figure 2.3 illustrates the progression of wetting in unsaturated soil, moving downward over time due to infiltration. This analysis is

intricate since water content and soil suction change across the wetting front, altering from higher water content to that of the soil below. There is no distinct point indicating the precise depth of wetting.

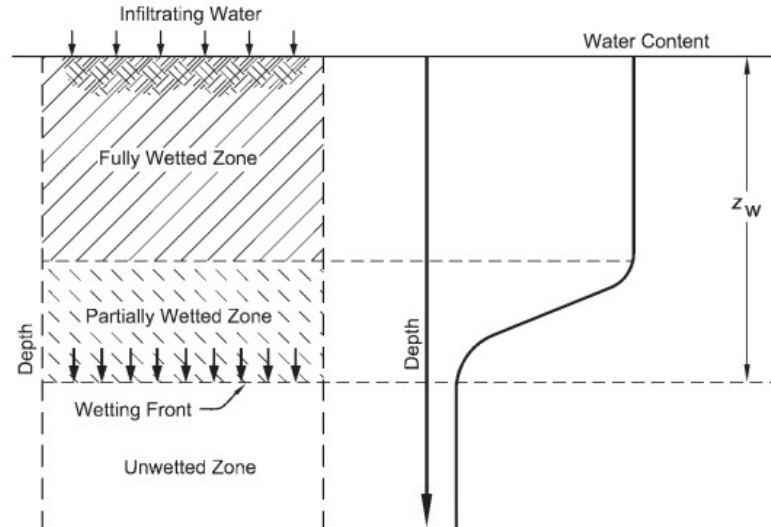


Figure 2.3: Progression of wetting in unsaturated soil, with the wetting depth represented as the depth to the bottom of the transition zone (Nelson & Miller, 1997)

The properties of unsaturated soils can be assessed using various laboratory and field techniques. These include methods like the pressure plate or filter paper method for measuring soil suction, and the pressure membrane apparatus or chilled mirror dew-point method for determining the soil-water characteristic curve. Additionally, the volume change behaviour of unsaturated soils can be studied through methods like an oedometer or triaxial tests (Nelson & Miller, 1997). Effective management of these systems requires a comprehensive understanding of their properties and behaviour (Nelson, *et al.*, 2015).

2.3.3. Active zone

The active zone is the depth at which soil moisture is influenced by climatic and environmental factors over time. As depicted in Figure 2.4, the active zone is situated near the soil surface, and its depth may vary depending on external factors such as surface drainage or irrigation. Problems related to expansive soils often occur when the water content in the active zone increases, causing the soil to swell and potentially damaging nearby infrastructure, such as building cracks (Lu & Likos, 2004). Understanding the progression of wetting in unsaturated soils is crucial for effective behaviour management. This process begins with wetting at the soil surface and progresses downward until reaching the bottom of the transition zone, where the soil becomes fully saturated. The wetting depth is defined as the depth to the bottom of the transition zone (Nelson & Miller, 1997). Researchers employ various laboratory and field techniques and equipment, such as soil moisture content sensors and tensiometers, to investigate wetting movement in unsaturated soils. These techniques provide valuable insights into unsaturated soil behaviour and can aid Geotechnical Engineers and Geologists in developing strategies to mitigate damage caused by expansive soils (Nelson, *et al.*, 2015).

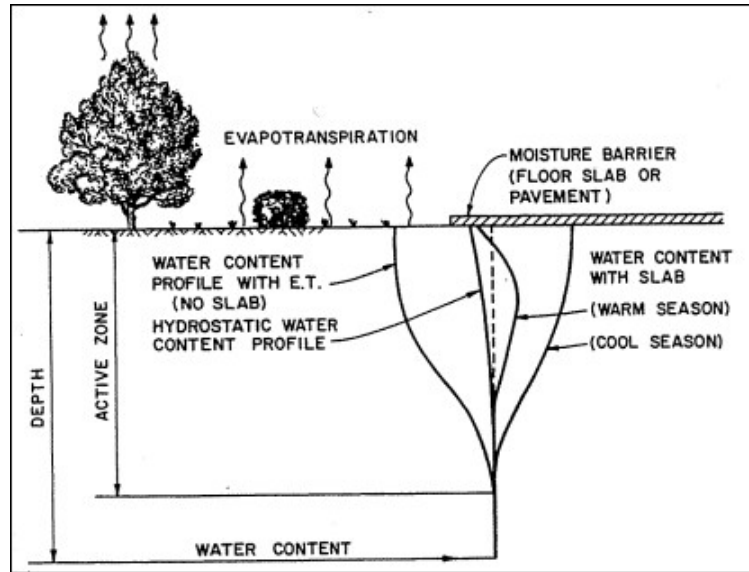


Figure 2.4: Water content curves in an active zone under structure and bare conditions (Nelson & Miller, 1997)

2.3.4. Soil suction

Soil suction is a crucial parameter for understanding the behaviour of unsaturated soils, including their hydraulic conductivity, strength, and deformation. Soil suction, also referred to as pore-water tension, is the force that retains water in the matrix of unsaturated soils by creating negative pressure in the pore water. Among the various types of soils, clays exhibit unique soil suction behaviour due to their high surface area and fine-grained nature (Wang Wai Ng & Menzies, 2007). Electrostatic forces play a significant role in clay-related behaviours, such as cation exchange capacity (CEC) and the swelling and shrinking of clays in response to changes in moisture content (Nelson, *et al.*, 2015).

The soil suction of clays is influenced by multiple factors, including clay mineralogy, soil texture, structure, and water content (Fredlund & Rahardjo, 1993). Clay mineralogy significantly impacts the soil suction of clays, as different clay minerals

exhibit distinct suction behaviours. For instance, smectites have a higher capacity to retain water than other clay minerals, resulting in more expansive behaviour. Soil structure and texture also play a substantial role in determining the soil suction of clays because pore size distribution and connectivity affect water availability in the soil matrix (Wang Wai Ng & Menzies, 2007).

Total suction in soil results from the combination of matric suction and osmotic suction, both of which vary with the soils water content. Matric suction arises from factors like pore size distribution, texture, and surface adsorptive forces, representing the force responsible for equalising moisture content between adjacent soil particles. It characterises the tension in the water and can be understood as the height to which water can be drawn into unsaturated soil, often referred to as capillary rise. This parameter is typically determined by allowing water to rise in a capillary tube inserted into dry soil (Nelson, *et al.*, 2015). Figure 2.5 illustrates the relationship between soil water and matric suction at three different stages of water content.

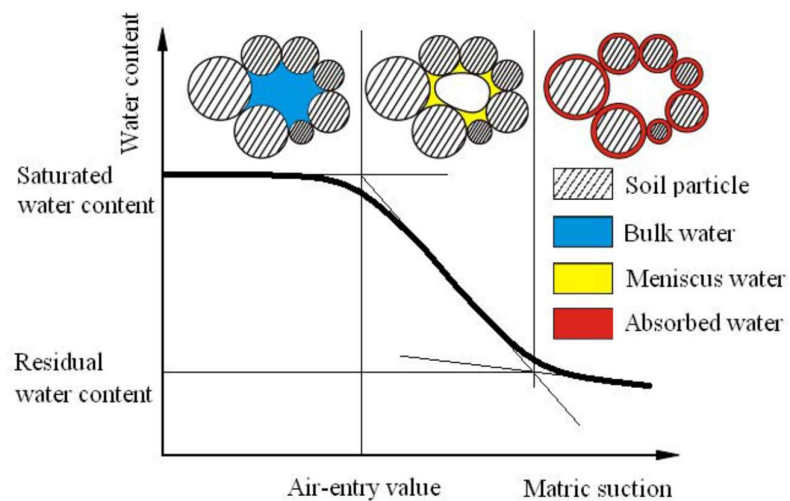


Figure 2.5: Soil water and matric suction at three different stages of water content (Nelson, *et al.*, 2015)

Osmotic suction, on the other hand, is influenced by variations in salt concentration within the soil water. Figure 2.6 provides insight into how osmotic suction operates in soil, depicting two ideal clay particles positioned in close proximity. Electrical charges on the clay particles trap salt cations within the clay micelle, resulting in a higher salt concentration in the water surrounding the particles compared to the external environment. This electrical field around the clay particle can be likened to creating a “pseudo-semipermeable” membrane. The relatively high salt concentration between the particles exerts pressure on the water molecules, resulting in the osmotic suction of the soil (Nelson, *et al.*, 2015).

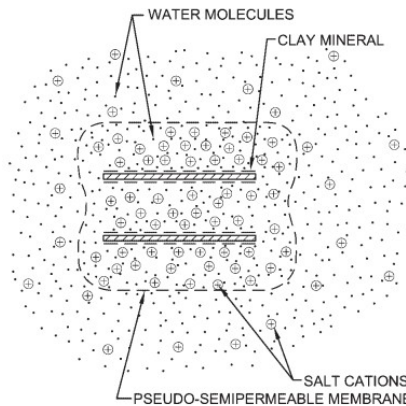


Figure 2.6: Pseudo-semipermeable membrane effect causing osmotic suction in clay (Nelson, *et al.*, 2015).

Soil suction in clay influences their behaviour, impacting on their hydraulic conductivity, strength, and deformation (Wang Wai Ng & Menzies, 2007). As soil suction increases, the soil becomes stiffer and less compressible, leading to enhanced strength and reduced deformation. Given the fine-grained nature and high surface area of clay, it is particularly prone to soil suction behaviour, emphasising its importance in the study of its behaviour (Fredlund & Rahardjo, 1993).

2.3.5. Concepts of suction

Soil suction comprises matric and osmotic components (Fredlund and Rahardjo, 1993). Total suction, s_t , is the sum of matric suction, s , and osmotic suction, π :

$$s_t = s + \pi \dots \dots \dots [2.1]$$

The matric component relates to the difference between pore-air pressure (u_a) and pore-water pressure (u_w) in soil. Suction forms due to menisci between particles, producing capillary effects. In expansive soils, suction arises from hydration and capillary (menisci) components (Mitchell, 1993). Thus, expansive soils show matric suction due to hydration and capillary forces. The osmotic suction component arises from chemical imbalances (dissolved solutes) in free water. All these components play a role in swelling clays.

2.3.6. State of stress

Two approaches describe unsaturated soil behaviour — volume change and shear strength: the effective stress approach (Bishop, 1959) and the two independent state variables approach (Fredlund and Morgenstern, 1977).

- I. Effective stress approach: Terzaghi (1936) proposed the concept of effective stress in soil. Effective stress (σ') represents the average stress carried by the soil skeleton. It comprises the difference between two parameters, total stress (σ) and pore water pressure (u). Bishop, (1959) proposed modified forms of effective.

$$\sigma' = (\sigma - u_a) + X (U_a - U_w) \dots \dots \dots [2.2]$$

Where:

Σ = Effective stress

X = A soil parameter related to the degree of saturation ranging from 0 to 1.

- II. Two Independent Stress Variables Approach: Researchers faced challenges in applying the effective stress equation to unsaturated soil behaviour (Bishop and Donald, 1961; Jennings and Burland, 1962; Burland, 1965) and developed a more adaptable framework with two independent stress variables. Fredlund and Morgenstern (1977) introduced this approach to describe unsaturated conditions using $(\sigma - u_a)$ at the macroscopic scale and $(u_a - u_w)$ at the pore scale, avoiding modifications to the traditional effective stress equation and assigning specific material properties to each variable. The total equilibrium of an unsaturated soil element corresponds to the equilibrium of each phase, with vertical equilibrium calculated as the difference between the total equilibrium and the sum of equilibrium equations for water, air, and contractile skin. Using the air phase as a reference yields the equilibrium equation for soil structure in the y-direction.

$$\left\{ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} - n_a \frac{\partial u_a}{\partial y} - n_w \frac{\partial u_w}{\partial y} + n_c f^* \frac{\partial (u_a - u_w)}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho g - n_a \rho_a g - n_w \rho_w g - n_c \rho_c g - F_{sy}^w - F_{sy}^a + n_c (u_a - u_w) \frac{\partial f^*}{\partial y} \right\} dx dy dz = 0 \quad \dots\dots\dots[2.3]$$

Where:

n_a = Porosity with respect to the air phase.

n_c = Porosity with respect to the contractile skin.

f^* = An interaction function between the contractile skin and the soil structure (Fredlund and Rahardjo 1993)

F_{sy}^a = an interaction body force between the solids and the air phase in the y-direction.

2.3.7. Volume change behaviour of unsaturated fine-grained soils

The one-dimensional consolidation theory estimates volume change based on applied stress, excess pore pressure, and time, but it is less significant for unsaturated soils (Fredlund and Rahardjo, 1993). Volume change issues in unsaturated soils mainly involve swelling and collapsing soils. Various models address volume change-stress-suction relationships (Alonso et al., 1990; Gens and Alonso, 1992; Kohgo et al., 1993; Cui and Delage, 1996), while other studies focus on soil collapsibility (Jennings and Knight, 1957). Volume change in unsaturated soils is typically explained through the effective stress approach (Bishop, 1959) or the two independent stress variables approach (Fredlund and Morgenstern, 1977).

2.3.8. Volume change behaviour: effective stress approach

Researchers have attempted to describe unsaturated soil behaviour with the effective stress approach, relating the effective stress parameter χ to the degree of saturation S_r (Bishop, 1959; Bishop and Donald, 1961; Jennings and Burland, 1962; Burland, 1965). Later, χ was quantified using capillary models. Gens (1996) categorized behaviour into three classes: class 1 models where $\chi=0$ (dry state), class 2 where χ depends on matric suction (near saturation), and class 3 where χ varies with S_r and suction s (unsaturated). Class 3 models are used where χ is a function of S_r and s (Aitchison, 1960; Karube and Kawai, 2001). Bishop (1959) proposed $\chi=S_r$, an assumption later supported by thermodynamic considerations (Houlsby, 1997) but not experimentally confirmed. Jennings and Burland (1962) found that effective stress did not predict collapse upon wetting, as flooding caused samples to collapse rather than expand. They used Bishop's equation to define χ as

the ratio of net normal stress to effective stress on the normal consolidation line (NCL) at the same void ratio. Croney and Coleman (1961) argued that χ lacks a unique relationship with S_r , as it is strongly influenced by soil structure, making correlation with S_r uncertain. Burland (1965) also suggested that $(\chi - u_a)$ and $(u_a - u_w)$ should not be combined into a single equation, a viewpoint shared by other researchers.

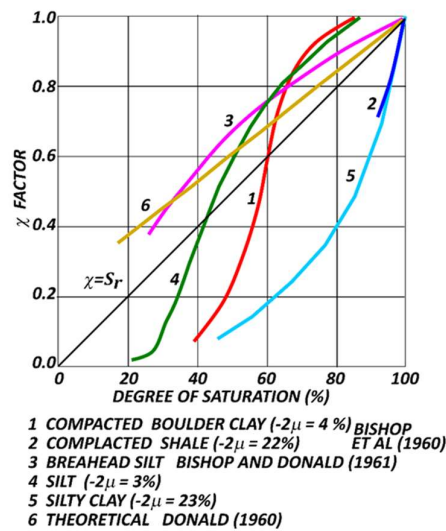


Figure 2.7: Curves of effective stress parameter or “factor” χ against the degree of saturation S_r for various soils (Jennings and Burland, 1962) redrawn for clarity.

2.3.9. Volume change behaviour: two independent stress variables approach

The deformation of unsaturated soils is influenced by state variables related to soil structure and the bulk water phase (Biot, 1941; Bishop and Donald, 1961; Croney and Coleman, 1961). Changes in void ratio or porosity indicate soil matrix deformation, while water content changes affect the water phase state (Fredlund and Rahardjo, 1993). Fredlund and Morgenstern (1977) defined unsaturated soil stress using two independent variables: net stress $(\sigma - u_a)$ at the macroscopic scale

and matric suction ($u_a - u_w$) at the pore scale, asserting that these stress variables independently govern soil behaviour. However, stress states within each phase may interact, ensuring compatibility in multiphase systems like unsaturated soils. Alonso et al. (1990) introduced the Barcelona Basic Model (BBM), a foundational framework for the stress-strain behaviour of unsaturated soils and expansive clays (Gens and Alonso, 1992). The BBM applies two independent stress variables, $(\sigma - u_a)$ and $(u_a - u_w)$, to hardening plasticity, showing that volumetric behaviour depends on initial and final stress, suction changes, and the loading-unloading path.

2.3.10. Numerical modelling of swell behaviour in clay

In expansive soils, swelling occurs with increased saturation during wetting. Some water attaches to clay particles at macro (menisci) and micro (osmotic, double-layer sorption) levels, forming the basis for many advanced models. Finite Element (FE) simulations use porous continuum mechanics with hydro-mechanical stress-strain coupling (Gens and Alonso, 1992) and soil water retention (Dieudonne et al., 2016), though they don't account for soil volume fraction changes. FE analysis models soil as a continuous medium in the Theory of Porous Media (TPM) (de Boer, 1998; Schrefler, 1990), with each point containing solid, wetting fluid, and non-wetting fluid phases. The classical TPM overlooks the transition from free to bound water in clay. Fuentes Lacouture (2014) and Macháček (2020) expanded TPM to include residual water and occluded air. Residual water has been vital to soil retention models, and it is reducible only by oven drying, not suction. Unlike free water, which flows by Darcy's law, residual water stays bound to the solid phase. While TPM mass transfer extensions exist in other fields, such as for swelling gels (Sauerwein and Steeb, 2018), they remain uncommon in soil mechanics.

2.3.11. Extended theory of porous media

Nitsch et al. (2023) expanded the TPM by adding residual water, a distinct swelling water phase, and a mass transfer process between free and bound pore water during swelling. Combined with a new mechanical model for expansive soils (Grandas Tavera et al., 2022), their framework predicts effective pore space reduction and the hydro-mechanical response of expansive soils through consistent mass balancing. In cases without swelling and residual water, this extended TPM simplifies back to the classical three-phase model. A third water phase was introduced, swelling water (w_s), to the porous medium, in addition to the solid skeleton (s), free pore water (w_f), pore air (a_f), and residual water (w_r). Swelling water, immobile and bound to clay particles by physico-chemical forces, drives the swelling behaviour. Figure 2.8 shows the expansive soil's five-phase structure and volume fractions (Nitsch et al., 2023).

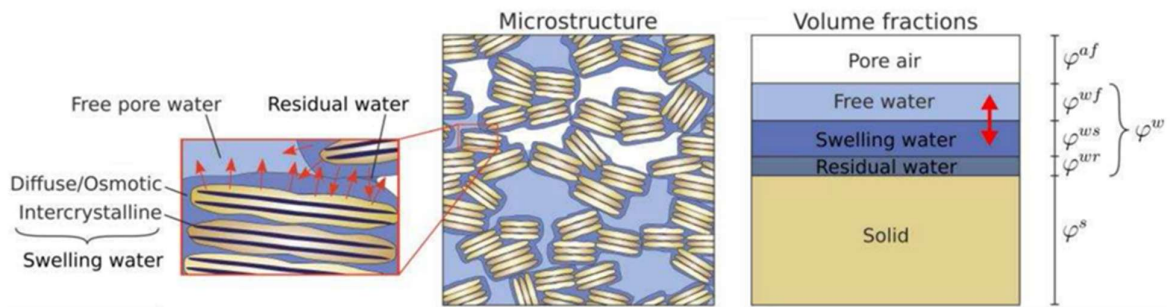


Figure 2.8: Schematic representation of the expansive soil as a five-phase porous medium: microstructure and volume fractions in the representative volume element (RVE) (Nitsch et al, 2023).

2.5. Construction of GSH in South Africa

In 1994, the African National Congress implemented the Reconstruction and Development programme, which aimed to provide low-cost housing to South Africans, including single-storey buildings suitable for single families (Nokulunga, *et al.*, 2018). According to a 2018 survey conducted by Statistics SA, it was found that 13.6% of households in South Africa resided in residences provided through state-subsidised housing initiatives (Statistics, 2018). Since 1994, nearly 4 million households in South Africa have received RDP houses from the government. Of these, the largest share is in Gauteng Province, which accounts for 31%, followed by Western Cape with 15%, and KwaZulu-Natal with 14%. These three provinces comprise 60% of the RDP houses distributed across the country (Mashwama, *et al.*, 2018). Table 2.1 depicts the number of GSH constructed by provinces in South Africa.

Table 2.1: GSH by province (Mashwama, *et al.*, 2018)

Province	GSH
Western Cape	571 997
Eastern Cape	386 802
Northern Cape	105 541
Free State	289 414
KwaZulu-Natal	559 302
North West	261 693
Gauteng	1 227 729
Mpumalanga	241 801
Limpopo	260 976

Over the years, the design of low-cost housing has evolved. Early housing developments prioritised quantity and cost, resulting in square-shaped structures. In recent times, the South African Government has actively encouraged developers to adopt more innovative housing designs to enhance quality and sustainability. A standard GSH unit typically covers an area of 30-45 square meters and includes an open kitchen, a seating area, bedrooms, and a bathroom (Greyling, 2010).

It was discovered that the construction layouts of GSH in South Africa lacks a standardised set of house plans. Through interviews with professionals involved in GSH housing projects (Vosloo, 2023), it was found that the development process can vary with regards to the layouts and floor area of GSH. These variations can be influenced by factors such as the project's budget, housing unit size, architectural drawings, and the scope outlined by the National Department of Human Settlement. Figures 2.9 to 2.11 depict commonly found GSH units.



Figure 2.9: Photo of an L-shaped GSH in Botshabelo, Free State



Figure 2.10: Photo of a square-shaped GSH in Thaba Nchu, Free State



Figure 2.11: Photo of an H-shaped duplex GSH in Ashbury, Bloemfontein

2.6. Review of raft foundation methods and design for active clay conditions

Shallow foundations play a vital role in the construction industry, supporting various structures (Holtz, *et al.*, 2013). They transmit the structure's load to the near-surface soil, typically utilised when the upper soil layers offer sufficient bearing capacity to support the applied loads (Knappett & Craig, 2012). Various shallow foundations exist, including spread footings, slab-on-grade, and raft foundations. Among these, spread footings, which involve concrete pads under load-bearing walls or columns, are the most used (Das & Sivakugan, 2019).

Foundation design must meet two core performance criteria: the ultimate limit state and the service limit state. The ultimate limit state is reached when the foundation can no longer support the structure, leading to potential failure. The service limit state occurs when the foundation's performance declines, typically due to severe cracking or settlement, causing the structure to lose functionality. These criteria ensure the foundation supports loads without excessive deformation, preventing structural damage (ultimate limit state) or functional impairment (service limit state) (Das, 2017).

For soil layers near the surface with sufficient load-bearing capacity or resistance, pad, strip footings, or raft foundations are recommended (Knappett & Craig, 2012). However, when dealing with expansive, heaving clay soils in South Africa, it is advisable to use raft foundations, as pad and strip footings may not be suitable (Diop, *et al.*, 2011). The NHBRC recommends using stiffened or cellular rafts, piled construction, split construction, or soil raft foundations on problematic and highly expansive clay soils (NHBRC, 1999). For single-story residential structures founded on expansive clay soils in South Africa, the NHBRC provides comprehensive recommendations for foundation design, construction procedures, and precautionary measures (NHBRC, 1999). Table 2.2 depicts NHBRC recommendations.

Table 2.2: Foundation design, building procedures, and precautionary measures for single-story residential structures founded on expansive soil horizons (NHBRC, 1999)

SITE CLASS	ESTIMATED TOTAL HEAVE (mm)	CONSTRUCTION TYPE	FOUNDATION DESIGN AND BUILDING PROCEDURES (Expected damage limited to Category 1)
H	<7,5	Normal	- Normal construction (strip footing or slab-on-ground foundation). - Recommended: Site drainage and plumbing/service precautions.
H1	7,5-15	Modified normal Soil raft	- Lightly reinforced strip footings. - Articulation joints at all internal/external doors and openings. - Light reinforcement in masonry. - Recommended: Site drainage and plumbing/service precautions.

			- Remove all or necessary parts of the expansive horizon to 1,0 m beyond the perimeter of the building and replace with inert backfill compacted to 03% MOD AACIITO density at -1% to +25 of optimum moisture content. - Normal construction with lightly reinforced strip footings and light reinforcement in masonry if residual movements are <7,5 mm or construction type appropriate to residual movements. - Recommended: Site drainage and plumbing/service precautions.
H2	15-30	Stiffened or cellular raft Piled construction Spit construction Soil raft	- Stiffened or cellular raft or articulated lightly reinforced masonry. - Recommended: Site drainage and plumbing/service precautions. - Piled foundations with suspended floor slabs with or without ground beams. - Recommended: Site drainage and plumbing/service precautions. - Combination of reinforced masonry and full movement joints. - Suspended floors or fabric-reinforced ground slabs acting independently from the building. - Recommended: Site drainage and plumbing/service precautions. - As for H1
H3	>30	Stiffened or cellular raft Piled construction Soil raft	- As for H2 - As for H2 - As for H1

2.6.1. Raft foundations designs for active clay soils

Raft foundations, similar to spread footings but covering the entire area under a building, are a common choice in construction when the underlying soil exhibits non-uniform and varying bearing capacities (Das & Sivakugan, 2019). These foundations, typically considered shallow, prove particularly valuable when faced with soft or unstable soils, such as active clay soils. Active clay soils, notorious for their high compressibility and susceptibility to substantial volume fluctuations due to environmental factors, can give rise to issues like differential movement and foundation instability (Williams & Pellissier, 1991). This section

investigates heave and moisture flow beneath shallow foundations. (Gupta, 1997) recommends using a raft foundation resting directly on the soil in the following:

- I. When the structural loads are heavy, or the permissible soil pressures are unacceptably low, necessitating a footing that covers more than the floor area of the structure.
- II. Where soil behaviour exhibits unpredictability, making it challenging to define and assess potential settlement or movement.
- III. When the structures and equipment to be supported are highly sensitive to movements, such as settlement or heave.
- IV. Where the structural design naturally lends itself to a raft foundation.
- V. Where the location exhibits poor bearing capacity, soil removal must counterbalance the superstructure's weight (compensated foundation).
- VI. When buildings apply significant bending moments to the foundation, it could lead to differential rotation and structural distress.

A raft foundation provides a stable and uniformly distributed support system for structures under specific circumstances and should be considered a viable option (Gupta, 1997). These foundations have gained popularity in GSH construction in regions affected by expansive soils, such as much of the Free State and Northern Cape (Bester, *et al.*, 2016). A typical raft foundation effectively limits the differential movements in the underlying soils to a level manageable by the superstructure (Day, 1991). The NHBRC advises that when the projected total heave reaches or exceeds 15 mm, opting for a stiffened or cellular raft foundation is advisable, as indicated in Table 2.1 (NHBRC, 1999).

2.6.2. Edge heave and centre doming on expansive clay soils

Raft foundations are continuous slabs resting directly on soil or bedding material, often supported by beams (Byrne & Berry, 2008). On expansive clay soils, heaving exerts uniform soil pressure on the foundation, which engineers calculate using the product of total load, load factors, and the reciprocal of the raft foundation area (Day, 1991). Expansive soils create two primary heave patterns: edge heave and centre doming.

Edge heave typically appears soon after construction, often after rainfall increases moisture content along the foundation's outer edges, creating noticeable moisture disparity (Duncan, 1992). Centre doming, a more gradual process, occurs as moisture migrates upward and accumulates centrally, forming a dome shape under the foundation and reducing moisture along the outer edges. This movement causes exterior wall cracks and outward tilting of the structure's walls, with prominent horizontal, vertical, and diagonal fractures, especially near the top (Duncan, 1992).

These movements, described by Tabassum and Bulut as edge and centre lift, are influenced by moisture cycles in expansive soils. In worst-case scenarios, centre lift (or edge drop) happens when moisture decreases around the slab perimeter, causing the soil to shrink relative to the interior soil. Conversely, edge lift occurs when the soil beneath the perimeter becomes wetter than under the slab's interior, leading to expansion. Figure 2.12 illustrates both centre and edge lift patterns of shallow slabs on expansive soils (Tabassum & Bulut, 2023).

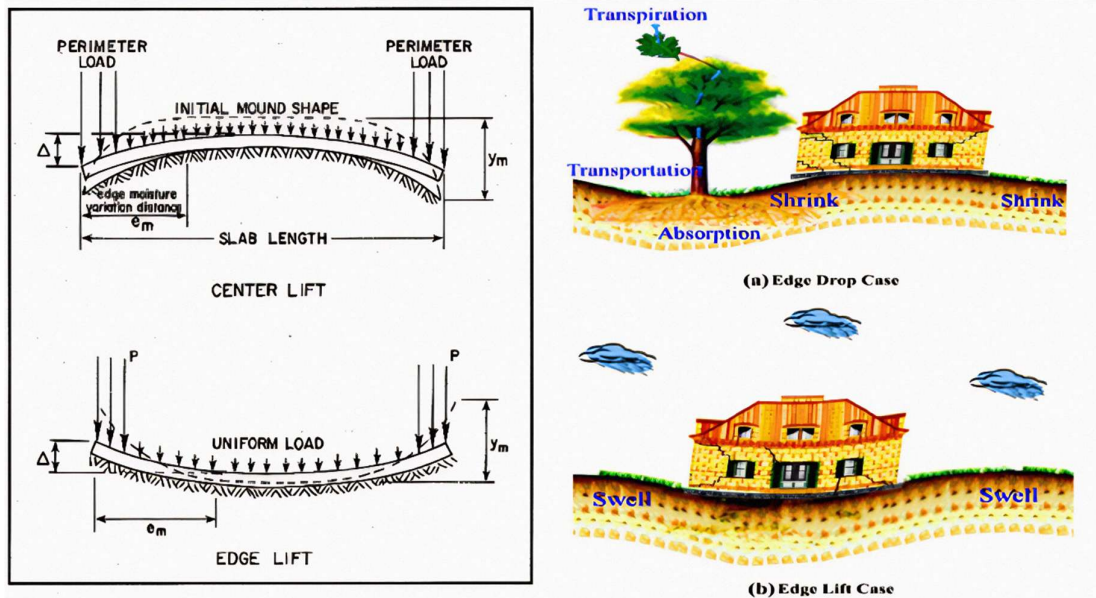


Figure 2.12: A slabs centre lift and edge lift on expansive soils on the left, and the damage caused by expansive soils on the right (Tabassum & Bulut, 2023)

2.6.3. Factors affecting moisture changes underneath foundations

Several factors can influence water content changes beneath a foundation. Environmental conditions, such as temperature fluctuations, seasonal weather variations, and periods of drought or high rainfall, significantly impact moisture levels in expansive clay soils, which respond by either expanding or contracting as moisture content changes (Duncan, 1992).

Construction activities and landscaping practices are also significant factors. Excavation during foundation work exposes large areas, increasing moisture loss through evaporation, particularly in warm weather. Additionally, removing vegetation, including trees and plants, can lead to gradual moisture changes in the soil over time. Unexpected factors, such as leaks from pipes beneath a structure, can further alter moisture levels around the foundation (USACE, 1990).

2.6.4. Raft foundation methodologies, design and past research

Raft foundation design methodologies are generally categorised into two main approaches: rigid and flexible models. Rigid models assume the foundation functions as a single, solid unit with uniform pressure distribution at its base to resist movement. As described by Teng (1962) and Peck, Hansen, and Thorburn (1974), this approach emphasises reinforcement to manage pressure variations in the soil. The flexible models adapt to soil behaviour variations beneath the foundation, employing flexible design principles to accommodate movement. Lytton (1972) and the Swinburne method (1975) illustrate this by dividing the foundation into independently analysed sections to adapt to soil heave, while Lytton and Woodburn (1973) and Pidgeon (1987) further consider moisture changes and heave patterns specific to expansive soils.

Rigid raft foundation models are built on the assumption that the entire foundation behaves as a single, unified structure. Teng (1962) established a design approach under this rigid assumption, where the raft foundation is designed to distribute bearing pressure evenly across its base. The foundation is analysed along two main directions, providing stability as it minimises differential movement across sections (Teng, 1962). Although treated as a single, continuous unit, sections of the foundation may still be examined independently to understand better how specific strips react to soil forces.

Peck, Hansen, and Thorburn (1974) expanded on rigid foundation design, describing a raft foundation as a flat slab positioned upside down, with minimal upward movement along the edges. This design simplifies assumptions about soil pressure by assuming it is distributed uniformly beneath the foundation and is

directly calculated using load factors (Peck, *et al.*, 1974). However, they also recognised that soil compressibility varies, which could affect the actual pressure compared to theoretical values (Gupta, 1997). Therefore, reinforcement is added as a safeguard, with extra steel recommended along the slab's top and bottom to maintain stability across the structure.

The Indian Standard Code of Practice (BIS, 1982). outlines two main approaches for raft foundation design, with the conventional method based on rigidity. This approach treats the foundation as a rigid block, assuming the soil pressure under the raft does not change with deflection. This simplicity makes it a common design choice, but additional reinforcement is advised to ensure stability against unforeseen movements. In this method, structural elements like shear forces and bending moments are calculated based on the combined actions of forces across the foundation, and the amount of reinforcement added is often twice the theoretical calculation.

In the United States, the Post-Tensioning Institute (PTI) method also follows a rigid model, focusing on reinforcing foundations to act as a single, stiff unit. Developed primarily for slab-on-ground or raft foundations, this approach advocates for using post-tensioned cables or conventional steel bars to manage soil movements effectively. This design often prefers post-tensioned cables, as they offer additional stiffness and resistance to differential soil pressures. Enhancing rigidity provides resilience in areas where soil movement may otherwise pose a risk to foundation stability (PTI, 2019).

Flexible models for raft foundations are designed to adapt to changes in soil conditions, especially for expansive soils where movement due to moisture

fluctuations is common. Lytton (1972) introduced a method that simplifies these flexible assumptions, dividing complex, non-rectangular raft foundations into smaller, rectangular sections. Each section is analysed independently, allowing the design to account for differential heave, soil depth, allowable structural deformation, and subgrade reaction modulus. This segmented approach provides an adaptable foundation model that can handle soil movement beneath different parts of the structure and is particularly effective for routine designs in expansive soil conditions (Lytton, 1972).

Lytton and Woodburn (1973) further advanced this approach by highlighting how moisture variations impact the interaction between the soil and foundation. They observed that soil-to-foundation contact is not uniform; moisture changes cause certain areas to rise or sink relative to others, leading to varying support across the raft. Their methodology accounts for these variations, with the foundation bridging low spots and compressing high areas, effectively adjusting to these inconsistencies. Using differential equations, they modelled the deflections of the foundation plate on an uneven soil surface, providing a more responsive design for expansive soils that experience frequent moisture shifts (Lytton & Woodburn, 1973).

Fraser and Wardle (1975) expanded on Lytton's model with the Swinburne method, a cost-effective design for housing foundations on expansive soils. They monitored multiple raft foundations over time in Australian conditions to observe real-world soil and moisture behaviour, specifically examining the natural dome shape that forms due to soil heave (Fraser & Wardle, 1975). Finite element modelling was used to represent the foundation, considering the raft and its stiffening beams as components resting on elastic soil. This analysis focused on the maximum

differential heave (Y_m) and the edge moisture variation (e), or edge penetration distance, crucial factors in designing foundations that can respond effectively to moisture-driven soil movement along the edges (Day, 1991).

Pidgeon (1980, 1987) recognised limitations in traditional design methods that relied on pre-existing mounds or domes, which often lacked accuracy. His approach begins with a level ground surface, expecting the foundation to settle instantly upon construction, followed by gradual changes in soil stresses, strains, and moisture content (Pidgeon, 1980). Pidgeon's design involves dividing the soil under the raft into multiple vertical columns, each with several layers, to calculate heave accurately. By adjusting the raft foundation to align with these soil movements, Pidgeon's iterative model reconciles the foundation's shape with the soil contact pressure, providing an adaptable foundation design that addresses the worst-case scenario of maximum swelling beneath the centre of the raft. This comprehensive approach accounts for moisture flow and foundation deflection variations, making it well-suited for challenging, expansive clay soils. Figure 2.13 (a-d) illustrates Pidgeon's proposed moisture flow patterns, representing the initial condition, edge heave, moisture content migration, a transitional phase, and eventual centre doming (Pidgeon, 1987).

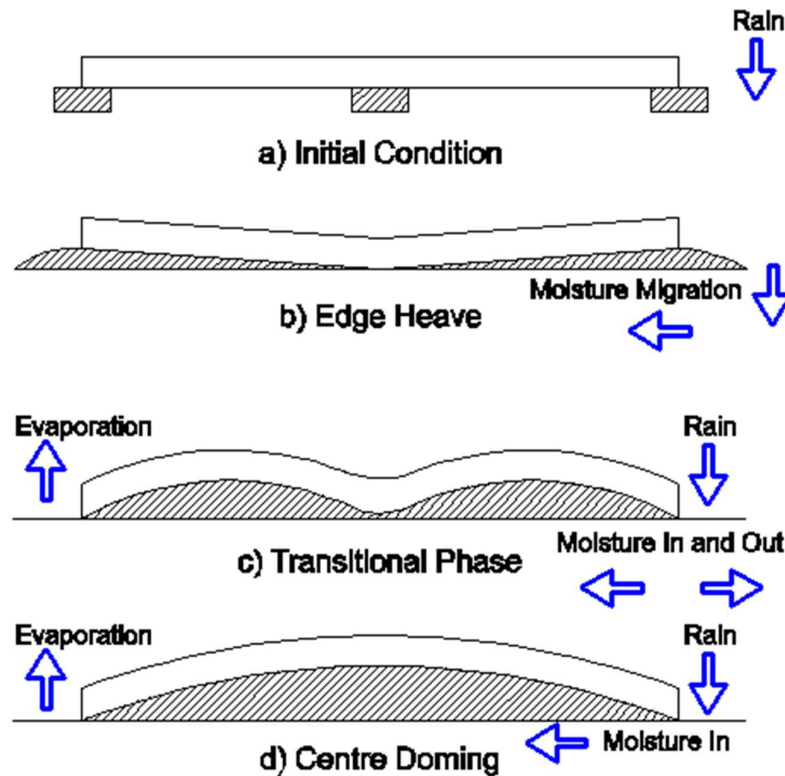


Figure 2.13: Centre doming under an impermeable cover (Pidgion, 1987)

Pidgion presented his final findings in 1987 in a guide to the universal method for the rational design of stiffened raft foundations for small structures. He recommended the following design steps:

- I. A plan of the foundation with the layout of stiffening beams and the position of wall loads. From this, the dimensions of the “base” rectangle, the offset lengths of any “L” shapes comprising the foundation, and the number of beams running in each direction of the “base” rectangle must be determined.
- II. The position and magnitude of any wall loads and the location of stiffening beams relative to the long axis of the “base” rectangle. As illustrated in Figure 2.14.

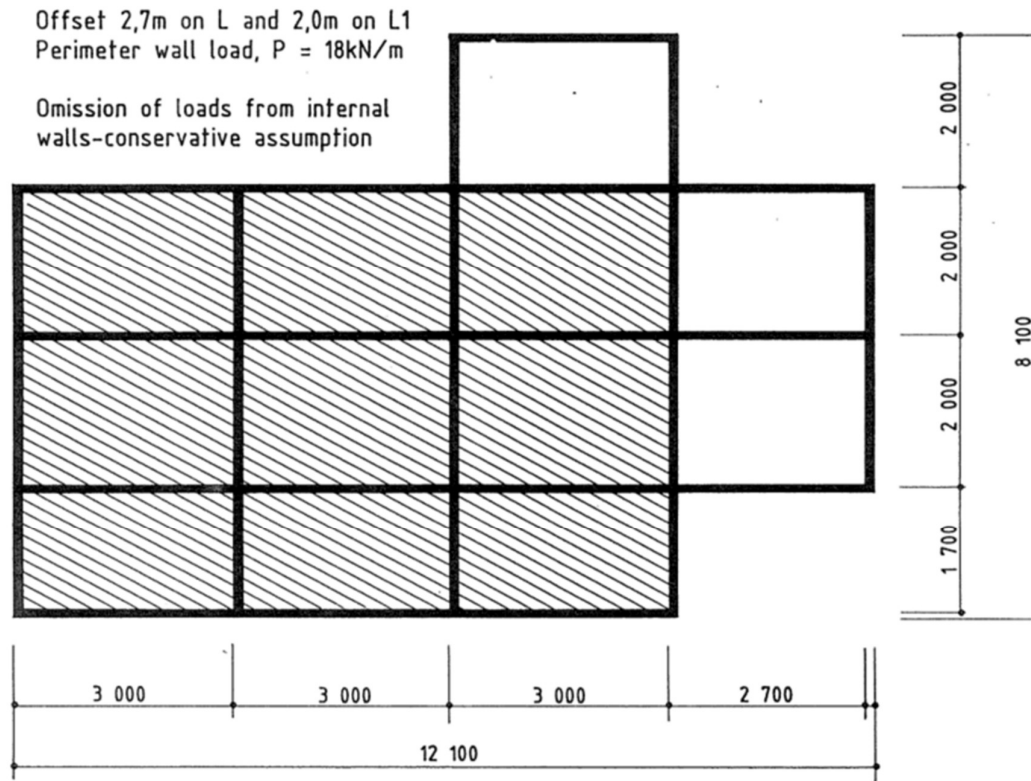


Figure 2.14: Typical layout of foundation beams for a stiffened raft foundation (Pidgeon, 1987)

- III. The magnitude of any uniformly distributed load.
- IV. An initial estimate of the required concrete cross-section in terms of overall beam depth, width, slab thickness, and flexural inertia. The long-term elastic modulus and Poisson's ratio of concrete should also be considered.
- V. The allowable deflection ratio for the type of superstructure intended to be constructed on the raft.
- VI. Mound stiffness is governed by the soils equivalent elastic mound modulus and Poisson's ratio.
- VII. Mound shape, either a flat-top mound with parabolic edges defined by a value of differential heave, Y_m , and an edge moisture variation difference, e , or a mound with no flat-top defined by the differential heave and a mound exponent, "m" as seen in Figures 2.15 and 2.16.

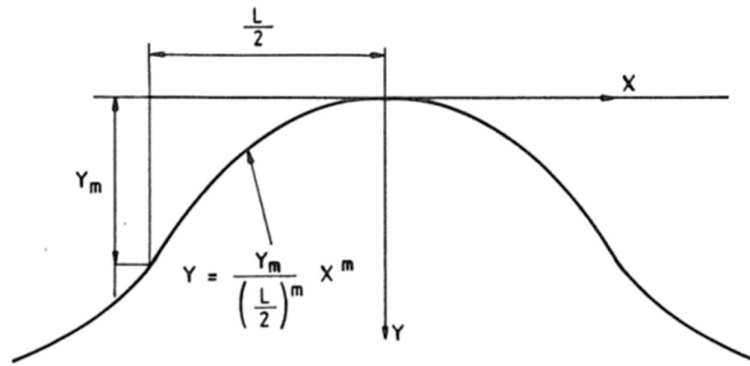


Figure 2.15: Unloaded mould with a shape defined by the mound exponent, m (Pidgeon, 1987)

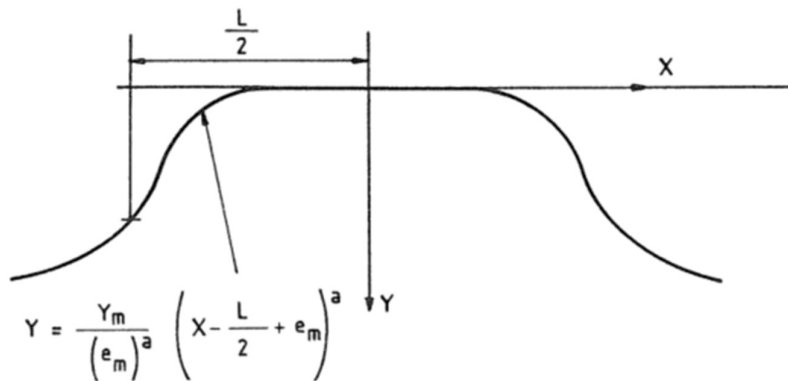


Figure 2.16: Unloaded mound with a flat top and parabolic or cubic shape edges (Pidgeon, 1987)

2.6.5. Field studies on foundation moisture patterns

Fityus, Smith, and Allman (2004) conducted a field study of surface movements on a flexible cover in Maryland, Australia, near Newcastle. This study investigated the long-term expansive soil behaviour underneath a flexible impervious cover and a stiffened raft slab. The site was established in 1993 and monitored for seven years. The study aimed to understand the physical processes driving reactive soil behaviour and to develop more reliable models of expansive soil behaviour. The site was instrumented to allow measurements of soil water content, moisture suction, and groundwater movements underneath a simulated lightly loaded building

foundation. The study also considered the effects of trees on changes in soil water content and ground movement (Fityus, *et al.*, 2004). The study's outcome emphasised aspects of foundation behaviour that are essential in expansive soil foundation practice. However, a significant limitation of this study was the use of two ground covers to simulate moisture boundary conditions, which may not fully represent real-world conditions. Moisture movement depends on temperature conditions influenced by solar radiation, which varies based on the architecture of the building (Bester, *et al.*, 2016).

A study in Botshabelo, in the Free State province, measured the moisture content under a GSH, primarily built on active clay soils. Models were generated to determine the moisture pattern underneath the raft foundation, revealing that doming occurs towards the re-entry corner of the building (Bester, *et al.*, 2016). The soil underneath this raft foundation predominately remains close to the fully expanded state, except on the northern side, where the water content in the upper layers may fall to the shrinkage limit (Bester, *et al.*, 2017). The study suggests that currently accepted patterns of heave may not provide helpful guidance for foundation design. Edge penetration also needs reconsideration, as this study shows no clear indication of the value of this parameter, which should be used to estimate mound shape and required stiffness. A centre dome is not recommended, as no clear evidence supports it (Bester, *et al.*, 2017).

2.6.6. Ventilated foundations

Cavity or ventilated foundation systems are a type of foundation system that allows for air circulation beneath a building (MPA, 2022). They are typically used in areas

with high soil moisture content, where moisture accumulation can cause foundation problems such as heave. They are designed to provide a space between the concrete foundation and expansive soil (Hamakareem, 2020). Open systems consist of vents or openings in the foundation walls that facilitate air circulation beneath the building (Geoplast, 2020).

Cavity foundations contribute to sustainability by reducing the volume of concrete used, the energy consumption in construction, and saving time and costs in the construction stage (Hamakareem, 2020). Despite these benefits, there has been limited research on how effective these cavity foundation systems are. Kalantari (2012) suggests a positive impact on moisture control and structural stability in expansive clay soils where a cavity is provided underneath the slab instead of laying slabs directly on such soils. This allows the soil to expand into this space, thereby minimizing movement and reducing potential damage to the structure.

The honeycomb design is one of the earliest cavity foundation approaches. It uses longitudinally split Sonotubes arranged so that their openings face the soil. The gaps between these tubes are partially filled with sand up to a depth of about 25cm (or approximately 2 inches). The Sonotube structures are designed to hold up during concrete pouring but break down when they come into contact with moisture afterwards. The idea of the honeycomb design is that as expansive clay soils will swell into these prefabricated voids. This will potentially ease the pressure caused by the expansive clay soil expansion (CHEN, 1988). Figure 2.17 is an illustration of the honeycomb design with split Sonotubes arranged so that their openings face the soil beneath.

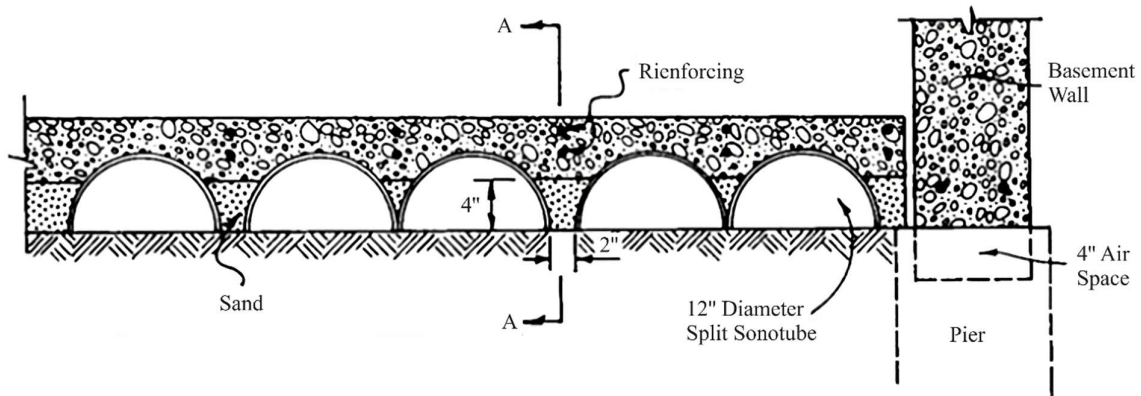


Figure 2.17: Honeycomb design on expansive soil (CHEN, 1988).

According to the Geoplast website, their modulo formwork system is suited for prefabricated housing projects. They claim that the modulo system is simple, quick, and compatible with fast construction methods. It enhances the durability of homes by elevating floors to protect against moisture damage and minimizes the use of concrete. By elevating the floor, the Modulo system minimises heat loss and enhances ventilation, which helps prevent moisture-related issues. Moreover, ventilated foundations like Modulo lead to better moisture management, lower the risk of structural problems, and improve indoor air quality (Geoplast, 2020). Figure 2.18 is an illustration of the Geoplast modulo formwork system.



Figure 2.18: Geoplast modulo system (Geoplast, 2020).

VoidForms are a type of sacrificial formwork designed to create a gap between the expansive soil and the foundation slab (Hamakareem, 2020). This gap will help in protecting the foundation from the heave of the underlying expansive clay soil. VoidForm serves as temporary support for freshly poured concrete, allowing it to gain strength to bear loads of the structure (VoidForm, n.d). Figure 2.19 shows the Sure Void system by VoidForm, which is specifically aimed at protecting structures from the pressures of clay soil expansion.



Figure 2.19: VoidForm's SureVoid system (VoidForm, n.d).

The wafflemat system is a foundation design that uses a "waffle" pattern of void spaces beneath a concrete slab. The system is designed to adapt to varying soil conditions while supporting structural loads. The system uses polyethylene forms that create air pockets under the slab, providing flexibility and resistance to soil expansion and water damage. This design prevents structural cracking and uplift from expansive soils and reduces construction costs by eliminating the need for

deep excavation and extensive soil preparation (Pacific Housing Systems, 2023).

Figure 2.20 shows a typical wafflemat system cross-section.

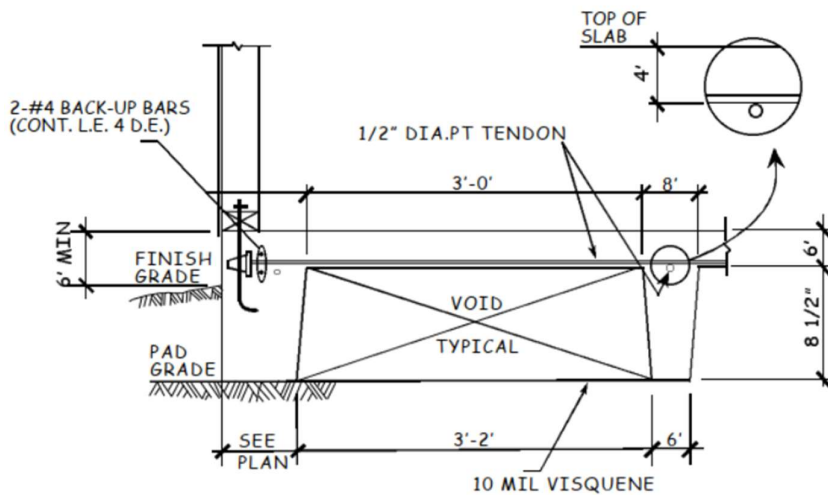


Figure 2.20: Typical wafflemat system cross-section (Pacific Housing Systems, 2023).

Despite claims by companies and foundation designers about the effectiveness of ventilated and cavity foundation systems, there is no concrete evidence to support these claims. Expansive clay soils, which are highly sensitive to moisture changes, might benefit from a foundation system that includes a cavity for moisture evaporation and soil expansion. However, no academic research has been found to support the claims of enhanced building longevity, with the only support for these claims coming from companies' websites and papers with very little evidence. Additionally, systems like Geoplast cannot be used in South Africa for GSH projects, as the Housing Department exclusively employs local materials and companies. As a result, Geoplast is excluded from GSH projects in accordance with the policy of the Local Economic Department of South Africa (LED, 2023).

CHAPTER 3: SCALE MODEL DEVELOPMENT AND INSTRUMENTATION FOR SM FOUNDATIONS

3.1. Introduction

The SMs are based on the GSH in Botshabelo, Free State Province. SM raft and cavity raft foundations were developed in the laboratory. These scale foundation models were designed to replicate a real GSH constructed in 2013 in Botshabelo, Free State Province. Data on moisture variation beneath the GSH's raft foundation was collected from 2014 to 2015 using CLSM probes instrumented underneath the foundation. The data obtained during 2014 and 2015 was utilised to validate the SM models of the foundations inside the laboratory. This chapter outlines the methodology used for modelling the SM raft and cavity raft foundations, including the scaling laws, the construction of a climate room, the creation of SM model foundations, the installation of CLSM probes to measure moisture content, implementation of OptoNCDT laser displacement sensors for measuring movement, fitting of strain gauges, and data analysis. A comprehensive approach is presented in this chapter for developing the SM and implementing the data collection.

3.2. Scaling laws

Scaling laws for shallow foundations, are mathematical models used to predict the behaviour of shallow foundations based on their physical and geometric characteristics. The models aim to anticipate how shallow foundations will perform under various conditions and in different soil types. This section discusses shallow foundation scaling laws, their historical development, and their underlying assumptions.

3.2.1. Scaling on shallow foundations

The concept of scaling laws for shallow foundations dates to the early 1960s when pioneers in Geotechnical Engineering, Terzaghi, Peck and Mesri (1996), and Meyerhof (1951), introduced mathematical models. Scaling laws rely on the principles of similarity and dimensional analysis, which entail reducing the size of a prototype foundation to create a smaller-scale model while preserving the same geometric and material properties (Meyerhof, 1951). Subsequently, this model is tested under controlled laboratory conditions to forecast how the prototype foundation will behave when subjected to real-world loading conditions (Terzaghi, *et al.*, 1996). Assumptions and applications underlying scaling laws for shallow foundation models rest on several key assumptions, which include the following:

- I. Homogeneity and isotropy of the soil.
- II. Linear elastic behaviour of the soil.
- III. Plane strain conditions.

The assumptions simplify the modelling process and enable the development of solutions for predicting the behaviour of shallow foundations (Bowles, 1997). Shallow foundation scaling models have diverse applications. They are utilised to predict how shallow foundations will perform under different loading conditions, encompassing vertical, horizontal, and eccentric loads. Additionally, the models aid in determining the optimal size and shape of a foundation for a given soil type and loading condition (Terzaghi, *et al.*, 1996).

Scale modelling plays a crucial role in Geotechnical Engineering by allowing for a comprehensive understanding of natural events or scenarios and their performance. It entails reproducing events as accurately as possible at a reduced scale to analyse their behaviour under varying loading conditions (Thusyanthan & Madabhushi, 2003). Numerous comparisons between the two are necessary to make meaningful predictions from scale to full-scale models (Taylor, 1995). However, a primary challenge in geotechnical event modelling is accurately simulating the stress levels and in-situ stresses experienced by materials beneath the surface (Jones, 2014). Typically, length scaling is inversely proportional to the gravity scale employed in modelling (Vorster, 2016). Table 3.1 presents scaling factors.

Table 3.1: Scaling factors (Vorster, 2016)

Quantity	Symbol	Unit	Scale factor
Length	L	L	1/N
Volume	v	L^3	1/N ³
Mass	m	m	1/N ³
Acceleration, Gravity	a,g	L/T^2	N
Force	F	mL/T^2	1/N ²
Stress	σ	m/LT^2	1
Moduli	E	m/LT^2	1
Strength	s	m/LT^2	1
Time (dynamic)	t(dyn)	T	1/N
Frequency	F	1/T	N
Time (diffusion)	t(dif)	T	1/N ²

To establish a connection between observed model behaviour and prototype phenomena, it is crucial to employ appropriate scaling laws. Taylor (1995) explains that the fundamental scaling law revolves around achieving the same stress conditions in the model as at a homologous point in the prototype (Taylor,

1995). The small-sized model is designed to closely resemble the actual structure and can be conveniently subjected to testing, with measurements subsequently recorded (Alves, *et al.*, 2017). The actual structure is referred to as the prototype, denoted as “P”, while the scaled-down structure is termed the model, “M”. The scaling factor, denoted as β , is expressed as the ratio of the length of the model to the length of the prototype ($L(m)/L(p)$). The utilisation of scaled-down models for experimentation is common, driven by limitations in the capabilities of testing facilities and the cost-effectiveness of conducting experiments on smaller-scale models (Ramu, *et al.*, 2013).

Scaling can be applied in either a scaling-up or scaling-down model, contingent on the specific application (Shehadeh, *et al.*, 2014). Typically, in addressing problems across various fields, three fundamental scale factors – mass, length and time – are independently considered without any inherent relation to one another. These three primary scale factors must be thoughtfully chosen when designing the scaled model. The initial step involves selecting a suitable set of fundamental dimensions (Simitises, *et al.*, 1992), followed by the inclusion of all relevant parameters and constants, such as gravitational acceleration (Taylor, 1995; Konkol, 2014). Scaling theory can establish similarities among structural systems and lead to time savings, provided that appropriate scaling laws are identified and validated (Ramu, *et al.*, 2013).

3.2.2. Scale selection of the models:

The scale selected for the Raft and Cavity Raft Foundation was one to six. The primary reason for this selection was the limited surface area of the laboratory room

(15 m²). It was essential to ensure that the scale model fit within the room and provided enough working space for instrumentation. A larger model was not feasible due to the need for water penetration in the soil. Choosing a one-to-six scale also simplified the artificial sunlight setup and software coding.

3.3. Expansive clay selection and CLSM probe instrumentation

3.3.1. Soil sample collection

The soil profile reveals the vertical arrangement of different soil layers at a specific site, with each layer described based on its moisture condition, colour, consistency, structure, texture, and origin (Jennings, et al., 1973). Moisture condition is assessed first, as it influences soil consistency and behaviour. Colour should be limited to two descriptors, like "reddish-brown," with any secondary colour patterns noted by size. Consistency indicates soil stiffness and is estimated by the effort required to penetrate the soil, providing a rough estimate of shear strength. Soil structure identifies any discontinuities, with granular structures typically found in non-cohesive soils and varied forms such as "slicken-sided" surfaces in cohesive soils. Soil texture describes the grain size distribution, as most soils contain a mixture of textures. Lastly, the origin of each layer, whether residual or transported, is determined using geological maps and local knowledge. These profile inspections should ideally be conducted before the soil dries out significantly, following the guidelines in the 1991 Code of Practice for Safety (Brink & Bruin, 2002).

3.3.3. Soil property testing to determine soil properties in South Africa

Sieve analysis and sedimentation analysis are techniques used to determine the distribution of soil particles based on their size. Mechanical sieving is the most

common method for conducting grain size analysis. This procedure involves the use of standard sieves with varying mesh sizes to separate soil particles by size. The sieves are arranged in descending order of size, with the soil sample placed on the top sieve. The stack is mechanically shaken for a specified duration to separate the particles. The percentage of particles passing through each sieve is determined and plotted on a graph to form a particle size distribution curve (Knappett & Craig, 2012).

The sedimentation method is used for grain size analysis to determine the particle size distribution of soil particles smaller than 0.075 mm. This method requires using a hydrometer to measure the specific gravity of a soil suspension in water. The soil sample is mixed with water and allowed to settle for a predetermined time before inserting the hydrometer into the suspension to measure its specific gravity. This measurement is then utilised to determine the particle size distribution of the soil particles. The grain size distribution of soil particles is essential to classifying soils into different categories based on the percentage of particles in each size range. The clay content of the soil, defined as the percentage of material smaller than 0.002 mm, is a critical parameter in soil classification because it significantly affects soil properties such as plasticity, shrinkage, and swelling. The clay content can be determined through hydrometer analysis (Das, 2007). Figure 3.1 illustrates the soil-separate-size limits according to various systems.

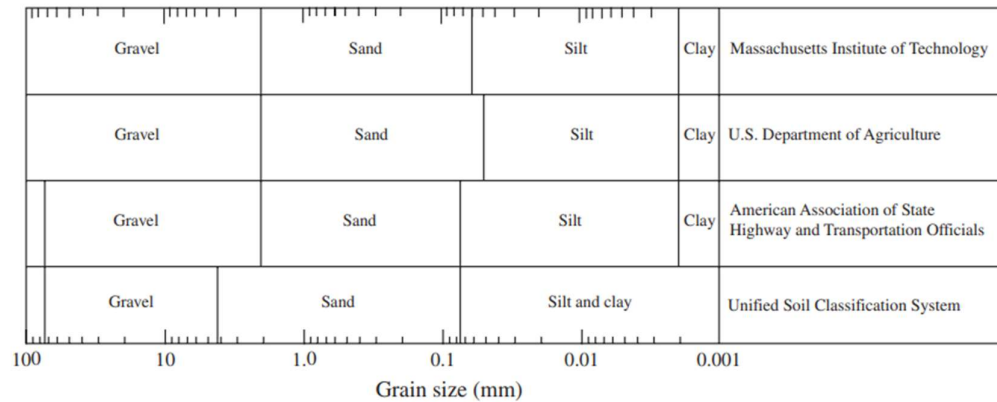


Figure 3.1: Soil-separate-size limits according to various systems (Das, 2007)

The Atterberg limits, developed by Swedish scientist Albert Atterberg in the early 1900s, are a set of tests designed to determine the moisture content at which fine-grained soil shifts from one physical state to another (Das & Sobhan, 2018). The three main limits include the Liquid Limit (LL), which identifies the moisture level where soil transitions from a plastic to a liquid state. The Plastic Limit (PL) indicates the moisture content where the soil changes from semi-solid to plastic. The Shrinkage Limit (SL) defines the moisture level at which soil stops shrinking upon drying, determined by observing the volume change of a drying soil sample. These tests provide insight into soil behaviour across different moisture conditions (Das & Sobhan, 2018).

Soil foundation indicator tests were used in the study to determine the engineering properties of soil for construction purposes (SABS, 2020). The tests (SABS, 2020) include:

- I. SANS 3001-GR1:2022. Civil Engineering Test Methods Part GR1: Wet preparation and particle size analysis.
- II. SANS: 3001-GR2:2022. Civil Engineering Test Methods Part GR2: Dry preparation and dry particle size analysis of gravels and sands.

- III. SANS 3001-GR3:2014. Civil Engineering Test Methods Part GR3: Particle size analysis of material smaller than 2 mm (Hydrometer Method)-
- IV. SANS 3001-GR5:2014. Civil Engineering Test Methods Part GR5: Wet preparation and air-drying of samples for plasticity index and hydrometer tests.
- V. SANS 3001-GR10:2013. Civil Engineering Test Methods Part GR10: Determination of the one-point liquid limit, plastic limit, plasticity index and linear shrinkage.
- VI. SANS 3001-GR11:2013. Civil Engineering Test Methods Part GR11: Determination of the liquid limit with the two-point method.
- VII. SANS 3001-GR12:2013. Civil Engineering Test Methods Part GR12: Determination of the flow curve liquid limit.
- VIII. SANS 3001-GR20: 2010 - Civil Engineering Test Methods Part GR20: Determination of the moisture content by oven-drying.

3.3.4. Heave determination methods used in South Africa

It is considered good practice to determine expected heave using multiple methods. Various approaches are available to predict the heave in clayey soils in South Africa. The selection of a specific method depends on the design engineer or laboratory, and the engineer needs to be aware of the limitations of the chosen method. The most frequently employed method in South Africa is Van der Merwe's (1964), designed initially for Highveld clay soils, based on indicator test results. The method focuses on the heave observations of buildings situated on Free State clays and has seen widespread application across South Africa for over half a century (Jones, 2017). The required inputs for this method include:

- I. The Plasticity Index (PI)
- II. The percentage of material passing through the 0,425 mm sieve
- III. The clay content

Van der Merwe's swell prediction chart (Figure 3.2) plots the PI of the entire sample against the clay content to determine the soil heave potential. This potential can be classified as low, medium, high, or very highly expansive. It is crucial to consider the in-situ moisture content as the soil's heave potential represents the total heave for a moisture change from a dry to a saturated state (Van der Merwe, 1964). Figure 3.2 illustrates Van der Merwe's chart used for heave prediction.

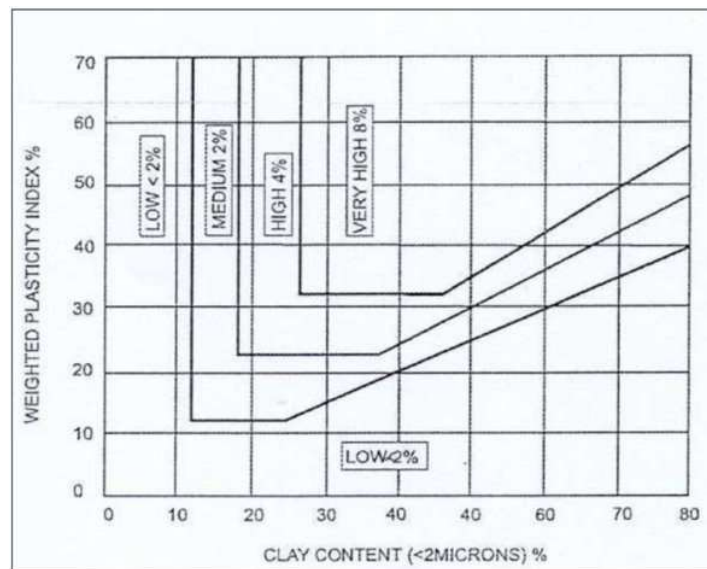


Figure 3.2: Van der Merwe's chart for heave prediction (Van der Merwe, 1964)

The Savage method (2007) offers an alternative to Van der Merwe's method (1964) for determining heave potential. This method utilises the ratio between the LL and PL to identify the types of clay in the soil. The plasticity ratio (R) is related exponentially to Skempton's activity index. Utilising Van der Merwe's well potential zones, the Savage method calculates from a chart the soil's swell potential based

on the value of R and the material passing through a 0.425 mm sieve. Savage developed a mathematical derivation of lines representing swell potential by a factor K, with specific values defining swell zones approximating those of Van der Merwe. By using the R-value (LL/PL) for soil and the gross PI, a quick assessment of active soils can be made using the chart in Figure 3.3. The heave potential can be classified as low, medium, high, very high, or extremely high expansive (Savage, 2007).

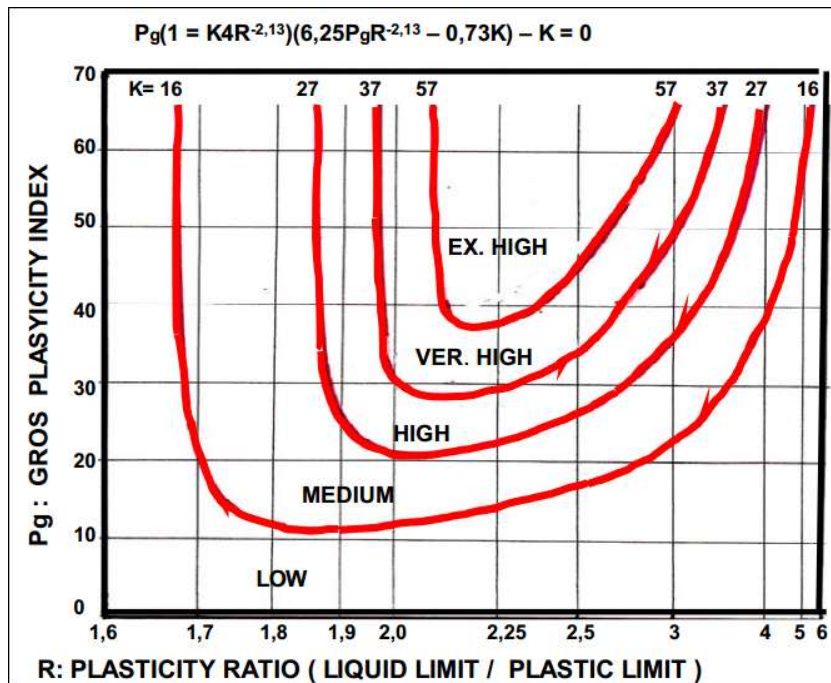


Figure 3.3: Soil swelling potential using the Atterberg limits of Plasticity Index and plasticity ratio (Savage, 2007)

3.3.5. Expansive clay used properties

To match the expansive clay found in Botshabelo GSH, similar clay with corresponding properties was obtained. The Botshabelo soil profile consisted of three layers, each with distinct characteristics. The first layer was moist, dark brown, and firm (clayey sand). The heave prediction for the first layer, based on Van der Merwe's method (1964), is medium, and the thickness of this layer was 150 mm.

The second layer of the soil profile was a moist, dusky blue firm clay, with a high-predicted heave according to Van der Merwe's method (1964), and a thickness of 750 mm. The third layer beneath the Botshabelo house was a moist, dark yellow, firm, clayey sand, with a predicted high heave based on Van der Merwe's method (1964) for this third layer, and the thickness measured was 200 mm.

For this study, moist black, stiff clay from Rosslyn, Pretoria, was chosen as the closest match in terms of properties to the expansive clay in Botshabelo. The clay layer on-site had a thickness of 1000 mm. Laboratory results for the clay soil properties are presented In Table 3.2.

As shown in Figure 3.4, 6,000 kg of moist, black clay was collected and transported to the Tshwane University of Technology Laboratory. The soil was placed inside a steel box constructed for the purposes of the study. The soil thickness inside the steel box was 600 mm. The soil was compacted to minimise voids and left to dry and wet for over one year before constructing the SM foundations.

Table 3.2: Foundation indicator laboratory results

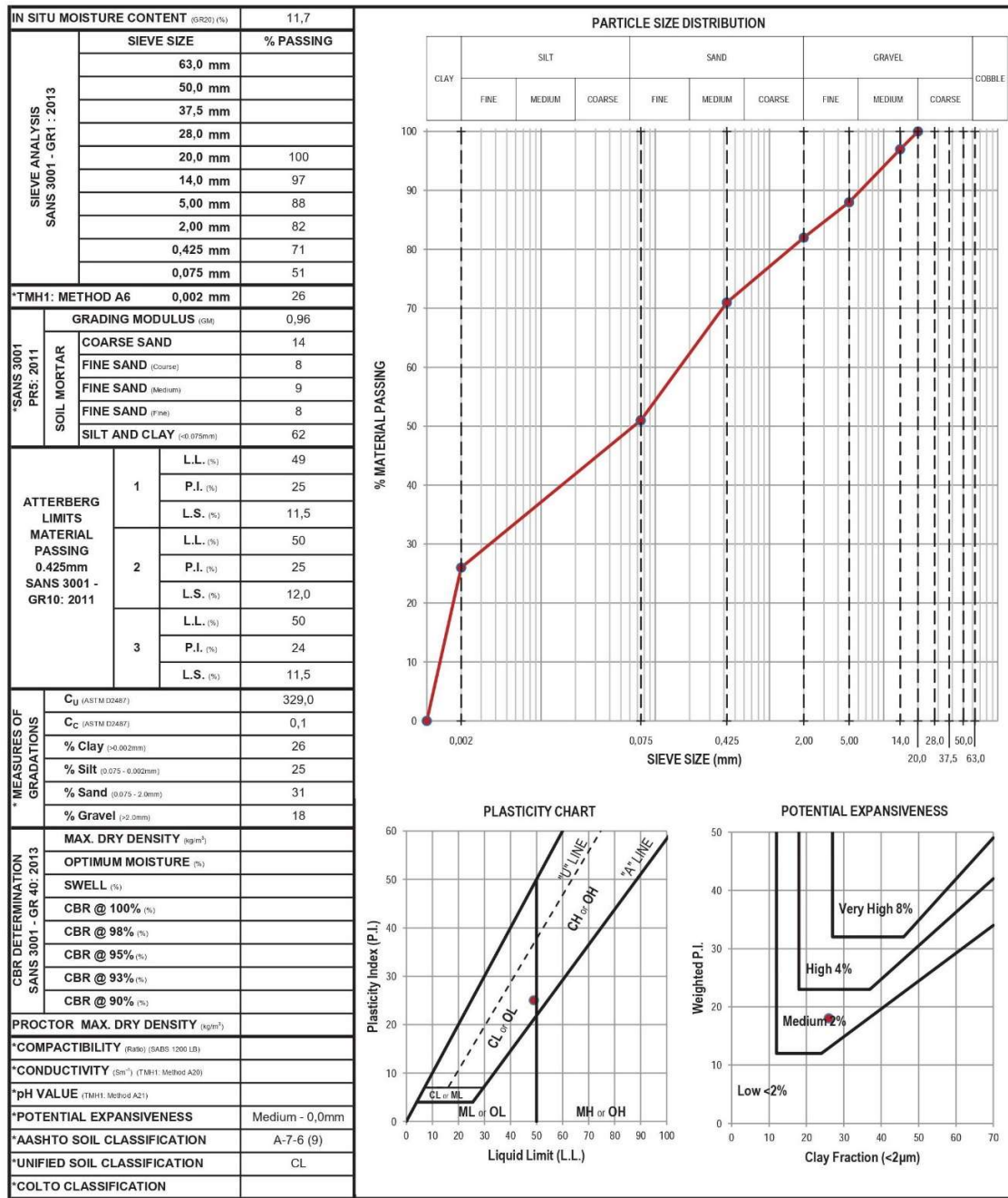




Figure 3.4: Moist black stiff clay

3.3.6. Field moisture measurement methods

Soil moisture measurement plays a vital role in soil science and Geotechnical Engineering, enabling the precise and reliable assessment of soil moisture levels for various applications, including irrigation, crop production, construction, and environmental studies (Hillel, 2003). There are several methods and instruments for field moisture measurement in soils.

The gravimetric method stands out as the most accurate means of measuring soil moisture. It involves measuring the weight of a soil sample before and after drying in an oven to determine moisture content. However, this method is time-consuming and requires a laboratory setting, making it impractical for field applications (Topp, *et al.*, 1980). Another commonly used technique is the tensiometer method, which measures soil moisture by determining the tension needed to extract water from the soil. It employs a ceramic tip connected to a water-filled tube with a vacuum gauge and can be used in the field. Nevertheless, it requires calibration and is limited to measuring the moisture content near the soil surface (Hillel, 2003).

The neutron scattering method is highly accurate, measuring soil moisture by detecting the amount of hydrogen in the soil using a neutron probe. This method can measure moisture content at various depths, but demands specialised equipment and expertise (Lv, *et al.*, 2014). The capacitance method offers a straightforward approach to measuring soil moisture by determining the soil's capacitance using a probe. The capacitance is directly proportional to the moisture content of the soil, and this method can assess moisture content at different depths. However, it is affected by soil type and electrical conductivity (Hillel, 1982).

One of the most widely used methods for measuring soil moisture is the electrical resistance method, which involves assessing the soil's electrical resistance using a probe. The resistance is inversely proportional to the soil's moisture content, and this method is relatively simple to use (Lv, *et al.*, 2014). The electrical resistance method can also detect variations in soil properties, such as temperature and electrical conductivity (Hillel, 2003).

Measuring moisture content using probes is common in agricultural and soil science, with many commercial products available (Zerizghy, *et al.*, 2013). In a study by Bester, *et al.*, 2016, CLSM probes (continuously logging soil moisture) were implemented. These probes can measure moisture content and temperature at different depths in a soil profile. These readings can be taken hourly, with the flexibility to customise reading intervals. If left at the default setting, the probe can store readings for approximately five months. In this study, measurements of soil water evaporation using CLSM probes and neutron water metres (NWM) were compared (Zerizghy, *et al.*, 2013). The research found that the measurements from

the CLSM probes closely matched the gravimetric soil water content, indicating their superior accuracy compared to NWM. However, it is worth noting that proper installation is essential to ensure full contact with the soil. Accurate and reliable soil moisture measurements are essential for various applications, including agriculture, construction, and environmental studies. CLSM probes were also successfully employed beneath a raft foundation in Botshabelo to measure moisture content underneath a GSH (Bester, *et al.*, 2016). Multiple methods are available for measuring soil moisture, each with advantages and limitations. The choice of the appropriate method depends on the desired level of accuracy, measurement depth, and ease of use required for the specific application (Hillel, 2003).

3.3.7. The installation of CLSM probes

CLSM probe selection was based on experience in Botshabelo, and DFM Technologies probes were chosen for their reliability and accuracy. The probes have also been widely used throughout Southern Africa in agriculture industries of crop farming. Fourteen CLSM probes were installed in a pattern similar to those underneath the GSH in Botshabelo, with some variations in probe length and four additional probes placed outside the foundation boundary. The CLSM probe installation layout is shown in Figure 3.5. A 300mm probe length was chosen as the most suitable for the research project.

The researcher marked the model foundation boundaries, and the CLSM probes were installed vertically as per the manufacturer's specifications. Installation locations are depicted in Figure 3.6. After calibration, the CLSM probes were covered by clay soil at depths of 200mm, 300mm and 400mm below the soil's

surface to safeguard the wiring potential damage during excavation and to monitor moisture levels at different layers.

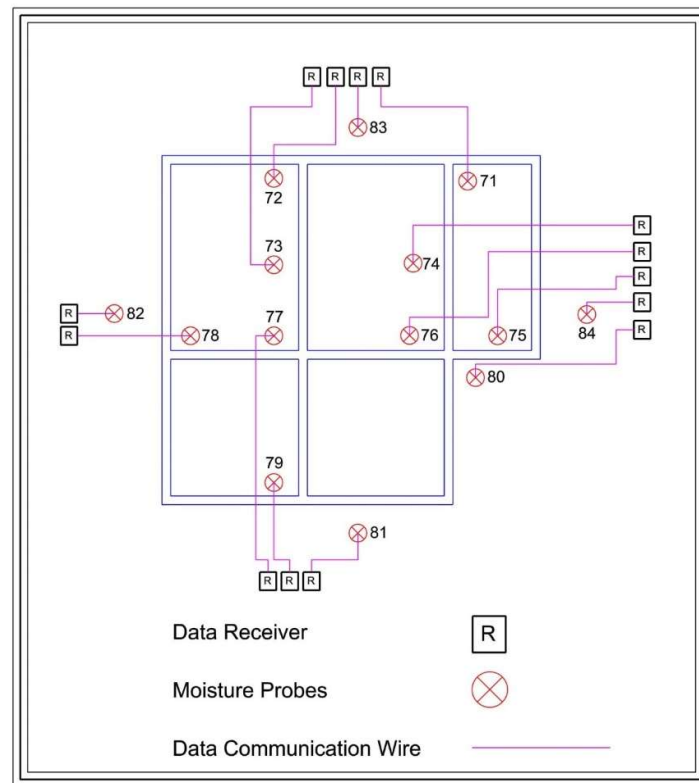


Figure 3.5: CLSM probes layout inside the laboratory



Figure 3.6: CLSM probes installation

3.3.8. Calibration of CLSM probes

The calibration process of the CLSM probes took five weeks. After the probes were installed into the soil, soil samples next to each CLSM probe were collected to determine the gravimetric moisture content. The soil sampling was repeated three times to determine the moisture content and the average change over time. Bulk densities were also recorded over the same period. The information was used to calculate volumetric moisture content for calibration. A linear equation was derived by analysing all the data, serving as a correction factor for the readings provided by the CLSM probes.

3.3.8.1. Gravimetric moisture content

Soil moisture content is expressed by weight as the ratio of the water weight present to the soil sample's dry weight and by volume as the water volume ratio to the soil sample's total volume. To determine the gravimetric moisture content for a specific clay soil sample, the water mass must be determined by drying the soil to its dry weight and measuring the mass before and after drying. The water mass is the difference between the weights of the wet soil weighed and oven-dry soil weighed. The drying of the soil sample is conducted at temperatures between 100°C and 110°C. The water content in gravimetric moisture content is expressed in Equation 3.1.

$$\theta_d = \frac{(Weight\ of\ wet\ soil + tare) - (Weight\ of\ dry\ soil + tare)}{(Weight\ of\ dry\ soil + tare) - (tare)} \dots\dots\dots [3.1]$$

3.3.8.2. Bulk density

Bulk density is the weight of dry soil per unit of volume and is expressed in Equation 3.2. More compacted soil with less pore space will have a higher bulk density, whereas less compacted soil will have a lower bulk density. Bulk density affects infiltration, available water capacity, and soil absorbency, all of which influence soil moisture content.

$$Bd = \frac{\text{Mass of soil}}{\text{Soil Volume}} \dots\dots\dots [3.2]$$

The bulk densities were determined and plotted against gravimetric moisture content for each CLSM probe sensor location in the soil.

3.3.8.3. Volumetric moisture content

Water content on a volumetric basis is expressed by equations 3.3 to 3.7:

$$\theta_{vd} = \frac{\text{Volume of water}}{\text{Volume of soil}} \dots\dots\dots [3.3]$$

But:

$$\text{Volume of water} = \frac{\text{Weight of water}}{\text{Water density}} \dots\dots\dots [3.4]$$

And:

$$\text{Volume of soil} = \frac{\text{Weight of dry soil}}{\text{Bulk density}} \dots\dots\dots [3.5]$$

Thus:

$$\theta_{vd} = \frac{\text{Weight of water}}{\text{Weight of dry soil}} \times \frac{\text{Bulk density}}{\text{Water density}} \dots\dots\dots [3.6]$$

Thus:

$$\theta_{vd} = \theta_d \times \frac{d_b}{d_w} \dots\dots\dots [3.7]$$

3.4. Construction of the climate room

This section covers the construction of the climate room, including key considerations like the sun's orientation to each area and the use of electronics to create an artificial sunlight system.

3.4.1. Suns orientation to the earth

The orientation of the sun impacts climate, weather patterns, and agricultural practices in the Southern Hemisphere. Seasonal variations in the sun's orientation result from its tilt on its axis, leading to varying angles at which the sun's rays strike the Earth throughout the year. In the Southern Hemisphere, the summer solstice falls around December 21, while the winter solstice occurs approximately on June 21. Summer brings longer days, shorter nights, and more intense sunlight, resulting in higher temperatures and increased evaporation. Conversely, winter shortens the days and lessens the intensity of sunlight, leading to lower temperatures and reduced water evaporation (CSIR, 2004).

In the Southern Hemisphere, the sun's daily movement appears to travel from east to west, reaching its zenith in the sky at solar noon, which typically occurs around local noon. Solar noon is when sunlight is most intense because the sun's rays strike the Earth at varying angles throughout the day (Observatory, 2021). This variation significantly impacts the temperature and evaporation of plants. The sun's declination changes with the seasons, as depicted in Figure 3.7. Over the course of a day in South Africa, the sun follows a symmetrical spherical arc within the vertical plane, ascending from the Southeast and descending in the Southwest before reaching its zenith at solar noon. When the sun's radiation meets a surface at a right

angle, it gets absorbed to a greater extent and reflects less, resulting in higher energy density per unit area than when rays strike at slanted angles. The magnitude of solar radiation can be calculated based on the angle of incidence of the radiation and a line perpendicular to the surface of the object. Additionally, a building orientation plays a crucial role in the amount and availability of solar radiation it receives, depending on the shadows cast by the building (CSIR, 2004).

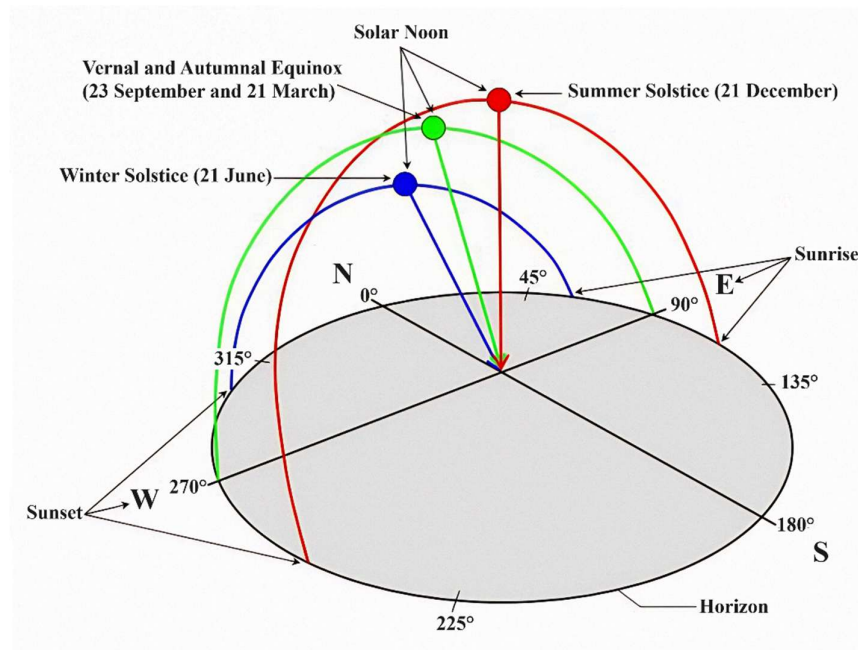


Figure 3.7: The apparent path of the sun in the sky during different seasons in South Africa (CSIR, 2004)

These variations in the sun's orientation throughout the seasons give rise to distinct climate zones, ranging from tropical to temperate to polar regions. Furthermore, the daily changes in the sun's orientation impact temperature patterns, which have critical implications for plant growth timing, crop yield, and irrigation practices. The intensity of sunlight also influences the evaporation rate (Izumi & Ramankutty, 2015). These seasonal and daily variations in the sun's orientation are the direct result of the Earth's axial tilt and rotation. Understanding these effects is essential

for various applications, such as climate modelling, weather forecasting, and agricultural management.

3.4.2. The implementation of artificial sunlight in the laboratory

An artificial simulator was designed and constructed to ensure the controlled evaporation of moisture within the laboratory. Thirty heater lights were strategically positioned in an array, striving to mimic the sun's path as closely as possible. The constraints of space and complexity limited the number of lights to thirty. The artificial sun's trajectory closely followed the natural sun's, accounting for seasonal variations. In the summer months, the sun rises from a low position on the horizon to reach its zenith, while in winter, it remains closer to the horizon. Table 3.2 provides the average vertical angles for January to February. Further details about the orientation of the sun in Botshabelo are included in APPENDIX J.

Table 3.3: Vertical orientation of the sun

Month	<i>January</i>	<i>February</i>	<i>March</i>	<i>April</i>	<i>May</i>	<i>June</i>
Angle	77°	69°	61°	53°	45°	38°
Month	<i>July</i>	<i>August</i>	<i>September</i>	<i>October</i>	<i>November</i>	<i>December</i>
Angle	45°	53°	61°	69°	77°	84°

Given the limited space available in the laboratory, some months required grouping artificial sun angles with the same lighting pattern. The selection of grouped months was deliberate, considering seasonal variations and solar orientation. The months were grouped as follows:

- I. January, November, and December
- II. February and October

- III. March and September
- IV. April and August
- V. May and July
- VI. June

Figure 3.8 offers a visual representation of the artificial sunlight layout, including the numbering of each heater light, while Figure 3.9 presents a photograph of the construction and layout of the artificial sunlight within the laboratory.

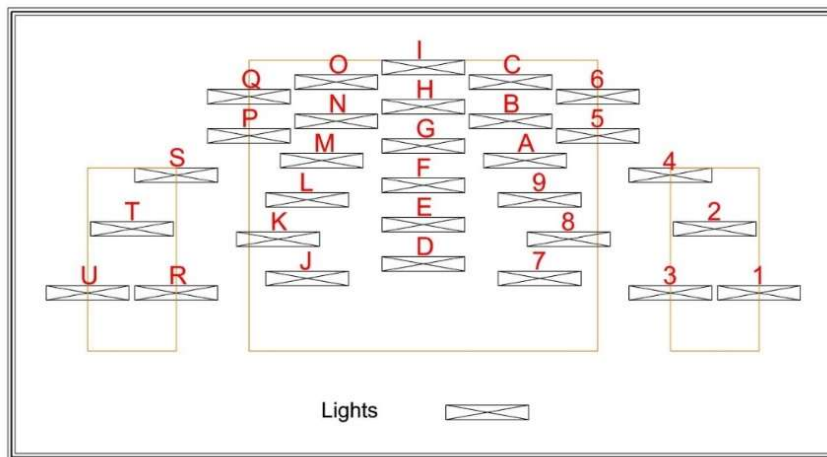


Figure 3.8: Artificial sun layout



Figure 3.9: Lights layout photograph

Solar radiation above the Earth's atmosphere has an intensity of approximately 1380 watts per square meter, commonly referred to as the Solar Constant. However, as the Earth rotates, this energy is distributed across its entire surface area ($4 \cdot \pi \cdot R_E^2$), resulting in a decrease in incoming solar radiation. The angle at which the sun's rays strike the Earth and the fact that at any given moment, half of the planet remains in darkness further reduces this radiation to approximately one-fourth of the solar constant, roughly 340 W/m^2 (Swart & Hertzog, 2016). The amount of insolation reaching the Earth's surface is additionally affected by atmospheric attenuation, which varies due to factors such as latitude, atmospheric conditions (e.g., dust, clouds, water vapour), altitude, and time of day. These factors make it exceedingly challenging to accurately replicate the sun's energy (Department of Energy, n.d.). The annual 24-hour global solar radiation average in South Africa is about 220 W/m^2 (Quansah, *et al.*, 2016).

To emulate the intense heat of the summer sun, the selected heater lights were operated with multiple lights switched on and off throughout the program created by the researcher. Each heater light had a power output of 1400W. Further details regarding the simulation setup is discussed in the next section, 3.2.7.

3.4.3. The electrical components of artificial sunlight inside the laboratory

3.4.3.1. Arduino

Arduino is an open-source electronic software introduced in Italy in 2005 to provide an accessible platform for individuals, especially students, to develop electronic projects. It is a programmable circuit board featuring a microcontroller, a programming environment, and numerous inputs and outputs. Arduino combines

both hardware and software and is designed for easy and rapid prototyping (Arduino, 2023). One of its key functions is to read inputs, such as light or sensor data, and then instruct the microcontroller accordingly. Arduino's programming language, which is based on Wiring, and its software environment (IDE), based on Processing, make it accessible and user-friendly (Arduino, 2023). The advantages of using Arduino include its affordability, cross-platform compatibility, open-source software, and a wide array of hardware options (Banzi and Shiloh, 2014; Arduino, 2023).

The microcontroller within an Arduino act as the central processing unit of the board, controlling all inputs and outputs. These inputs and outputs include functions like sensor readings, motor control, and interfacing with other devices. The Arduino's programming environment enables users to write code and upload it to the board for execution (Banzi & Shiloh, 2014). Arduino's programming language, based on a simplified version of C++, is well-suited for beginners. The software package includes a code editor, compiler, and uploader, allowing users to write, modify, and transfer code to the board for execution (Arduino, 2023). Arduino's versatility extends to various applications, including robotics, automation, and education. It can be used to control lights, motors, and a wide range of electronic systems. Arduino offers several advantages over other microcontroller platforms, including its ease of use, cost-effectiveness, and flexibility. Being open-source, Arduino allows users to modify and adapt their designs, and it benefits from a robust community that provides ample resources and online support (Banzi & Shiloh, 2014).

3.4.3.2. Relay switches

Relay switches are commonly employed to control electrical circuits in a diverse range of applications. One of the most prevalent types of relays is the electromagnetic relay switch, which consists of a coil, an armature, and a set of contacts. When an electric current passes through the relay's coil, it generates a magnetic field that attracts the armature, causing the contact switch to close. When the current ceases, the armature returns to its initial position, opening the contacts once more (Wendt, 2017). Another frequently used type is the solid-state relay, which employs semiconductors like transistors and thyristors to regulate the flow of current (Wendt, 2017).

The choice of relay switch depends on the specific application and performance requirements. Electromagnetic relays are preferred for scenarios involving high currents from the control circuit, while solid-state relays are favoured for situations that necessitate high-speed switching or compact, lightweight designs. Relay switches find broad utility across various fields, including the automation industry where they control the operation of machinery and equipment (Morrison, 2002). In power systems, relay switches are essential for managing the flow of electricity and safeguarding electrical equipment from damage (Schweber, 2018).

3.4.3.3. The electrical wiring of artificial sunlight inside the laboratory

In Figures 3.10 and 3.11, the circuit diagram of the heater lights can be observed. The heater lights are labelled with a numbering system from 1 to 9 and A to U, totalling thirty in all. All the wiring for the heater lights was connected to two 5V 16-channel relay boards. The relay boards are designed to switch high-current electrical

loads for AC or DC, such as the heater lights used in this study. A 5V 16-channel Relay Interface Board can control various appliances or equipment with a large current. In this case, it is controlled by multiple devices directly, including an Arduino.

The 5V 16-Channel Relay is connected to an Arduino UNO and an Arduino Nano. The Arduino is an open hardware development board used to design and build devices that interact with the real world. The Arduino Nano is a miniature version of the Arduino UNO, functioning similarly but with a smaller form factor. Notable differences with the UNO include the absence of a DC power jack, the use of a mini USB port instead of a USB B port, and the absence of the USB-TTL converter chip. The Arduino UNO was connected to the Arduino Nano due to the need for more digital ports. Thirty digital ports were required, with each heater light representing a digital port.



Figure 3.10: Photograph of the circuit of heater lights

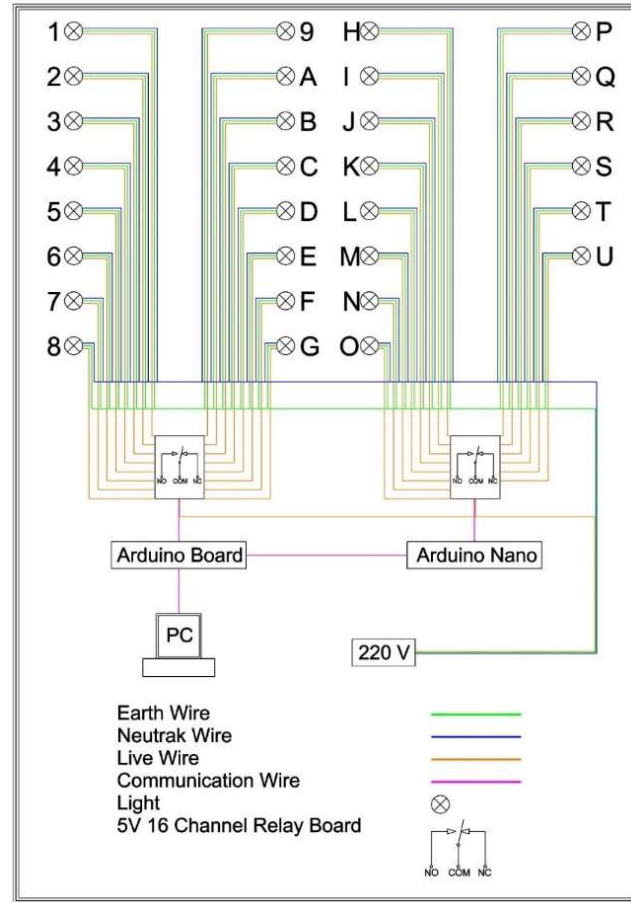


Figure 3.11: Circuit diagram of the heater lights

The Arduino UNO and Arduino Nano communicate with a software program that assigns each heater light, relay, and digital port a unique identity, as shown in Table 3.4. The scale used for this study is one to six, which also applies to the scaling of time. This means that a one-year simulation can be completed in approximately two months. In Table 3.4, the scaled-down average times for each month can be observed. Rounded, average scaled-down times were selected to simplify the program and maintain a constant time range throughout.

Table 3.4: Arduino mapping for the program developed.

	LIGHTS AND TIME IN (MIN)											NIGHT (MIN)	DAY (MIN)
January	JD9-1 (1) (2)	JD10-1 (2) (3)	JD12-1 (4) (5)	JD14-1 (6) (7)	JD5-1 (C) (17)	JD10-2 (I) (N3)	JD16-2 (O) (N9)	JD7-2 (Q) (N11)	JD5-2 (S) (N13)	JD4-2 (T) (N14)	JD3-2 (U) (N15)		
x31				JD13-1 (5) (6)	JD6-1 (B) (12)	JD9-2 (H) (N2)	JD15-2 (N) (8)	JD8-2 (P) (N10)					
	12	12	12	12	13	13	13	12	12	12	12	100	140
February	JD9-1	JD10-1 (2) (3)	JD12-1 (4) (5)	JD13-1 (5) (6)	JD6-1 (B) (12)	JD9-2 (H) (N2)	JD15-2 (N) (8)	JD8-2 (P) (N10)	JD5-2 (S) (N13)	JD4-2 (T) (N14)	JD3-2 (U) (N15)		
x28	11	12	12	12	12	12	12	12	12	11	11	106	134
March	JD11-1 (3) (4)	JD7-1 (A) (11)	JD1-1 (G) (A3)	JD14-2 (M) (N7)	JD6-2 (R) (N12)								
x31	25	25	25	25	25							113	127
April	JD11-1 (3) (4)	JD8-1	JD2-1 (F) (A2)	JD13-2 (L) (N6)	JD6-2 (R) (N12)								
x30	23	23	24	23	23							122	118
May	JD11-1 (3) (4)	JD16-1 (8) (9)	JD3-1 (E) (A1)	JD12-2 (K) (N5)	JD6-2 (R) (N12)								
x31	21	22	22	22	21							130	110
June	JD15-1 (7) (8)	JD4-1 (D) (A0)	JD11-2 (J) (N4)										
x30	34	35	34									136	104
July	JD11-1 (3) (4)	JD16-1 (8) (9)	JD3-1 (E) (A1)	JD12-2 (K) (N5)	JD6-2 (R) (N12)								
x31	20	20	21	20	20							137	103
August	JD11-1 (3) (4)	JD8-1	JD2-1 (F) (A2)	JD13-2 (L) (N6)	JD6-2 (R) (N12)								
x31	21	21	22	21	21							132	108
September	JD11-1 (3) (4)	JD7-1 (A) (11)	JD1-1 (G) (A3)	JD14-2 (M) (N7)	JD6-2 (R) (N12)								
x30	22	23	23	23	22							125	115
October	JD9-1	JD10-1 (2) (3)	JD12-1 (4) (5)	JD13-1 (5) (6)	JD6-1 (B) (12)	JD9-2 (H) (N2)	JD15-2 (N) (8)	JD8-2 (P) (N10)	JD5-2 (S) (N13)	JD4-2 (T) (N14)	JD3-2 (U) (N15)		
x31	10	11	11	11	11	11	11	11	11	11	10	116	124
November	JD9-1 (1) (2)	JD10-1 (2) (3)	JD12-1 (4) (5)	JD14-1 (6) (7)	JD5-1 (C) (17)	JD10-2 (I) (N3)	JD16-2 (O) (N9)	JD7-2 (Q) (N11)	JD5-2 (S) (N13)	JD4-2 (T) (N14)	JD3-2 (U) (N15)		
x30				JD13-1 (5) (6)	JD6-1 (B) (12)	JD9-2 (H) (N2)	JD15-2 (N) (8)	JD8-2 (P) (N10)					
	11	11	11	12	12	12	12	12	12	11	11	108	132
December	JD9-1 (1) (2)	JD10-1 (2) (3)	JD12-1 (4) (5)	JD14-1 (6) (7)	JD5-1 (C) (17)	JD10-2 (I) (N3)	JD16-2 (O) (N9)	JD7-2 (Q) (N11)	JD5-2 (S) (N13)	JD4-2 (T) (N14)	JD3-2 (U) (N15)		
x31				JD13-1 (5) (6)	JD6-1 (B) (12)	JD9-2 (H) (N2)	JD15-2 (N) (8)	JD8-2 (P) (N10)					
	12	12	12	12	13	13	12	12	12	12	12	101	139

3.4.4. The coding of artificial sunlight inside the laboratory

Creating a software program to simulate the lighting arrangement over the course of 365 days was a crucial aspect of the study. The program needed to accurately simulate the movement of the sun both vertically and horizontally. The program was developed using C# (C sharp) in Visual Studio, an integrated development environment (IDE) provided by Microsoft. Visual Studio is a versatile tool for developing computer programs, including websites, applications, web services, and mobile apps. It features a code editor with support for code refactoring and component development. The IDE supports multiple programming languages, allowing for the incorporation of coded solutions and facilitating project and solution management. It also aids in machine-level code debugging.

For this project, the programming language selected was C#. C# is a high-level language that supports multiple programming paradigms. It allows for implicitly typed variable declarations and implicitly typed arrays with a collection initializer. This language choice provides the advantage of widespread availability of troubleshooting resources and existing plugin solutions. Tutorials and solutions for C# programming are also readily accessible. The mapping of the Arduino UNO and Arduino Nano served as the foundational building blocks for the coding.

Figure 3.12 illustrates the program interface, showcasing the lighting layout, time, date and duration of the scaled time represented by a green bar. The lightbox changes from grey to orange when a heater light is switched on. After a light's timer completes, the next heater light switches on. A 5-second delay was introduced between each turning on and off sequence to prevent overloading of the circuit. In

the event of the circuit overloading, a relay will blow, ensuring the program's reliability throughout the simulation period. The C# coding for the artificial sun simulator can be found in Appendix L.

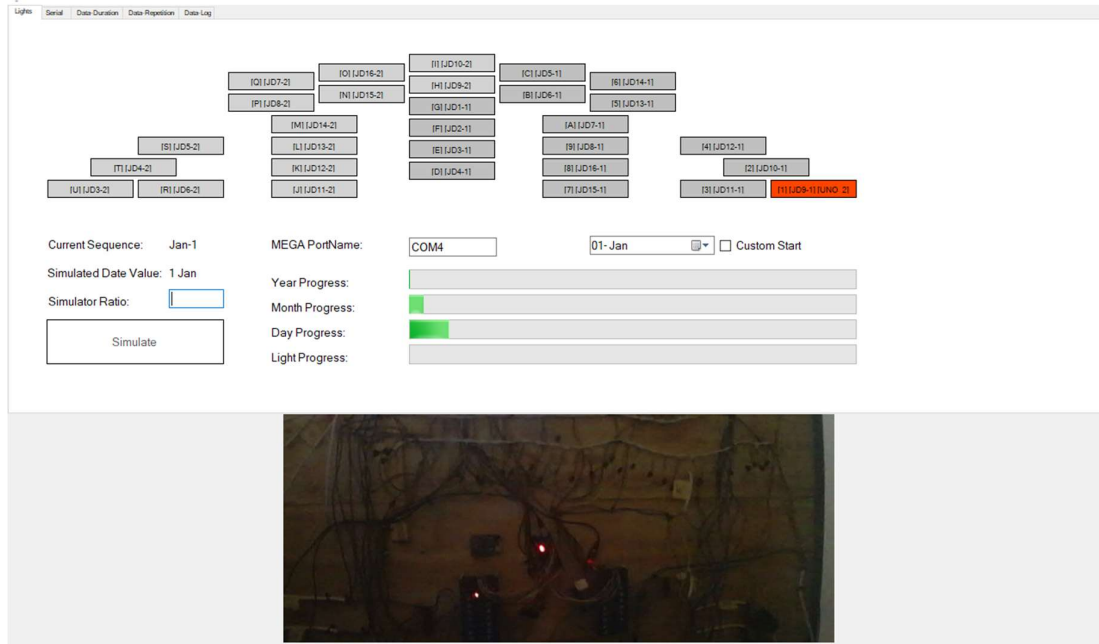


Figure 3.12: Program interface

3.4.5. The simulation of rainfall

An appropriate simulation was developed to reproduce rainfall conditions within the laboratory. The setup included a water tap and a water flow meter. The option of simulating rainfall from above was not considered due to the electronic devices installed inside the SM, and in order to safeguard them from potential water-related effects. A lateral rainfall simulation approach was selected as a more viable alternative. Fine-spring sprinklers were selected to ensure uniform rainfall coverage during the simulation. These were strategically positioned in the corners of the simulation area, as illustrated in Figure 3.13. The simulated rainfall volume is based on the rainfall in Botshabelo but scaled down to one-sixth of the actual rainfall that characterises the Botshabelo region. These choices were made to support

authenticity while maintaining the ability to control the study. Readings were taken from the water flow metre with each simulated rainfall period to track the amount of simulated rainfall across the experimental area. Simulating rainfall was imperative to secure dependable data.

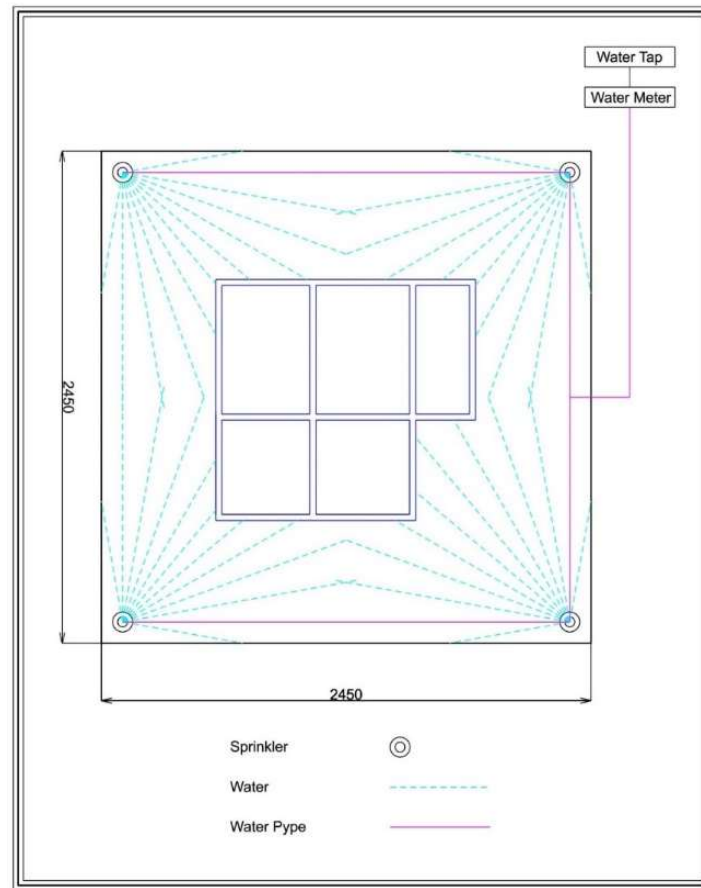


Figure 3.13: Sprinklers layout for simulating rainfall

3.5. Construction of scale model foundations and monitoring

Within the laboratory, two distinct types of foundations were constructed. The first is the SM foundation, which was designed and based on measurements taken from the stock raft foundation in Botshabelo. The second structure is a cavity raft foundation, sharing the same geometry and layout as the raft foundation but with a

suspended slab floor that eliminates the soil-concrete slab interface. As the SM was constructed, many of its building elements had to be proportionally scaled down.

3.5.1. 3D printing

3D printing, involves constructing 3D models layer by layer. While this technology has been in existence for several decades, recent advancements in software, hardware, and materials have significantly increased in popularity. The capability to efficiently and cost-effectively produce intricate shapes and customised products has rendered 3D printing an attractive option for a wide range of industries (TWI, 2021). 3D printing has revolutionised manufacturing processes, enabling the rapid and cost-effective creation of complex geometries and personalised products (HUBS, 2021).

To secure the OptoNCDT laser displacement sensor into the appropriate positions on the steel frame, various 3D-printed brackets were designed and tested. Multiple tests were conducted on the 3D filaments used to print the brackets. Based on considerations of temperature resistance and strength, polyethylene terephthalate glycol filament (PETG) was chosen over polylactic acid filament (PLA). PETG has a melting temperature of 255°C, PLA's melting temperature is only 220°C. Table 3.4 summarises the factors considered before making the final filament material selection. The decision to opt for PETG over PLA was due to the room's temperatures.

Table 3.5: PETG and PLA properties

Property	PETG	PLA
Strength	Strong	Less strong
Durability	Durable	Less durable

Cost	More expensive	Less expensive
Moisture resistance	More resistant	Less resistant
Warping resistance	Less resistant	More resistant
Ease of printing	More difficult	Easier

Figure 3.14 illustrates the concept of 3D drawings for the brackets. The 3D-printed brackets were tested according to the following criteria:

- I. Ease of inserting and removing the OptoNCDT laser within the bracket.
- II. Whether the readings were accurate while inserting and removing the laser.
- III. Positioning the 3D printed brackets near the heater lights and measuring deformations using callipers.
- IV. Applying a load on the 3D printed brackets and measuring deformations, observing whether the brackets return to their original position.

The final design selected for the 3D-printed brackets featured a fork-shaped configuration that securely held the OptoNCDT laser in place. The design involved clamping the laser between the two points of the fork using a clamp. Positioning the OptoNCDT laser in the fork design involved placing it in the bracket's back corner and securing it through clamping. A fill percentage of thirty was used when printing the 3D-printed brackets, providing a balance of strength and rigidity.

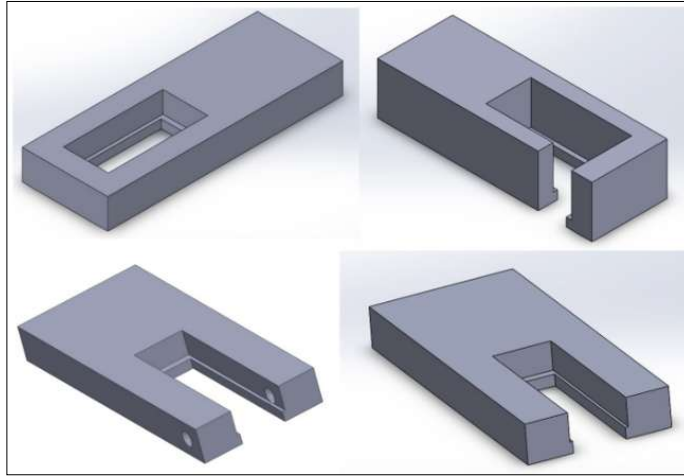


Figure 3.14: Bracket designs for OptoNCDT lasers on the steel frame

Twenty four (24) 3D-printed brackets were printed and attached to the steel frame. The brackets were numbered to correspond with a specific laser, ensuring that each laser was used at six locations. The A1 to D6 numbering system was implemented to provide a clear and organised way to identify and track different lasers within the setup. This numbering system reduced the potential for errors and ensured that measurements from each laser were correctly collected and analysed. All the readings from the OptoNCDT laser displacement sensor were captured daily when the artificial sun inside the laboratory was off.

3.5.2. Manufacturing of scale bricks

Scaled-down bricks were produced by the researcher to construct the walls of the SM structures. These walls serve a crucial role in replicating the structural dynamics. First, they apply a load from the top onto the scaled foundation models. Secondly, they cast shadows on the southern side of the scaled buildings during daylight hours. These shadows reduce the heat energy reaching the area opposite the artificial sun, simulating real-world conditions observed in Botshabelo.

Botshabelo's GSH construction typically involves low-cost bricks, with common masonry brick sizes being 390 x 90 x 190 mm or 390 x 190 x 190 mm. The latter option was chosen for the masonry bricks due to challenges in manufacturing smaller bricks to scale one to six. The bricks manufactured for the research project were cement bricks with a compressive strength of 5 MPa, as tested in the laboratory.

A 3D-printed mould was made from polylactic acid (PLA) plastic was created to produce the masonry bricks used in constructing the SM. Each mould could cast six bricks at a time. Figure 3.15 displays the 3D-printed moulds. Bricks were cast daily for two months, with an estimated requirement of approximately three thousand bricks to construct two scaled models.



Figure 3.15: 3D-printed moulds for manufacturing bricks scaled one to six

Figure 3.16 presents the completed cast-scaled bricks, which were allowed to dry and cure further. After twelve hours inside the mould, the bricks were placed inside a container for further curing. Attempting to remove the bricks from the moulds after twenty-four hours proved problematic as the cement-cast bricks could no longer be extracted. To resolve this issue, a release agent was applied to the moulds before

casting in batches. It allowed for easy extraction without compromising the integrity of the bricks.



Figure 3.16: The manufacturing of scale one to six bricks

3.5.3. The construction of the SM raft and cavity raft foundations

Appendix K showcases the drawings of the SM raft and cavity raft foundations in sections X-X and Y-Y. The size of the SM foundations is scaled down to one-sixth that of the Botshabelo house. The concrete used for casting the SM foundations had a strength of 18MPa on day 7.

The foundation layout was measured, and the building line was marked as a guideline. Wetting the soil was necessary before digging the trenches. Due to the small size of the trenches, spatulas were used for excavation, as traditional digging equipment was not practical. Dry topsoil made digging with spatulas challenging and time consuming.

The construction of the SM cavity raft foundation followed a similar approach to the SM raft foundation, with the primary difference being the model's suspended slab and its ventilated design. Trenches were excavated using spatulas and then filled

with the same mixture used for the SM raft foundation. Two rows of bricks with ventilation holes were constructed, followed by the placement of a precast slab, creating a cavity with ventilation.

After the foundations were completed, the cast bricks were laid by, mixing cement mortar and carefully placing each brick to ensure it was as level as possible. Builders' lines and small spirit-level tools were used to maintain straight and accurate walls. Constructing one layer of brickwork took approximately three hours. Figure 3.17 shows the construction process of the walls. No door or window openings were included to protect water-sensitive equipment and monitoring devices inside the SM from potential damage during simulated rainfall.

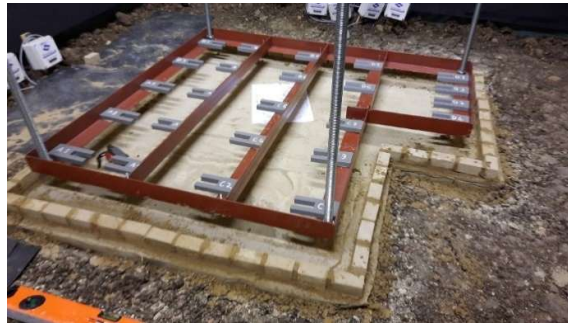


Figure 3.17: The construction of the SM house

Figure 3.18 displays an almost completed SM house. Once the walls were completed, a removable flat roof was constructed using plywood cut to fit the SM house. The roof served two primary purposes: to minimise water ingress into the SM, and to shield instrumentation and monitoring devices from excessive heat energy.



Figure 3.18: Completed SM house

3.6. Instrumentation monitoring of SM raft and cavity raft foundations

3.6.1. Laser displacement sensors

Laser displacement sensors (LDS) are a widely adopted technology for measuring the distance between a sensor and a target object using a laser beam (MICRO-EPSILON, 2022). This non-contact method is characterised by its high accuracy, speed, and the valuable data it provides. Laser displacement measurements have consistently proven reliable in civil infrastructure assessments and play a pivotal role in monitoring structural displacements, ensuring infrastructure safety and stability. LDS accurately measures structural movements and provides real-time data for infrastructure monitoring (Ma, *et al.*, 2023). The fundamental principle of operation is based on measuring the time-of-flight (TOF) of a laser beam. The LDS emits a laser beam toward the target object, and the sensor detects the reflected beam, measuring the time it takes for the laser beam to travel to the target and back. The distance between the sensor and the target can be calculated using the speed of light (Maekawa, *et al.*, 2016).

Various types of LDS are available in the market, each with its own set of advantages and limitations (Donati, 2023). They are as follows:

- I. **Confocal LDS:** Utilises a confocal optical system to measure the distance between the sensor and the target object (Donati, 2023). It boasts high axial resolution and is employed for measuring an objects height, thickness, and distance with exceptional precision (Mueller, *et al.*, 2016).
- II. **Triangulation LDS:** Employs an optical triangulation system to measure the distance between the sensor and the target object. It excels in measuring objects with rough surfaces (Kim & Lee, 2021).
- III. **Interferometric LDS:** Utilises the interference pattern of a laser beam to measure the distance between the sensor and the target object. This type offers high resolution and is suitable for measuring the distance of objects with smooth surfaces (Donati, 2023).

Figure 3.19 depicts the assembly of the laser sensors, illustrating the laser light focused through the emitting lens, along with the wiring connections and colour coding. To reach the models, the OptoNCDT laser displacement sensor cables had to be extended by 10 metres and connected to a four-channel receiver powered by a 24V power supply.

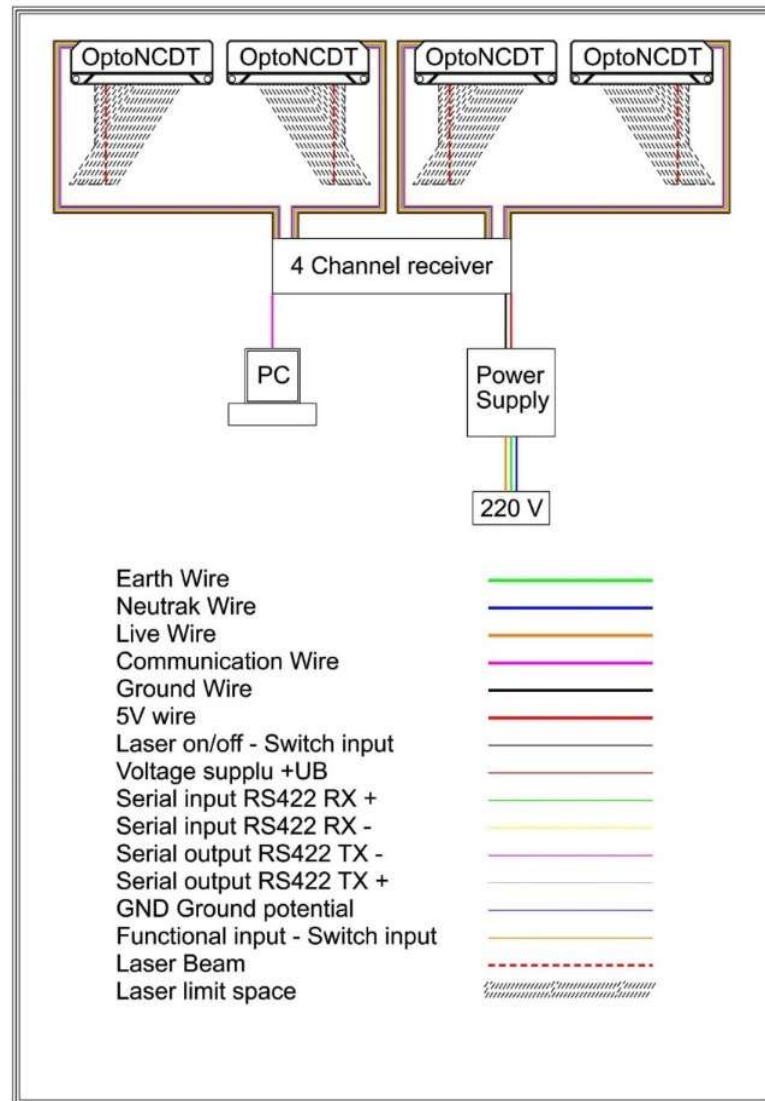


Figure 3.19: Wiring of OptoNCDT lasers

The OptoNCDT laser displacement sensors were connected to a four-channel receiver for data communication with computer software and to supply power to the sensors. This receiver collects and processes signals from the four OptoNCDT laser devices and amplifies the signals, providing clean and precise data to external computer software. Figure 3.20 illustrates the connections made to the four-channel receiver of the laser optical displacement sensors.

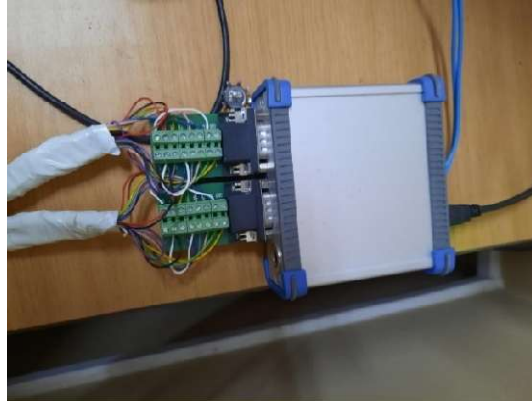


Figure 3.20: Four-channel receiver of the laser optical displacement sensors

The SensorTOOL software, available for free on MICRO-EPSILON's website (MICRO-EPSILON, 2022), processes data received from the OptoNCDT laser displacement sensors in millimetres. The OptoNCDT lasers are commonly used in industrial manufacturing and are known for their reliability and accuracy, with an accuracy setting of up to two decimal places or one-hundredth of a millimetre for measuring the laboratory's models. Figure 3.21 displays a screenshot of the SensorTOOL software homepage, showing four OptoNCDT lasers connected to the four-channel receiver, allowing for the simultaneous measurement of four points. In Figure 3.22, the software interface is presented, where movement data is collected and subsequently stored in an Excel spreadsheet for data analysis.

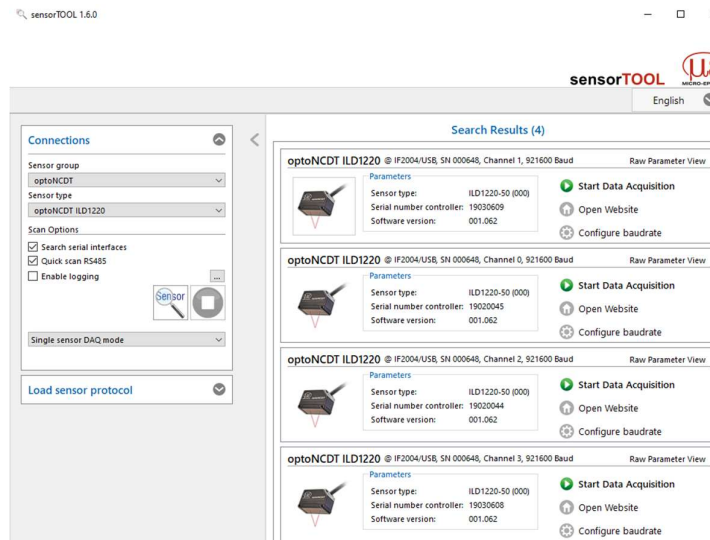


Figure 3.21: Screenshot of the SensorTool software homepage

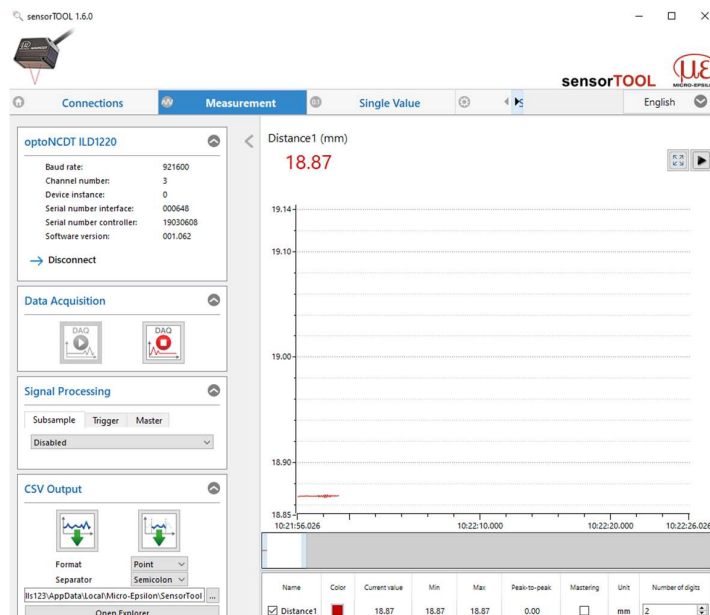


Figure 3.22: Screenshot of the data collection page in SensorTool software

The measurement of the SM movement was crucial to the success of the project. The OptoNCDT lasers have a measuring range of between 15 and 65mm, providing a high degree of accuracy within this range. To ensure precise measurements, it was necessary to isolate the OptoNCDT laser displacement sensor from the surrounding structures and position it within the detection range. Due to the cost constraints associated with the OptoNCDT lasers, only four were obtained. While

this limited the number of readings on the model foundations, a bracket system was devised and constructed to address this limitation. The bracket system was positioned above the model foundations within the required range. Constructed from a 50 x 50 x 3mm angle iron, the steel bracket system was secured with four 20mm threaded rods and locking bolts on the bracket's top and bottom. The 20mm threaded rods adjusted the steel bracket's position, ensuring optimal placement. These rods were then connected to another steel structure above the SM's location, which was also made from 50 x 50 x 3 mm angle iron and fixed to the laboratory's concrete walls using eight M12 rawlbolts. Figure 3.23 provides an illustration of the steel frame for the OptoNCDT laser displacement sensor.

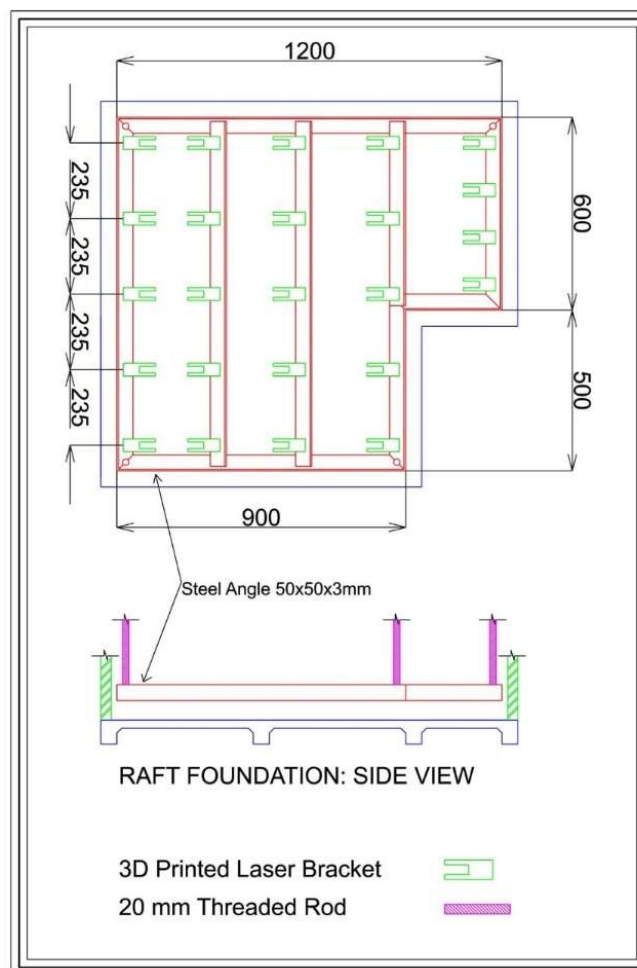


Figure 3.23: Steel frame layout for OptoNCDT lasers for measuring movement

3.6.2. Concrete strain in shallow foundations

3.6.2.1. Factors affecting concrete strain in foundations

Several factors can influence the strain experienced by concrete in shallow foundations, including the magnitude of the applied load, the stiffness of the underlying soil, the strength of the concrete, the properties of the reinforcement, and the foundation's geometry (Fulton, 2018). The magnitude of the applied load is a pivotal factor, determining the stress levels in concrete, thereby directly affecting the resulting strain. Equally significant is the stiffness of the underlying soil; softer soils may lead to greater deformations and strain within the concrete. The strength of the concrete and the properties of the reinforcement used can also exert an influence on the strain levels observed in the foundation. Furthermore, the geometry of the foundation, encompassing its shape and size, can significantly impact strain level (Bowles, 1997). Designers must consider these factors while contemplating the implications of concrete strain, accounting for various loading conditions (Fulton, 2018). Excessive strain can result in structural cracking, posing a risk to the overall integrity of the construction. Thus, it is essential to determine the foundations safe strain thresholds under different loading conditions and its potential for long-term deformation and settlement (Bowles, 1997).

3.6.2.2 Concrete strain measurements

The measurement of concrete strain is indispensable in guaranteeing structural stability and safety (Fulton, 2018). Several methods exist to measure strain, with strain gauges and displacement sensors being prominent examples (Freire, 2009). These methods enable the accurate measurement of strain at various points within the foundation, providing valuable insights into the structure's overall behaviour

under load. Additionally, mathematical models can be used to predict concrete strain, drawing upon information regarding the applied load, soil stiffness, concrete strength, reinforcement properties, and foundation geometry. These models aid designers in optimising foundation design to suit specific loading conditions (Bowles, 1997).

One widely adopted type of concrete strain gauge is the electrical resistance strain gauge. This gauge operates on the principle that when a wire or foil is subjected to strain, its cross-sectional area decreases, increasing electrical resistance. The alteration in resistance is subsequently measured and used to calculate strain (Freire, 2009). The appropriate strain gauge type selection depends on the application's specific requirements and the desired accuracy. Electrical resistance strain gauges are prevalent in Civil Engineering due to their high accuracy and reliability. They find application in various Civil Engineering scenarios, including monitoring deformation and strain in bridges, buildings, and other structures (Freire, 2009). Strain gauges are also integral in the testing of mechanical properties of concrete specimens within laboratory settings (KYOWA, n.d.)

3.6.2.3. Strain measurement on the SM foundations

Strain refers to the change in length relative to the original length before any deformation occurs. Strain measurement is vital in assessing the behaviour of concrete structures. The study focuses on evaluating strains to understand the behaviour of the two SM foundations. Figure 3.24 illustrates the placement of strain gauges SM raft foundation. Gauges were positioned in both the X-X and Y-Y directions to obtain readings in both directions for analysis purposes.

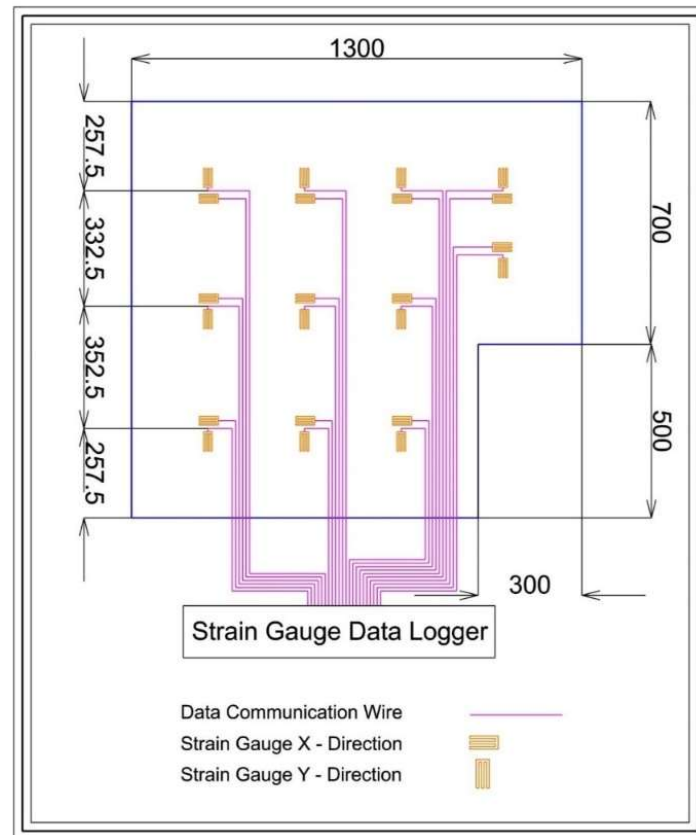


Figure 3.24: Strain gauge layout on SM raft foundation

Figure 3.25 shows the placement of strain gauges on the SM cavity raft foundation. Given that the floor was suspended, the strain gauges along the foundation beams came into contact with the soil. In contrast, the entire slab of the SM raft foundation and beams were in contact with the clay soil.

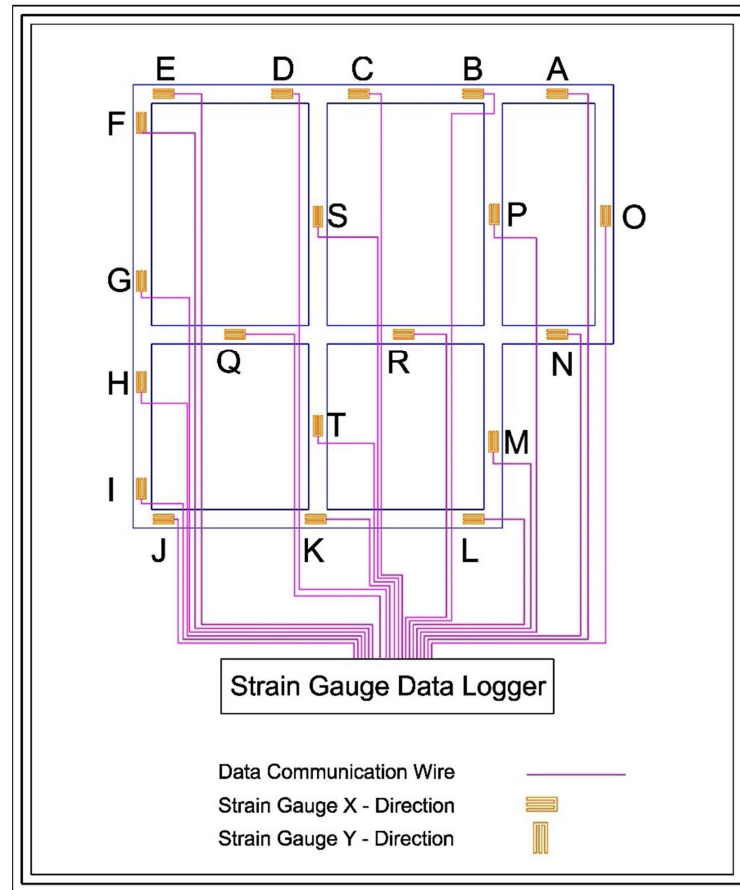


Figure 3.25: Strain gauge layout on SM cavity raft foundation

Figure 3.26 displays the strain gauge meter used for taking readings. This instrument is from Tokyo Instruments and has proved to be reliable. Strain readings were collected daily, and the data was captured in an Excel sheet. The importance of the strain readings lies in tracking their changes during the simulation period. All data is presented in Chapter 4 and Appendices G and H.



Figure 3.26: Strain gauge with strain meter

3.7. Research data management and analysis

3.7.1. Data analytics using 3DField

3DField is a versatile software tool widely used for data analysis in field modelling. It enables users to create 2D or 3D models and analyse various parameters through contouring. Additionally, it enables the generation of 3D maps depicting real-world locations. This tool finds primary application in urban planning, Civil Engineering, and Architecture, where it serves as a powerful instrument for visualising proposed developments and building designs. It excels in facilitating precise simulations of the impact of new structures on their surroundings and assessing design feasibility (Galouchko, 2019).

3DField stands out for its user-friendly interface, making it invaluable due to its ease of use and accuracy. Furthermore, 3DField fosters effective communication among stakeholders by offering precise and faithful representations of plans (Galouchko, 2019). Notably, 3DField has been successfully implemented in a study that measured moisture variation patterns beneath a GSH in Botshabelo and used contouring techniques to generate models (Bester, *et al.*, 2016).

3.7.2. Data analytics using contouring techniques

Contouring is a cartographic technique that employs shading, colour contouring, hachure, and layer tinting to accurately represent a map's topography or regions. This technique finds widespread applications in various fields, including Geology, Geography, and Civil Engineering. Cartographers have relied on contouring for centuries to create maps that accurately depict terrain, making them clear and easily interpretable. Today, contouring has become an indispensable tool for

cartographers, allowing them to represent the terrain and map areas in the most suitable manner. Commercial interpolation software packages are widely utilised for contouring purposes (Heywood, *et al.*, 2011).

Contouring is a method that relies on the concept of isolines, which are lines connecting points of equal value. In contouring, isolines join points of equal elevation. The contour interval, signifying the spacing between isolines, is typically determined considering the map's scale and the nature of the depicted terrain. A smaller contour interval allows for a more intricate representation of terrain, while a larger interval is suitable for less detailed maps (Heywood, *et al.*, 2011).

Typically, shading is used to represent changes in elevation, with lighter shades indicating higher elevations and darker shades representing lower elevations (Burrough, *et al.*, 2015). In Civil Engineering, contouring plays a vital role in depicting terrain elevation and slope, which is essential for infrastructure design, including roads and bridges (Chang, 2019). Studies have compared the performance of various interpolation techniques. In a study by Kiliç *et al.*, (2022), Inverse distance weighted, Kriging, and minimum curvature were compared for estimating soil organic carbon content. The study revealed that Kriging produced the most accurate estimates, followed by Inverse distance weighted and minimum curvature (Kiliç, *et al.*, 2022). Among other commonly used interpolation techniques and methods are the following (Galouchko, 2019):

- I. **The minimum curvature method:** Widely used in earth sciences, this method generates an interpolated linearly elastic surface that minimises

bending while passing through each data point. Although it produces a smooth surface, it does not qualify as an exact interpolator.

- II. **The natural neighbour method:** This approach considers a set of Thiessen polygons, based on a Delaunay triangulation. It employs a weighted average of neighbouring points but does not extend contours beyond the convex hull of the data points.
- III. **Triangulation:** It creates triangles by connecting data points in a way that triangle edges do not intersect with one another. This method is an exact interpolator and works best when data is evenly distributed over the grid area.
- IV. **Radial Basis Functions (RBF):** A group of data interpolation methods that are exact interpolators, these methods attempt to honour the data while introducing smoothing factors to produce a smoother surface. These functions define the optimal set of weights to apply to the data during interpolating.

3.7.3. Data capture collection & storage

Throughout the research project, a substantial amount of data was collected, organised, and analysed using Microsoft Excel and DFM probe utility software. The data was gathered from various sources, including soil samples and instrumentation installed in and around the SM foundations. The dataset is invaluable for developing models to analyse moisture variation patterns and differential movements in expansive clay soils, thereby enhancing an understanding of soil and model behaviour under various conditions. During the weekly data collection, the moisture probes were continuously monitored and inspected to ensure accuracy, and any errors in the logged data were addressed to ensure data quality.

The detailed analysis of the data, conducted using Microsoft Excel and DFM probe utility software, contributed to the development of accurate models that are of great significance in the field of foundation engineering on expansive clay soils. The insights derived from this data provide a strong foundation for the development of new and improved foundation designs suitable for implementation on expansive clay soils.

A two-tiered storage system has been employed to ensure the security and availability of the collected data. All research data is stored on external hard drives, which are regularly backed up to prevent data loss. Additionally, a cloud-based storage solution, Microsoft OneDrive, was utilised to provide remote access to the data and enhance its security.

3.7.4. Data analysis

Data analysis for this study involved the use of both Excel and 3DField software, each providing unique tools for visualizing and interpreting patterns in the dataset, including moisture, movement, and strain data.

Using Excel, the data analysis process included the following steps:

- I. Data Collection and Preparation: Collected data was imported into Excel and organized into a tabular format with rows and columns for easier handling.
- II. Data Cleaning: Data was validated and cleaned to remove errors, with Excel tools like filtering, sorting, and conditional formatting aiding in this process.

- III. Data Analysis: Excel's range of tools, such as statistical functions, pivot tables, and charts, were employed to analyse data on moisture, movement, and strain, offering insights into trends and patterns.
- IV. Graph Generation: Various graph types, including line charts, scatter plots, and bar graphs, were used to visualize changes in the dataset, particularly focusing on moisture, differential movement, and strain.
- V. Interpretation: The final step involved interpreting the generated graphs and identifying patterns within the data.

In addition to Excel, 3DField software was utilized to develop visual models that presented moisture patterns and differential movement on a colour scale, enhancing data comprehension through 3D heat maps. The data analysis steps using 3DField were as follows:

- I. Studying the Data: A comprehensive understanding of the dataset structure, variables, and information was achieved through close examination.
- II. Identify Errors: The dataset was checked for errors, including missing values and duplicate entries, and repeat readings were taken to verify movement data and strain readings.
- III. Define Cleaning Rules: Criteria for data cleaning were set, including handling of specific data errors, such as voltage spikes in DFM moisture probe data, which led to deletion of affected rows.
- IV. Export Cleaned Data: Once cleaned in Excel, data was exported to dedicated files for further analysis.
- V. Import Data: The cleaned data was imported into 3DField for modelling and visualization.

- VI. Data Analysis: 3DField tools were used to create models and visual representations of moisture patterns and differential movements.
- VII. 3D Heat Maps for Moisture Concentration and Movement: Colour gradients in the heat maps highlighted areas of high and low moisture, making it easier to identify zones of buildup and movement patterns for model assessment.
- VIII. Interpretation: The final step involved interpreting the results from 3DField models, focusing on moisture distribution and movement dynamics within the study area.

CHAPTER 4: RESULTS, DISCUSSION, AND RECOMMENDATIONS

4.1. Introduction

This chapter provides an overview of the results obtained from the analysis of the raft foundation in Botshabelo, as well as the simulation SM raft and cavity raft foundations constructed in the laboratory. The discussion includes the findings related to moisture variation, differential movement, and strain readings for each type of foundation. Furthermore, this chapter offers design considerations and recommendations for the raft foundation based on the findings from both Botshabelo and the SM raft foundation, with specific emphasis on the cavity raft foundation in the laboratory.

4.2. Botshabelo GSH raft foundation analysis from 2014

The Botshabelo GSH site, located 50 km southeast of Bloemfontein and 15 km west of Thaba Nchu in the Free State, was investigated by Bester et al. (2016). Expansive soils are widespread in Botshabelo. Monitoring of moisture variation beneath the raft foundation began in 2014, with results presented in Appendices A and B. These findings were previously documented in the researcher's Master's dissertation and shared in three conference proceedings.

Several noteworthy patterns emerged from Appendices A and B:

- I. Moisture changes on the east side of the building, beneath the raft foundation, followed a seasonal pattern. Summer months had higher moisture content due to rainfall, while winter periods saw reduced moisture due to lower rainfall. At a depth of 150 mm, moisture fluctuated by 8% over the study period. The architectural design, specifically the re-entry corner on

the southeast side, kept this area shaded from direct sunlight, resulting in the highest moisture content among recorded readings, with a change of approximately 3-4% across the soil profile. The north side, exposed to direct sunlight, displayed the lowest moisture content, leading to clay shrinkage and cracking. Rapid moisture changes were observed following rainfall.

- II. Contrary to the common assumption that the central area beneath the raft foundation would have the highest moisture concentration, moisture content remained relatively constant in this region. Findings suggest that moisture levels in the centre of a raft foundation do not exceed those in the southeastern re-entry corner.
- III. The south side, not exposed to direct sunlight, showed minimal solar influence, leading to stable moisture content during winter months. The upper layer (150 mm) had the lowest moisture content among soil profiles, with variations not exceeding 2%.
- IV. The west side, exposed to the afternoon sun, exhibited lower moisture content compared to other recorded readings beneath the foundation in 2014. After 2015, moisture levels on this side dropped significantly due to paving installed in front of the main entrance. This emphasizes how post-construction practices, such as paving and landscaping, can impact structure performance on active clay soils. Landscaping around the foundation, with proper drainage, should be maintained to mitigate these effects. Moisture changes levelled out toward the end of March 2015.

Edge penetration distance is a critical parameter in raft foundation design. It is defined as the distance from the point where soil moisture content becomes nearly

constant to the outer edge of the boundary beams. Previous studies by Pidgeon (1980), Pidgeon and Pellissier (1987), and Fityus et al. (2004) have indicated that edge penetration distance is affected by factors such as moisture conditions beneath the foundation, temperature, rainfall, and soil properties. Notably, these studies did not account for the foundation's shape or the effects of building shadows, as they were conducted on flat, simulated foundations uniformly exposed to sunlight.

The uneven moisture patterns differ from Duncan's (1992) and Tabassum & Bulut (2023) findings. They suggested that centre doming typically occurs in the middle of a structure. However, greater moisture changes were found at the foundation edges, as they are more exposed to climatic factors. The centre remained relatively stable, but the moisture concentration is located at the re-entry corner of the GSH. This uneven distribution suggests that moisture does not spread evenly across. Factors such as environmental conditions, structural shape, and sun orientation influence the resulting heave. Understanding these patterns can guide design adjustments.

In Figure 4.1, the moisture content is plotted against the building length of the GSH in Botshabelo, with the y-axis representing building length in metres and the x-axis representing moisture content. Results indicate that assigning a single factor to determine each layer's influence on edge penetration distance is challenging. The data suggests the moisture dome is closer to the re-entry corner than the raft foundation's centre. This observation challenges the assumption of a symmetrical dome, indicating potential issues with this concept.

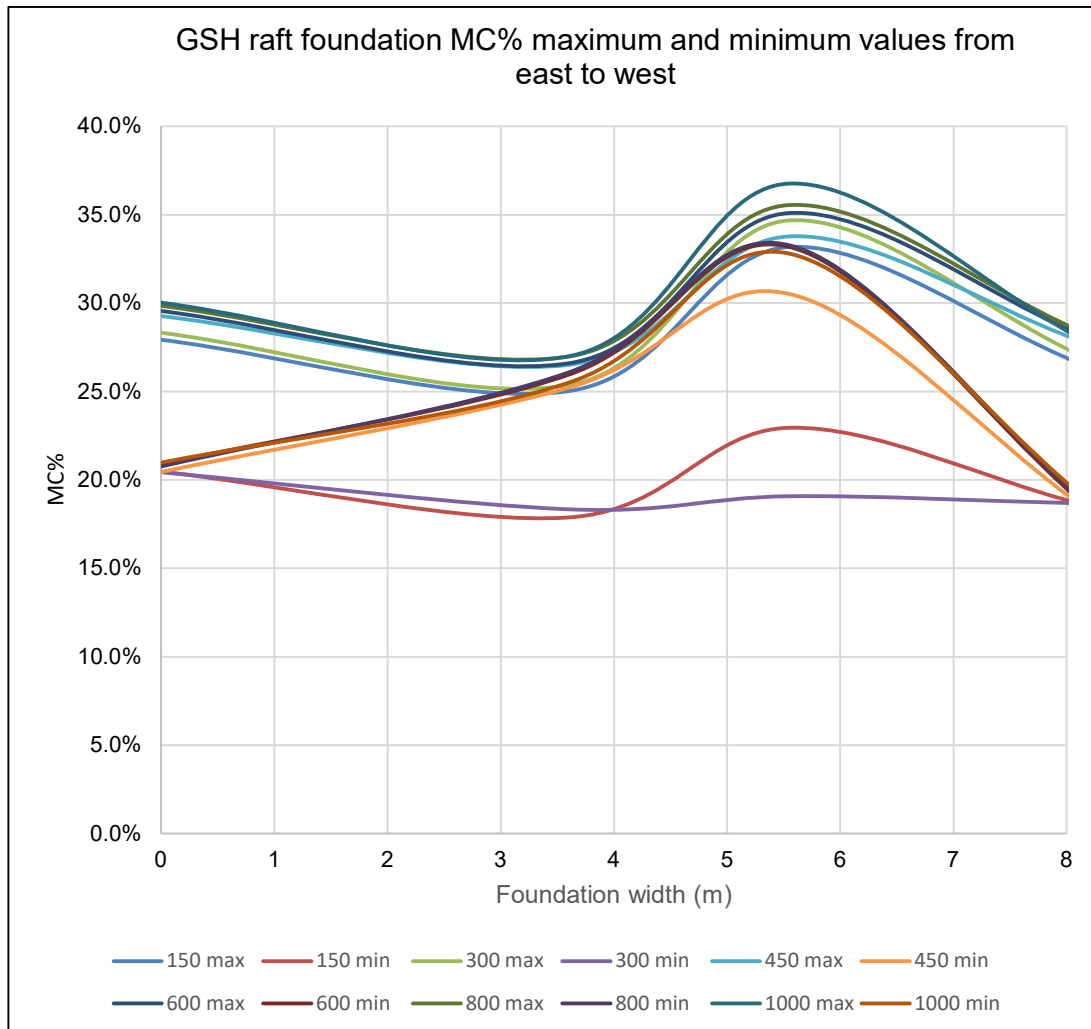


Figure 4.1: Botshabelo GSH raft foundation moisture content maximum and minimum values from east to west at various depths

Figure 4.2 illustrates the same house, this time from south to north, with the y-axis representing the direction from south to north and the x-axis representing moisture content. It is evident that there is a significant range of moisture variation on the north-facing side compared to the south-facing side. This observation raises questions about the stiffness of the north and west beams of many raft foundations constructed on active clay materials, indicating a potential design concern.

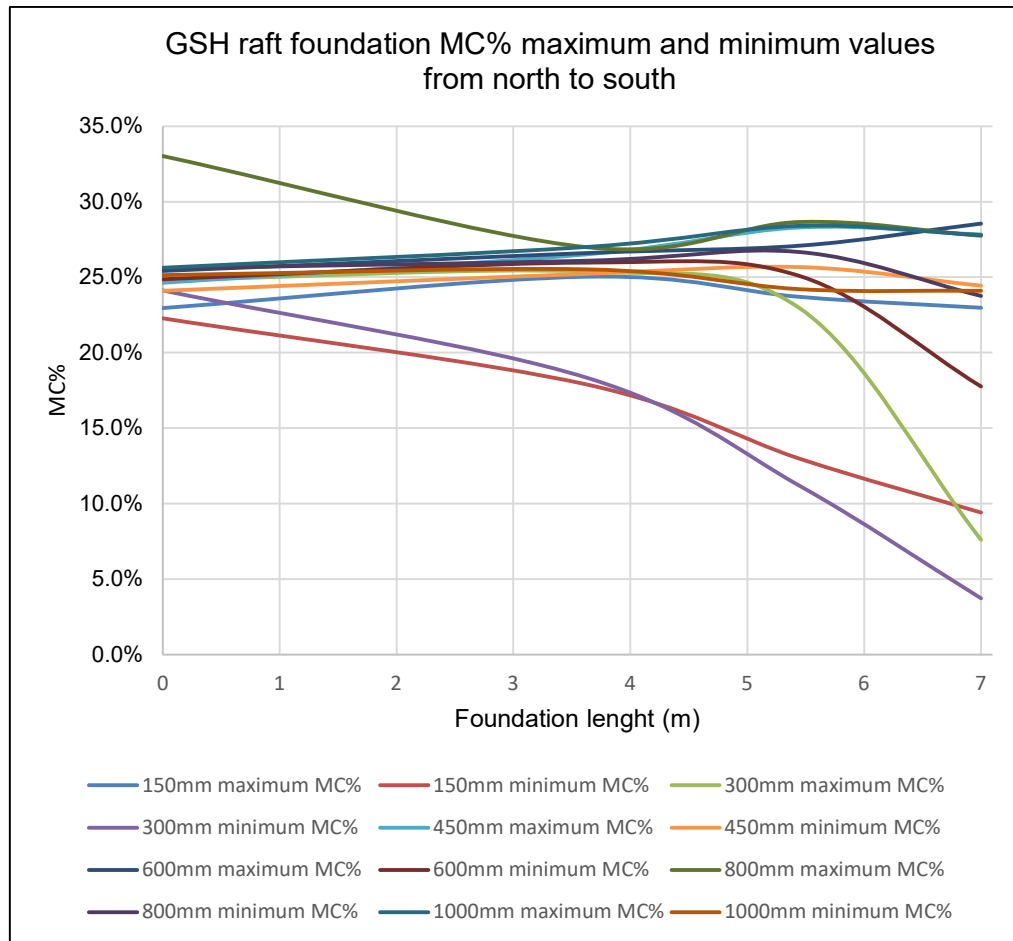


Figure 4.2: Botshabelo GSH raft foundation MC% maximum and minimum values from north to south at various depths

Upon closer examination, the moisture concentration does not appear to be in the centre of the GSH raft foundation. It is situated in the area least exposed to solar energy. The results challenge the concept of an approximately symmetrical dome-shaped heave in simulated foundation tests. The edge penetration distance also lacks a clear value or parameter based on the data, which makes estimating the mound shape and required stiffness challenging. The findings do not support the notion of a flat-top dome since the soil beneath the foundation primarily remains in a fully expanded state, except on the north side where the upper layers may approach the shrinkage limit.

4.3. SM cavity raft foundation analysis

This section focuses on analysing the SM cavity raft foundation within a laboratory setting. It covers parameters such as moisture variation, differential movement, edge penetration distance, and strain measurements.

4.3.1. Moisture movement analysis

Figure 4.3 illustrates the raft foundation's 3D moisture content heat map in December, oriented from the southwest corner. The heat map shows a greater moisture concentration at the re-entry corner, while moisture content decreases towards the north, the sun-facing side. Additionally, areas cast in shadow, such as on the south side, retain higher moisture levels. Additional heat maps illustrating these patterns are provided in Appendix G.

Water movement within unsaturated soils affects the moisture distribution observed in the SM raft foundation. According to Fredlund and Rahardjo (1993), water movement is influenced by soil texture, structure, and pore size. These factors influence suction levels and moisture retention in expansive soils. Higher suction levels near the surface lead to greater moisture content variations, which can be observed. The relationship between moisture content and soil suction is relevant. Higher suction will cause swelling and affect the SM foundation at the re-entry corner, where moisture accumulates. Seasonal changes exacerbate this behaviour, causing shrinkage and swelling to the expansive clay.

Nelson and Miller (1997) described the active zone concept is the depth at which environmental factors, such as rainfall and temperature, influence soil moisture. Soil depth is essential for controlling shrinkage and swelling, especially in seasonal variation. The moisture distribution in the SM raft foundation aligns with soil suction principles affecting moisture movement in unsaturated soils. In the SM, the northern edge experienced greater shrinkage due to higher soil suction at the surface, where direct sunlight accelerates moisture loss. Identifying the impact of soil suction can inform design recommendations for addressing these effects.

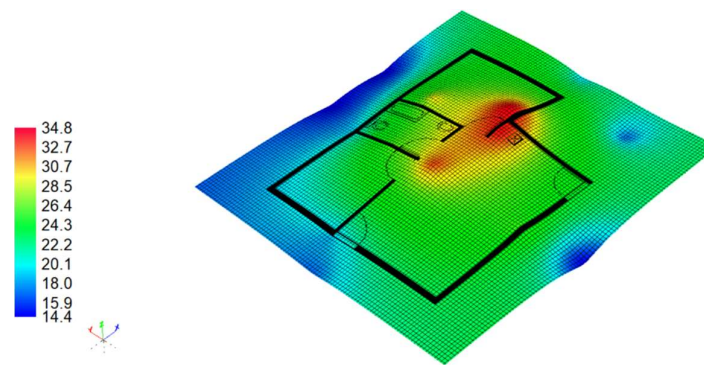


Figure 4.3: Year 2 – December: 3D moisture content (MC%) heat map of the SM raft foundation, orientation from the southwest corner.

Figure 4.4 presents the average moisture content at a depth of 200 mm below the SM raft foundation. A clear distinction between the moisture content data of the exterior and interior boundaries is evident. The data shows that moisture can evaporate more quickly at the exterior boundaries, where it is exposed to the air, compared to the interior boundary, which is covered. Additionally, the change in moisture content over time is prolonged due to the clay soil's extremely low permeability and high density. The high clay content of the clay material further retains water molecules. Notably, probe 71 experiences the most significant moisture content change among the internal boundary probes, likely due to the

formation of deep cracks forming on the north side. It should be noted that the north side is also prone to rapid moisture loss during dry periods.

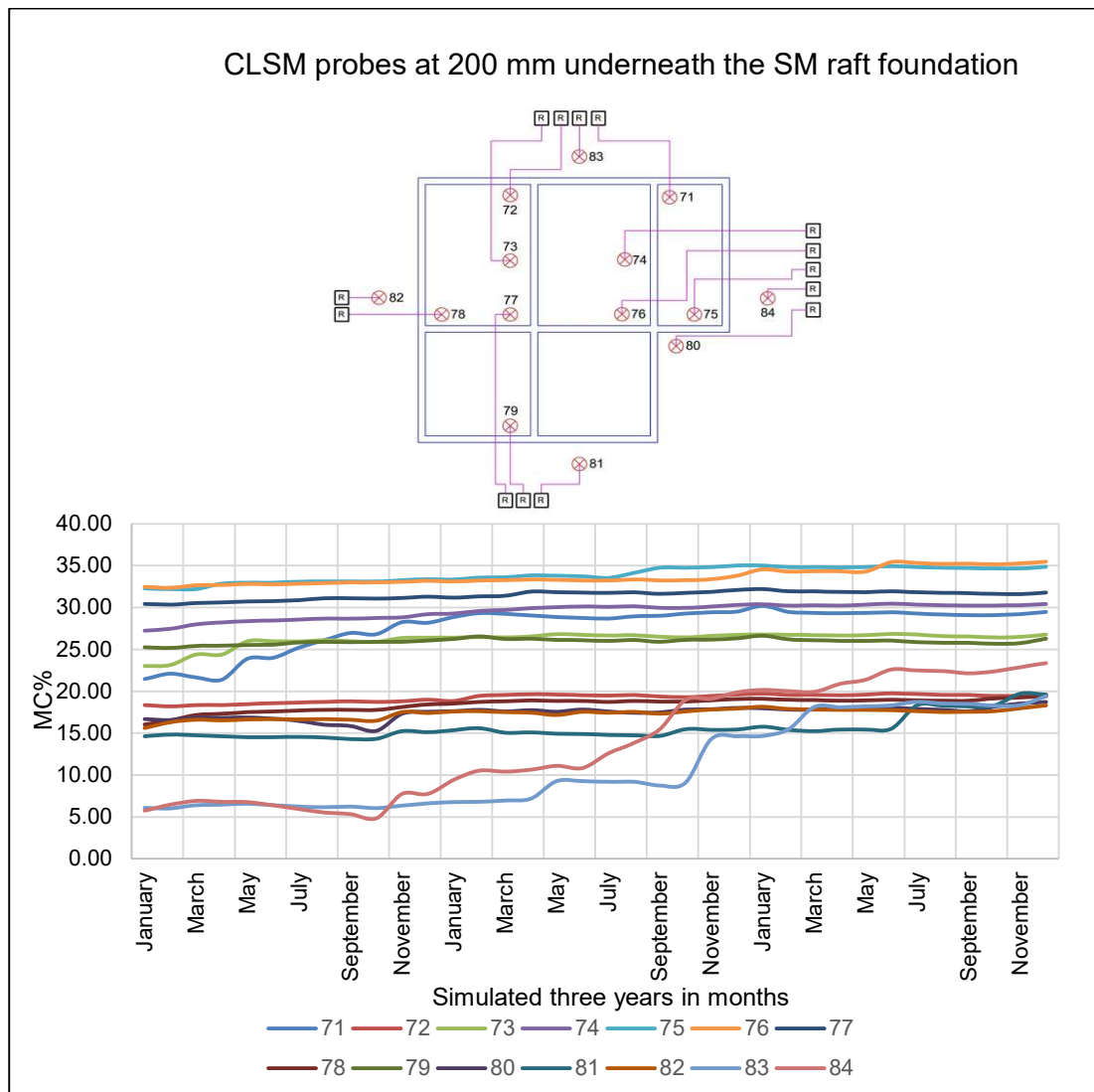


Figure 4.4: CLSM probes at 200 mm underneath the SM raft foundation

Figure 4.5 presents the average moisture content at a depth of 300 mm below the SM raft foundation. A noticeable differentiation between the exterior and interior boundaries is observed, with overall changes in moisture content being less pronounced compared to the 200 mm depth. Point 84, one of the outside CLSM probes, registers the most significant increase in moisture content (approximately 10%).

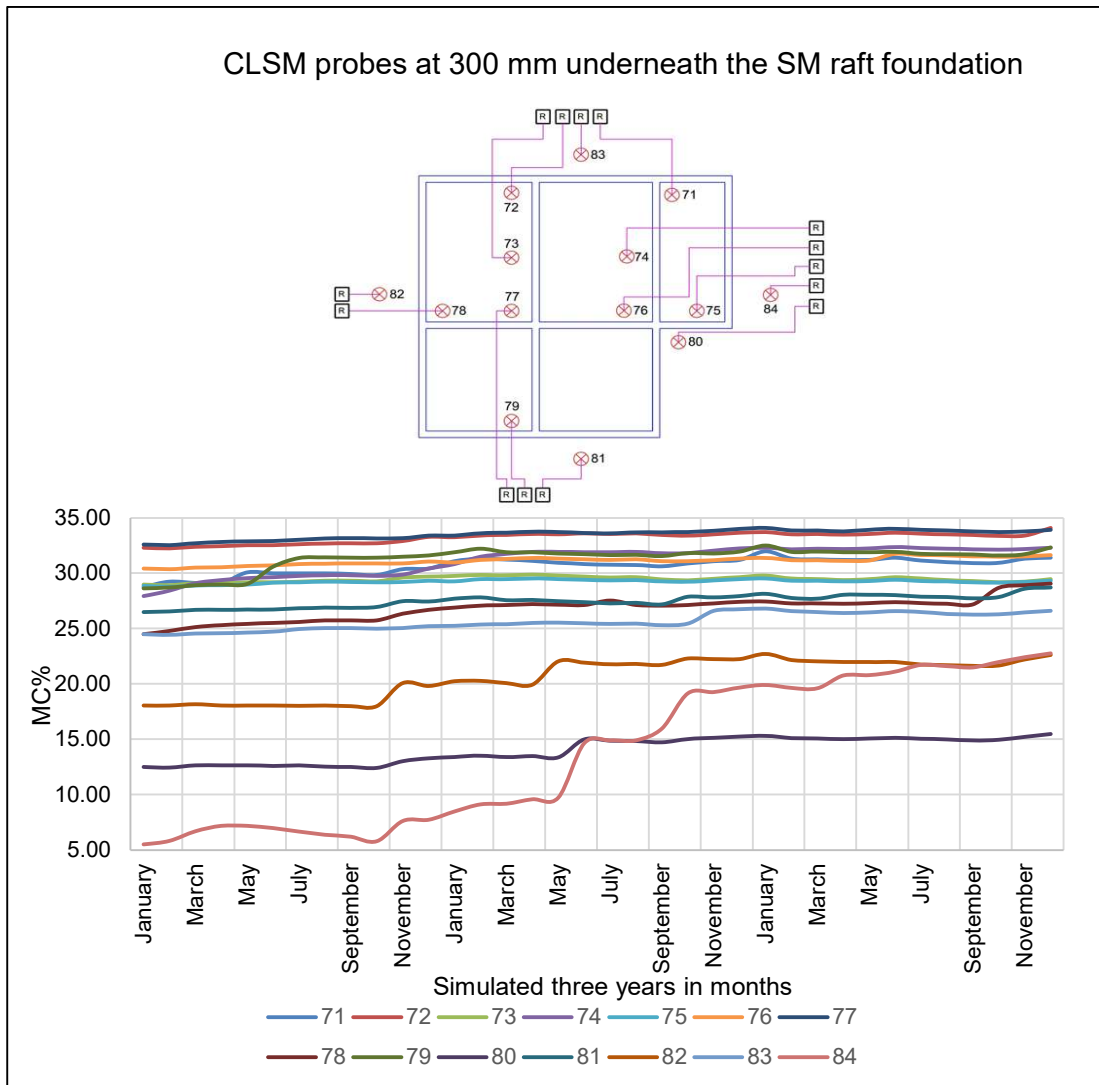


Figure 4.5: CLSM probes at 300 mm underneath the SM raft foundation

Figure 4.6 depicts the average moisture content at a depth of 400 mm below the SM raft foundation. Similar to the previous depths, the data reveals a contrast between the exterior and interior boundaries, with generally smaller overall changes in, once again, point 84, located outside the SM raft foundation, which experiences a substantial increase in moisture content (approximately 10%). The moisture increase at this location will not significantly influence the foundation since it is on the exterior perimeter of the SM raft foundation.

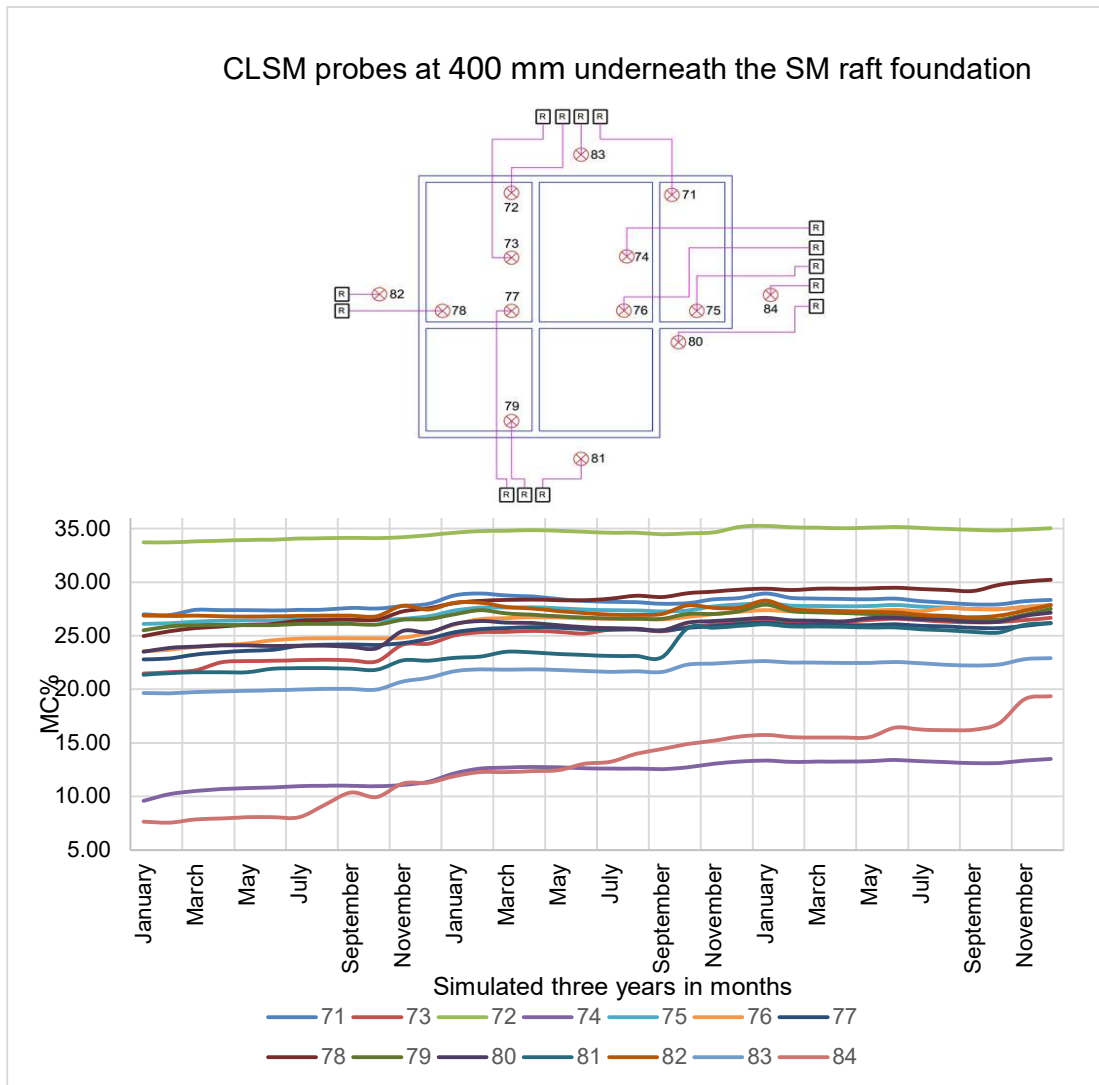


Figure 4.6: CLSM probes at 400 mm underneath the SM raft foundation

The findings from the SM raft foundation closely resemble those observed in Botshabelo, suggesting a consistent pattern. The same pattern is observed in Appendices B and C. The concentration of moisture is found at the re-entry corner, and the north-facing sides exhibit the lowest moisture content. It is important to note that the SM raft foundation provides a more comprehensive view due to the additional CLSM probes in the soil compared to the GSH in Botshabelo.

4.3.2. Differential movement analysis

The differential movement across the SM raft foundation highlights the importance of incorporating stiffness requirements in design. Movement in various SM foundation locations can have significant structural implications, especially in expansive clay soils. For GSH, Bester et al. (2016) suggest that added stiffness along the north and west beams can mitigate stresses caused by heave at the foundation edges. Reinforcing these areas may reduce foundation deflection from seasonal heave, thus improving structural stability. Considering environmental conditions and soil behaviour instead of assuming uniform moisture exposure provides a more resilient design framework.

Differential movement in a raft foundation is a critical design factor, referring to uneven vertical displacement experienced by different foundation sections, which can lead to structural implications. Understanding this movement is essential for ensuring the long-term stability of structures built on expansive clay soils.

In Figure 4.7, the movement of the southwest corner of the SM raft foundation is depicted. The data indicates an upward trajectory, with movement observed over three simulated seasons. The south-facing sides of buildings in the southern hemisphere are typically not exposed to direct sunlight, resulting in colder conditions during the winter months when in shadow. Only during the summer months does this area receive brief solar radiation. Thus, solar energy has had minimal influence on the south-facing side for over twelve months.

The back west side of the SM raft foundation is exposed to heat energy for approximately half of the year. Heat exposure is most significant during the warmer months when the sun's horizontal alignment is wider. The movement pattern in the SM raft foundation model is upward, with an approximate heave of 2 to 2.5mm observed during the simulated three-year period. The movement pattern of the SM raft foundation can also be observed in Appendix E.

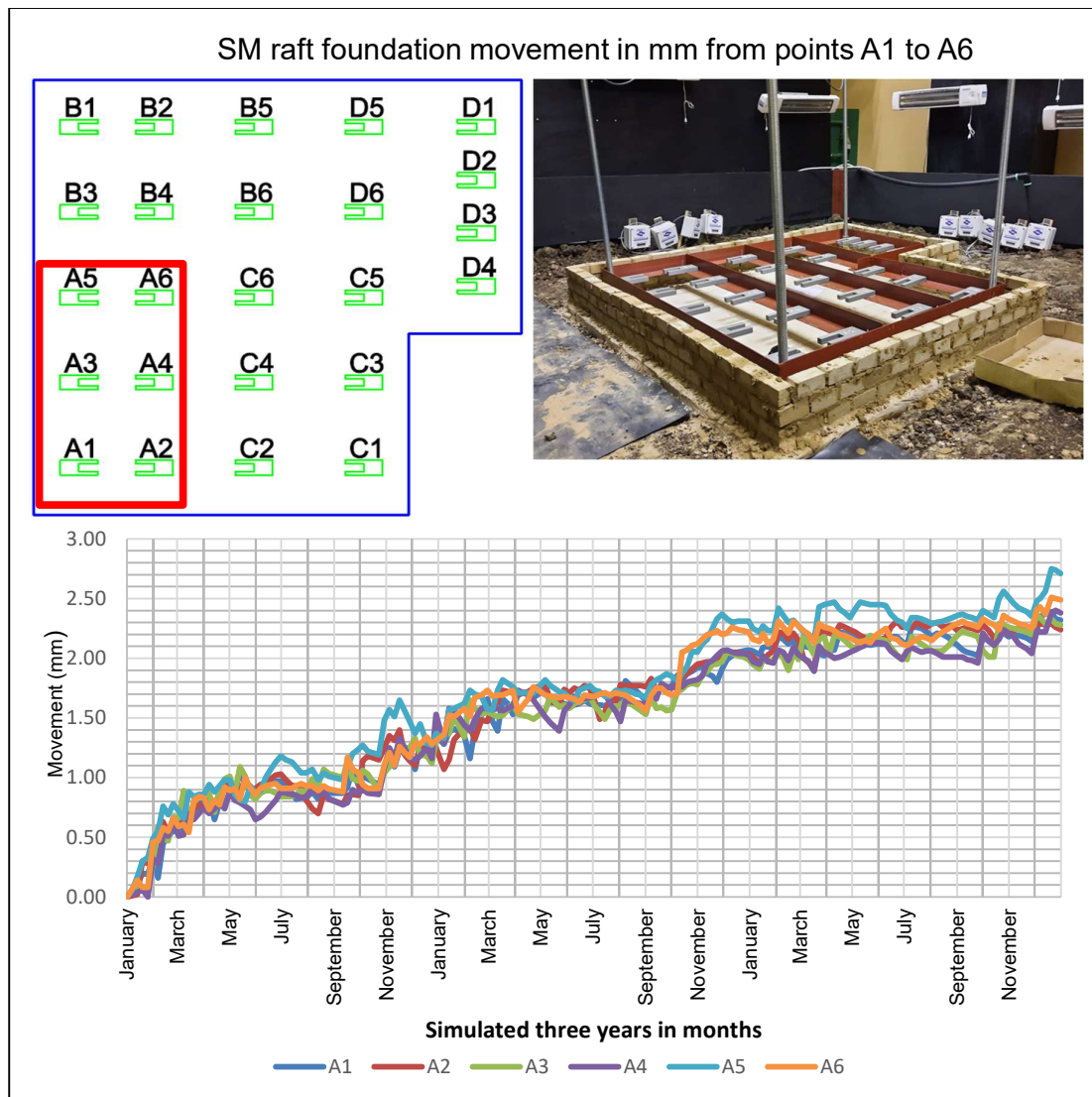


Figure 4.7: SM raft foundation movement in mm from A1 to A6

Figure 4.8 shows the expansive clay soil on the south-facing side of the SM raft foundation during a simulated winter. Shrinkage cracks begin to form, albeit not

deeply or extensively, as the soil loses moisture at a slow rate due to the lack of direct heat exposure. Once precipitation occurs, the expansive clay soils in this location will heave and expand, although not as rapidly as in other areas around the SM raft foundation. The south side experiences slower moisture evaporation due to colder conditions.



Figure 4.8: The south-facing side of the expansive clay soil

In Figure 4.9, the movement of the northwest corner of the SM raft foundation is shown. All data points on the SM raft foundation start at zero, and for the most part, the movement trajectory exhibits an upward trend over the three simulated seasons. However, a downward movement on the graph is observed just before the simulated November and December periods. The decline in the graph is attributed to moisture evaporation and shrinkage that takes place during the simulated winter period in the first year. With the first simulated rainfall period following year one, the movement

of the SM raft foundation resumes an upward trajectory. This heaving is a result of deep shrinkage cracks that form, allowing moisture to penetrate deeply.

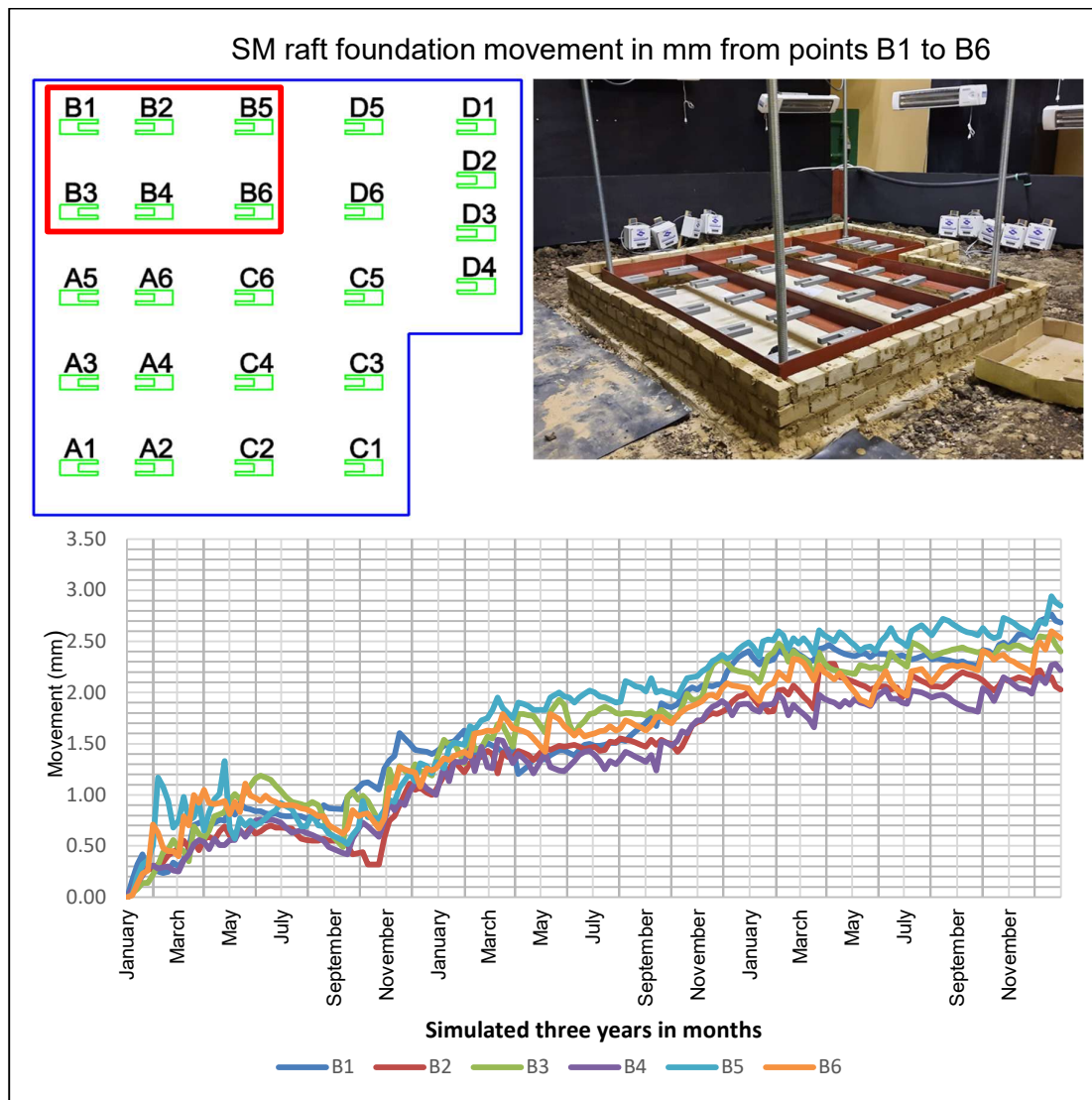


Figure 4.9: SM raft foundation movement in mm from B1 to B6

Figure 4.10 presents the north-facing side of the expansive clay soil. The north-facing side receives the most exposure to heat energy during the simulated day. Consequently, moisture loss occurs more rapidly on this side compared to the south-facing side of the SM. This rapid moisture loss leads to more significant shrinkage and more noticeable shrinkage cracks, which tend to be deeper into the expansive clay soil. After rainfall, the moisture penetrates the expansive clay soil more deeply,

and the rate of moisture absorption on the north-facing side is faster than on the south-facing side. This difference is attributed to variations in the moisture content of the expansive clay soils. A similar phenomenon was observed in Botshabelo (Appendix B). Following rainfall, the expansive clay soil expands and swells quickly. Subsequently, when the rain subsides, the expansive clay soil is exposed to direct solar heat, causing the clay material to shrink rapidly.



Figure 4.10: The north-facing side of the expansive clay soil

Figure 4.11 illustrates the movement of the southeast corner of the SM raft foundation. Similar to the southwest corner, this area tends to be the coldest. All data points start at zero, and the SM movement exhibits the most significant upward trajectory as the three simulated seasons progress. Direct sunlight does not reach the south-facing facades of buildings in the southern hemisphere. The re-entry corner of the structure tends to collect most of the moisture after rainfall, as the expansive clay moisture content is much higher at the re-entry corner compared to

the rest of the SM. The moisture concentration at the re-entry corner turns it into a pivot point for doming. The movement patterns supported by the 3DField modelling results in Appendix E that confirm this behaviour. The expansive clay remains moist year-round, significantly impacting the characteristics of the SM raft foundation. Therefore, the orientation of the re-entry corner with respect to the sun's position is a crucial design consideration. When the re-entry corner faces north, it will receive more heat energy throughout the year, resulting in characteristics similar to points B1 to B6 and D1 to D6.

Point C5 experienced the most heave. This point is located almost directly adjacent to the re-entry corner of the SM raft foundation. Due to its location, moisture can easily migrate beneath point C5. As it receives little direct exposure to heat energy, moisture tends to accumulate there over time. The area around C5 is expected to be the peak location for heave doming. Therefore, the placement of C5, in proximity to the re-entry corner, is a critical consideration for raft foundation design.

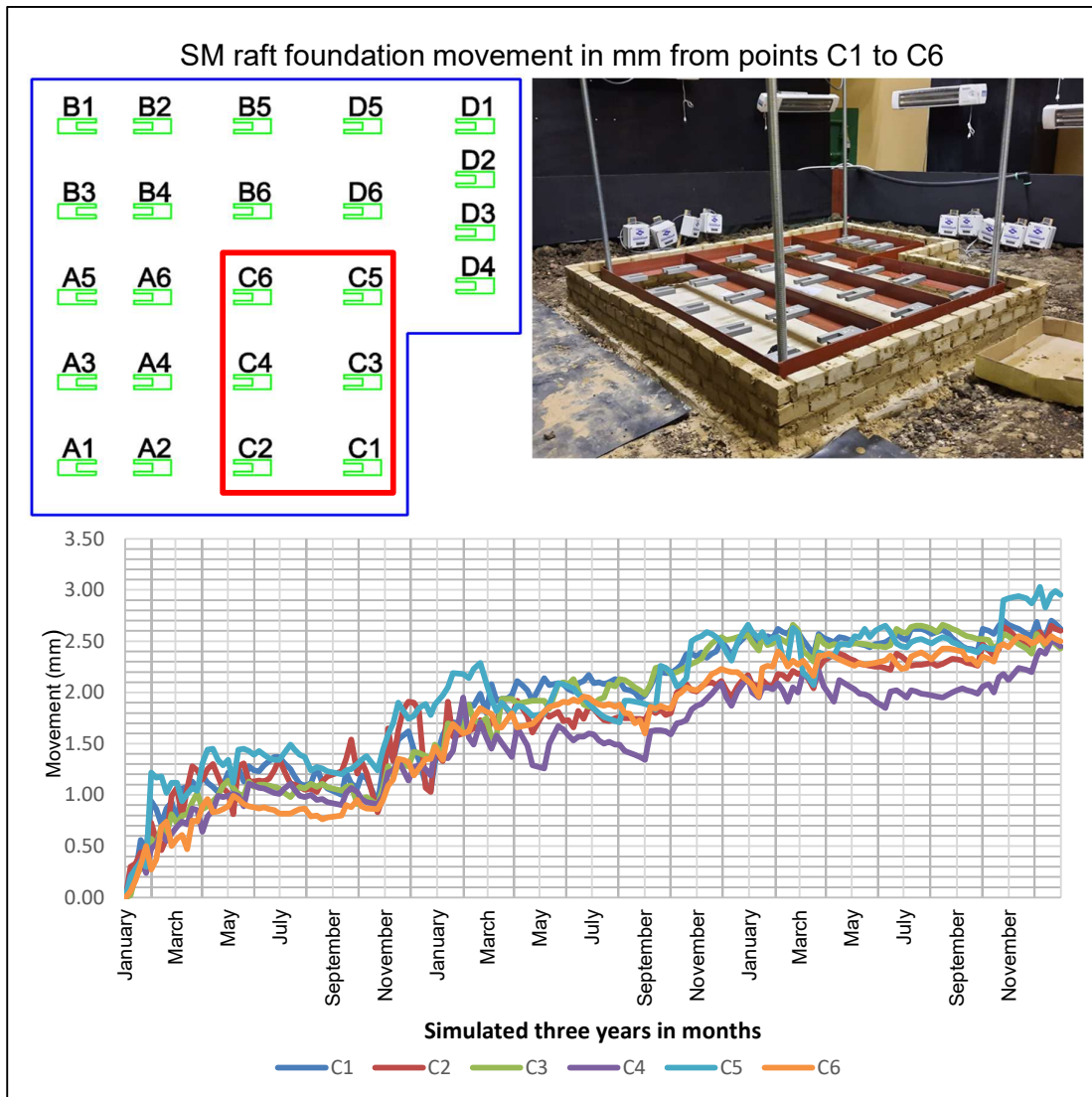


Figure 4.11: SM raft foundation movement in mm from C1 to C6

In Figure 4.12, the movement of the northeast corner of the SM raft foundation is represented. The northwest corner exhibits similar characteristics to the northeast corner. All data points start at zero. A minor downward shift in vertical movement occurs in the first simulated year. Similar observations to those made for the northeast apply here. The decline in vertical movement in the graph results from the moisture evaporation of the expansive clay. The rapid moisture loss causes the expansive clay to shrink, resulting in the formation of larger and deeper cracks.

These shrinkage cracks are prominent and, following rainfall, allow water to penetrate the soil at a faster rate.

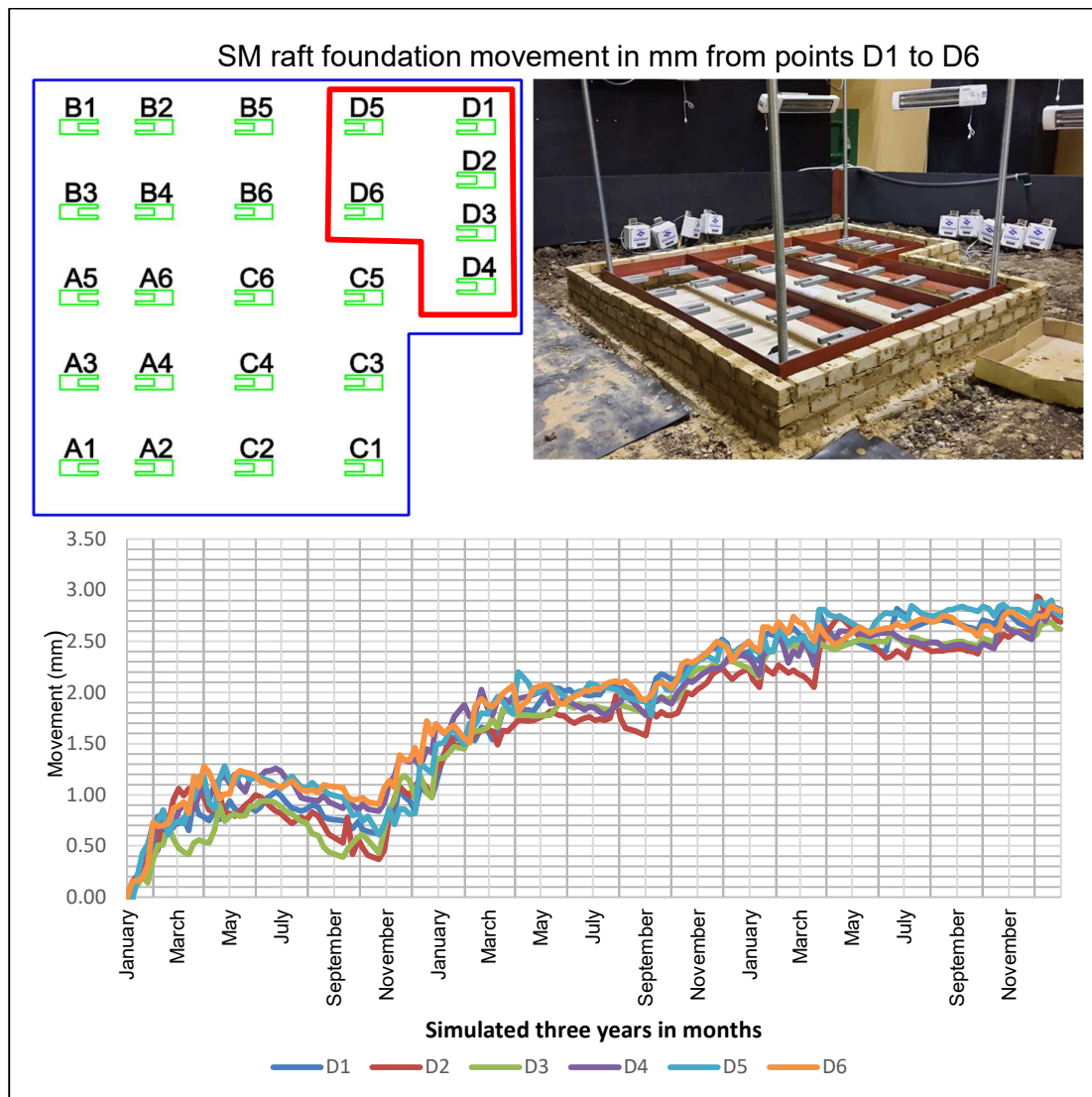


Figure 4.12: SM raft foundation movement in mm from D1 to D6

Figure 4.13 illustrates the 3D movement heat map of the Raft Foundation for December of Year 2. As seen in Appendix G, these heat maps show the most vertical movement occurring at the re-entry corner, which is sheltered from direct heat and allows the easiest path for moisture penetration. These differential movement patterns highlight the importance of the shape and orientation of a structure.

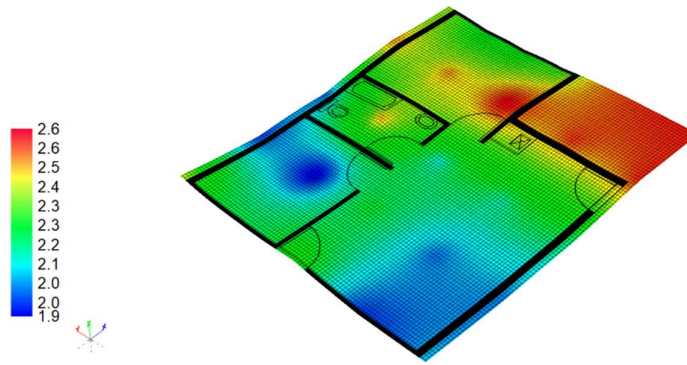


Figure 4.13: Year 2 – December: 3D movement heat map of the SM raft foundation, orientation from the Southwest corner.

4.3.3. Edge penetration analysis of the SM raft foundation

The influence of soil suction on moisture distribution is essential in determining edge penetration distance, where environmental exposure causes varied moisture migration beneath the foundation. Nelson and Miller (1997) highlighted the importance of moisture influence depth, which depends on soil suction properties. These findings suggest that different soil suction and the locations around the foundation affect edge penetration more than initially considered. This uneven moisture dome, with shrinkage on the northern side, emphasizes the need to tailor the foundation design to estimate the edge penetration which is determined by solar exposure.

Figure 4.14 shows the SM raft foundation movement in simulated year three, which was chosen to reflect the foundation's expected equilibrium. The direction is from west to east over internal beams (A5, A6, C6, C5, and D4), with an internal beam running east to west underneath. The graph reveals that the most significant heave occurred around point C5, the re-entry corner, with approximately 1mm of movement attributed to the SM foundation's north-facing orientation, which

contributes to moisture retention, making C5 more prone to heaving. This highlights the impact of sunlight exposure on soil behaviour. Movement at the east and west edges of the SM was approximately 0.7 mm, less than a point C5. Consequently, due to potential moisture variations, the researcher considers the re-entry corner a critical consideration in raft foundation design.

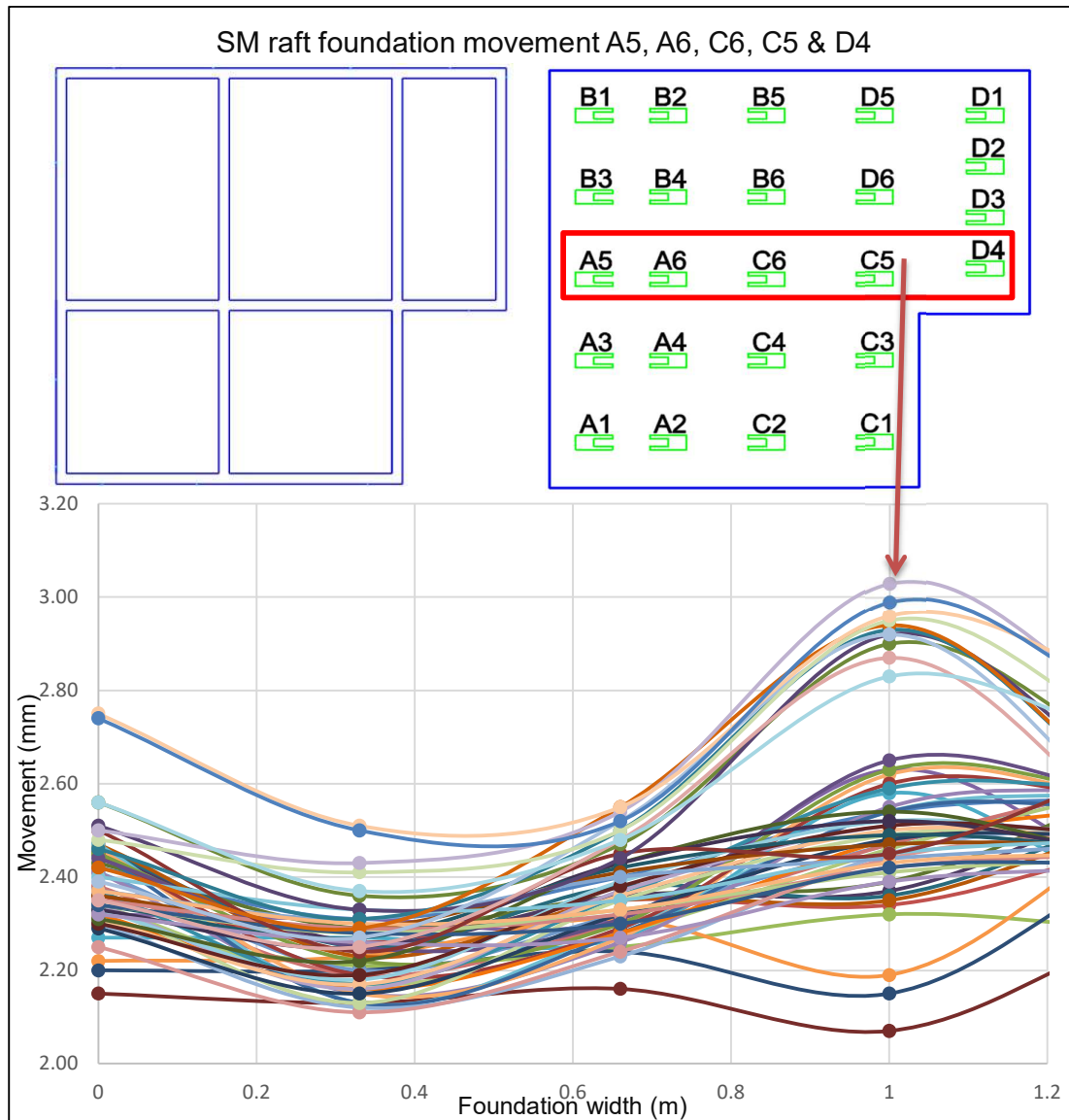


Figure 4.14: SM raft foundation movement in (mm) from east to west (A5, A6, C6, C5 & D4)

Figure 4.15 shows the movement of the SM raft foundation during the third simulated year in the direction of east to west (B3, B4, B6, D6 and D2). B3, B6, and D2 points have beams underneath from south to north. The most significant vertical movement occurred on the east side, close to the re-entry corner. The east side (point D2) experienced the most significant movement of 0.87 mm.

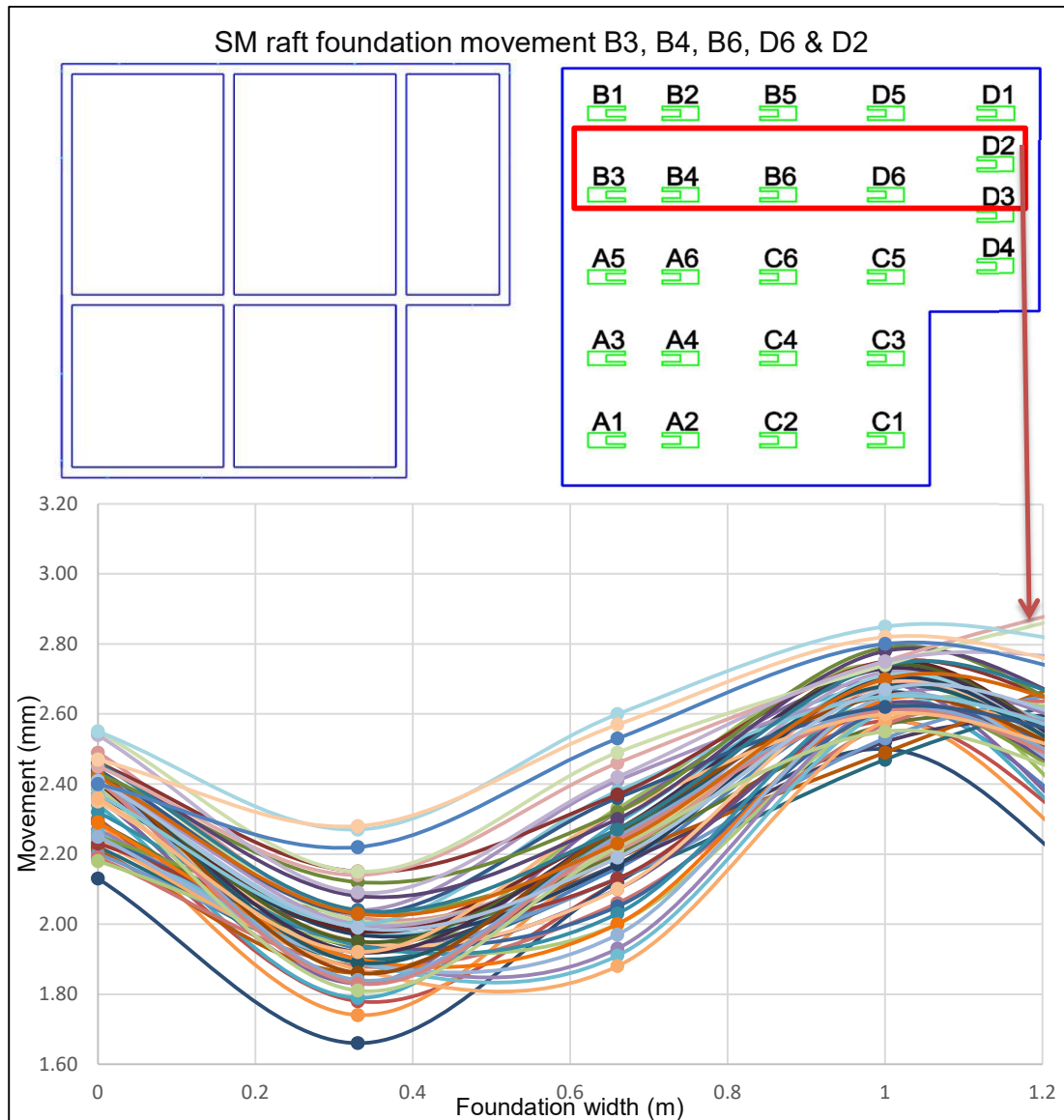


Figure 4.15: SM raft foundation movement in (mm) from east to west (B3, B4, B6, D6 & D2)

Figure 4.16 shows the vertical movement of the SM raft foundation during simulated year three from south to north at points C1, C3, C5, D6, and D5. A beam runs from south to north beneath these points. The critical point is C5, located at the re-entry. The data suggests a dome forms beneath C5. Vertical movement on the north side of the SM was 0.5 mm, compared to 0.3 mm on the south side. The difference in movement supports the theory that the north side is more susceptible to heaving.

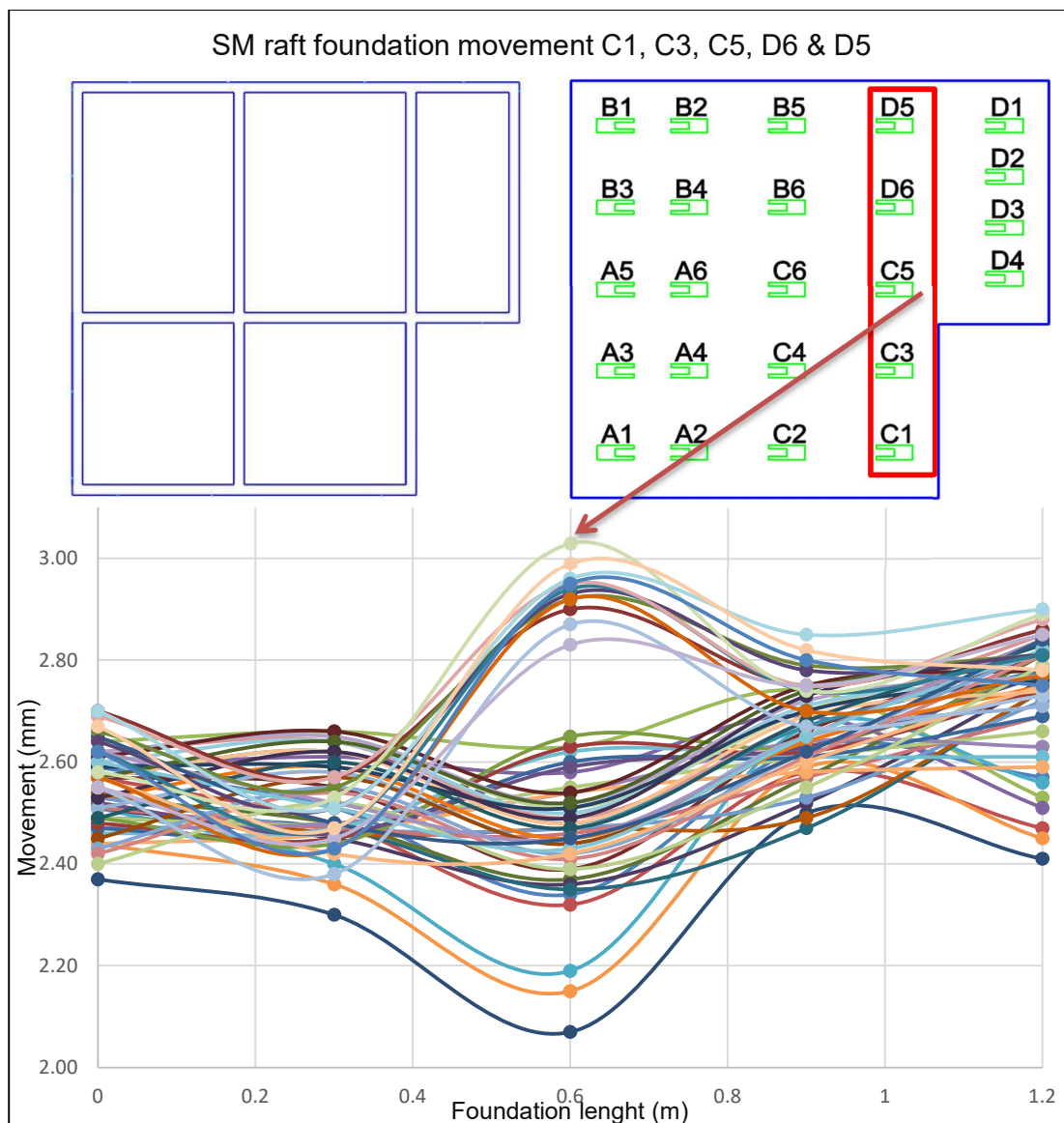


Figure 4.16: SM raft foundation movement in (mm) from south to north (C1, C3, C5, D6 & D5)

Figure 4.17 shows the vertical movement of the SM raft foundation at points B5, B6, C6, C4 and C2. Beams underneath B5, C6, and C2 run from east to west. Therefore, points B6 and C4 are supported on the ground surface. The vertical movement pattern resembles a bending moment diagram of a suspended slab supported by beams. It appears that the expansive clay is lifting the beams of the SM raft foundation, creating this pattern.

Figure 4.18 shows the vertical movement of points B2, B4, A6, A4, and A2 on the SM raft foundation from south to north. Beams run in an east-to-west direction beneath points B2, A6, and A2, while points B4 and A4 are on the ground surface. The observed vertical movement pattern once again resembles a bending moment diagram of a suspended slab supported by beams. It appears that the expansive clay is elevating the SM raft foundation beams.

The observations in Figures 4.17 and 4.18 do not support the centre doming theory and are more complex than expected. A multiple peak waveform develops, influenced by the positions and directions of the beams underneath the SM raft foundation. Another factor to consider is the orientation to the sun, where a more significant fluctuation of vertical movement is found on the north-facing side compared to the south-facing side.

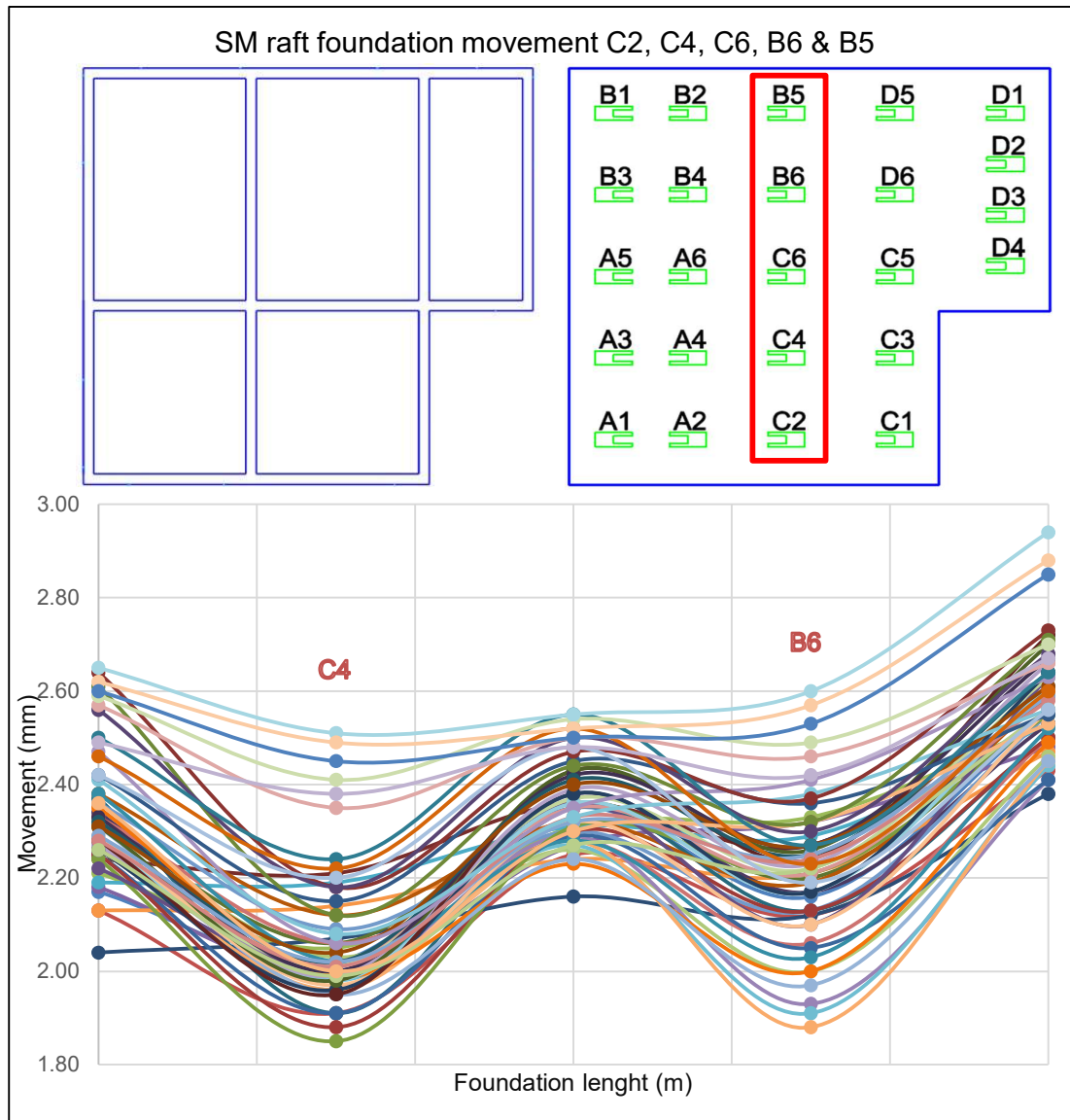


Figure 4.17: SM raft foundation movement in (mm) from south to north (C2, C4, C6, B6 & B5)

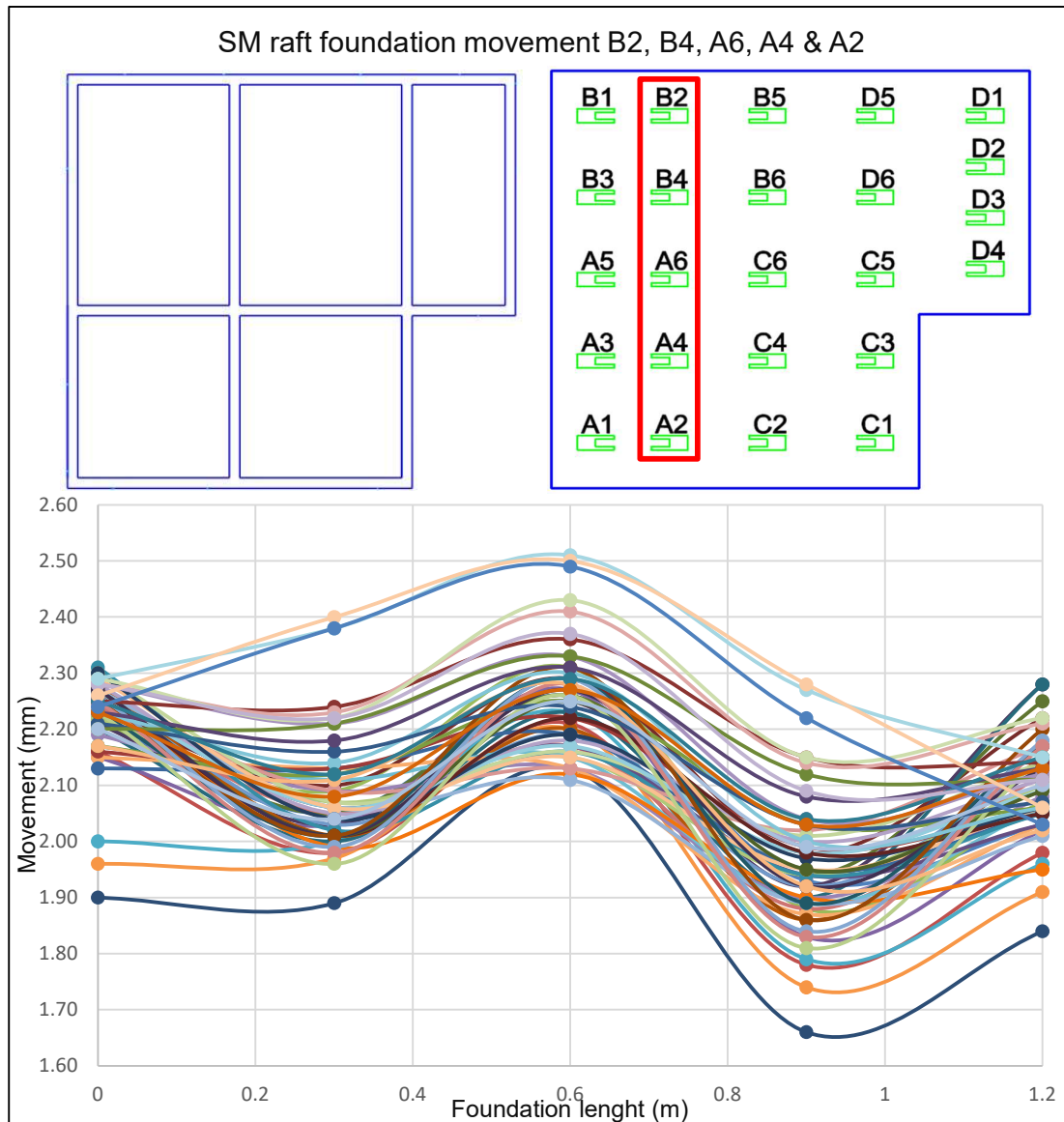


Figure 4.18: SM raft foundation movement in (mm) from south to north (A2, A4, A6, B4 & B2)

The edge penetration proposed by previous studies (Bester, et al., 2017) requires reconsideration. Upon studying all the data, there is no clear indication of the value of this parameter, which can be used to estimate mound shape. Several variables, such as the orientation to the sun, moisture variations, predictable heave, soil properties, beam spacing and building dimensions, can impact the edge penetration distance. Furthermore, the edge penetration distance will undoubtedly differ

depending on which side it is determined from. A flat-top dome with a defined edge penetration distance is not observed, as no evidence supports it.

4.3.4. Strain analysis of the SM raft foundation

Strain was measured over a three-year simulation on the SM raft foundation, covering the entire area where the SM was in contact with expansive clay. Foundation strain occurs in the direction of the applied force and is measured over the original dimensions. The primary force that concrete may undergo is expansion and uplift due to swelling expansive clay. Concrete exhibits diversity in material size and characteristics, leading to non-uniform internal strains and stresses when loaded. Some locations experience higher strains and stresses. Thermal strain in concrete is determined during heating without an external load. Thermal strains are considered instantaneous for practical purposes. The strain readings were collected a few minutes before exposure to heat energy (simulation of the sun). The thermal strain does not significantly affect the concrete SM raft foundations because the roof protects against heat energy.

In Figure 4.19, the strain of the SM raft foundation can be observed. The strain was measured across the concrete slab where interfaces between phases with different properties are found between the expansive clay soil and concrete. The strain data readings were collected at twenty locations over a three-year simulation period. During this time, the strain pattern follows a clear trajectory as the seasons change. The strain on the SM raft foundation starts at a peak of between three hundred and seven hundred $\mu\text{m}/\text{m}$.

During the simulated summer months, the strain peaks, while it drops during the winter months. A plausible explanation for the change in strain is the swelling and shrinkage of the expansive clay over time. The strain gauges are highly sensitive and can detect minimal value changes. As time progresses, there is a general downward trajectory of the strain readings of the SM raft foundation. It is also noticeable that the strain readings become closer to each other as time proceeds.

Two possible explanations for this phenomenon are considered. Firstly, concrete becomes harder and stronger with time as the cement bonds and reacts with water molecules, leading to a decrease in strain readings.

The second potential reason for the decrease in the change in strain is associated with the SM raft foundation experiencing heightened stress due to the heaving of the expansive clay soil at the outset of year one. During construction, the soil tends to be dry. Exposed soil may potentially lose more moisture. Once the concrete is poured over the soil, the moisture losses beneath the foundation become less significant than when the soil was exposed. Upon the occurrence of the first simulated rainfall, the expansive clay soil will undergo more rapid swelling until it reaches an equilibrium state. The rapid heaving of the expansive soil exerts additional stress on the foundation. As time progresses, the rate of swelling of the expansive clay gradually diminishes.

In Figure 4.19, the simplified strain graph in Appendix H is presented. The simplified graphs aim to offer a more precise representation of the strain data. By simplifying the graphs, complex variations in strain over time become more apparent, highlighting the key trends observed in the seasonal patterns.

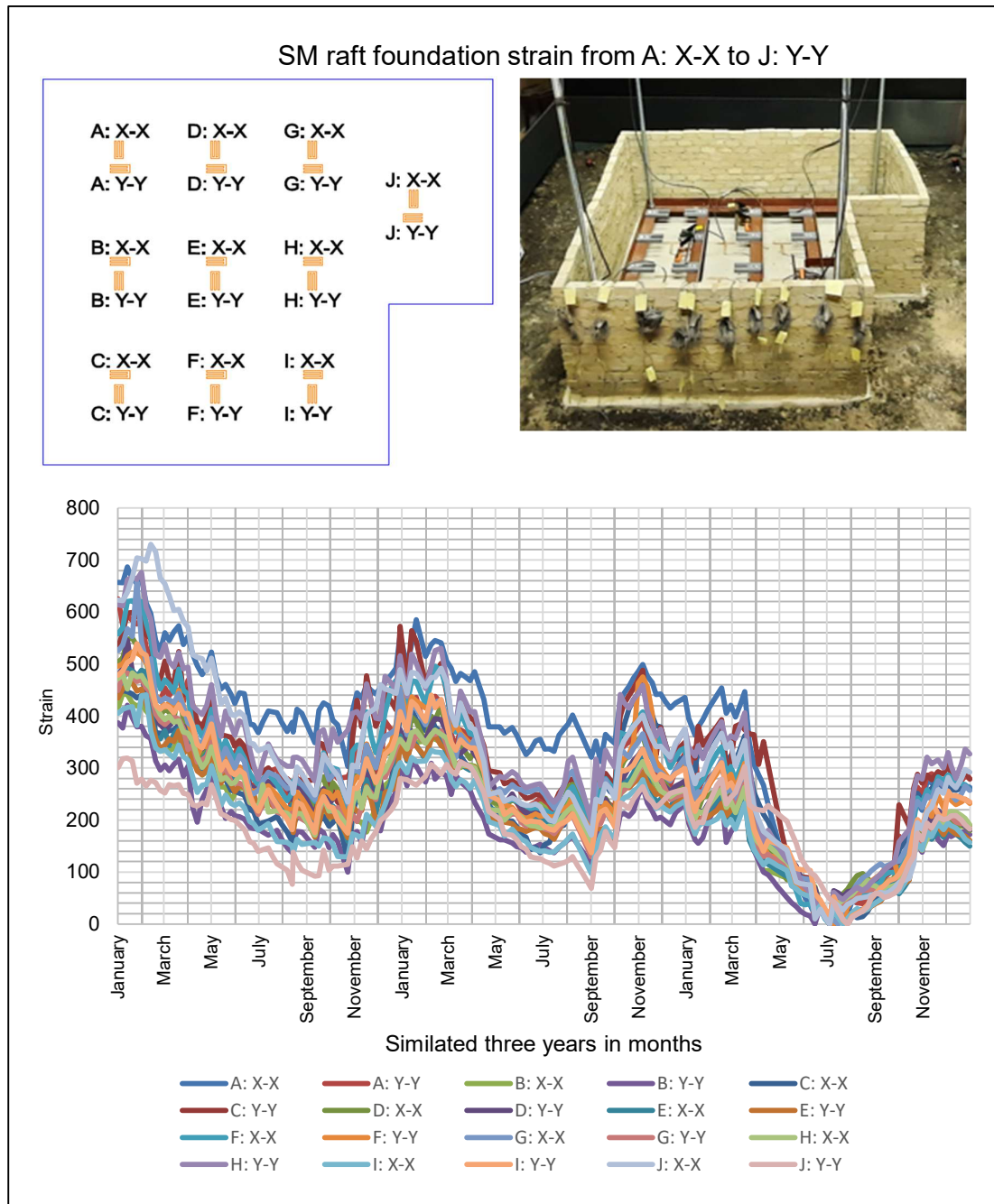


Figure 4.19: SM raft foundation strain from A: X-X to J: Y-Y

4.3.5. Summary of the SM raft foundation

The assessment of the performance of the SM raft foundation was conducted under different laboratory conditions. Data collected in the study revealed insights into factors such as strain patterns, load distribution, and the impact of soil properties on

foundation performance. The findings provide a clearer understanding of foundation dynamics, offering valuable insights for practical applications in engineering and construction.

The primary finding emphasises the importance of building orientation towards the sun. When the re-entry corner is situated towards the south in the southern hemisphere, the area tends to collect water. Moisture concentration occurs just inside the foundation, leading to differing moisture evaporation patterns in the expansive clay. The north-facing side experiences higher moisture loss compared to the southern side, which retains relatively more moisture. Rapid heaving of expansive clay on the northern side can be expected after rainfall. There is no clear evidence supporting the development of a flat-top dome as described in previous studies. Additionally, the occurrence of a clear flat-top dome, along with a well-defined edge penetration distance, is unlikely based on the results of this study.

4.4. Comparison between the Botshabelo GSH raft foundation and the SM raft foundation simulation in the laboratory

In 2014, an SM raft foundation based on the layout, orientation to the sun, and dimensions of the Botshabelo GSH was constructed. Scaling laws were applied to various aspects, aligning time and structure dimensions. Both the SM raft foundation and a ventilated foundation were constructed on expansive clay with similar properties, despite the logistical and cost restrictions preventing the acquisition of identical soil from Botshabelo. The comparison between the two foundations allowed for the testing of whether the behaviours and characteristics observed in

the scale model align with real-world observations. The comparison confirms and supports the hypotheses and assumptions made during the SM study.

Figure 4.20 shows four different months of moisture content patterns modelled by 3DField underneath the Botshabelo GSH at a depth of 150 mm. These months are January, May, August, and December. In Appendix B, all the 3DField models of Botshabelo can be seen. Two key observations can be made by examining the moisture patterns: the lowest moisture content tends to be on the north-facing side, and the re-entry corner consistently exhibits the highest moisture content. These patterns remain constant during both summer and winter months. Figure 4.21 depicts the identical four-month simulation period, showcasing the moisture variation underneath the SM raft foundation in the laboratory. Moisture content is measured at a depth of 200 mm beneath the SM. In Appendix C, all the 3DField models of the SM raft foundation can be seen. The patterns closely resemble those of the Botshabelo GSH. The moisture content tends to be lower at the north-facing side of the model, with a moisture concentration at the re-entry corner. It is essential to note that the moisture pattern underneath the SM raft foundation provides a notably more complete representation due to the presence of fourteen probes, as opposed to just seven beneath the GSH in Botshabelo. This additional instrumentation enhances interpretation. These similarities are observed when comparing the models in Appendix B and C.

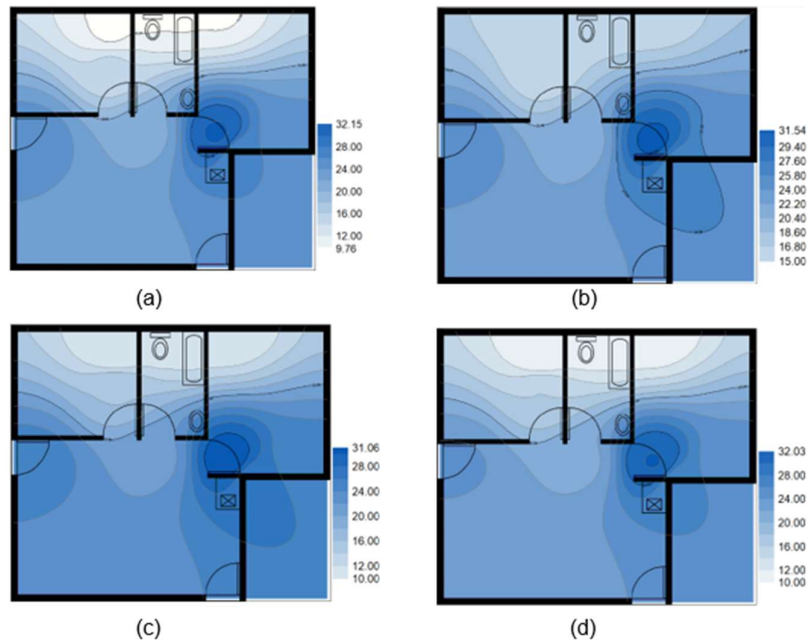


Figure 4.20: Botshabelo GSH 2014 moisture content at depth 150mm of (a) January, (b) May, (c) August and (d) December

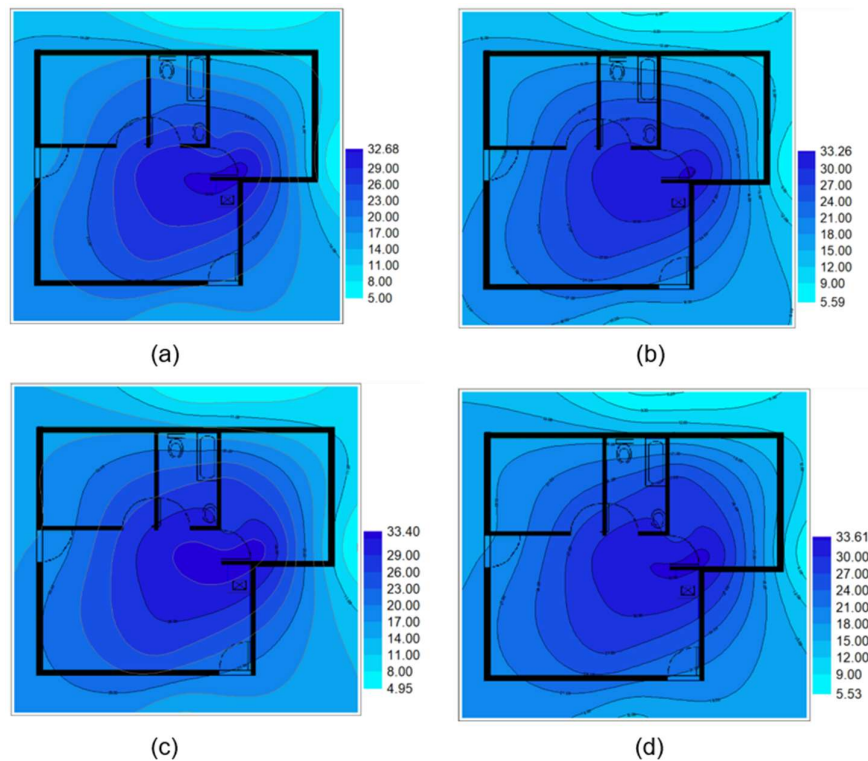


Figure 4.21: SM raft foundation year one moisture content of (a) January, (b) May, (c) August and (d) December

Figure 4.22 illustrates the movement pattern of the SM raft foundation in the laboratory during the simulated months of January, May, August, and December.

Appendix E displays the complete array of vertical movement patterns over the three-year simulated period. The vertical movement pattern closely resembles the moisture variation pattern of the GSH in Botshabelo and that of the SM raft foundation. The two main points of interest are the re-entry corner and the north-facing side. The re-entry corner experiences the most significant upward movement due to the moisture concentration at that specific point, while the north-facing side exhibits the lowest point, particularly the north-west side. The north side receives most of the solar heat energy during the day, leading to more rapid moisture loss and consequent shrinkage of the clay material.

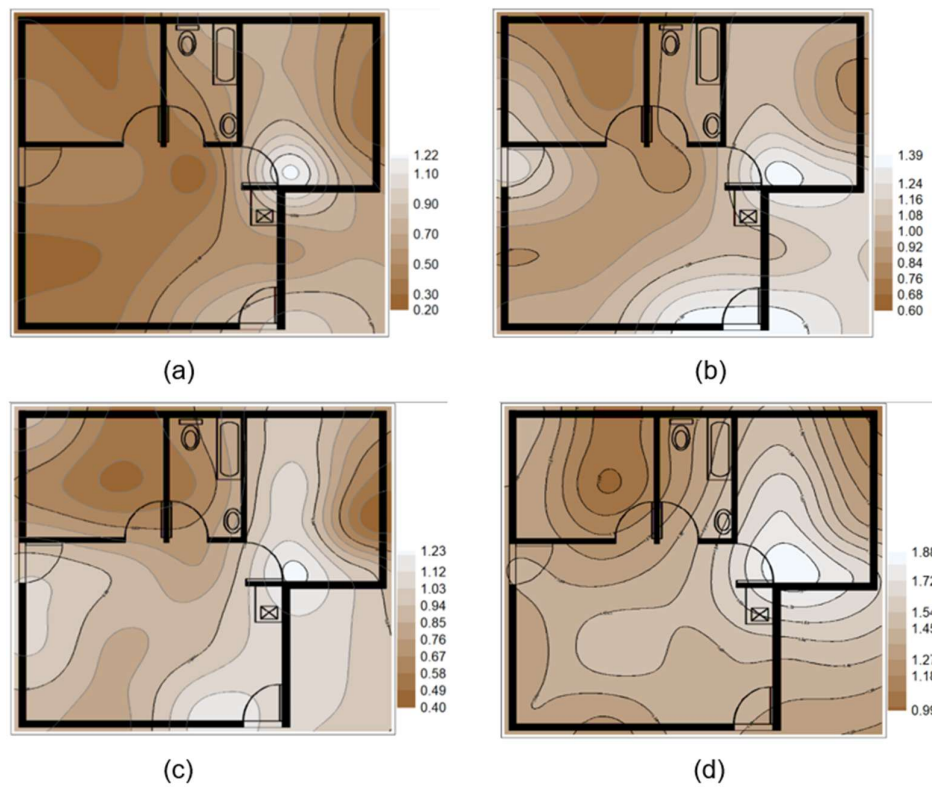


Figure 4.22: SM raft foundation differential movement in (mm) for (a) January, (b) May, (c) August and (d) December

By comparing the results from Appendix B, C and E, an inference can be made that the GSH raft foundation can be scaled in a controlled laboratory environment using

the methodology applied by the researcher. The study's primary focus is the solar heat or artificial sun's energy influence on the moisture pattern underneath the structure. Alternative approaches, such as a centrifuge, cannot replicate the effects of heat energy or solar radiation. Unlike a centrifuge that rotates around a fixed axis, simulating the sun's movement requires dynamic modifications across multiple angles and orientations throughout a simulated year. The SM modelling endeavour yielded successful outcomes when comparing the results to the real-world scenario in Botshabelo.

4.5. The SM cavity raft foundation analysis

In this section, we analysed the ventilated or cavity raft foundation, the SM, within the laboratory. The researcher will examine various aspects of the study, including moisture variation, vertical movements, edge penetration distance, and strain measurements of the SM cavity raft foundation.

4.5.1. Moisture movement analysis underneath the SM cavity raft foundation

Figure 4.23 shows the SM Cavity Raft Foundation's 3D moisture content heat map from December of Year 2. The heat map indicates that the north-facing edges, exposed to direct heat, experience accelerated moisture loss, leading to lower moisture content in these areas. The south side, which is more shaded, retains more moisture, reducing soil contraction in this region. The re-entry corner shows the highest moisture retention. Additional 3D heat maps illustrating these patterns are provided in Appendix G.

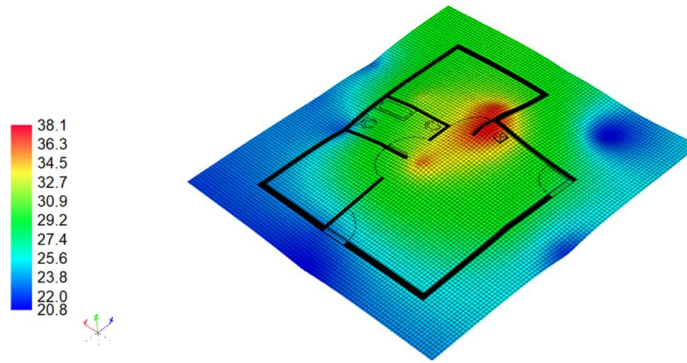


Figure 4.23: Year 2 – December: 3D moisture content (MC%) heat map of the SM cavity raft foundation, orientation from the Southwest corner.

Figure 4.24 displays the average moisture content at a depth of 200 mm beneath the SM cavity raft foundation, highlighting a noticeable difference between external and internal boundaries. The outer boundary shows higher moisture evaporation, while the interior boundary, being covered, retains more moisture. The northwest, north, and northeast-facing sides exhibit more moisture variation compared to the centre or south locations, closely resembling the previous model's behaviour at this depth.

In Figure 4.25, the moisture content of the expansive clay is portrayed at a depth of 300 mm beneath the SM. Moisture changes are not as prominent as in Figure 4.24. The moisture content changes over time are less significant than in the SM raft foundation. One possible explanation for this is that the moisture can evaporate horizontally through the clay soil since the foundation slab is suspended and has ventilation holes. The point with the most significant moisture content change over time is point 84, located outside the SM's boundary.

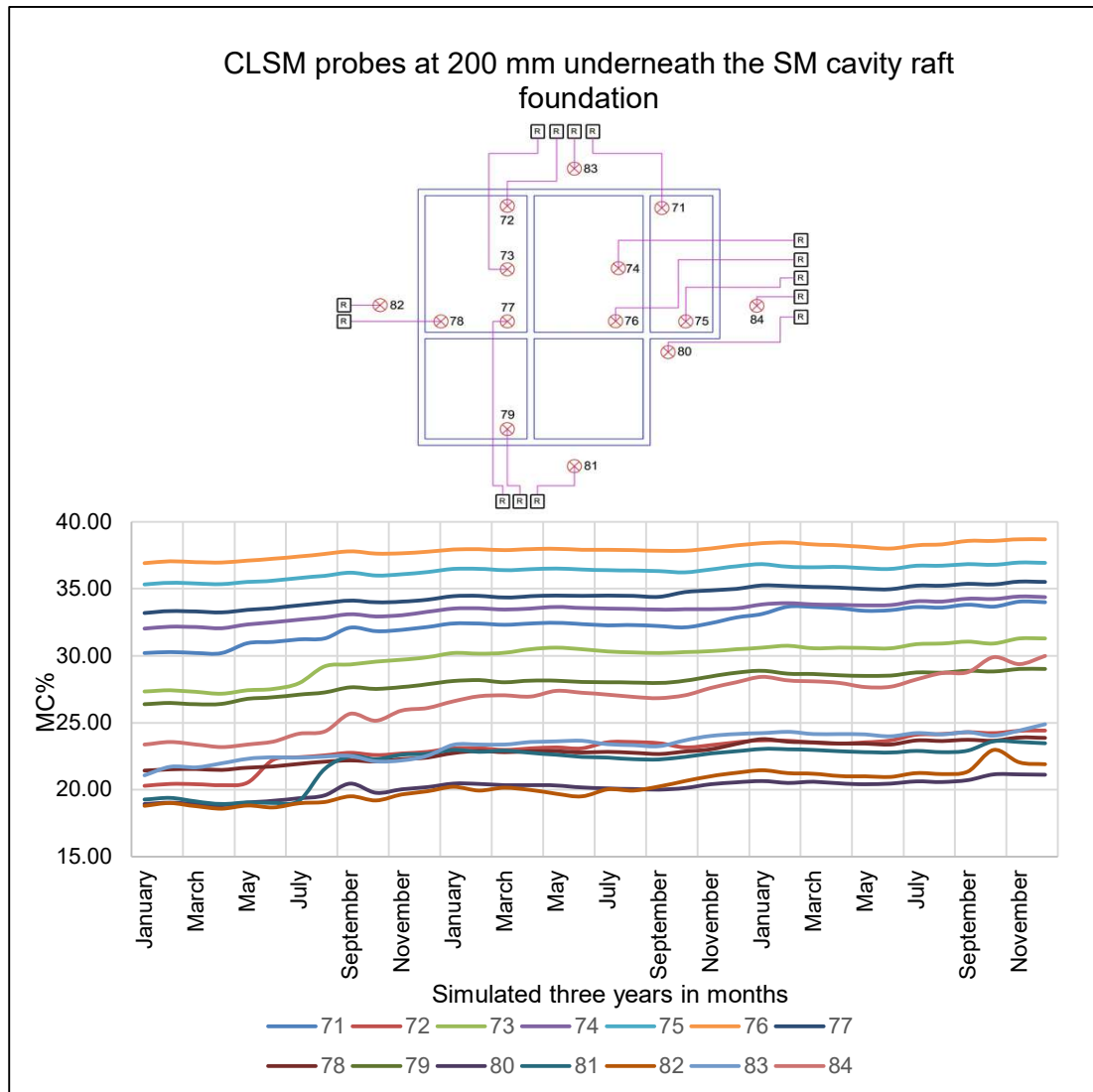


Figure 4.24: CLSM probes at 200mm underneath the SM cavity raft foundation

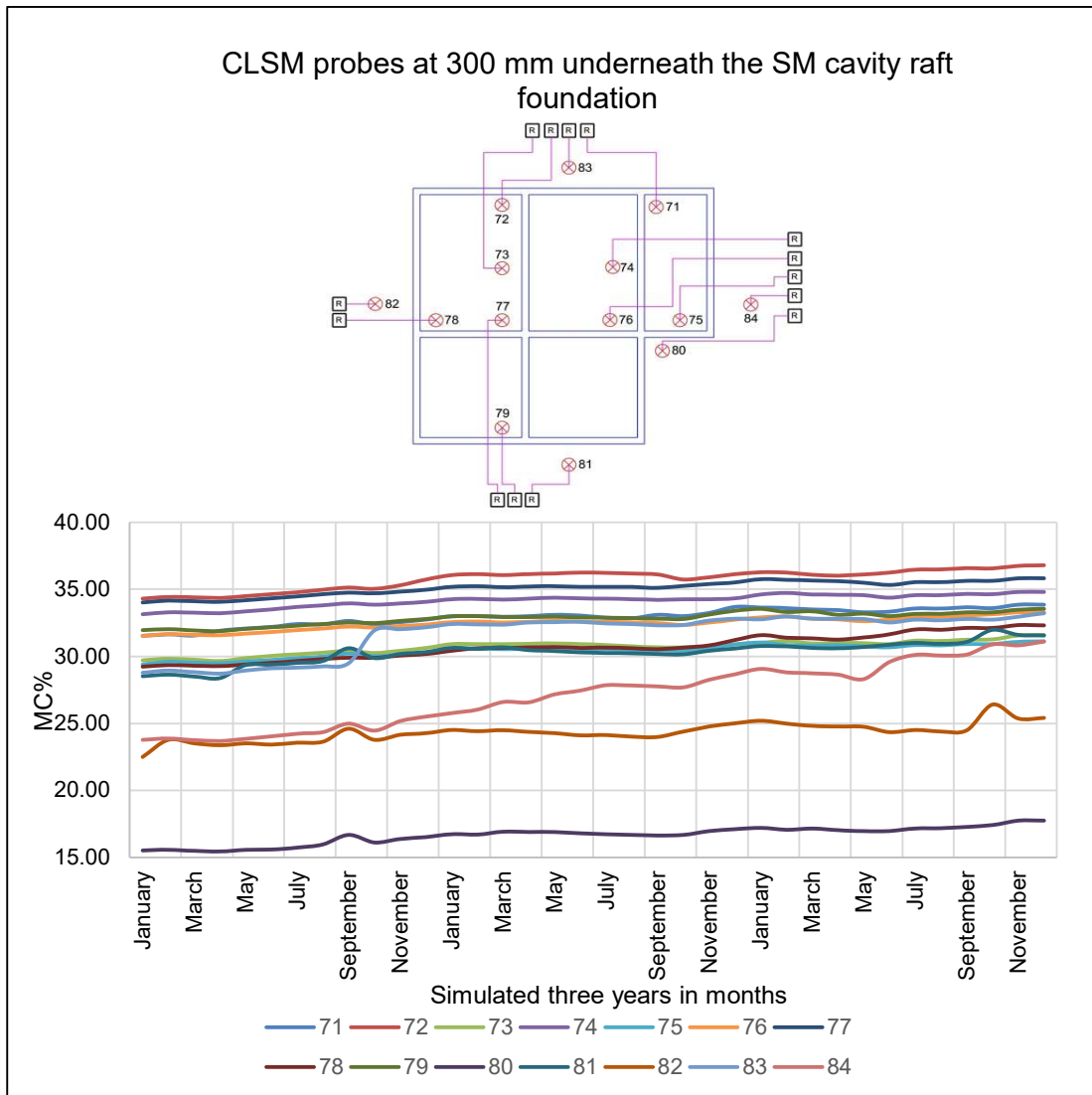


Figure 4.25: CLSM probes at 300mm underneath the SM cavity raft foundation

Figure 4.26 shows average moisture content at a depth of 400 mm, where levels remain relatively stable compared to shallower depths, likely due to the soil's low permeability and high clay content. Point 84 again shows the most prominent change, with a 7% increase in moisture, though this is unlikely to affect the foundation as it lies on the SM's outer perimeter.

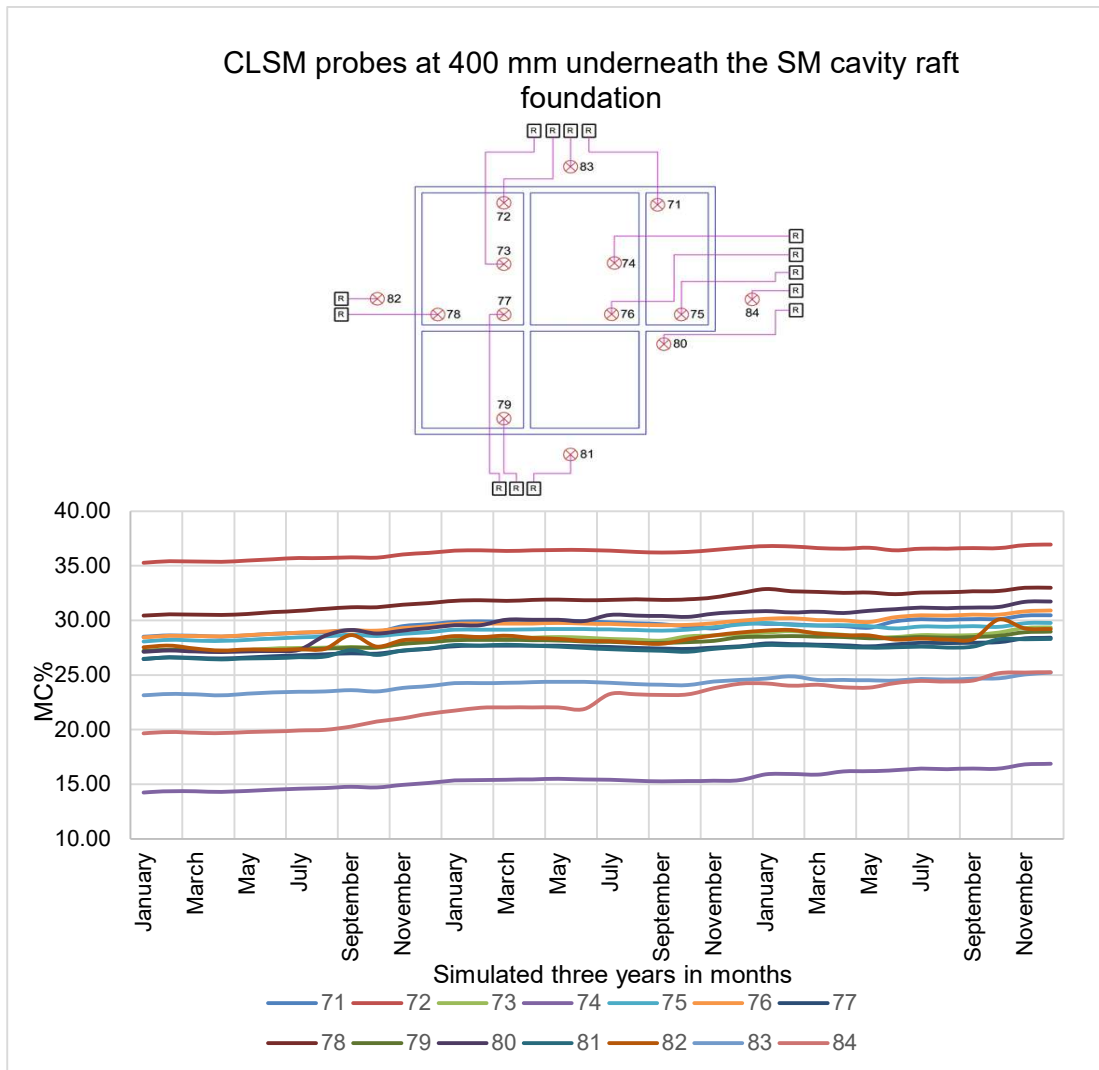


Figure 4.26: CLSM probes at 400mm underneath the SM cavity raft foundation

4.5.2. Differential movement analysis of the SM cavity raft foundation

Once a state of equilibrium is achieved, stability can be observed in the SM cavity raft foundation. This observation aligns with the assumptions by Hamakareem (2020) on ventilated foundation systems, which can control heave by managing moisture levels beneath a foundation. The cavity raft systems can regulate moisture since the ventilation helps release excess moisture and prevent accumulation under the foundation slab. This airflow helps with reducing expansive clay swelling. These

findings also align with Chen's (1988) honeycomb foundation and Geoplast for expansive soils, which allows airflow.

Figure 4.27 shows the vertical movement of the SM cavity raft foundation at the southwest corner. All data points began at zero, with settlement observed in the first six months of the simulated period, ranging from 0.4 mm to 1.2 mm. This settlement likely resulted from constructing the SM cavity raft immediately after the simulated period for the SM raft foundation, leaving the soil moist from a simulated wet season. Due to the artificial sun's heat, moisture quickly dissipated around the perimeter, causing the expansive clay to shrink and resulting in minor settlement. After this initial settlement, vertical movement remained stable for the rest of the three-year simulation. This stability suggests that the ventilation in the SM cavity raft foundation effectively regulated moisture through evaporation, reducing foundation movement. The probable mechanism is that expansive clay heaves into the cavity during rainfall, following the path of least resistance, while ventilation holes allow moisture to evaporate and escape. The graph shows a consistent pattern of small vertical movements during wet and dry periods, supporting the theory that the SM cavity raft foundation effectively manages moisture content and heave.

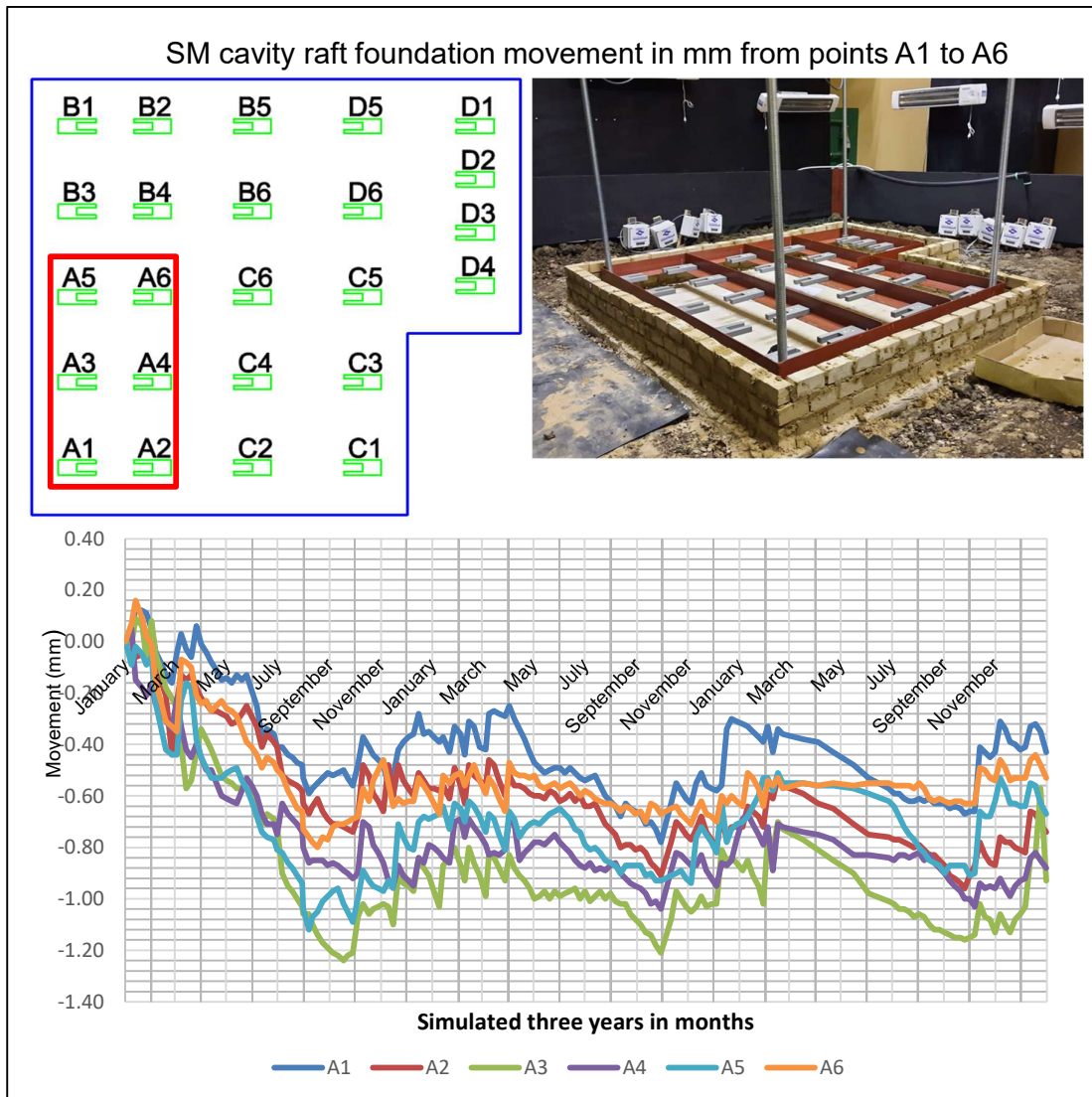


Figure 4.27: SM cavity raft foundation movement in mm from A1 to A6

The vertical movement data points at the northwest corner of the SM are represented in Figure 4.28. The north-facing side of the model is most exposed to heat energy during the simulated year and could potentially be most affected by rapid moisture changes. Points B1, B2, B3 and B4 experienced settlement due to the shrinkage of the expansive clay soil in the first simulated year period. Settlement of the SM cavity raft foundation did not occur at points B5 and B6. Possible hypotheses could be that the interior beam running underneath point locations B5, B6, C6, C4 and C2 has sufficient stiffness to prevent settling, as with the corners.

This is also the case for other corners, where the initial settlement occurred within the first simulated six months, followed by a stabilising period with minimal movement. The locations with the highest structural strength in the SM are where multiple beams intersect, providing rigidity. After the initial settlement, the vertical movements remain constant. This pattern persists throughout the simulated seasonal changes, with simulated rainfall having little to no effect overall on the movement of the SM. The SM's cavity and ventilation assist in controlling heave and facilitating moisture evaporation.

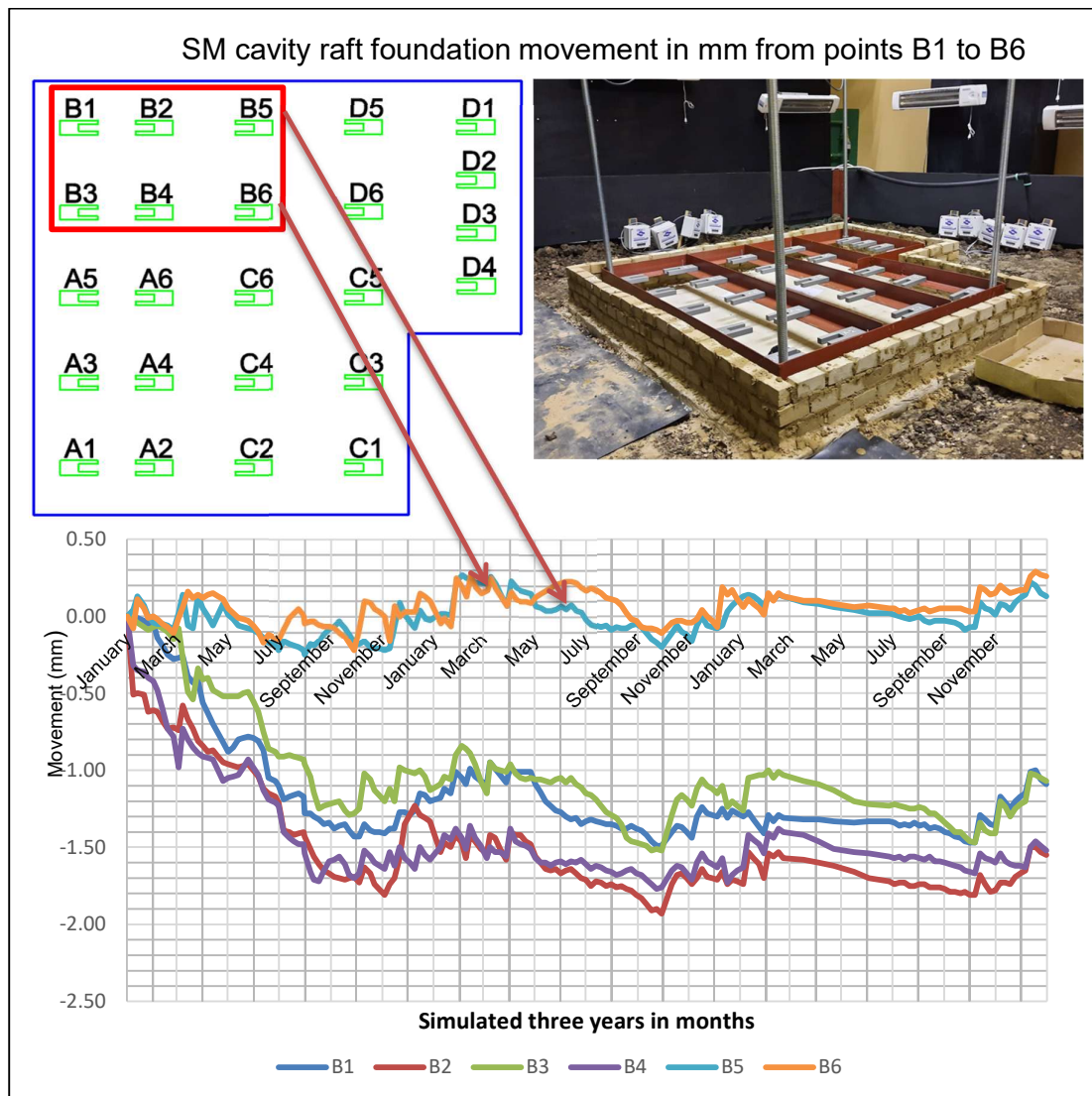


Figure 4.28: SM cavity raft foundation movement in mm from B1 to B6

Figure 4.29 shows the southeast location of the SM, which corresponds to the re-entry corner prone to water collection. Points C5 and C4 experienced the most heave, with approximately 1.2mm at C6 and 0.8mm at C4, both located in the centre of the SM cavity raft underneath the beam. Point C1 is suspected of experiencing settlement, similar to other corners of the SM, but it is less prominent due to the limited heat energy reaching the far south corner. This results in less moisture evaporation over time and higher moisture content than the rest of the clay soil. This corner also experienced the most heave after rainfall.

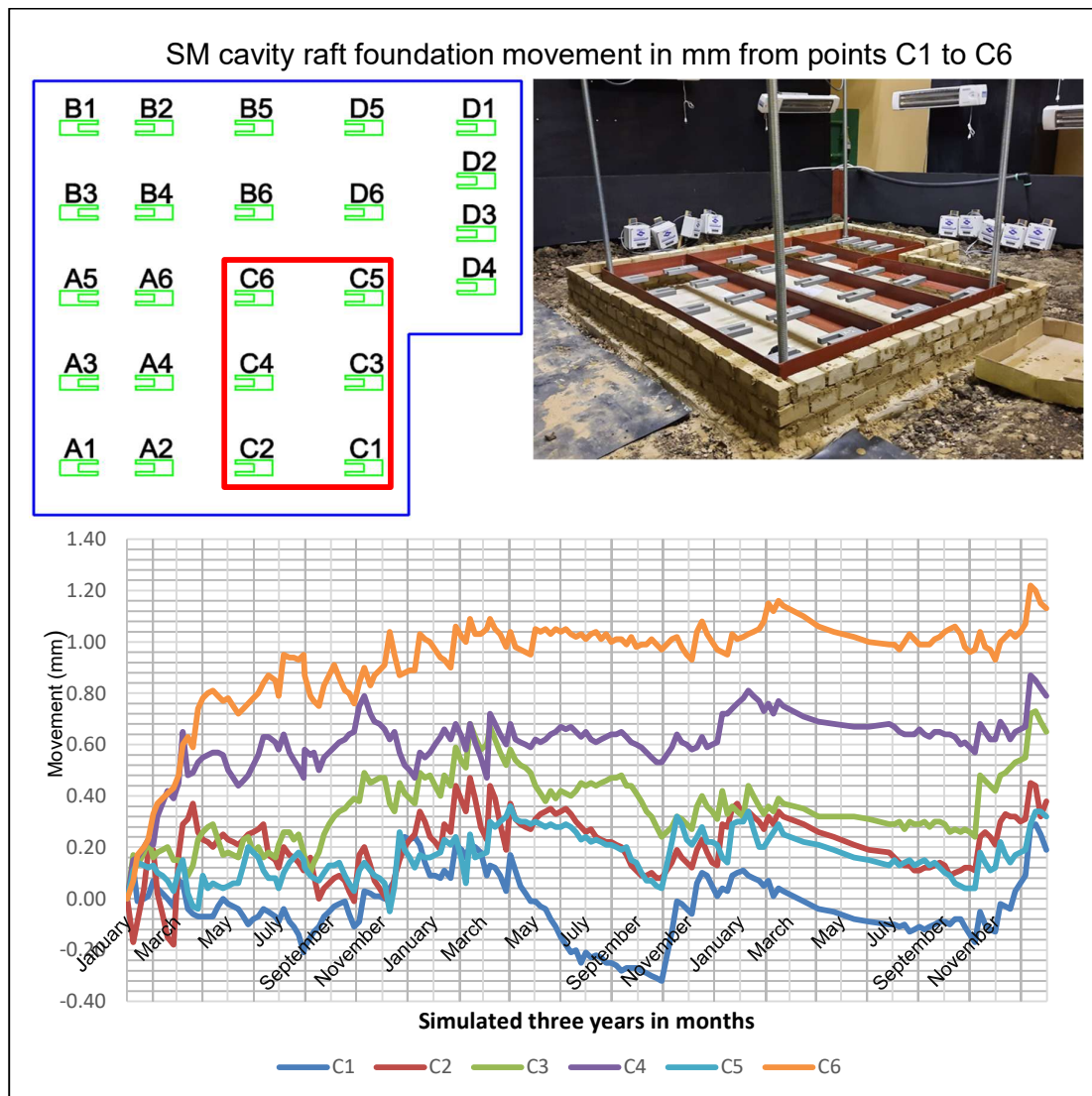


Figure 4.29: SM cavity raft foundation movement in mm from C1 to C6

Figure 4 - 30 represents the northwest location of the SM. Points D1, D5, and D6 experienced very little settlement in the first simulated six months compared to points D2, D3 and D4, which underwent slight heaving over the three-year simulated period. Overall movement around the northwest remained stable after the initial vertical movements. Points D2, D3 and D4 experienced the most heave, approximately 0.9mm. Once again, the ventilation holes helped control moisture and movement by allowing the clay to expand inside the cavity and facilitating moisture evaporation, resulting in minor movement changes for the SM.

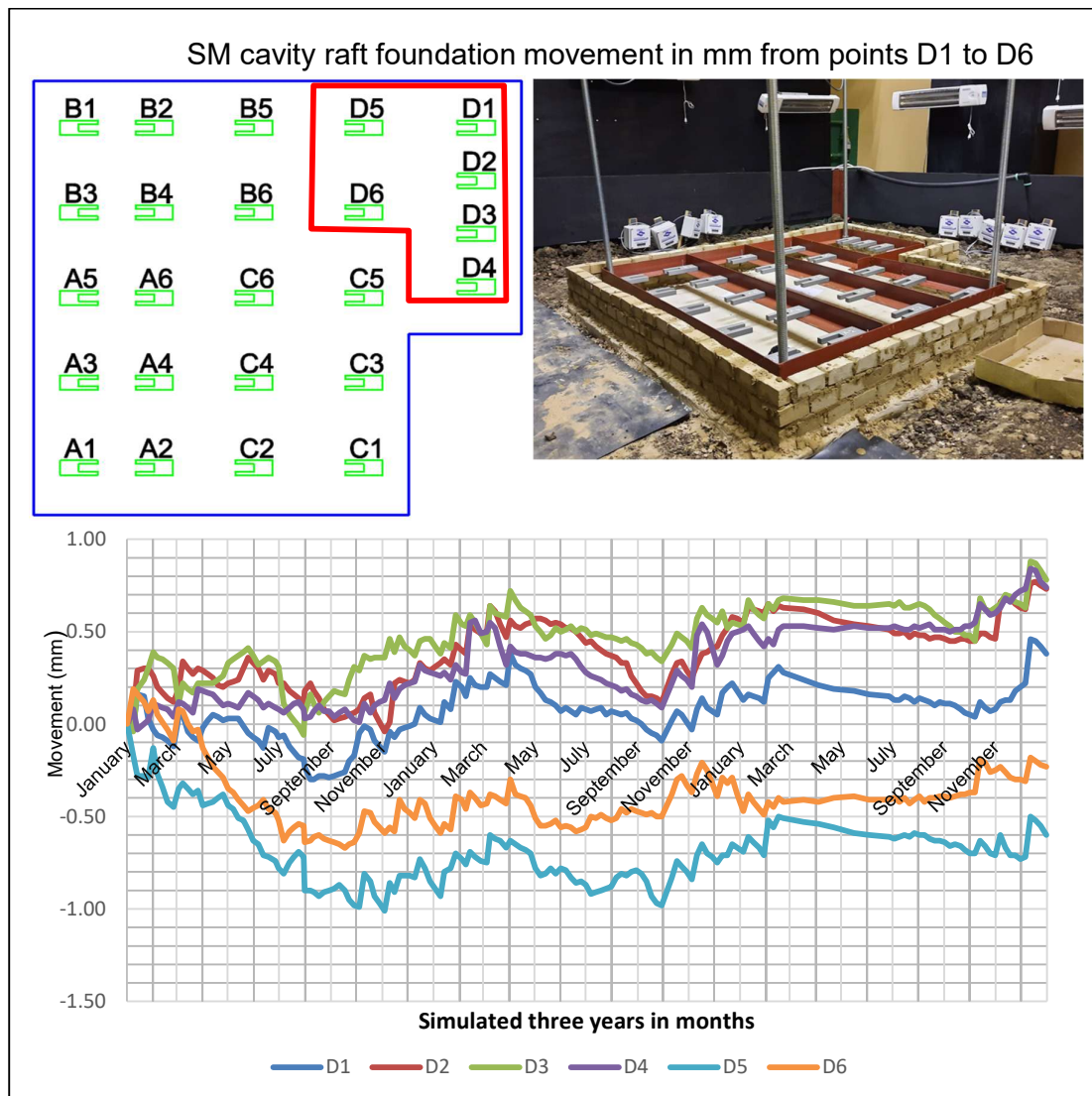


Figure 4.30: SM cavity raft foundation movement in mm from D1 to D6

Figure 4.31 illustrates a 3D movement heat map for the SM cavity raft foundation, oriented from the southwest corner in December of Year 2. The heat map shows settlement along the north-facing edges, where increased sunlight exposure accelerates moisture loss. This results in higher soil shrinkage and downward movement. The heat maps show less movement at the re-entry corner, which is shaded from direct heat energy and thus retains moisture in the clay soil. A slight amount of heave is observed at the re-entry corner, while settlement is observed at the northwest corner. A state of equilibrium is achieved relatively quickly, where no further significant movement in heave or settlement. Additional heat maps illustrating these patterns are provided in Appendix G.

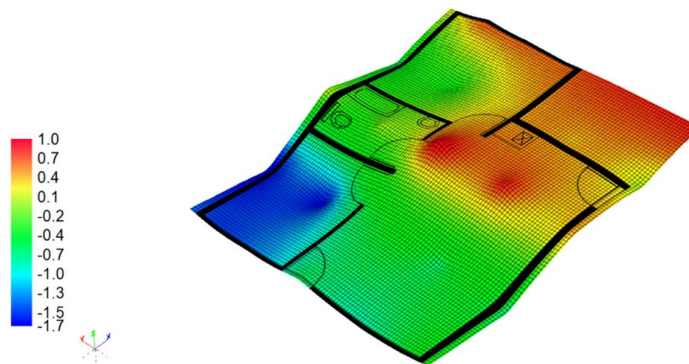


Figure 4.31: Year 2 – December: 3D movement heat map of the SM cavity raft foundation, orientation from the Southwest corner.

4.5.3. Edge penetration analysis of the SM cavity raft foundation

In this section, the researcher will discuss the findings related to the edge penetration distance in the SM cavity raft foundation. This section bears a resemblance to section 4.3.3, with the main difference being that only the SM cavity raft foundation beams were in direct contact with the soil, given that the slab was

suspended. The edge penetration distance is measured from the exterior beam's edge inward to the centre of the raft foundation. Figure 4.32 illustrates the difference in movement (in mm) from east to west during the third simulated year of the SM cavity raft foundation.

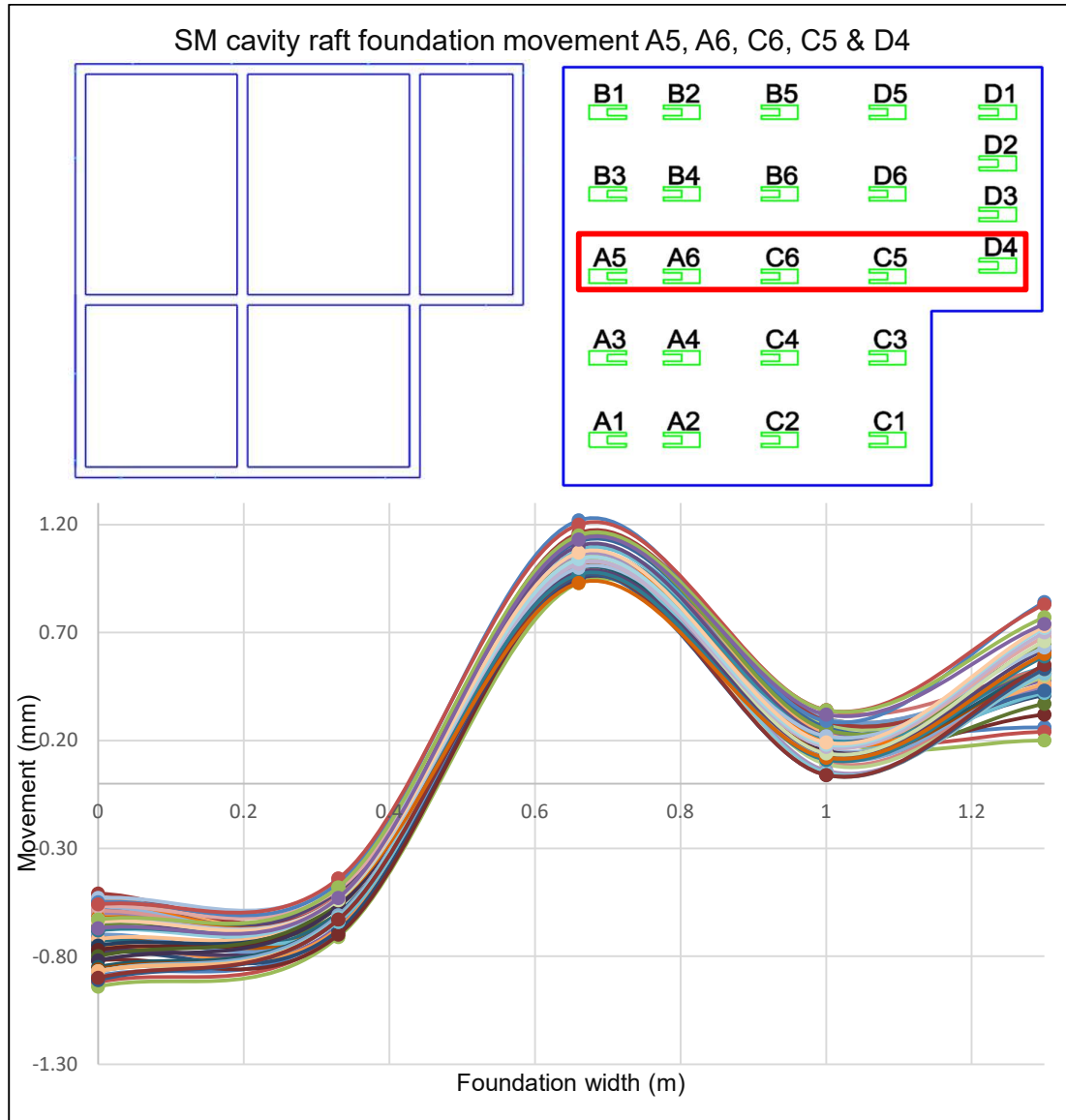


Figure 4.32: SM cavity raft foundation movement (in mm) from south to north (C2, C4, C6, B6 & B5)

The selection of the third year is based on the expectation that the SM cavity raft foundation would have achieved a state of equilibrium within the soil's movement

patterns by that time. All the data points followed a consistent trajectory during the simulated third year. There is no significant change in movement once the expansive clay reaches equilibrium beneath the SM. The most significant movement observed on the SM cavity raft foundation occurred on the model's west side, measuring 0.5mm, as opposed to the SM raft foundation, which experienced 0.7 mm (as discussed in section 4.3.3). The highest vertical movement recorded for the SM raft foundation during year three was 1mm at the re-entry corner, while the SM cavity raft foundation exhibited 0.3mm of vertical movement at the re-entry corner (point C5) during the same period.

Figure 4.33 shows the movement from south to north during the third simulated year for the SM cavity raft foundation. The north side experienced the most movement, measuring 0.4 mm at point B5, compared to the same point B5 of the SM raft foundation, which measured 0.6 mm during the same period. The north-to-south movement pattern remains consistent and follows a similar path throughout the simulated year three. The vertical movement pattern follows the same trajectory, in contrast to the SM raft foundation, which may exhibit more erratic vertical movement patterns during year three. The study of the SM cavity raft foundation provides evidence of the benefits of having ventilation beneath a suspended slab.

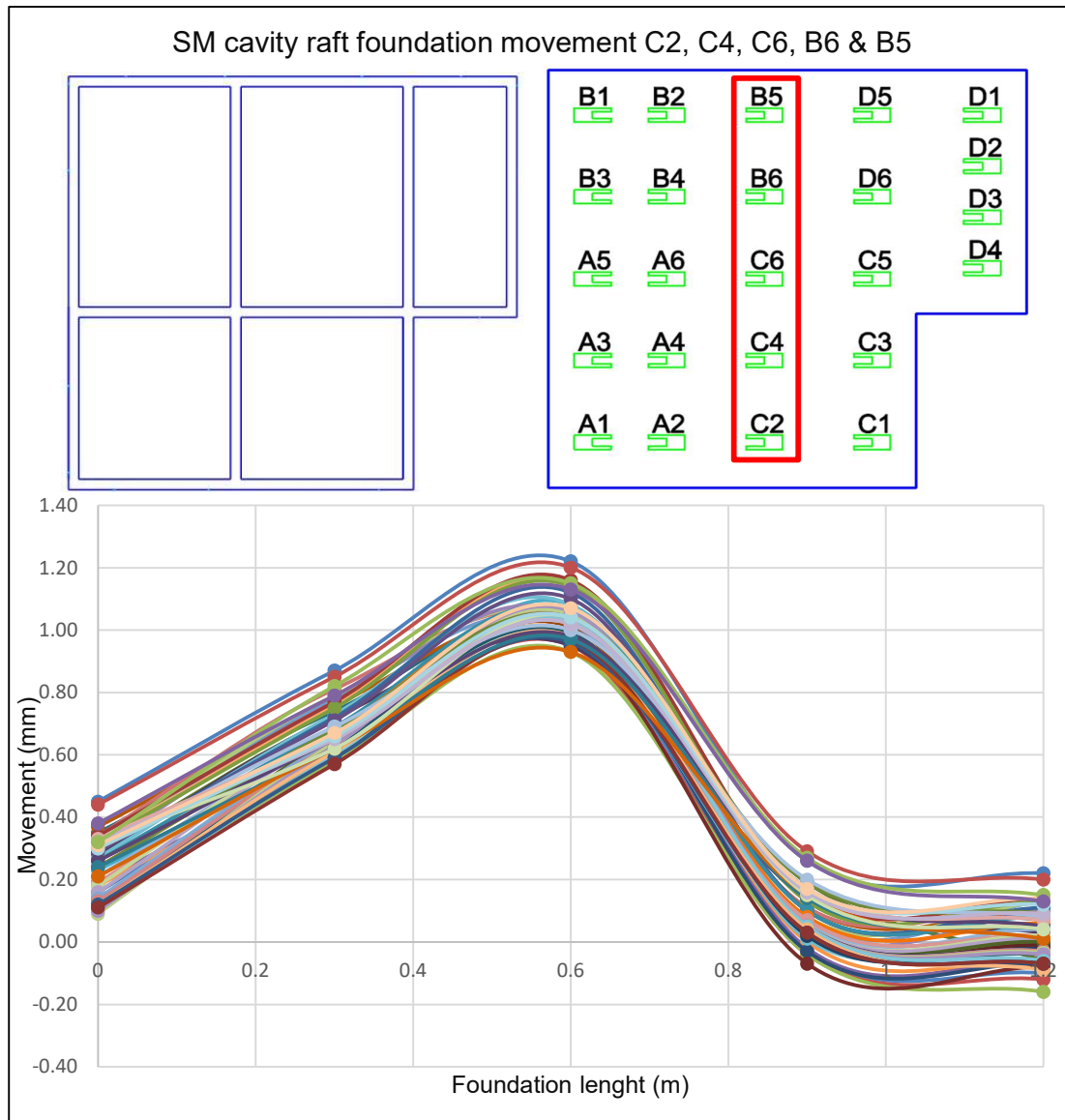


Figure 4.33: SM cavity raft foundation movement (in mm from south to north (C2, C4, C6, B6 & B5))

4.5.4. Strain analysis of the SM cavity raft foundation

This section examines the strain analysis findings of the SM cavity raft foundation. Figure 4.34 presents the strain readings of the SM over three simulated years. Strain measurements were taken at the interfaces between phases with different properties, specifically between the expansive clay and concrete beams. Strain gauges were placed where the beams contacted the expansive clay, with data

collected at twenty locations over three simulated years. The strain gauge readings exhibited two distinct patterns. Points A to O (outer beams) displayed a different pattern compared to points P to T (inner beams). The outer beams of the SM cavity raft foundation exhibited a pattern similar to that of the SM raft foundation at the start of year one, with strain ranging between 300 and 800 $\mu\text{m}/\text{m}$. This pattern displayed seasonal peaks in summer and drops during winter, with a notable decline shortly after construction, eventually stabilizing at equilibrium.

In contrast, the internal beams displayed a unique pattern not seen elsewhere, with significantly lower strain readings. Equilibrium was reached after six simulated months, after which strain for the inner beams remained within the 100 $\mu\text{m}/\text{m}$ range. Given that strain and stress are related, higher strain typically corresponds to higher stress in beams of similar dimensions and materials, indicating that the internal beams experienced much lower stress than the outer beams. The substantial difference in strain readings can be attributed to the effectiveness of the ventilation design. The ventilation system mitigated moisture buildup in the expansive clay and maintained equilibrium within the SM. Rainfall-induced moisture would flow under the beams into the interior, causing the expansive clay to swell and heave into the cavity while moisture evaporated through the ventilation holes. This moisture control and heave mitigation stabilised the internal beams, resulting in relatively constant strain readings. Appendix H presents a simplified representation of the strain data, including strain graphs.

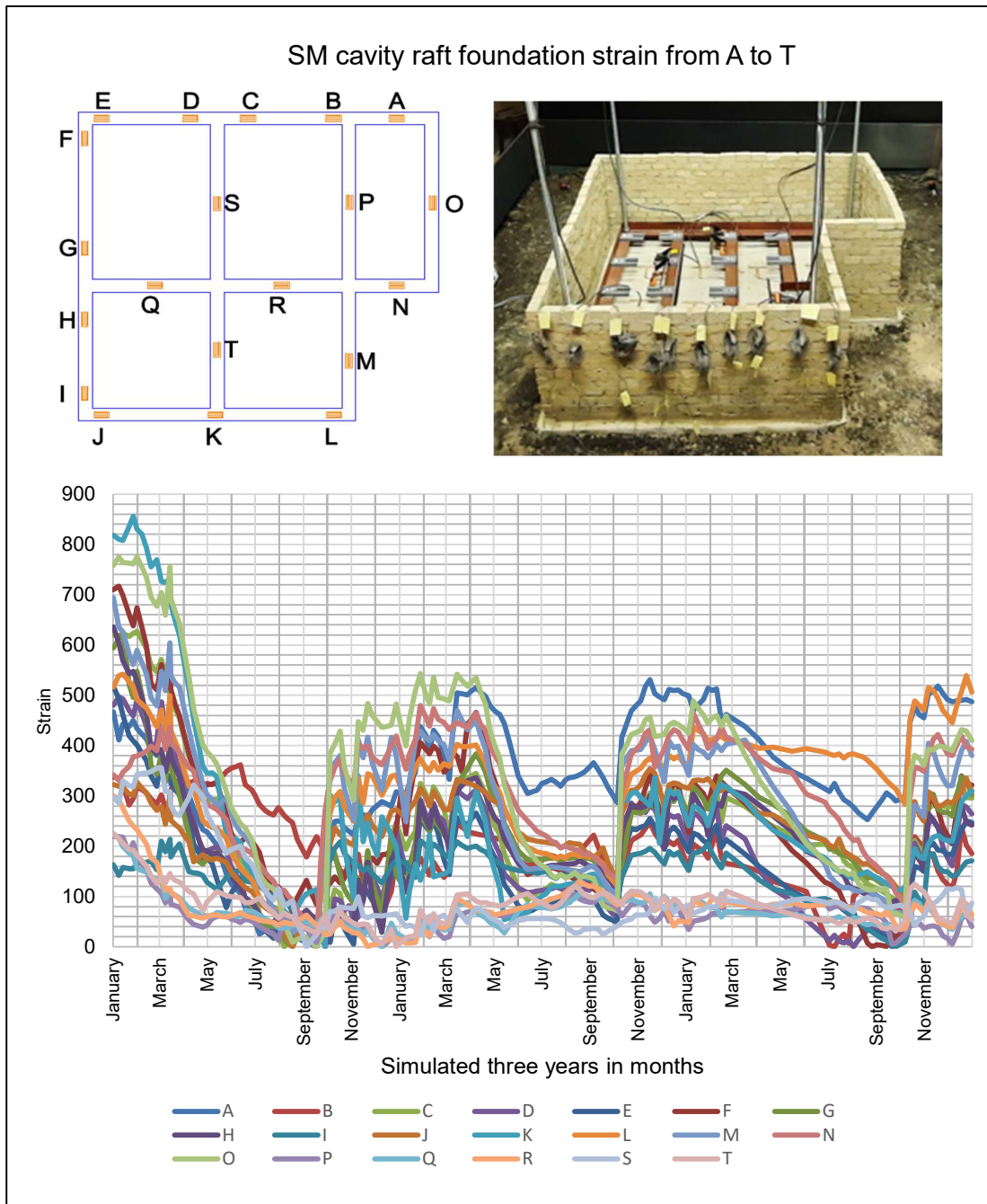


Figure 4.34: SM cavity raft foundation strain from A to T

4.5.5. Summary of the SM cavity raft foundation

The results show that cavity raft systems with ventilation offer promise for structures on expansive clays by controlling moisture content and reducing heave. The SM cavity raft foundation controlled moisture and, thus, minimised heaving. It presents

a potential solution for structures built on expansive clay soils. However, one drawback of the cavity raft foundation is its potential for settlement, which was observed soon after the construction of the SM model. Designers should account for potential settlement and incorporate preventive measures into their designs. However, the cavity raft foundation reaches settlement equilibrium quickly, limiting vertical movement after the initial period.

4.6. Summary: comparison between the SM raft and SM cavity raft foundation

The comparison between the SM raft foundation and the SM cavity raft foundation reveals essential differences. The main distinction is that the cavity raft foundation quickly achieves equilibrium, meaning its movement decreases to an almost minimal level. On the other hand, the SM raft foundation retains moisture beneath it, preventing it from reaching a stable state. Both foundations show similar moisture distribution patterns, with higher moisture levels in the south-facing re-entry corner and greater variations on the north-facing side due to direct heat exposure. Studies by Pidgeon (1980), Pidgeon & Pellissier (1987), and Fityus et al. (2004) indicate that factors like moisture, temperature, rainfall, and soil properties affect edge penetration distance. However, the results show that shape, orientation, and building shadows contribute to uneven moisture patterns. A design like a cavity raft foundation can potentially minimize moisture buildup issues and enhance stability since it will not experience problems such as edge penetration distance. However, for the cavity raft foundation, considerations should be made on potential settlement since it may experience settlement soon after construction.

CHAPTER 5: DESIGN RECOMMENDATIONS

5.1. Current raft foundation design approaches and limitations based on the findings of the study

Various designs and approaches exist for designing raft foundations on expansive soils. Common procedures utilised in South Africa are those developed by Pidgeon (1987), Lytton (1972), Welsh (1979), and Day (1991), as discussed in the literature review. All these methods require input of various elements before a method can be applied. These elements include the type of soil mound, the geometry of the soil mound, edge penetration distance, the soil structure interaction model, the load representation of the structure, the shape of the foundation and its representation, and the concrete section analysis. As recommended by Pidgeon (1987) in the universal method, the typical design steps followed by most design methods are as follows:

- I. Design the layout of the raft foundation, including the arrangement of stiffening beams and the position of the wall loads. The beam locations are measured from the base of the L-shaped foundation and should be run in each direction.
- II. Position wall loads and the location of stiffening beams relative to the long axis of the base rectangle.
- III. Apply a uniformly distributed load. Typically, a load of 1kPa is applied for a typical dwelling . Alternatively, it can be calculated by the designer for a more precise load distribution.
- IV. Estimate the cross-sectional area of the concrete, including beam depth, width, slab thickness, and flexural inertia.
- V. Select the long-term elastic modulus of the concrete and Poisson's ratio.

- VI. Determine the allowable deflection for the type of superstructure to be constructed. For solid brickwork with no joints, it should be 1 in 3500; for brickwork with joints not exceeding 4 m, 1 in 1000.
- VII. Determine the modulus of the subgrade reaction (k-value) using Pidgeon's equivalent elastic modulus of the soil.
- VIII. Determine the mound shape that will form and the edge penetration distance. It can be either a flat-top mound with parabolic edges based on the differential heave and edge penetration distance or a flat-top mound with no defined differential heave and mound exponent.
- IX. Determine the beam and slab dimensions, steel properties, and elastic modulus.

The current design procedures rely on the designer to estimate an appropriate mound and its geometry. Based on the mound that will form, the designer must select an appropriate edge penetration distance. The raft foundation design must have sufficient stiffness to avoid exceeding the desired deflection. In Figure 5.1, the edge penetration distance is represented based on previous studies by Pigeon (1987).



Figure 5.1: Edge penetration distance

From the results of this study, it is believed that the current design approach may overlook critical factors, such as the shape of the building layout and its orientation to the sun. The existing methods for raft design also fail to account for the complexity

of accurately predicting soil mound behaviour and how it changes over time. The current designs are susceptible to failure, particularly on highly expansive clays. It is suggested that the current designs on expansive clays may underestimate the complexities involved and should be reconsidered. A more robust approach is needed, which takes into account factors such as the building's orientation and higher rigidity in the raft's beams or an alternative approach that allows moisture underneath to escape.

5.2. Design recommendations based on the study findings

Based on the findings and observations from the study, two design procedures are proposed for foundations on GSH (highly expansive clay soils) that are expected to be more reliable. The first procedure pertains to designing a raft foundation, while the second introduces a new cavity raft design concept.

5.2.1. Design recommendations for raft foundations

The following design procedures and recommendations are proposed based on the findings:

- I. Design the layout of the raft foundation, including the arrangement of stiffening beams and the position of wall loads. Ensure that the beam locations are as evenly spaced as possible. Refer to Figure 5.2 for recommended beam layouts that can be adopted.
- II. Determine the locations of wall loads and stiffening beams in relation to the long axis of the base rectangle. Consider the effects of roof loading on outer wall loads.

- III. Apply an appropriate uniformly distributed load. Typically, a load of 1kPa is used for a typical dwelling, as recommended by Pidgeon (1987).
- IV. Calculate the initial estimation of the cross-sectional area of the concrete, which should encompass overall beam depth, width, slab thickness, and flexural inertia.
- V. Specify the long-term elastic modulus of the concrete and Poisson's ratio.
- VI. Determine the allowable deflection for the type of superstructure to be constructed. For solid brickwork with no joints, it should be 1 in 3,500; for brickwork with joints not exceeding 4m, it should be 1 in 1,000.
- VII. Consider the building's orientation to the sun.
- VIII. Determine the location of the re-entry corner of the building. Refer to Figure 5.2 for re-entry corner (REC) locations in relation to the sun.
- IX. Identify the region (indicated by the black dot) where moisture concentration is expected to occur.

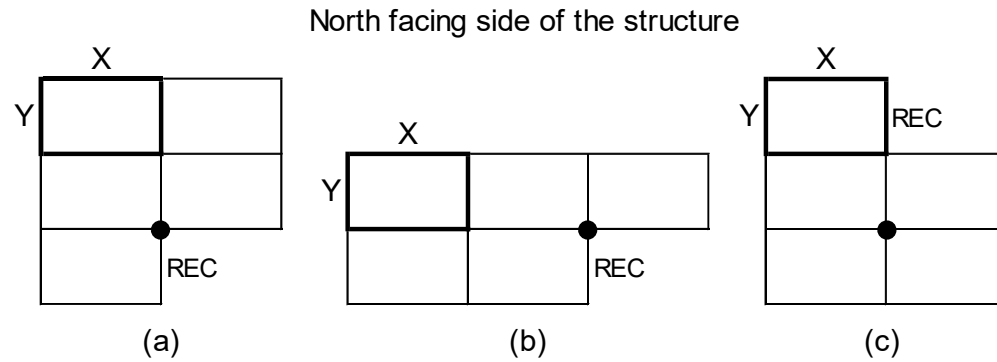
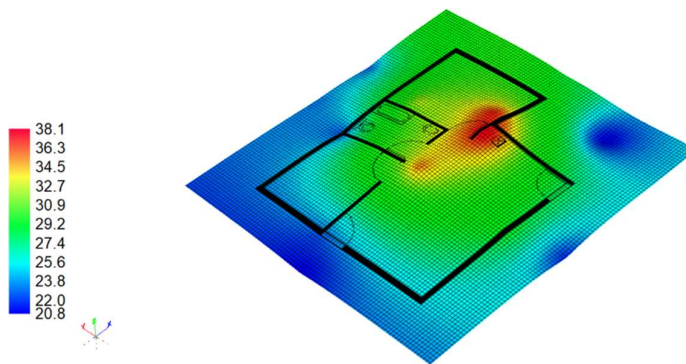


Figure 5.2: Raft foundation orientation of the sun, pod design and location of the REC



- X. Depending on the building's orientation, moisture concentration will move accordingly. If the re-entry corner (REC) is on the south side, moisture will move towards that location, as shown in examples (a) and (b). If the REC is on the north-facing side, moisture concentration will shift towards the south and be located more centrally, as demonstrated in example (c) in Figure 5.2.
- XI. Determine the location of the pod furthest away from the potential moisture content concentration. Since multiple layout design possibilities exist, the furthest pods should be determined on a case-by-case basis. In examples (a), (b) and (c) in Figure 5.2, the north-west pod is identified (indicated by thick black lines).

- XII. Identify the direction of the longest potential beam of the pod furthest away. For example, if the beam in the Y direction is the longest, the deflection should be determined in that direction.
- XIII. Assume one side is fixed, and the other acts as a cantilever unsupported by the soil. Refer to Figure 5.3 for an example of fixed-end and loading conditions.

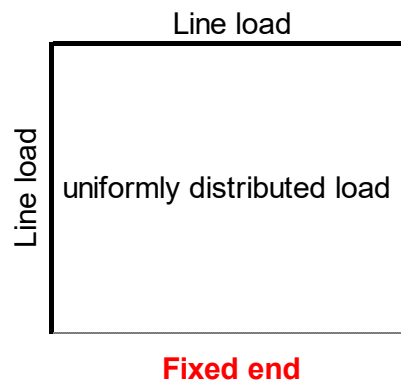


Figure 5.3: Fixed end and loading conditions example

- XIV. Calculate the deflection of the pod. For solid brickwork with no joints, the deflection should be 1 in 3,500, and for brickwork with joints not exceeding 4m, it should be 1 in 1,000.
- XV. Achieve optimal design using thin and deep beams as part of the raft foundation design.
- XVI. Adopt consistent beam dimensions and slab thickness throughout the raft foundation design. Avoid using different designs for each beam.
- XVII. If the deflection exceeds the recommended limits, reconsider and redesign the beam layout, dimensions, and slab thickness.
- XVIII. Install paving around the structure to channel water away. Ensure that the paving extends at least one meter all around the structure.

These design recommendations are proposed for use on high and very expansive clay soils. The data obtained from this study suggests that accurately determining the mound, as recommended by previous researchers, is highly unlikely. While the proposed solution may incur higher initial construction costs compared to current raft design methods, it offers improved durability and reduced maintenance costs over the structure's service life. Furthermore, the new design approach is expected to reduce the risk of complete failure in numerous locations within the GHS foundations across South Africa, particularly in areas with expansive clay soils. In cases where the raft foundation proposal is deemed too costly, the cavity raft foundation approach can be considered.

5.2.2. Design recommendations for cavity or ventilated raft foundations

As there is no established theory for the design of a cavity raft foundation. Elements from the raft foundation design were incorporated, and bearing capacity components considered. Since the cavity raft foundation does not involve elements such as edge penetration distance, which is controlled by the foundation's air ventilation concept, these elements will not be considered. The following design procedures and recommendations are based on the research findings:

- I. Design the layout of the cavity raft foundation, including the arrangement of beams and the positioning of wall loads. Ensure that the beam locations are evenly spaced. Refer to Figure 5.4 for recommended beam layout suggestions that can be adopted.

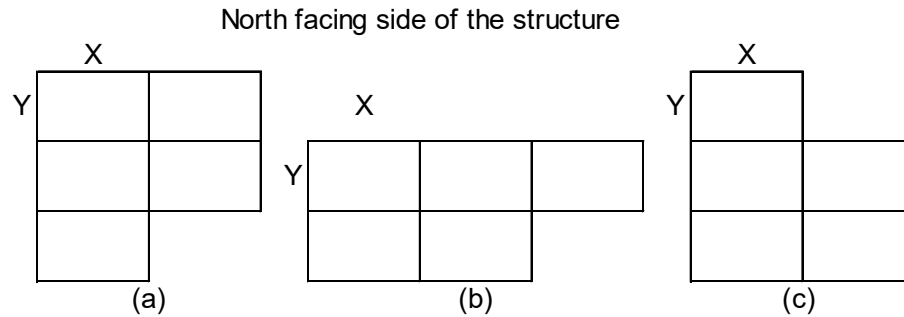


Figure 5.4: The proposed cavity raft foundation beam layouts.

- II. Calculate load conditions. Determine wall loads and position stiffening beams relative to the long axis of the base rectangle. Additionally, account for the imposed roof loading when considering exterior wall loads. Apply a uniformly distributed load. Typically, a load of 1kPa is used in a typical dwelling, as recommended by Pidgeon (1987).
- III. Determine the bearing capacity. Since the slab is suspended, the designer should access the bearing capacity of the soil conditions. The proposed method to be used is Terzaghi's Ultimate Bearing Capacity.
- IV. Specify the long-term elastic modulus of the concrete and Poisson's ratio.
- V. Define the allowable deflection for the type of superstructure to be constructed. For solid brickwork with no joints, it should be 1 in 3,500, and for brickwork with joints not exceeding 4m, it should be 1 in 1,000.
- VI. Design the cavity raft foundation suspended slab as a two-way spanning slab.

Utilise Figure 5.5 as a template for reference.



Figure 5.5: Cavity raft foundation slab

- VII. Identify the locations of the ventilation holes for the cavity raft foundation. It is recommended to have one ventilation hole for every metre. The diameter of the ventilation holes should not be less than 100mm. The holes should encircle the entire structure, including the internal beams.
- VIII. Suspend the slab of the cavity raft foundation. The minimum height from the natural ground level should not be less than 300mm.
- IX. Adopt consistent beam dimensions and slab thickness throughout the cavity raft foundation.
- X. If the deflection for solid brickwork with no joints exceeds 1 in 3,500 or for brickwork with joints exceeds 1 in 1,000, reconsider and redesign the beam layout, dimensions, and slab thickness from the beginning.
- XI. Install paving around the structure to channel water away. Ensure that the paving extends at least one meter all around.
- XII. Construction methods for the cavity raft foundation can vary, from precast beam and slab construction to foundation strip footings with brickwork between the suspended slab and strip footings. All construction methods should incorporate ventilation holes, or the design will be inadequate. Alternative solutions can also be considered.

This design is recommended for high and very expansive clay soils. However, it is not suitable for soils prone to settlement or collapsible soils.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

A significant portion of the South African population relies on GSH, and the country is grappling with a growing housing crisis. The South African Government constructed 2.7 million low-cost houses by 2014 (Harsch, 2014). As of 2018, Statistics SA reported that 13.6% of South African households were residing in GSH or state-subsidised homes (Statistics, 2018). However, an estimated backlog of 2.5 million GSH remains in South Africa (Houston, 2022). The backlog in GSH construction has surged to 1.2 million in Gauteng alone in recent years (Sobuwa, 2022). The GSH are typically built on low-cost, less desirable land on the outskirts of major cities and municipalities. Land often consists of expansive clay soils that can cause significant damage to buildings. The lightweight construction of the houses makes them highly vulnerable to being lifted by expansive clay soils, posing a substantial risk to residents and resulting in costly repairs.

This study has highlighted the critical challenges of constructing GSH and light-structured houses on expansive clay soils. It has also identified limitations in current design methods for building GSH raft foundations and has provided recommendations for improving the design and construction process. In this final chapter, the primary conclusions of the thesis will be presented.

6.2. Limitations and shortcomings of the study

The use of scale models is a common practice in investigational research for large structures or buildings due to the constraints of on-site testing capacity. Small-scale

modelling of structural behaviours inevitably carries limitations as fully replicating the actual scenario becomes nearly impossible. The modelling accuracy depends on various factors, including model material properties, construction precision, and loading techniques. Fundamental scale factors, such as dimensions, mass, length, and time, must be carefully selected with a scaled-down model. Given the nature of the study, additional factors including the orientation and movement of the artificial sun, had to be taken into account. Further investigation and research is recommended using a full-scale model foundation to validate the findings related to differential movement and heave. However, this could not be undertaken in this study, as a suitable building could not be identified to instrument. Finding a willing homeowner who would agree to such an investigation was challenging, and the cost of constructing a full-scale model house is substantial.

Another constraint and challenge encountered was measuring the ventilation underneath the SM cavity raft foundation. Difficulties were experienced in obtaining suitable equipment for this task, primarily due to the size of the SM models and the numerous ventilated openings beneath the system. Future research could explore this aspect, and it is recommended that more ventilation holes be incorporated in the cavity raft foundation design to ensure adequate airflow and ventilation.

6.3. Important findings of the study

- I. Sun's Orientation and Moisture Movement: The sun's orientation to the structure predominantly affects moisture movement beneath the foundation constructed on expansive clay soil. Seasonal changes impact solar radiation exposure, where the north-facing side receives the most solar energy

(southern hemisphere). The findings of this study corroborates with the findings of the studies by Bester *et al.* (2016, 2017) regarding Botshabelo's GSH constructions, showing that the north-facing sides exhibit lower moisture levels. This leads to rapid soil expansion during rainfall, illustrating the consistent impact of sun orientation on soil moisture dynamics under raft foundations. The north side of the building consistently shows lower moisture content than other sides and is susceptible to rapid expansion during rainfall. The north-facing side of the structure experiences more significant variation, by drying out quickly. Therefore, water absorption is much faster during rainfall.

- II. Areas with limited sunlight tend to maintain more constant moisture levels. The re-entry corner of the structure consistently shows the highest moisture content. This location is shielded from direct sunlight, resulting in higher moisture content due to lower temperatures than north-facing areas. The study's findings indicate that dome or mould formation occurs off-centre toward the re-entry corner, and not at the foundation's centre.
- III. In a square foundation scenario, moisture content (MC%) is likely to be higher on the southern side of the building due to more intense solar radiation from the north. Contrary to previous suggestions, less sunlight on the south side leads to an off-centre dome or mould formation towards the south side of the foundation.
- IV. Dome or Mould Formation: Contrary to the current theory that dome or mould formations occur centrally, this study found it to be off-centre, typically towards the colder side with less solar exposure. This finding is significant as

it challenges the previously accepted patterns in raft foundation designs, as supported by Tabassum and Bulut (2023), Pigeon (1987) and Day (1991).

- V. The determination of edge penetration distance by existing design methods is unlikely to be correct. Moisture variation throughout the year is constant and depends on factors such as rainfall intervals, temperature, and the structure's shape. It is recommended to design raft foundations by considering potential moisture concentration due to the building's orientation to the sun. Once the potential moisture concentration is identified, the furthest pod of the raft foundation should be designed as if it were a cantilever.
- VI. Cavity Raft Foundation Performance: The cavity raft foundation is effective on expansive clay soils because it enables moisture evaporation through ventilation holes. This foundation type reaches a state of equilibrium more rapidly, thus reducing movements within the structure over time. The ventilation within the foundations plays a vital role in regulating the soil's moisture content, thus minimizing the risk of heave that could damage the structure.
- VII. The data collected in this study supports the effectiveness of cavity foundations in controlling heave from occurring. The findings align with previous theoretical concepts proposed by Geoplast or Voidform that advocate for the use of such designs. The findings suggest it is a practical application to limit heaving from occurring.

6.4. Recommendations

The study's findings suggest the following recommendations applicable to GSH or any lightweight housing structure built on expansive clay soils in South Africa.

- I. If the soil conditions at the construction site are suitable, the new stiffened raft foundation approach which is recommended in the study is likely the most satisfactory solution for new GSH construction.
- II. In cases where the construction site features highly expansive clay conditions, designers should consider a cavity raft foundation approach as a feasible solution for new GSH construction.
- III. Raft foundation design should aim to limit long-term differential deflections and distortions to ensure that the deflection ratios across the centre and along the edges of the rafts do not exceed 1 in 1,000. This deflection ratio is sufficient if buildings have internal and external articulation joints, and brickwork meets the standards. The rafts must provide approximately twice this stiffness if no articulation joints are present.
- IV. Installing a sloping apron of paving away from the building can increase the distance that moisture must migrate underneath the foundation. This can significantly enhance the success of building construction on active clays.
- V. To maintain more constant moisture levels underneath the foundation on expansive clays, take measures to prevent water from pooling near the buildings. Avoid planting trees or shrubs closer to the houses than one and a half times their mature height.
- VI. Integration of technological advances into at least one design per government subsidised housing project, especially in areas affected by soil related problems. Designers should explore the integration of technologies such as smart sensors to monitor and study structural health continuously. This could lead to real-time adaptive management strategies which could be implemented in future projects.

6.6. Summary

It was noted by Bester *et al.* (2016) that moisture content measurements under raft foundations of GSH built on clay soil suggest that currently accepted patterns of heave are unlikely to provide good guidance for foundation design. Tabassum and Bulut (2023) also suggested that edge penetration is challenging to predict. They emphasised the need for further research in residential house slabs and foundations, involving the measurement of moisture, temperature, and displacement sensors over an entire weather cycle to develop models that capture the actual movement of the slab versus model predictions (Tabassum & Bulut, 2023). The instrumentation used in this study has demonstrated its convenience and dependable performance. The instrumentation and modelling have yielded new predictions of moisture conditions that must be considered in the design of foundations on expansive soils. The design of a wide range of reliable and cost-effective raft foundations is crucial. The recommended design methods aim to reduce the potential for structural failures in GSH construction. The intention is to implement similar instrumentation in various other lightweight structures to facilitate further modelling developments. In the current context, applying the findings from this research study can result in improved estimates of moisture patterns and a more realistic design for foundations in GSH construction on expansive clays in South Africa.

CHAPTER 7: REFERENCES

- ALVES, M., OSHIRO, R.E., CALLE, M.A.G. & MAZZARIOL, L.M. 2017. Scaling and structural impact. *Procedia Engineering* 173:391-396.
- AITCHISON, G.D. 1960. Some interactions of compaction, permeability, and post-construction deflocculation affecting the probability of piping failure in small earth dams. Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering Montreal, Canada, pp. 442-445.
- ALONSO, E.E., GENS, A. & JOSA, A. 1990. A constitutive model for partially saturated soils. *Géotechnique* 40(3), pp. 405-430.
- ANEKE, F.I., MOHAMED, M. & MOUBARAK, A.H. 2019. Shear strength behaviour of stabilized unsaturated expansive subgrade soils for highway backfill. In: *Bituminous Mixtures and Pavements*, VII, pp. 111-122.
- ARDUINO. 2023. *Arduino Software*. (<https://www.arduino.cc/en/software>) Accessed on 01 November 2021.
- BADENHORST, W.S. 2017. An Investigation into Current Procedures for Estimating Heave Potential in Clays. *MEng Dissertation. Central University of Technology, Free State*.
- BANZI, M. & SHILOH, M. 2014. *Getting Started with Arduino*. 3rd ed. Make: Community. ISBN: 9781449363338.
- BESTER, D.M., STOTT, P.R. & THERON, E. 2016. The movement of soil moisture under a government subsidy house. In: *Proceedings of the First Southern African Geotechnical Conference*, pp. 41-46.
- BESTER, D.M., THERON, E. & STOTT, P.R. 2017. The determination of edge penetration distance underneath a raft foundation on expansive clays. In:

- Proceedings of the 9th South African Young Geotechnical Engineers Conference*, pp. 619-629.
- BIS. 1982. *The Indian standard code of practice for design and construction of raft foundations* (IS:2950 (Part1) - 1981). 2nd ed. New Delhi: Bureau of Indian Standards.
- BISHOP, A.W. 1959. The principle of effective stress. *Teknisk Ukeblad* 106(39), pp. 859-863.
- BISHOP, A.W. & DONALD, I.B. 1961. The experimental study of partly saturated soil in the triaxial apparatus. *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering Paris, France*, pp. 13-21.
- BIOT, M.A. 1941. General theory of three-dimensional consolidation. *Journal of Applied Physics* 12(2), pp. 155-164.
- BOWLES, J. 1997. *Foundation analysis and design*. 5th ed. New York: The McGraw-Hill Companies, Inc.
- BRADLOW, B., BOLNICK, J., & SHEARING, C. 2011. Housing, institutions, money: the failures and promise of human settlements policy and practice in South Africa. *Environment & Urbanization*, 23(1), 267–275.
- BRADY, N.C. & WEIL, R.R. 2016. *The nature and properties of soils*. 15th ed. Columbus: Pearson.
- BRINK, A.B.A. & BRUIN, R.M.H. Eds. 2002. *Guidelines for soil and rock logging in South Africa*. 2nd impression. Association of Engineering Geologists; South African Institution of Civil Engineering; and South African Institute for Engineering and Environmental Geologists.

- BURLAND, J.B. 1965. Some aspects of the mechanical behaviour of partly saturated soils. In *Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas*. Sydney: Butterworths, pp. 270-278.
- BURROUGH, P.A., MCDONNELL, R.A. & LLOYD, C.L. 2015. *Principles of geographical information systems*. 3rd ed. Oxford: Oxford University Press.
- BUTUT, R. & LYTTON, R.L. 2002. Slab-on-ground: A finite element method analysis. In: *Proceedings of Texas Section American Society of Civil Engineers*, Texas.
- BYRNE, G. & BERRY, A.D. 2008. *A guide to practical geotechnical engineering in Southern Africa*. 4th ed. Johannesburg: Franki.
- CHANG, K-T. 2019. *Introduction to geographic information systems*. 9th ed. New York City: McGraw-Hill Education, ISBN: 9781259929649.
- CHEN, Y.L. (1988). "Foundations on Expansive Soils." Elsevier Science Publishing Company Inc., New York, pp. 714-728.
- CUI, Y.J. & DELAGE, P. 1996. Yielding and plastic behaviour of an unsaturated compacted silt. *Géotechnique* 46(2), pp. 291-311.
- CSIR. 2004. Solar position and tracking. In: *Renewable Energy for Rural Livelihoods: A Review of South Africa's Programmes*. Council for Scientific and Industrial Research, pp. 2-23.
- CSIR. n.d. *Expansive clay soil related damage to housing in South Africa*. (<https://www.csir.co.za/expansive-clay-soil-related-damage-housing-south-africa>)
Accessed on 05 December 2022.
- DAS, B.M. 2007. *Fundamentals of geotechnical engineering*. 3rd ed. Mason: Thomson Learning. ISBN: 9780495295747.

- DAS, B.M. 2017. *Shallow foundations bearing capacity and settlement*. 3rd ed. Boston: Cengage Learning.
- DAS, B.M. & Sivakugan, N. 2018. *Principles of foundation engineering*. 9th ed. Boston: Cengage Learning. ISBN: 9780357158722.
- DAS, B.M. & Sobhan, K. 2018. *Principles of geotechnical engineering*. 9th ed. Boston: Cengage Learning.
- DAY, P. 1991. Design of raft foundations for houses on expansive clay using Lytton's method. In: *SAICE Structural Division, Volume Course on design of foundation to suit various soil conditions*, pp. 1-15.
- DE BOER, R. 1998. Theory of porous media: highlights in historical development and current state. *Applied Mechanics Reviews* 51(5), pp. 305-329.
- DE BRUIJN, C.M.A. 1973. Moisture redistribution in southern African soils. *Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering* 2(2):37-44.
- DEVKOTA, B., KARIM, R., RAHMAN, M. & NGUYEN, H.B.K. 2022. Accounting for expansive soil movement in geotechnical design: A state-of-the-art review. *Sustainability*, 14(23):1-27.
- Dieudonné, A.C., Charlier, R., & Collin, F. (2016). Constitutive models for unsaturated soils: a review. *Computers and Geotechnics*, 80, 217-230.
- DI MAIO, R., PIEGARI, E., TODERO, G. & FABBROCINO, S. 2015. A combined use of Archie and van Genuchten models for predicting hydraulic conductivity of unsaturated pyroclastic soils. *Journal of Applied Geophysics* 112:249-255.
- DIOP, S., STAPELBERG, F., TEGEGN, K., NGUBELANGA, S. & HEATH, L. 2011. *A review on problem soils in South Africa*. Cape Town: Council for Geoscience.

- DONATI, S. 2023. *Photonic instrumentation: Sensing and measuring with lasers*. 1st ed. Boca Raton, London: CRC Press.
- DOUGLAS, J. & NOY, E.A. 2011. *Building surveys and reports*. 4th ed. Chichester: John Wiley & Sons, Ltd. ISBN: 9781444391091.
- DUNCAN, C.I. 1992. *Soils and foundations for architects and engineers*. New York: Springer. ISBN: 9780442006044.
- FITYUS, S.G., SMITH, D.W. & ALLMAN, M.A. 2004. Expansive soil test site near Newcastle. *Journal of Geotechnical and Geoenvironmental Engineering* 130(7):686-695.
- FRAZER, R.A. & WARDLE, L.J. 1975. Analysis of stiffened raft foundations on expansive soil. In: *Symposium on Recent Developments in the Analysis of Soil Behaviour and their Application to Geotechnical Structures*, pp. 89-98.
- FREDLUND, D.G. & MORGENSTERN, N.R. 1977. Stress state variables for unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering* 103(GT5), pp. 447-466.
- FREDLUND, D.D. & RAHARDJO, H. 1993. *Soil mechanics for unsaturated soils*. New York: John Wiley & Sons, Inc.
- FREIRE, J.L.F. 2009. *Electrical resistance strain gages*. Encyclopaedia of Life Support Systems (EOLSS). (<http://www.eolss.net/Sample-chapters/C05/E6-194-07.pdf>) Accessed on 16 May 2021.
- FUENTES LACOUTURE, J.C. 2014. Advances in the theory of porous media applied to soil mechanics. *International Journal of Engineering Research and Applications* 4(8), pp. 1-7.

- FULTON, B. 2018. *Concrete Technology*. 10th ed. Boca Raton: CRC Press.
- GALOUCHKO, V. 2019. *Contour maps software 3DField and 3DSurface*. (<http://3dfmaps.com/>) Accessed on 02 December 2022.
- GENS, A. 1996. Constitutive modelling in unsaturated soil mechanics. In ALONSO, E.E., and DELAGE, P., eds., *Unsaturated Soils*. Rotterdam: Balkema, pp. 1179-1200.
- GENS, A. & ALONSO, E.E. 1992. A framework for the behaviour of unsaturated expansive clays. *Canadian Geotechnical Journal* 29(6), pp. 1013-1032.
- GEOPLAST. 2020. *Geoplast official website*. (<https://www.geoplastglobal.com/en/>) Accessed on 20 January 2020.
- PAIGE-GREEN, P. & TURNER, D.P. 2008. Preliminary identification of problem soils for infrastructure projects. In: *Problem soils in South Africa Conference*, Midrand, pp. 10.
- GREYLING, C. 2010. *The RDP housing system in South Africa*. Pretoria: University of Pretoria.
- GRIM, R.E. 1962. *Applied Clay Mineralogy*. New York: McGraw-Hill.
- HAMAKAREEM, M.I. (2020). "Void Forms in Foundation Construction: Their Types and Applications." [Online] The Constructor. Available at: <https://theconstructor.org/geotechnical/void-forms-concrete-foundation-applications/287101/?amp=1> [Accessed 9 Nov. 2023].
- HARSCH, E. 2014. *Winding path to decent housing for South Africa's poor*. (<https://www.un.org/africarenewal/web-features/winding-path-decent-housing-south-africa%E2%80%99s-poor>) Accessed on 5 August 2023.

- HAZEN, R.M., Sverjensky, D.A., Azzolini, D. & Bish, D.L. 2013. Clay mineral evolution. *American Mineralogist* 98(11-12):2007-2029.
- HEYWOOD, D.I., Cornelius, S. & Carver, S. 2011. *Introduction to geographical information systems*. 3rd ed. Harlow: Pearson.
- HILLEL, D. 1982. *Introduction to soil physics*. New York: Academic Press.
- HILLEL, D. 2003. *Introduction to environmental soil physics*. 1st ed. San Diego: Academic Press.
- HOLTZ, R.D., KOVACS, W.D. & SHEAHAN, T.C. 2013. *An Introduction to geotechnical engineering*. 2nd ed. Upper Saddle River: Pearson Education.
- HOULSBY, G.T. 1997. The work input to an unsaturated granular material. *Géotechnique* 47(1), pp. 193-196.
- HOUSTON, A. 2022. *Daily Maverick*.
(<https://www.un.org/africarenewal/web-features/winding-path-decent-housing-south-africa%E2%80%99s-poor>) (Accessed on 12 October 2023).
- HUBS. 2021. *3D printing for aerospace and aviation*.
(<https://www.hubs.com/knowledge-base/aerospace-3d-printing-applications/>)
Accessed on 21 May 2021.
- IIZUMI, T. & RAMANKUTTY, N. 2015. How do weather and climate influence cropping area and intensity. *Global Food Security* 4:46-50.
- JENNINGS, J.E., BRINK, A.B.A. & WILLIAMS, A.A.B. 1973. Revised guide to soil profiling for civil engineering purposes in southern Africa. *The Civil Engineer in South Africa* (Transl.) 15:3-12.
- JENNINGS, J.E.B. & BURLAND, J.B. 1962. Limitations to the use of effective stresses in partly saturated soils. *Géotechnique* 12(2), pp. 125-144.

- JENNINGS, J.E.B. & KNIGHT, K. 1957. The additional settlement of foundations due to a collapse of structure of sandy subsoils on wetting. Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering London, UK, pp. 316-319.
- JONES, B.R. 2014. *Geotechnical centrifuge modelling of the behaviour of compressible clay horizon underlying a reinforced sand foundation*. MSc Dissertation. University of Pretoria, Pretoria, p. 93.
- JONES, G.A. 2017. An empirical preliminary prediction of heave. *Journal of the South African Institution of Civil Engineering*, 59(4), pp. 64-66 pages.
- JONES, L.D. & JEFFERSON, I. 2012. Expansive soils. In: *ICE Manual of geotechnical engineering*. Institution of Civil Engineers, pp. 413-441.
- KILIÇ, M., GÜNDOĞAN, R., GÜNAL, H. & CEMEK, B. 2022. Accuracy Assessment of Kriging, artificial neural network, and a hybrid approach integrating spatial and terrain data in estimating and mapping of soil organic carbon. *PloS ONE*: 179(9): 1-22.
- KALANTARI, B. 2012. Foundations on Expansive Soils: A Review. *Research Journal of Applied Sciences, Engineering and Technology*, 4, pp. 3231-3237.
- KARUBE, D. & KAWAI, K. 2001. The role of pore water in the mechanical behaviour of unsaturated soils. *Géotechnique* 51(1), pp. 1-13.
- KIM, J.H. & LEE, J.H. 2021. Low cost omnidirectional 2D distance sensor for indoor floor mapping applications. *Current Optics and Photonics* 5(2):298-305.
- KNAPPETT, J.A. & CRAIG, R.F. 2012. *Craig's soil mechanics*. 8th ed. New York: Spon Press.
- KOHGO, Y., IIZUKA, A. & OKA, F. 1993. An elasto-plastic model for unsaturated soil in three-dimensional stresses. *Soils and Foundations* 33(2), pp. 1-17.

- KONKOL, J. 2014. Derivation of the scaling laws used in geotechnical centrifuge modelling-application of dimensional analysis and Buckingham II Theorem. *Technical Sciences* 17:31-44.
- KYOWA. n.d. *Kyowa Electronic Instruments - Strain Gage Civil Engineering*. (https://www.kyowa-ei.com/eng/technical/engineering/engineering_transducers.html) Accessed on 19 June 2021.
- LAMONT, J. & SPINK, T. 2005. Soil and rock. In: *Building Surveys and Reports*. Chichester: John Wiley & Sons, Ltd., pp. 87-99.
- LED. 2023. Local Economic Development. Cooperative Government Traditional Affairs. (<https://www.cogta.gov.za/index.php/local-economic-development-led/>) Accessed on 3 June 2023.
- LU, N. & LIKOS, W.J. 2004. *Unsaturated soil mechanics*. New Jersey: John Wiley & Sons, Inc.
- LV, L., FRANZ, T.E., ROBINSON, D.A. & JONES, S.B. 2014. Measured and modeled soil moisture compared with cosmic-ray neutron probe estimates in a mixed fores. *Vadose Zone Journal* 13(12):1-13.
- LYTTON, R.L. 1972. Raft foundation design. *Structural Engineer* 50(11):379-385.
- LYTTON, R.L. & WOODBURN, J.A. 1973. Design and performance of mat foundations on expansive clay. In: *Proceeding of the 3rd International Conference on Expansive Soils*, pp. 301-307.
- MACHACEK, J. 2020. Extensions of the theory of porous media for expansive soils. *Acta Polytechnica* 60(4), pp. 285-292.

- MAEKAWA, A., NODA, M. & SHINTANI, M. 2016. Experimental study on a noncontact method using laser displacement sensors to measure vibration stress in piping systems. *Measurement* 79:101-111.
- MA, Z., CHOI, J. & SOHN, H. 2023. Structural displacement sensing techniques for civil infrastructure: A review. *Journal of Infrastructure Intelligence and Resilience* 2(3):1-18.
- MEYERHOF, G.G. 1951. The ultimate bearing capacity of foundations. *Géotechnique* 2(4):301-332.
- MICRO-EPSILON. 2022. *Smart laser triangulation displacement sensor*. (https://www.micro-epsilon.com/displacement-position-sensors/laser-sensor/optoNCDT_1420_basic/) Accessed on 5 February 2022.
- MILLER, D.J., DURKEE, D.B., CHAO, K.C. & NELSON, J.D. 1995. Simplified heave prediction for expansive soils. In: *Proceedings of the First International Conference on Unsaturated Soils*. Rotterdam: Balkema, pp. 891-897.
- MITCHELL, J.K. 1993. *Fundamentals of Soil Behavior*, 2nd edn. New York: John Wiley & Sons.
- MORRISON, R. 2002. *The fields of electronics: Understanding electronics using basic physics*. New York: John Wiley & Sons, Inc. ISBN: 9780471222903.
- MOTLHABANE, K.L. 2015. Reactive versus proactive management system: Reconstruction and Development Programme (RDP) housing delivery's unintended consequences. *Public and Municipal Finance*, pp. 43-54, 4(1).
- MPA. 2022. MPA: The concrete centre. (<https://www.concretecentre.com/Information>) Accessed on 30 May 2022.

- MUELLER, T., Jordan, M., Schneider, T. Poesch, A. & Reithmeier, E. 2016. Measurement of steep edges and undercuts in confocal microscopy. *Micron* 84:79-95.
- NCUBE, S. & FEY, M. 2019. Investigating the origin of problematic soils in South Africa. In: *Proceedings of the 16th African Regional Conference on Soil Mechanics and Geotechnical Engineering*, pp. 137-142.
- NELSON, J.D. & MILLER, D.J. 1997. *Expansive soils: Problems and practice in foundation and pavement engineering*. New York: John Wiley & Sons Inc. ISBN: 9780471181149.
- NELSON, J.D., CHAO, K.C., OVERTON, D.D. & NELSON, E.J. 2015. *Foundation engineering for expansive soils*. New York: John Wiley & Sons, Inc. ISBN: 9780470581520.
- NETTERBURG, F. 2019. *Identification of potentially expansive clay soils from soil structure*. In: *Proceedings of the 17th African Regional Conference on Soil Mechanics and Geotechnical Engineering*, pp. 357-364.
- NGUYEN, T., NGO, H., GUO, W. & ZHANG, J. 2018. A review on adsorbents used for wastewater treatment. *Environmental Science and Pollution Research* 25(11):10596-10615.
- NHBRC. 1999. *Design and construction requirements*. NHBRC Home Building Manual.
- Nitsch, A., Machacek, J., Wichtmann, T., & Grandas Tavera, C.E. (2023). Advancements in constitutive modelling of expansive soils. *Proceedings of the 10th International Conference on Unsaturated Soils*, Sydney, Australia, pp. 123-130.
- NOKULUNGA, M., THWALA, D. & CLINTON, A. 2018. Challenges of reconstruction and development program (RDP) houses in South Africa. In: *Proceedings of*

the International Conference on Industrial Engineering and Operations Management, pp. 1695-1702.

PACIFIC HOUSING SYSTEMS, 2024. Wafflemat System Design Considerations. In: Wafflemat Design Whitepaper. [PDF] Pacific Housing Systems. Available at: <https://www.scribd.com/document/242239235/Wafflemat-Design-Whitepaper> [Accessed 10 May 2024].

PECK, R.B. & HANSON, W.E. & THORNBURN, T.H. 1974. *Foundation Engineering*. 2nd ed. New York: John Wiley & Sons, Inc. ISBN: 9780471675853.

PELLISSIER, J.P. & WILLIAMS, A.A.B. 1991. Development of raft foundations for small structures on heaving clay. *Geotechnics in the African Environment* 1:294-255.

PIDGEON, J.T. 1980. The rational design of raft foundations for houses on heaving soil. In: *Seventh Regional Conference for African Soil Mechanics and Foundation Engineering*. ACCRA, pp. 291-299.

PIDGEON, J.T. 1987. The result of a large scale field experiment aimed at studying the interaction of raft foundation and expansive soils. In: *International Conference on Soil Structure Interactions*. Paris: ENPC Press.

PIDGEON, J.T. & PELLISSIER, J.P. 1987. The behaviour of an L-shaped raft subjected to non-uniform support conditions. In: *International Conference on Soil Structure Interactions*. Paris: ENPC Press.

PIDGEON, J.T. 1988. Guide to the universal method for the rational design of stiffened raft foundations for small structures. In: *The design of stiffened raft foundations and articulated structures on expansive clay soils*. CSIR.

PONS, Y., CAPILLON, A. & CHEVERRY, C. 2000. Water movement and stability of profiles in drained, clayey and swelling soils: at saturation, the structural

stability determines the profile porosity. *European Journal of Agronomy* 12:269-279.

PTI. 2019. *Standard requirements for design and analysis of shallow post-tensioned concrete foundations on expansive and stable soils*. 2nd ed. PTI DC-10: Slab-on-Ground Committee: Post-Tensioning Institute. ISBN: 978131085526.

QUANSAH, D., ADARAMOLA, M. & MENSAH, L. 2016. Solar Photovoltaics in Sub-Saharan Africa – Addressing Barriers, Unlocking Potential. In: *Energy Procedia*, 106, pp. 97-110. <https://doi.org/10.1016/j.egypro.2016.12.108>.

RAMU, M., RAJA, V.P. & Thyla, P.R. 2013. Establishment of structural similitude for elastic models and validation of scaling laws. *KSCE Journal of Civil Engineering* 17(1):139-144.

RENEWABLE ENERGY | Department: Energy | REPUBLIC OF SOUTH AFRICA. n.d. Accessed on 2 March 2021. Department of Energy. Available online: https://www.energy.gov.za/files/esources/renewables/r_solar.html.

ROGERS, J. D., OLSHANSKY, R., & ROGERS, R. B. (2004). Damage to foundations from expansive soils. [online] Available at: https://web.mst.edu/~rogersda/expansive_soils/DAMAGE%20TO%20FOUNDATIONS%20FROM%20EXPANSIVE%20SOILS.pdf. Accessed on 10 April 2024.

ROGERS, J.D., OLSHANSKY, R. & ROGERS, R.B. 1985. Damage to foundations for expansive soils. In: *Submitted to Ground Failure, National Research Council*. Washington DC.

RUTHERFORD, A.B., RUBIDGE, B. & HANCOX, J. 2015. Sedimentology and Palaeontology of the Beaufort Group in the Free State Province Supports A Reciprocal Foreland Basin Model for the Karoo Supergroup, South Africa. *South African Journal of Geology*, 118, 355-372. [doi:10.2113/gssajg.118.4.355](https://doi.org/10.2113/gssajg.118.4.355)

SABS. 2020. SANS Standards Division 3001.
(<https://tut4lifeac.sharepoint.com/sites/LibraryDownloads/SABS/index.html>)
Accessed on 10 June 2021.

SAUERWEIN, M. & STEEB, H. 2018. A framework for the analysis of swelling behaviour in porous media. *Acta Mechanica* 229(3), pp. 1231-1248.

SAVAGE, P.F. 2007. Evaluation of possible swelling potential of soil. In: *Proceedings 26th South African Transport Conference (SATC 2007)*. Pretoria, pp. 277-283.

SCHREFLER, B.A. 1990. The finite element method in soil consolidation (with applications to surface subsidence). In ZIENKIEWICZ, O.C., TAYLOR, R.L., and NITHIARASU, P., eds., *The Finite Element Method*, 5th edn. Oxford: Butterworth-Heinemann, pp. 731-800.

SCHWEBER, B. 2018. *Relay. Encyclopaedia Britannica*.
(<https://www.britannica.com/technology/relay-electronics>) Accessed on 15 October 2021.

SHEHADEH, M., SHENNAWY, Y. & EL-GAMAL, H. 2014. Similitude and scaling of large structural elements: Case study. *Alexandria Engineering Journal* 54:147-154.

SIMITSES, G.J., STARNES, J.H. & REZAEPAZHAND, J. 1992. Structural similitude and scaling laws for plates and shells. *SMIA* 88(1):295-310.

SOBUWA, Y. 2022. Waiting list for RDP houses swells to 1.2 million in Gauteng. In: *City Press* of 16 August 2022.
(<https://www.news24.com/citypress/news/waiting-list-for-rdp-houses-swells-to-12-million-in-gauteng-20220816>) Accessed on 5 August 2023.

STATISTICS SA. 2018. The latest household statistics and more.
(<https://www.statssa.gov.za/?p=11241>) Accessed on 13 October 2023.

- STOTT, P.R. 2017. *Identification and assessment of problematic expansive soils*. Bloemfontein: Central University of Technology.
- STOTT, P. R., SMITH, Z., & THERON, E. 2023. Alleviating the problem of cracking of masonry buildings on expansive clay by building flexibility into the masonry. *Journal of the South African Institution of Civil Engineering*, 65(1), 7-18.
- STRYDOM, J.H. & PELLISSIER, J.P. 1991. The investigation, design and monitoring of concrete raft foundations on expansive soils: A case study of preliminary performance. *Geotechnics in the African Environment* 1:401-408.
- SWART, A. & HERTZOG, P. 2016. Varying percentages of full uniform shading of a PV module in a controlled environment yields linear power reduction. *Journal of Energy in Southern Africa*. 27:28. <https://doi.org/10.17159/2413-3051/2016/v27i3a1556>.
- TABASSUM, N. & BULUT, R. 2023. Residential house foundations on expansive soils in changing climates. *A Journal of Policy Development and Research* 25(1):199-212.
- TAYLOR, R.N. 1995. *Geotechnical centrifuge technology*. London: Blackie Academic & Professional.
- TENG, W.C. 1962. *Foundation Design (Civil Engineering and Engineering Mechanics Series)*. Reprint 1992. Englewood Cliffs: Prentice-Hall, Inc.
- TERZAGHI, K. 1936. The shear resistance of saturated soils. Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering Cambridge, MA, USA, pp. 54-56.
- TERZAGHI, K., PECK, R.B. & MESRI, G. 1996. *Soil Mechanics in Engineering Practice*. 3rd ed. New York: John Wiley & Sons, Inc.

- THUSYANTHAN, N.I. & MADABHUSHI, S.P.G. 2003. *Scaling of seepage flow velocity in centrifuge models*. In: *Cambridge University Engineering Department Technical Report*.
- TOPP, G., DAVIS, J.L. & ANNAN, A.P. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research* 16(3):574-582.
- TWI Global. 2021. *What is 3D printing? Technology definition and types*. (<https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing>) Accessed on 20 May 2021.
- USACE. 1990. Engineering and design. In: *US Army Corps of Engineers - Engineer Manual*. Washington, DC: USACE Publications.
- USNAVY. 2021. *Altitude and azimuth of the sun or moon during one day*. Astronomical Applications Department, United States Navy. (<https://aa.usno.navy.mil/data/AltAz>) Accessed on 10 May 2021.
- VAN DER MERWE, D.H. 1964. The prediction of heave from the plasticity index and percentage clay fraction of soils. *Transactions of the South African Institute of Civil Engineers* 6:103-107.
- VANAPALLI, S.K. & FREDLUND, D.G. 2000. Comparison of different procedures to predict unsaturated soil shear strength. In: *Advances in Unsaturated Geotechnics, Proceedings of the GeoDenver Conference*, edited by C.D. Shackelford, S.L. Houston & N.Y. Chang. Reston: American Society of Civil Engineers, pp. 195-209.
- VELDE, B. 1995. Composition and mineralogy of clay minerals. In: *Origin and mineralogy of clays*, edited by B. Velde, New York, Springer-Verlag, pp. 8-42.
- VELDE, B. & BARRÈ, P. 2010. *Soil, plants and clay minerals*. New York: Springer.

VOIDFORM. (N.D.). "VoidForm | Protect Your Project." [Online] Available at: <https://voidform.com/> [Accessed 9 Nov. 2023].

VORSTER, P. 2016. *Centrifuge modelling of railway embankments under static and cyclic loading*. Pretoria: University of Pretoria.

VOSLOO, P. 2023. Interview on GSH layouts and floor plans typically used in South Africa. Interviewed on 13 October 2023.

WANG WAI NG, C. & MENZIES, B. 2007. *Advanced unsaturated soil mechanics and engineering*. London: CRC Press. ISBN: 9780429153433.

WENDT, Z. 2017. *Solid state vs. electromechanical relays*. (<https://www.arrow.com/en/research-and-events/articles/crydom-solid-state-relays-vs-electromechanical-relays>) Accessed on 10 November 2021.

WHITLOW, R. 2001. *Basic soil mechanics*. 4th ed. Pearson Education Limited: Prentice Hall.

WILLIAMS, A.A.B. 1991. The extraordinary phenomenon of chemical heaving and its effect on buildings and roads. In: *Geotechnics in the African Environment Volume 1*, edited by G.E. Blight, A.B. Fourie, I. Luker, D.J. Mouton & R.J. Scheurenberg. London: Routledge, pp. 91-98.

WILLIAMS, A.A.B. & PELLISSIER, J.P. 1991. New options for foundations on heaving clay. In: *Geotechnics in the African Environment Volume 1*, edited by G.E. Blight, A.B. Fourie, I. Luker, D.J. Mouton & R.J. Scheurenberg. London: Routledge, pp. 243-247.

WILLIAMS, A.A.B., PIDGEON, J.T. & DAY, P.W. 1985. Problem soils in South Africa-State of the Art. Expansive soils. *The Civil Engineering in South Africa*, pp. 367-377.

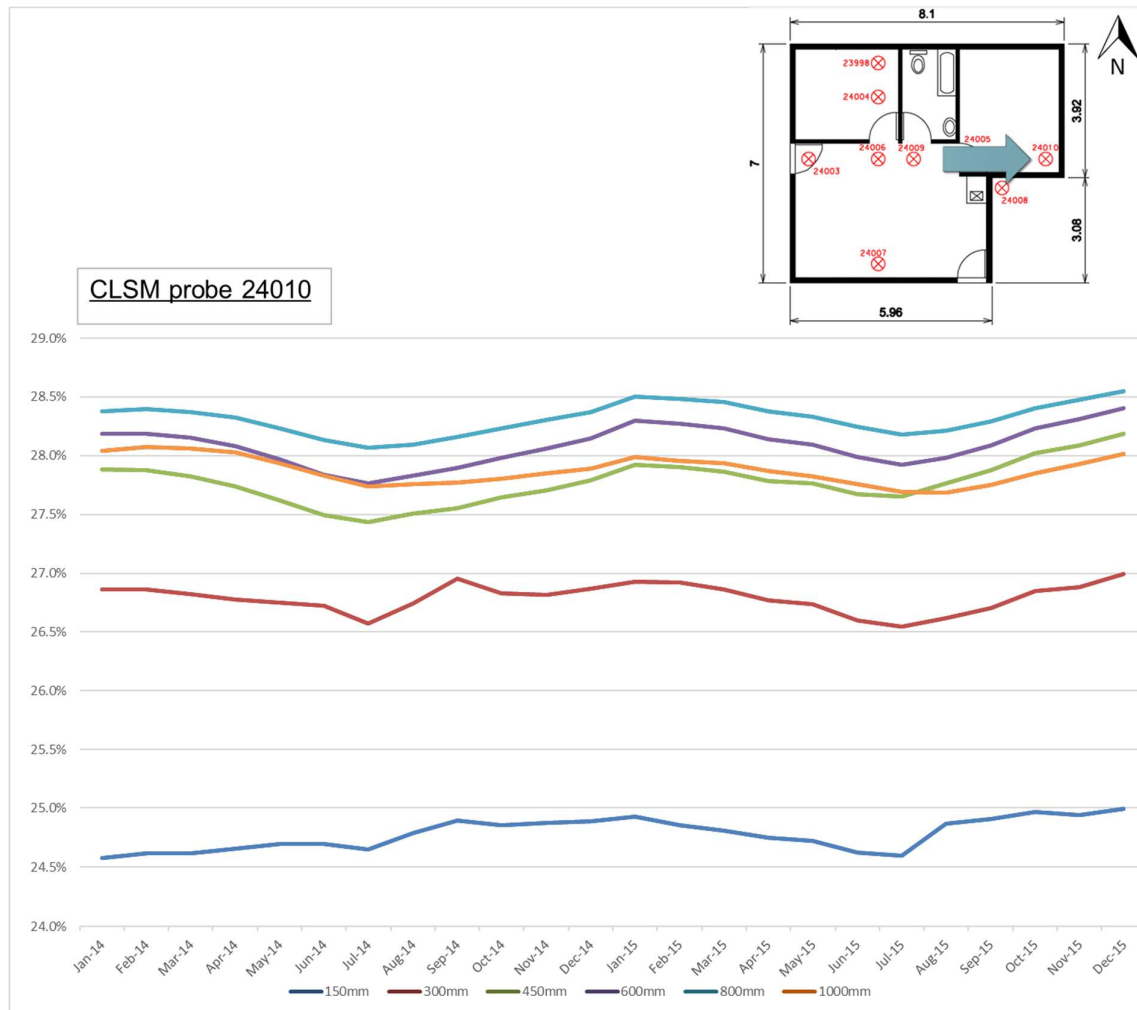
YOTSUJI, K., TACHI, Y., SAKUMA, H. & KAWAMURA, K. 2021. Effect of interlayer cations on montmorillonite swelling: Comparison between molecular dynamic simulations and experiments. *Applied Clay Science* 204(2):16034.

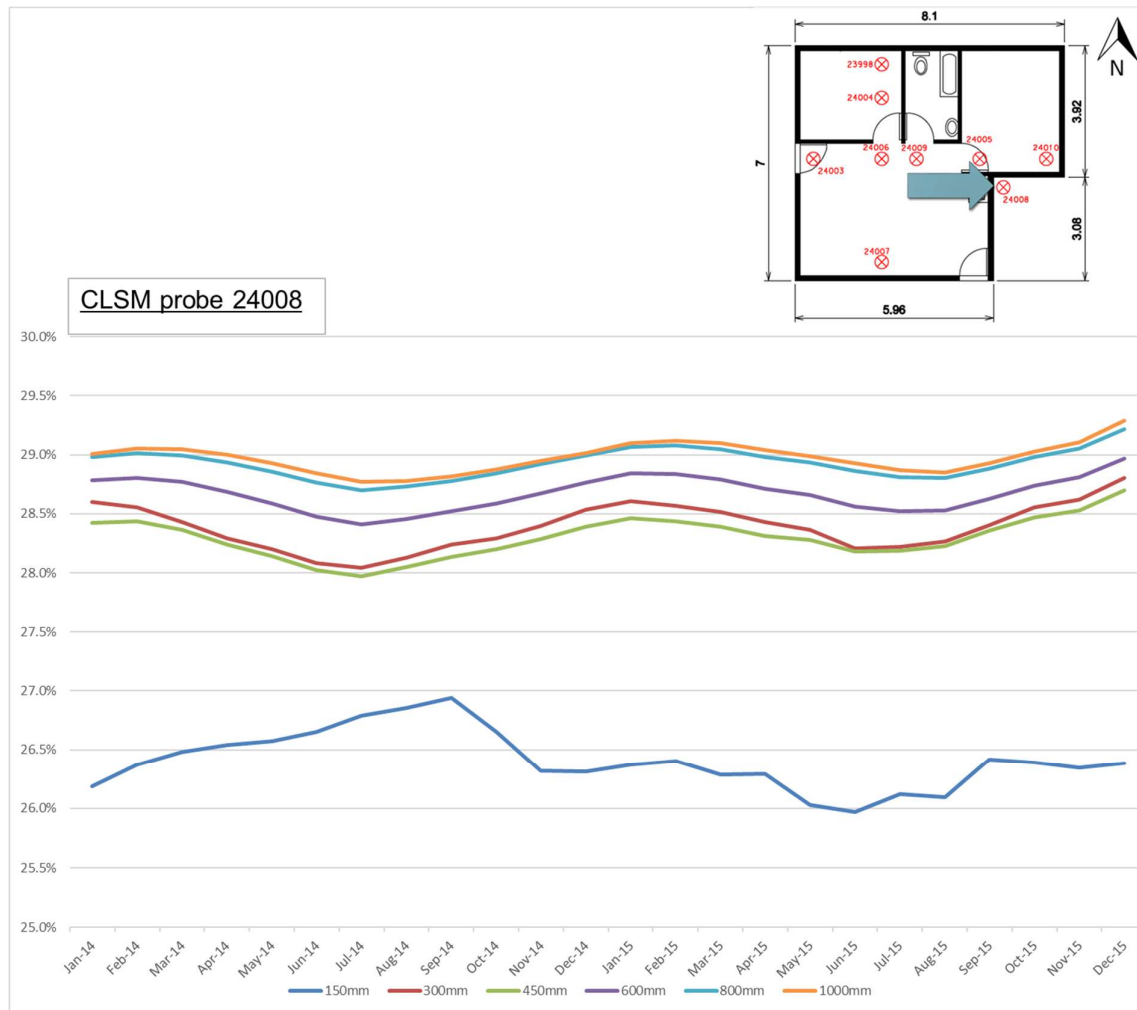
ZERIZGHY, M.G., VAN RENSBURG, L.D. & ANDERSON, J.J. 2013. Comparison of neutron probes and DFM capacitance instruments in measuring soil water evaporation. *Water SA* 39(2):183-190.

ZUZILE, M. 2019. Government spends R3bn fixing shoddy RDP houses. *Business Day*. (<https://www.businesslive.co.za/bd/national/2019-04-02-government-spends-r3bn-fixing-shoddy-rdp-houses/>) Accessed on 2 June 2023.

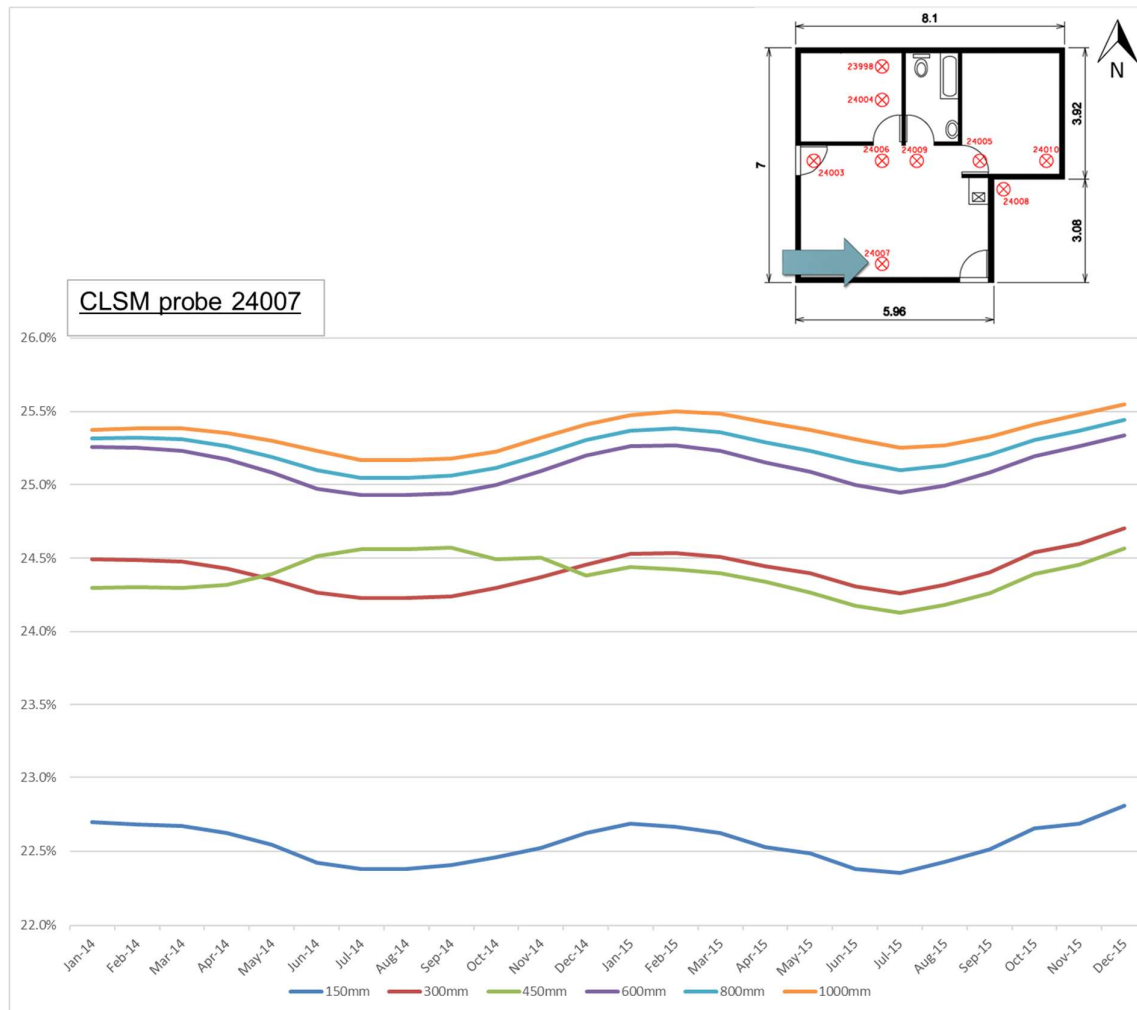
APPENDIX: A

The variation in moisture content of the Botshabelo GSH raft foundation
throughout 2014

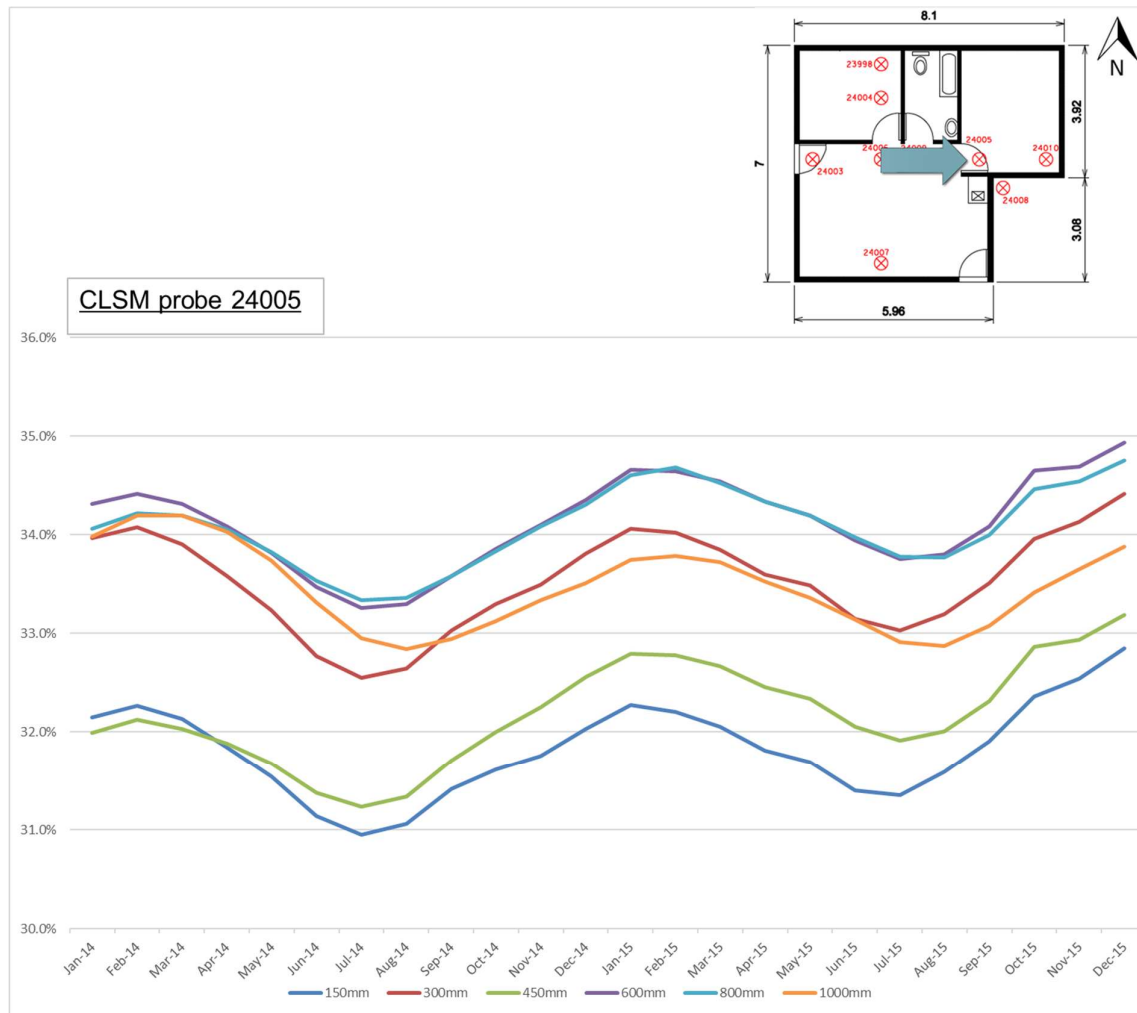




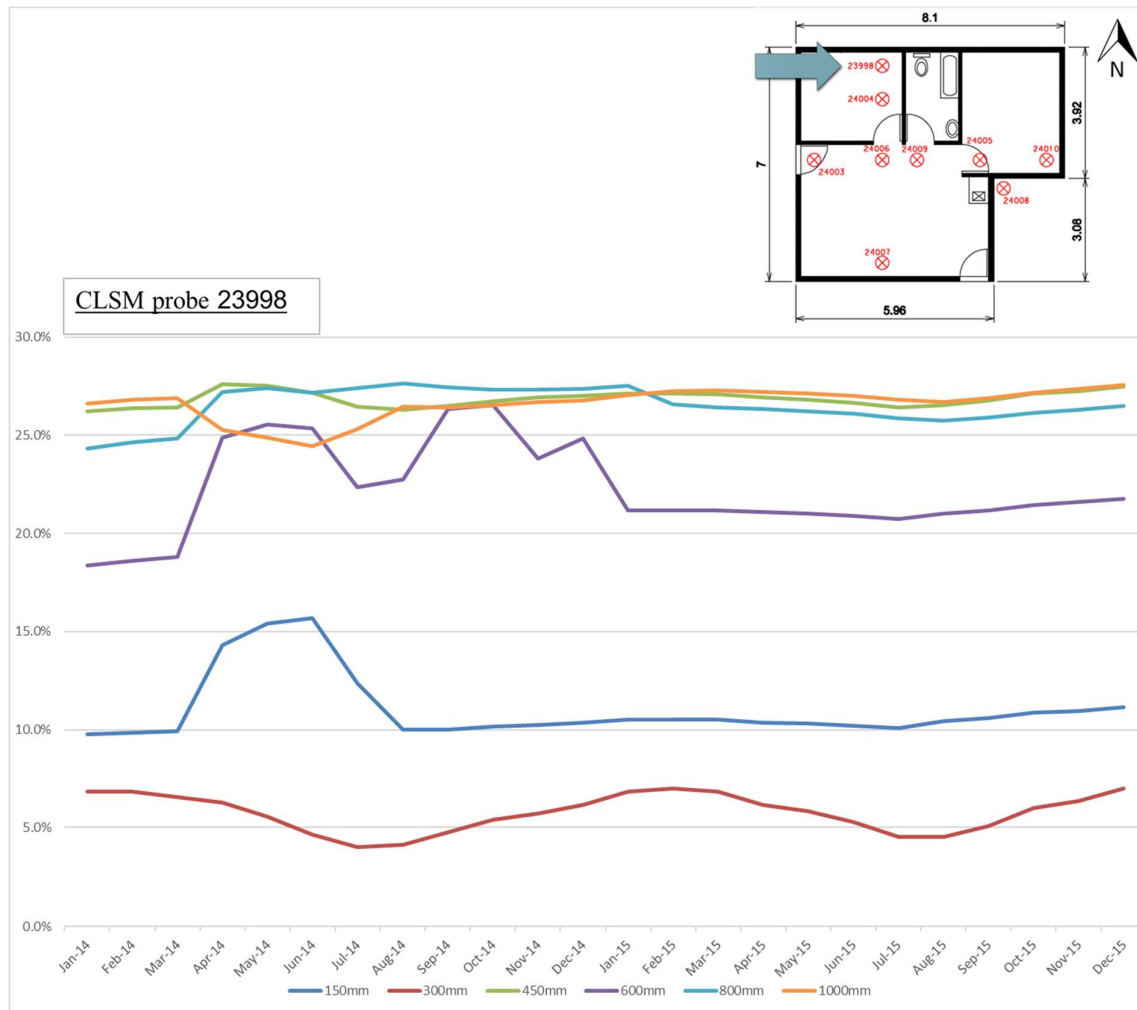
APPENDIX A - Figure 2: Botshabelo GSH CLSM probe 24008

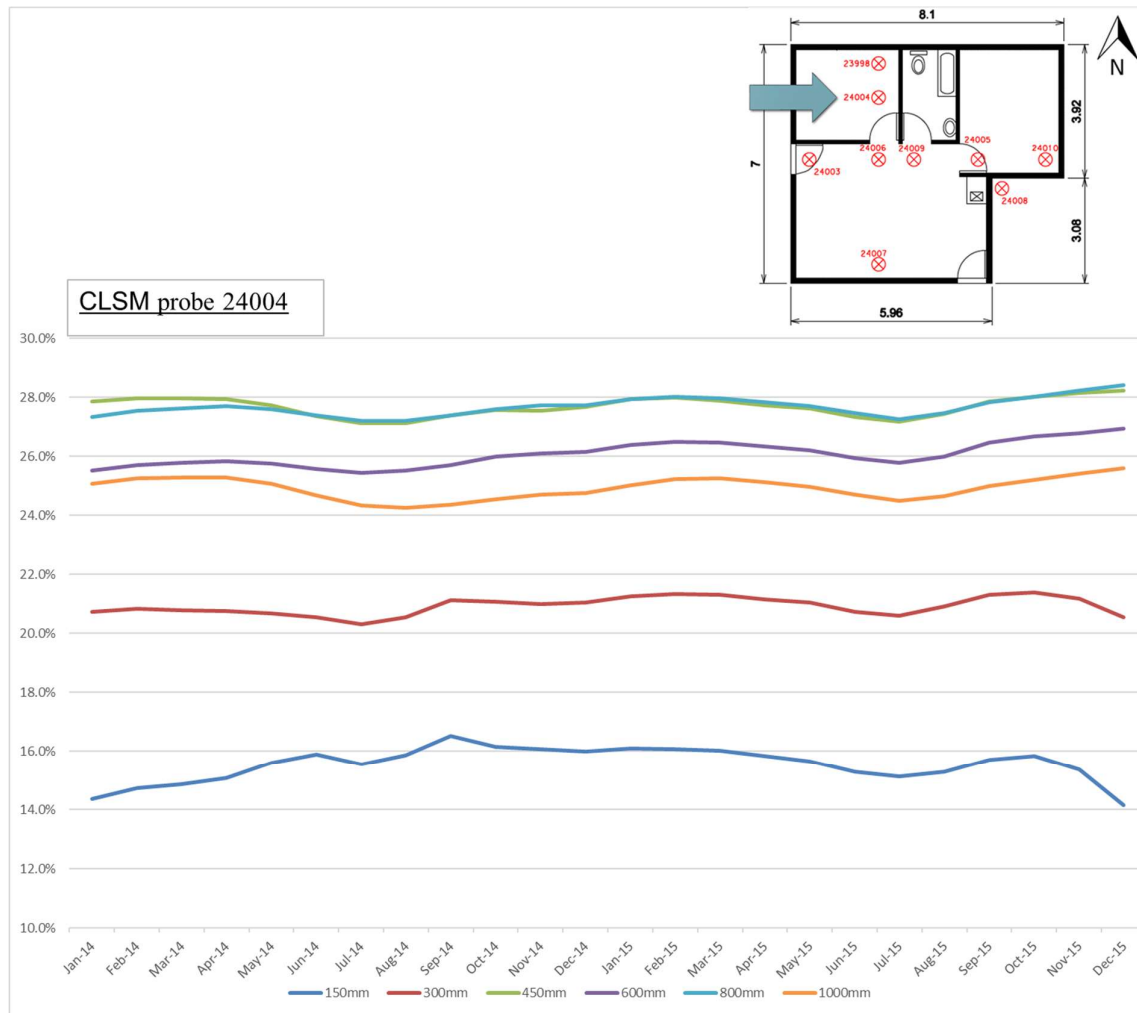


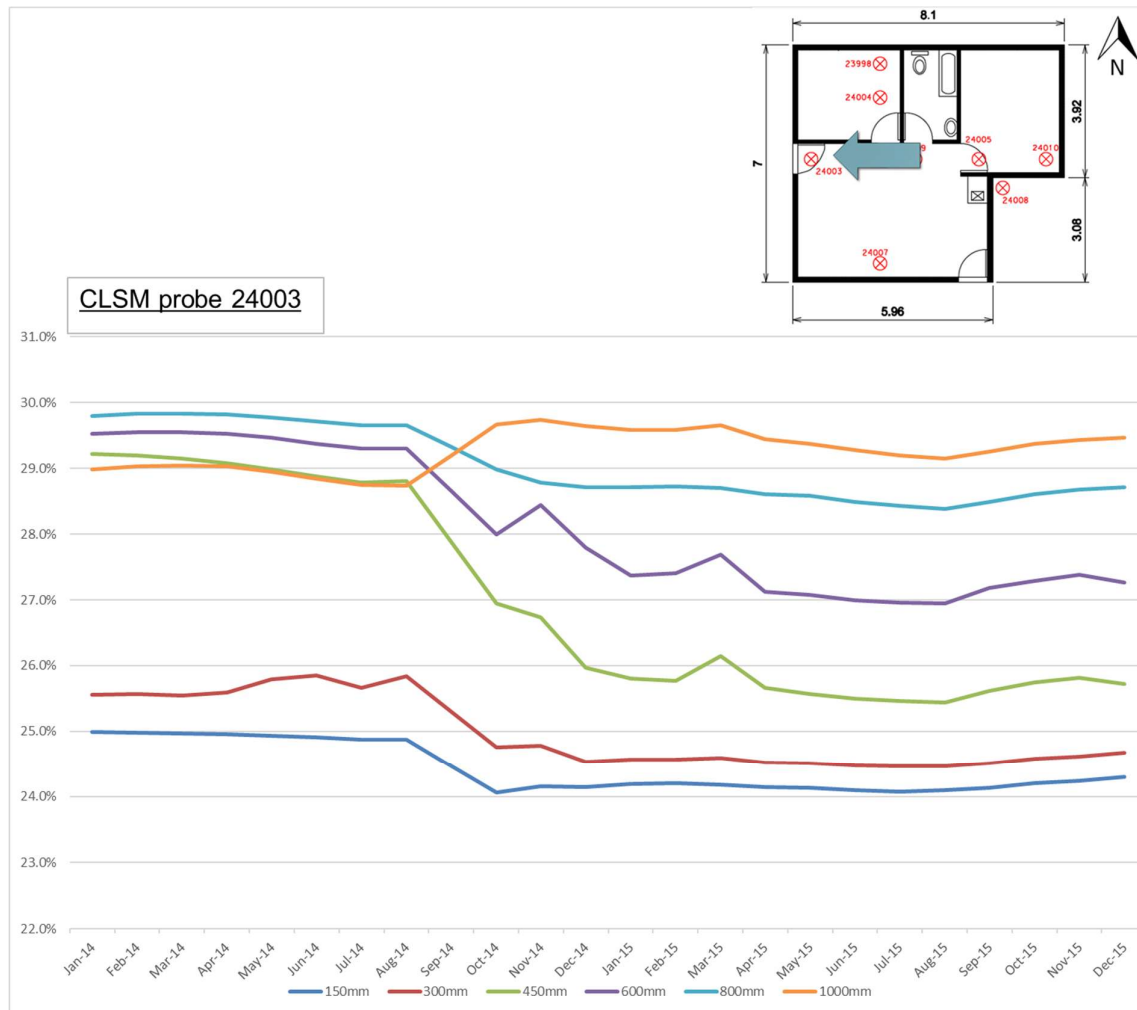
APPENDIX A - Figure 3: Botshabelo GSH CLSM probe 24007



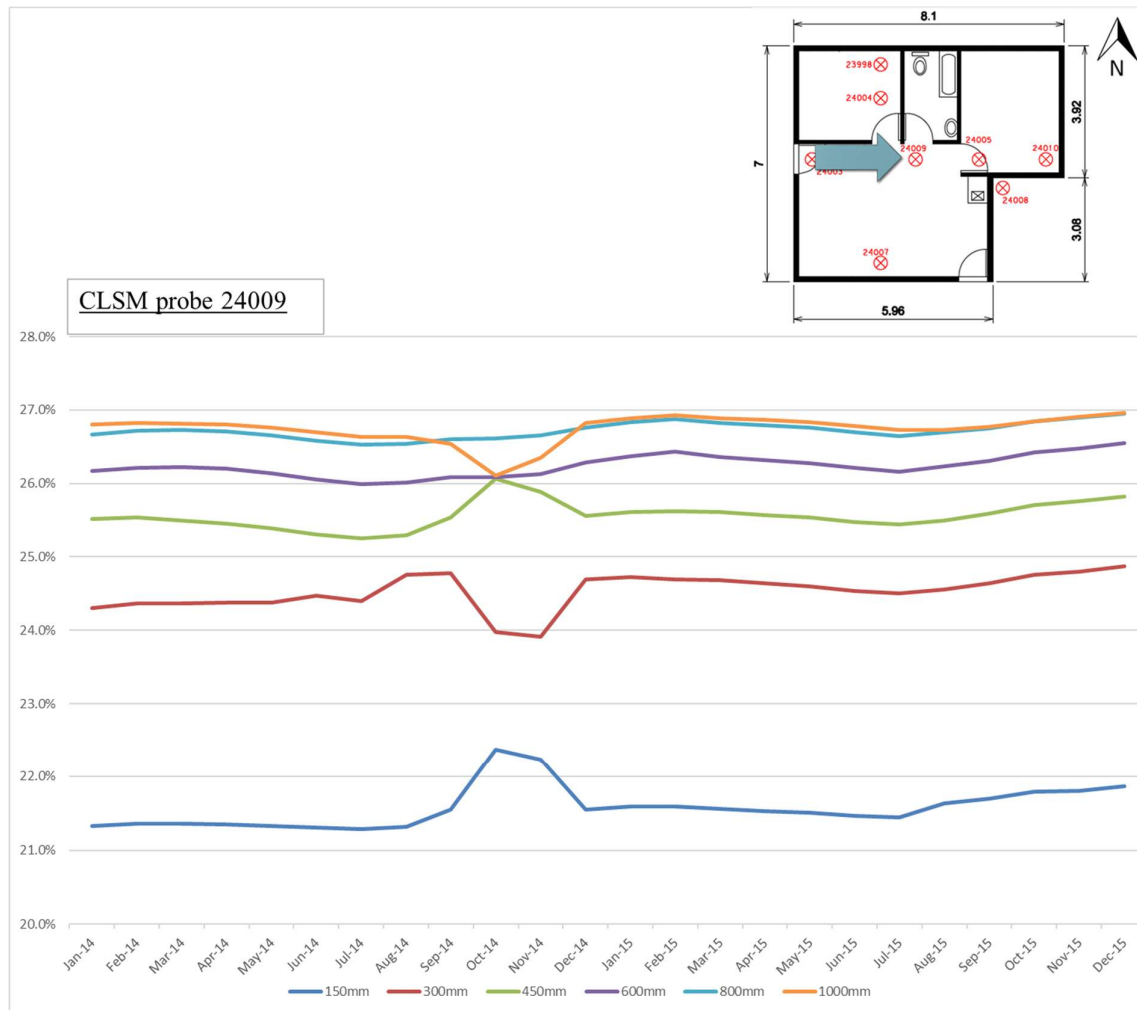
APPENDIX A - Figure 4: Botshabelo GSH CLSM probe 24005







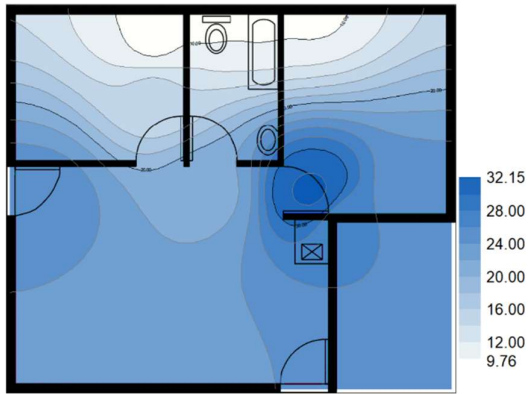
APPENDIX A - Figure 7: Botshabelo GSH CLSM probe 24003



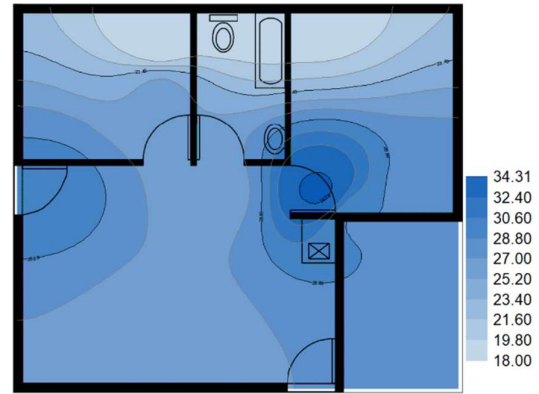
APPENDIX A - Figure 8: Botshabelo GSH CLSM probe 24009

APPENDIX B

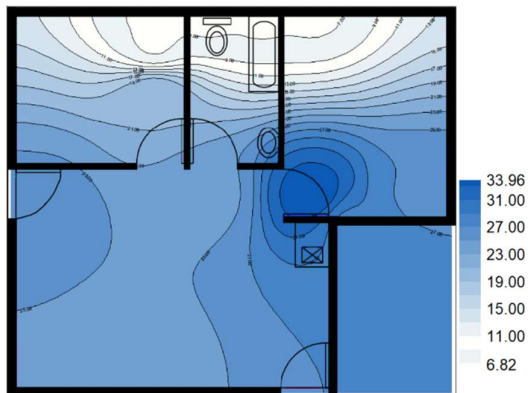
The variation in moisture content underneath the GSH in Botshabelo, Free State,
using 3DField modelling



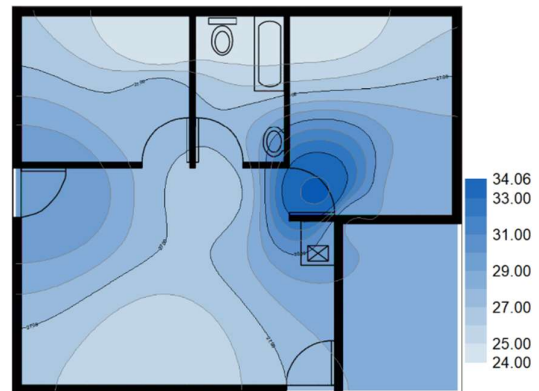
APPENDIX B - Figure 1: Botshabelo
GSH 2014 January 150mm MC: 9%-
32%



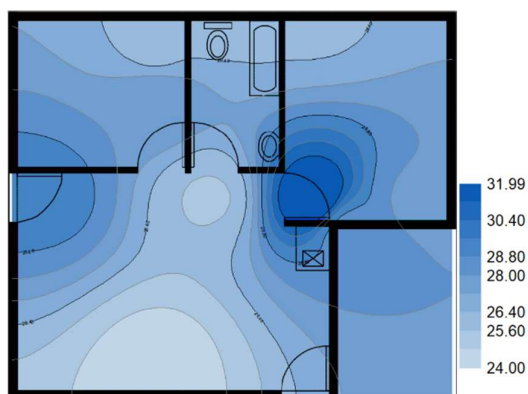
APPENDIX B - Figure 4: Botshabelo
GSH 2014 January 600mm MC: 18%-
35%



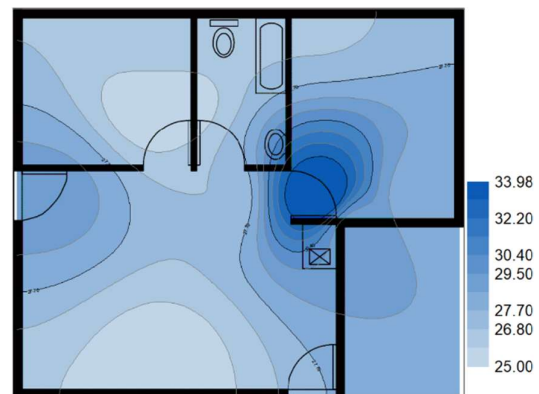
APPENDIX B - Figure 2: Botshabelo
GSH 2014 January 300mm MC: 7%-
34%



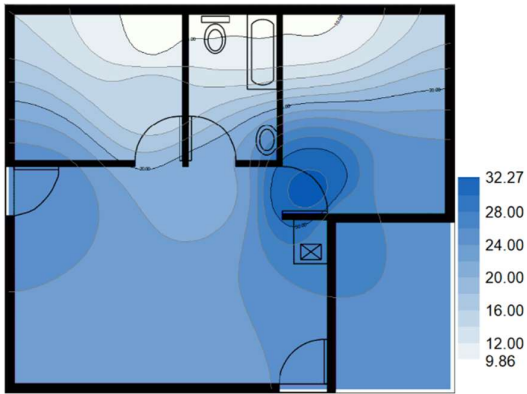
APPENDIX B - Figure 5: Botshabelo
GSH 2014 January 800mm MC: 24%-
34%



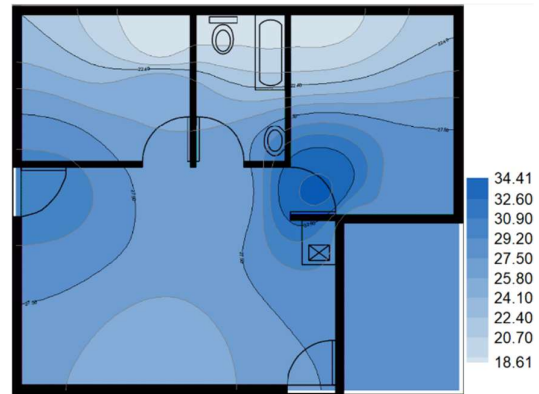
APPENDIX B - Figure 3: Botshabelo
GSH 2014 January 450mm MC: 24%-
32%



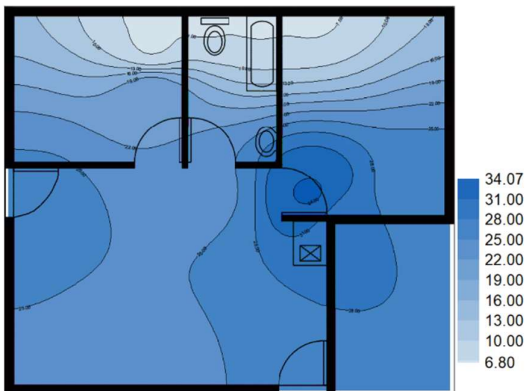
APPENDIX B - Figure 6: Botshabelo
GSH 2014 January 1,000mm MC:
25%-34%



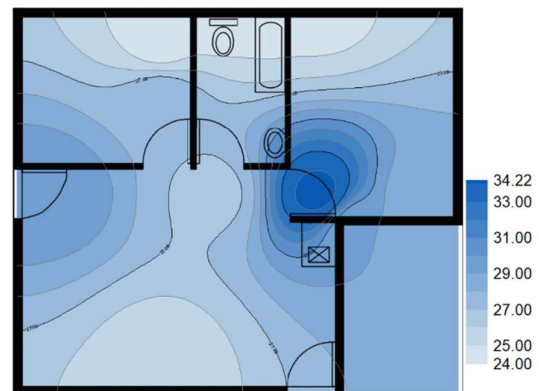
APPENDIX B - Figure 7: Botshabelo
GSH 2014 February 150mm MC: 9%-
32%



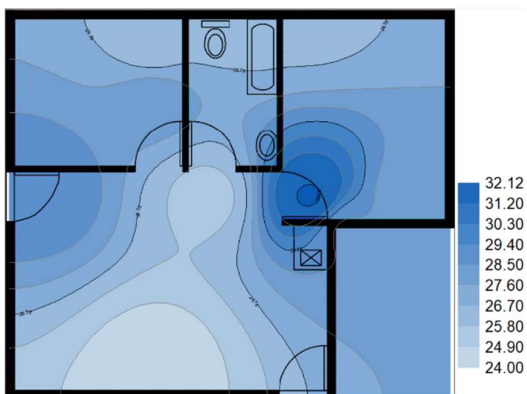
APPENDIX B - Figure 10: Botshabelo
GSH 2014 February 600mm MC: 18%-
35%



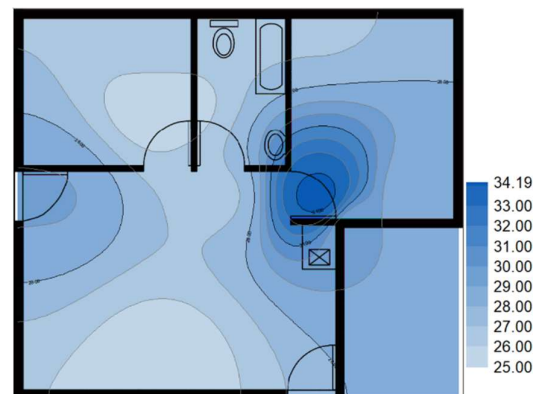
APPENDIX B - Figure 8: Botshabelo
GSH 2014 February 300mm MC: 6%-
34%



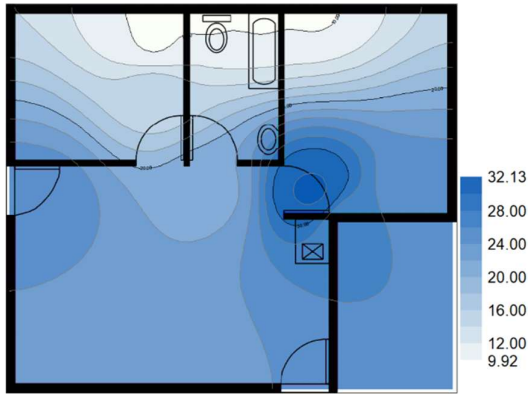
APPENDIX B - Figure 11: Botshabelo
GSH 2014 February 800mm MC: 24%-
34%



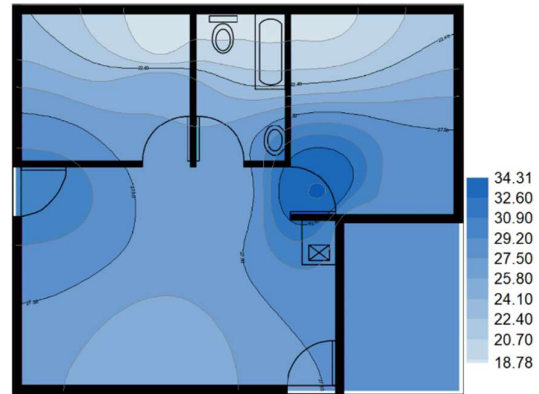
APPENDIX B - Figure 9: Botshabelo
GSH 2014 February 450mm MC: 24%-
32%



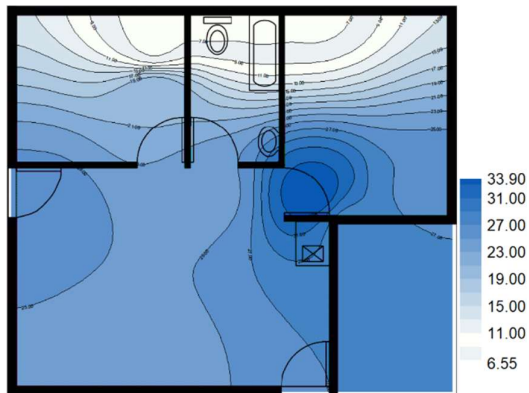
APPENDIX B - Figure 12: Botshabelo
GSH 2014 February 1,000mm MC:
25%-34%



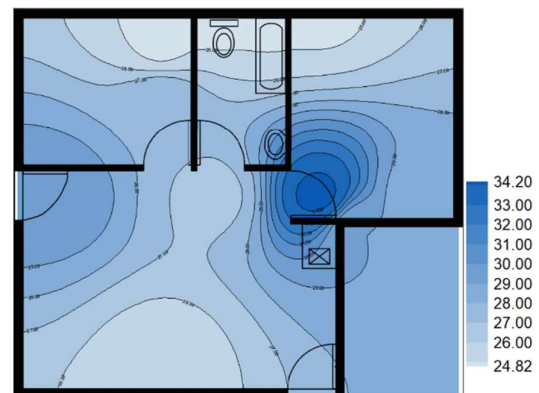
APPENDIX B - Figure 13: Botshabelo
GSH 2014 March 150mm MC: 10%-
32%



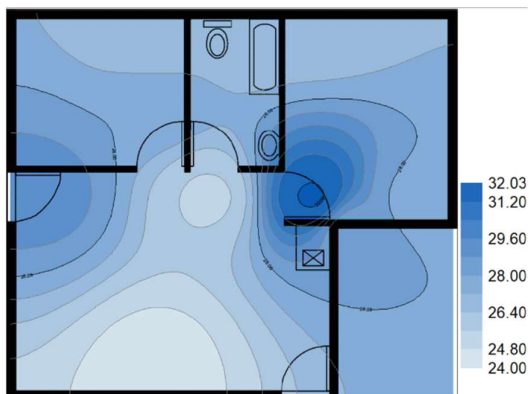
APPENDIX B - Figure 16: Botshabelo
GSH 2014 March 600mm MC: 18%-
34%



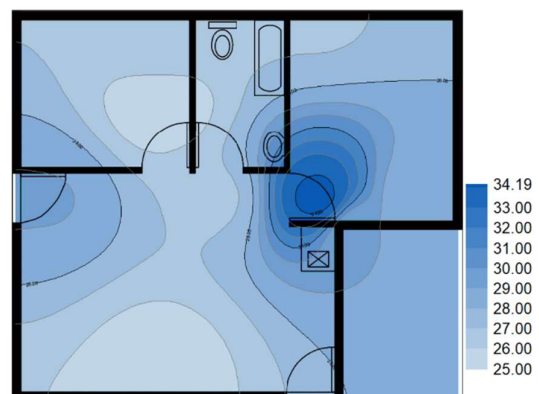
APPENDIX B - Figure 14: Botshabelo
GSH 2014 March 300mm MC: 6%-
34%



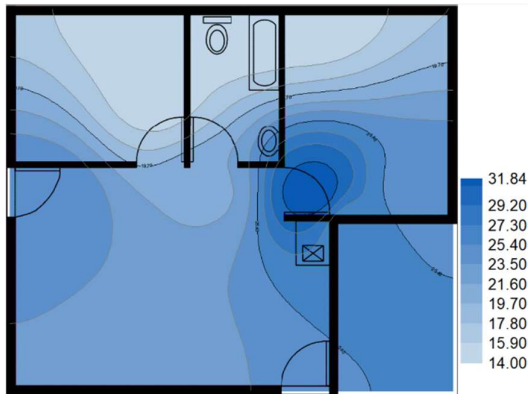
APPENDIX B - Figure 17: Botshabelo
GSH 2014 March 800mm MC: 24%-
34%



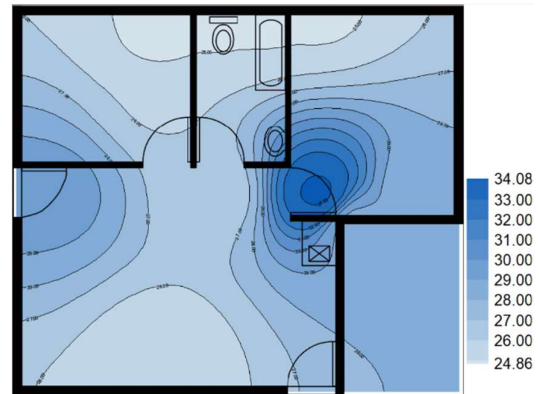
APPENDIX B - Figure 15: Botshabelo
GSH 2014 March 450mm MC: 24%-
32%



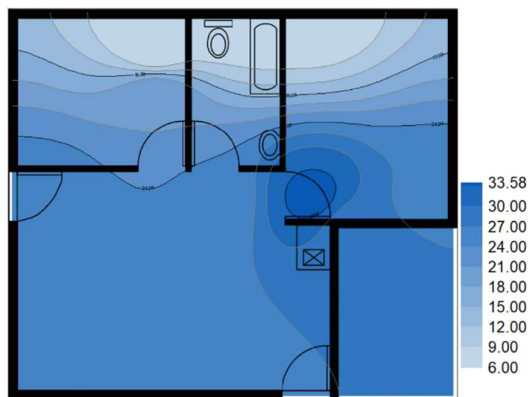
APPENDIX B - Figure 18: Botshabelo
GSH 2014 March 150mm MC: 25%-
34%



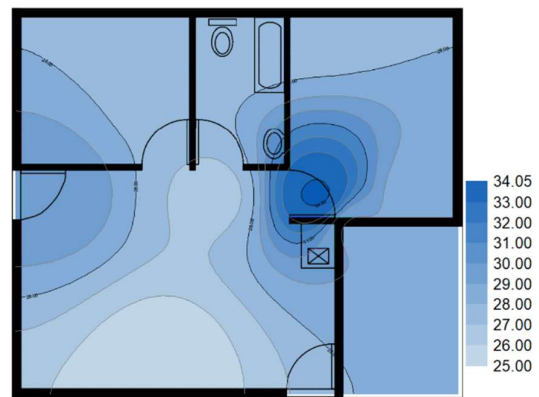
APPENDIX B - Figure 19: Botshabelo
GSH 2014 April 150mm MC: 14%-32%



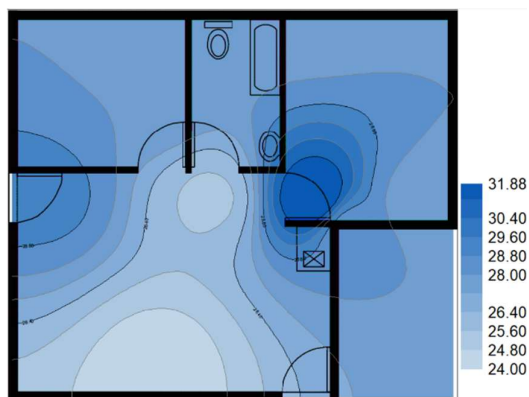
APPENDIX B - Figure 22: Botshabelo
GSH 2014 April 600mm MC: 25%-34%



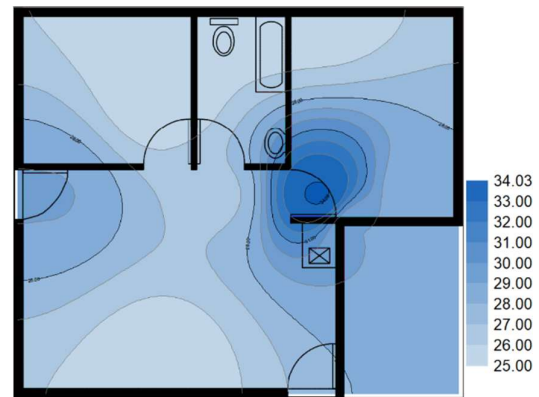
APPENDIX B - Figure 20: Botshabelo
GSH 2014 April 300mm MC: 6%-34%



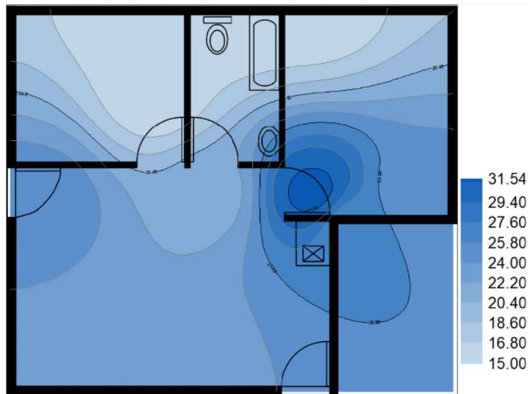
APPENDIX B - Figure 23: Botshabelo
GSH 2014 April 800mm MC: 25%-34%



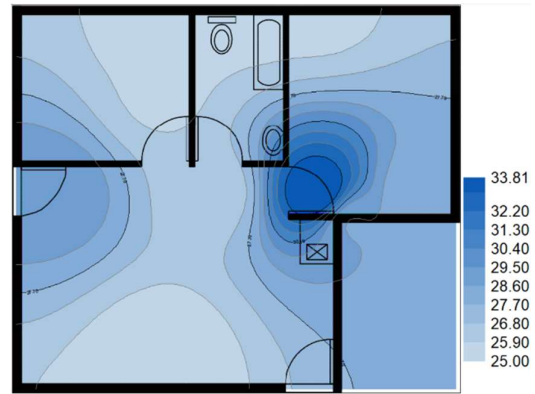
APPENDIX B - Figure 21: Botshabelo
GSH 2014 April 450mm MC: 24%-32%



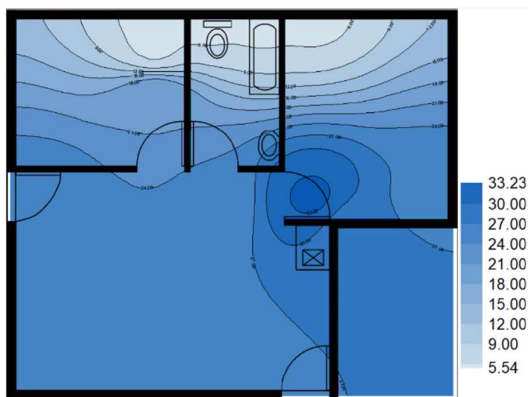
APPENDIX B - Figure 24: Botshabelo
GSH 2014 April 1,000mm MC: 25%-
34%



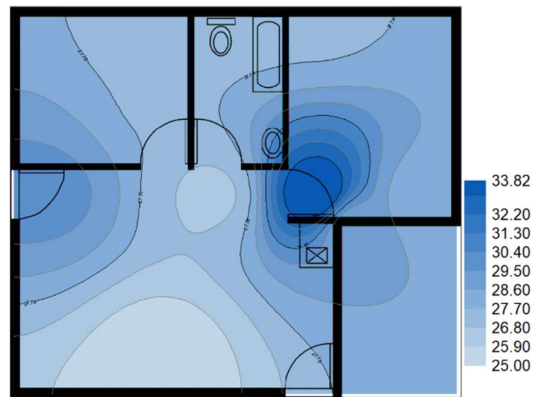
APPENDIX B - Figure 25: Botshabelo
GSH 2014 May 150mm MC: 15%-31%



APPENDIX B - Figure 28: Botshabelo
GSH 2014 May 600mm MC: 25%-34%



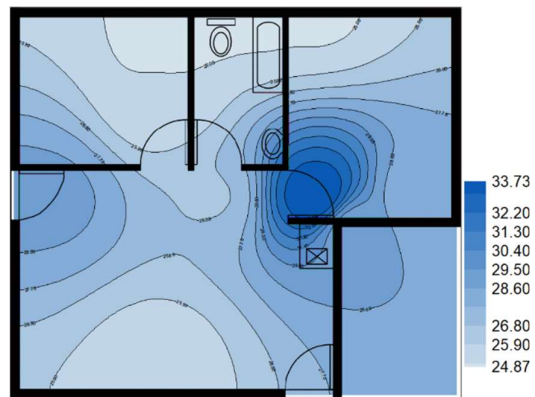
APPENDIX B - Figure 26: Botshabelo
GSH 2014 May 300mm MC: 6%-33%



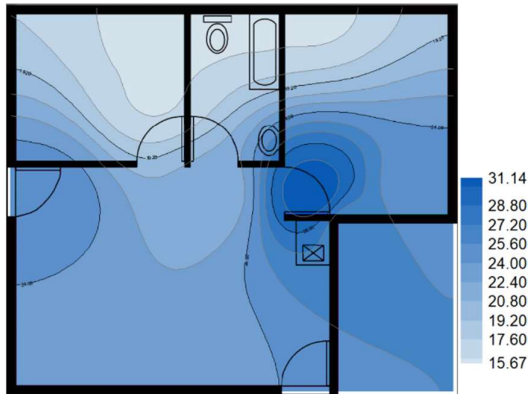
APPENDIX B - Figure 29: Botshabelo
GSH 2014 May 800mm MC: 25%-34%



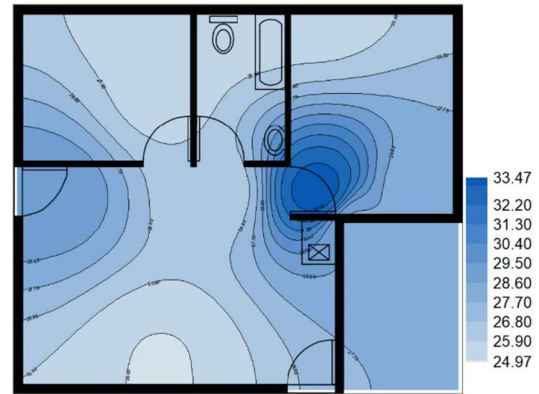
APPENDIX B - Figure 27: Botshabelo
GSH 2014 May 450mm MC: 24%-32%



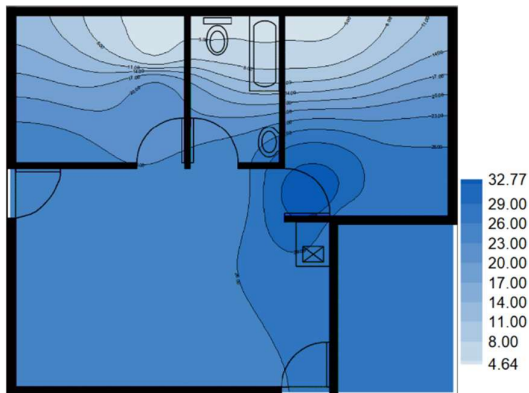
APPENDIX B - Figure 30: Botshabelo
GSH 2014 May 1,000mm MC: 25%-
34%



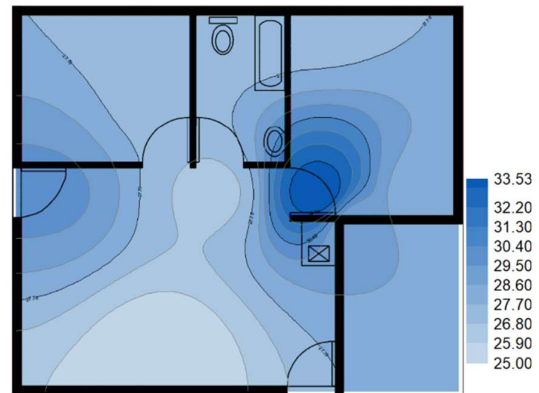
APPENDIX B - Figure 31: Botshabelo
GSH 2014 June 150mm MC: 16%-
31%



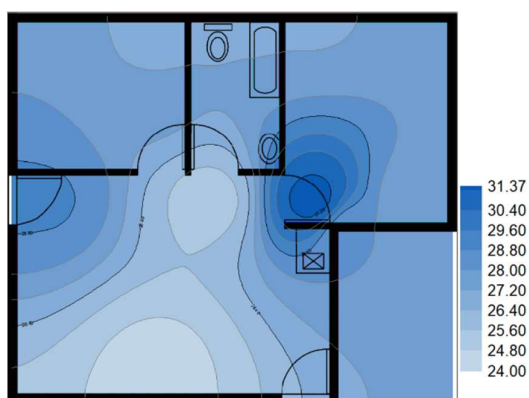
APPENDIX B - Figure 34: Botshabelo
GSH 2014 June 600mm MC: 25%-
33%



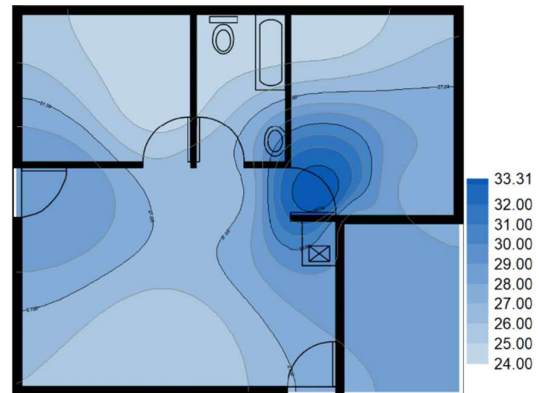
APPENDIX B - Figure 32: Botshabelo
GSH 2014 June 300mm MC: 5%-33%



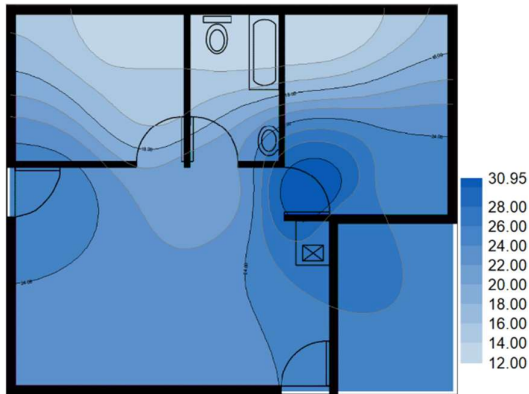
APPENDIX B - Figure 35: Botshabelo
GSH 2014 June 800mm MC: 25%-
33%



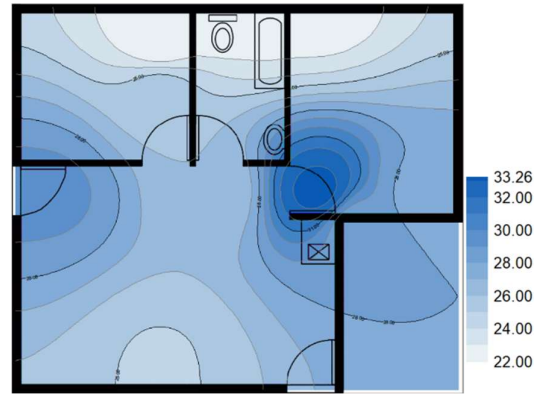
APPENDIX B - Figure 33: Botshabelo
GSH 2014 June 450mm MC: 24%-
31%



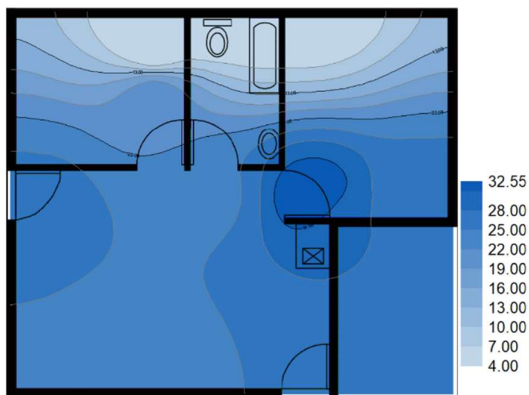
APPENDIX B - Figure 36: Botshabelo
GSH 2014 June 1,000mm MC: 24%-
33%



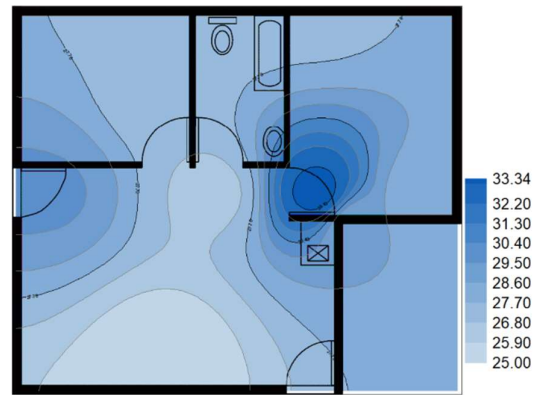
APPENDIX B - Figure 37: Botshabelo
GSH 2014 July 150mm MC: 12%-31%



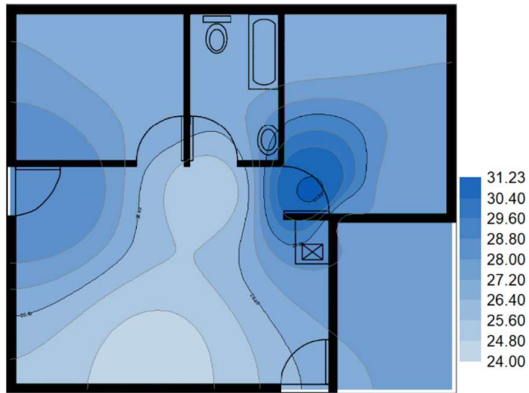
APPENDIX B - Figure 40: Botshabelo
GSH 2014 July 600mm MC: 22%-33%



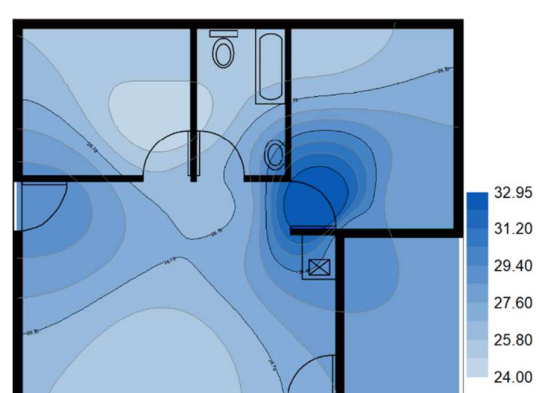
APPENDIX B - Figure 38: Botshabelo
GSH 2014 July 300mm MC: 4%-32%



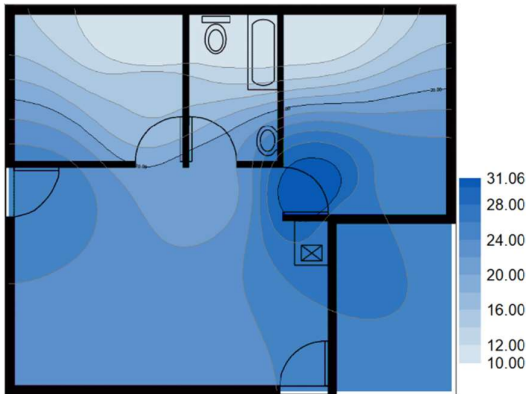
APPENDIX B - Figure 41: Botshabelo
GSH 2014 July 800mm MC: 25%-33%



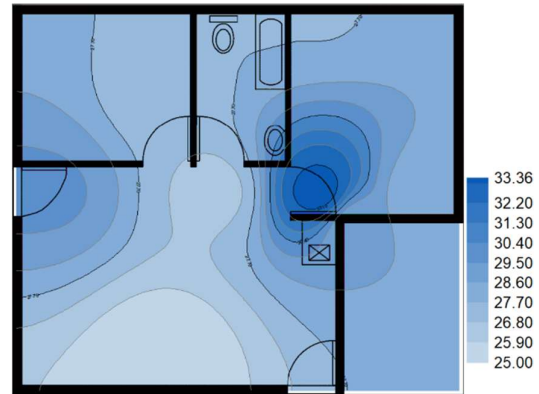
APPENDIX B - Figure 39: Botshabelo
GSH 2014 July 450mm MC: 24%-31%



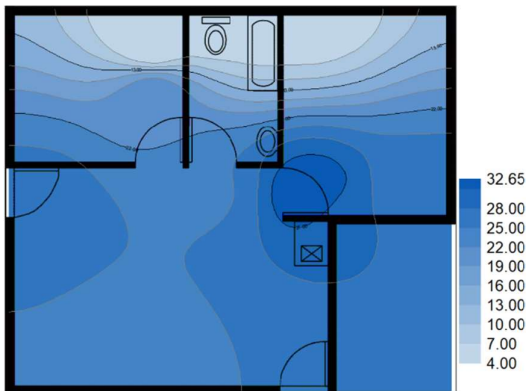
APPENDIX B - Figure 42: Botshabelo
GSH 2014 July 1,000mm MC: 24%-
33%



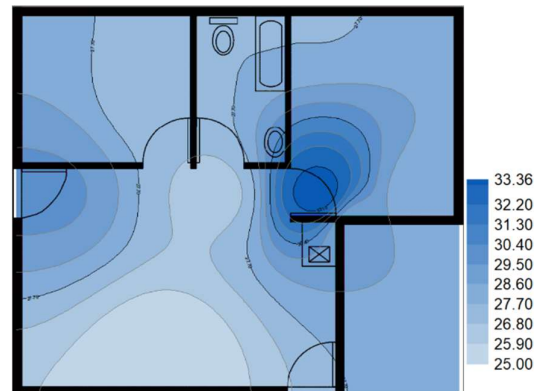
APPENDIX B - Figure 43: Botshabelo
GSH 2014 August 150mm MC: 10%-
31%



APPENDIX B - Figure 46: Botshabelo
GSH 2014 August 600mm MC: 23%-
33%



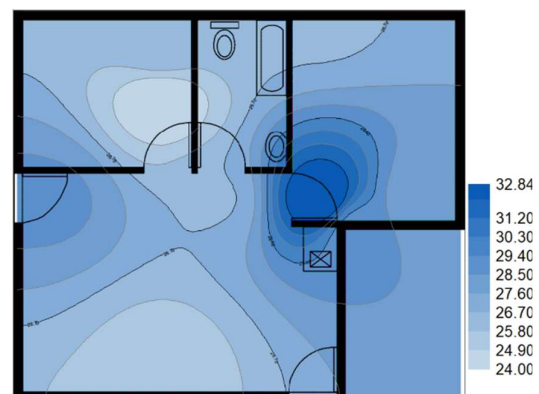
APPENDIX B - Figure 44: Botshabelo
GSH 2014 August 300mm MC: 4%-
33%



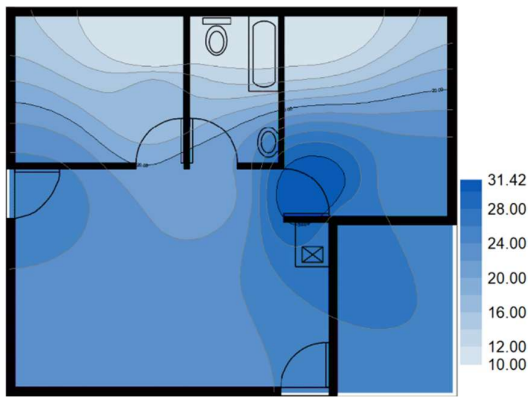
APPENDIX B - Figure 47: Botshabelo
GSH 2014 August 800mm MC: 25%-
33%



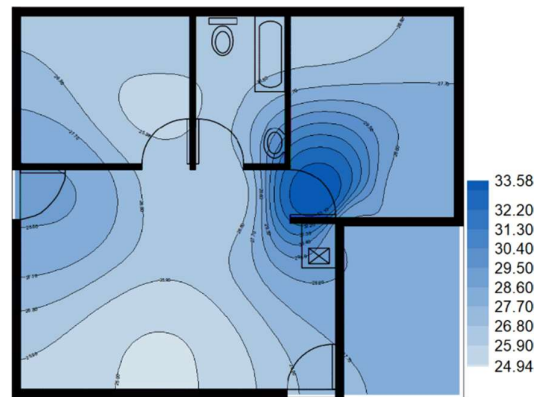
APPENDIX B - Figure 45: Botshabelo
GSH 2014 August 450mm MC: 24%-
31%



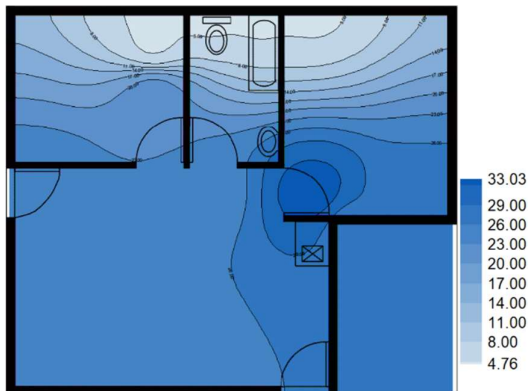
APPENDIX B - Figure 48: Botshabelo
GSH 2014 August 1,000mm MC: 24%-
33%



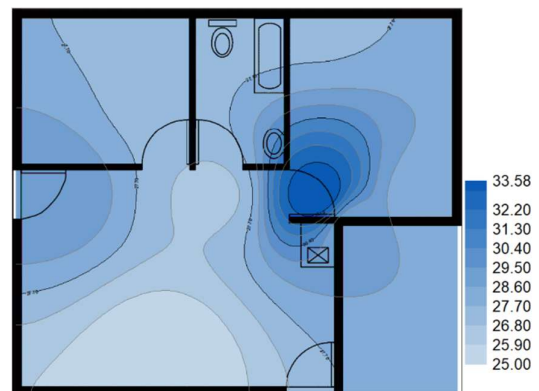
APPENDIX B - Figure 49: Botshabelo
GSH 2014 September 150mm MC:
10%-31%



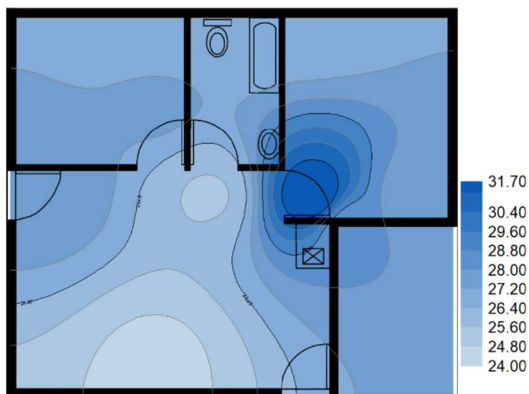
APPENDIX B - Figure 52: Botshabelo
GSH 2014 September 600mm MC:
25%-34%



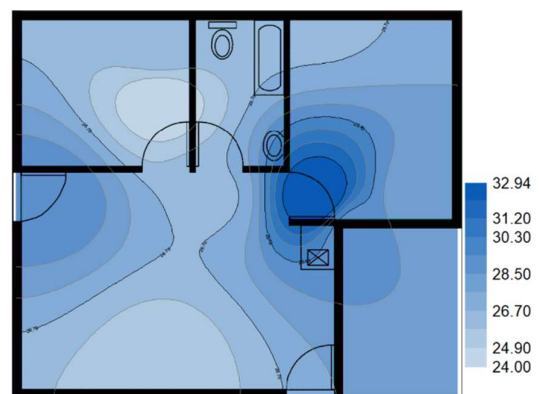
APPENDIX B - Figure 50: Botshabelo
GSH 2014 September 300mm MC:
5%-33%



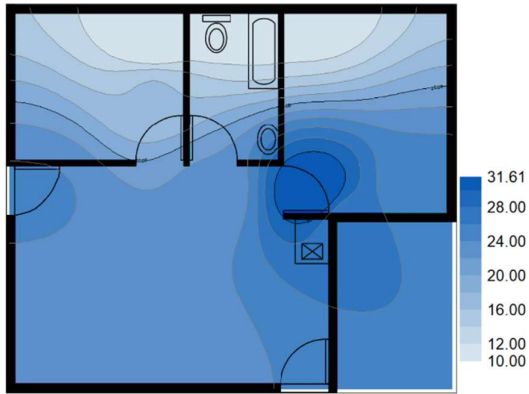
APPENDIX B - Figure 53: Botshabelo
GSH 2014 September 800mm MC:
25%-34%



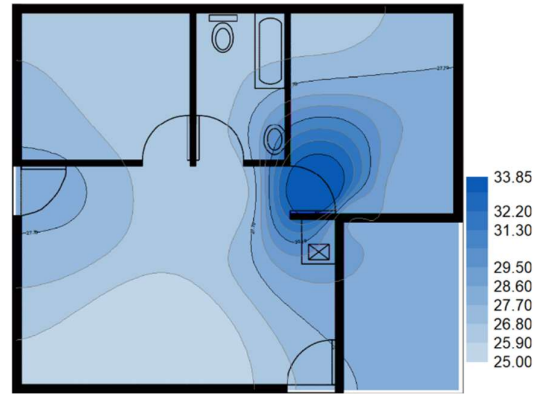
APPENDIX B - Figure 51: Botshabelo
GSH 2014 September 450mm MC:
24%-32%



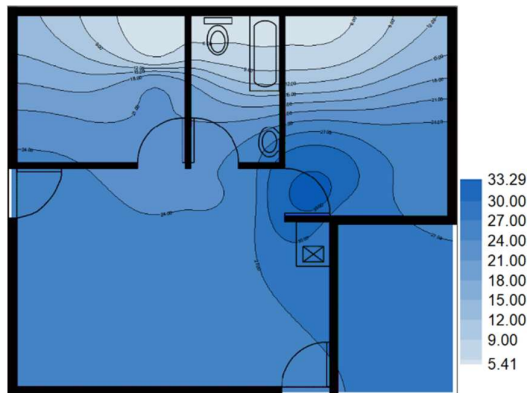
APPENDIX B - Figure 54: Botshabelo
GSH 2014 September 150mm MC:
24%-33%



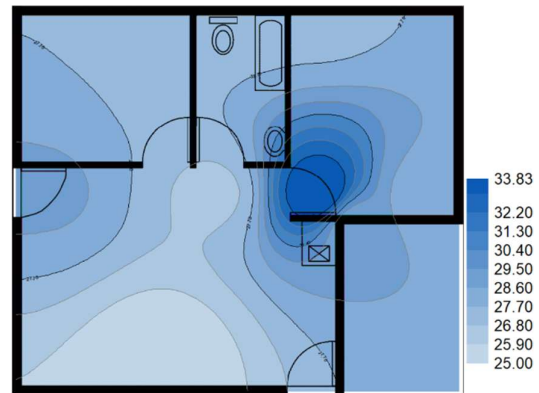
APPENDIX B - Figure 55: Botshabelo
GSH 2014 October 150mm MC: 10%-
32%



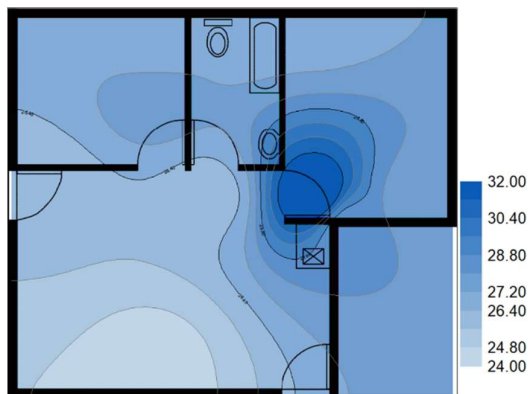
APPENDIX B - Figure 58: Botshabelo
GSH 2014 October 600mm MC: 25%-
34%



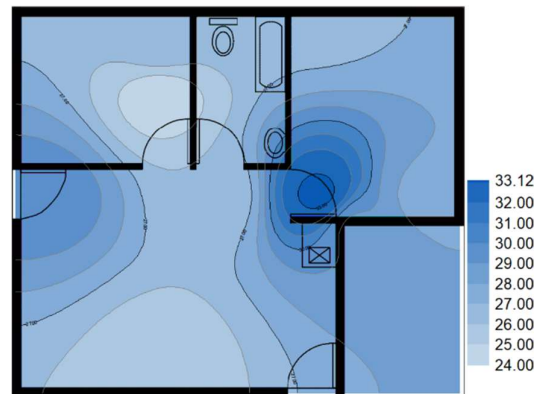
APPENDIX B - Figure 56: Botshabelo
GSH 2014 October 300mm MC: 5%-
33%



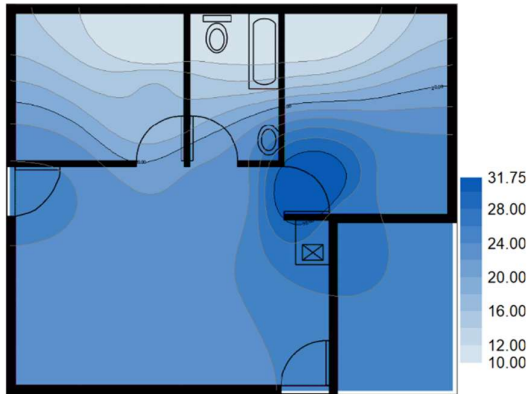
APPENDIX B - Figure 59: Botshabelo
GSH 2014 October 800mm MC: 25%-
34%



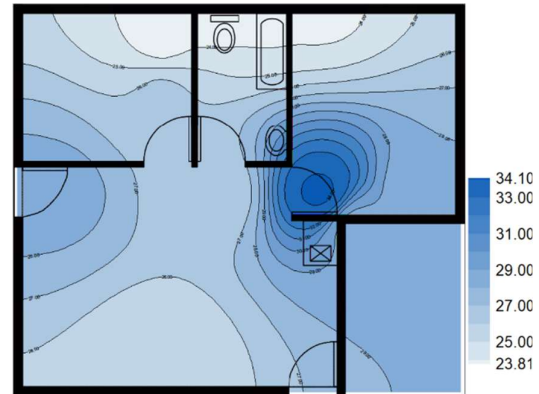
APPENDIX B - Figure 57: Botshabelo
GSH 2014 October 450mm MC: 24%-
32%



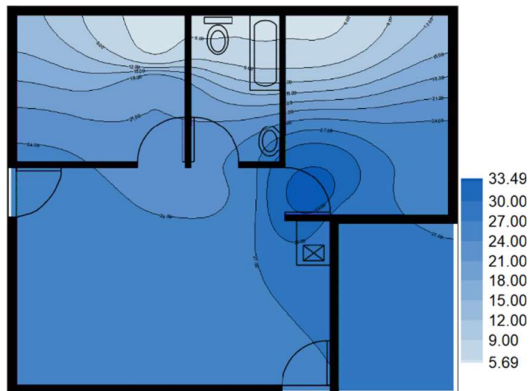
APPENDIX B - Figure 60: Botshabelo
GSH 2014 October 1,000mm MC:
24%-33%



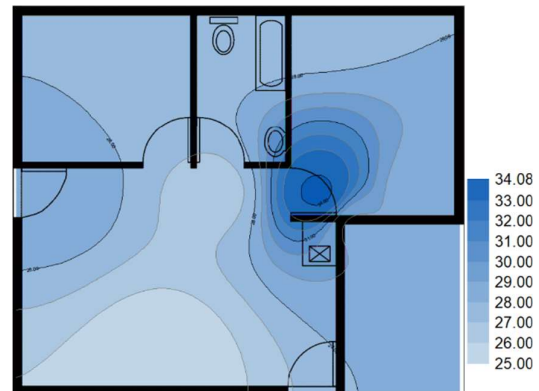
APPENDIX B - Figure 61: Botshabelo
GSH 2014 November 150mm MC:
10%-32%



APPENDIX B - Figure 64: Botshabelo
GSH 2014 November 600mm MC:
23%-34%



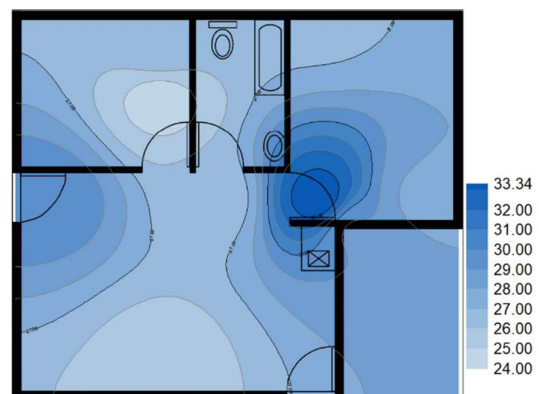
APPENDIX B - Figure 62: Botshabelo
GSH 2014 November 300mm MC:
6%-34%



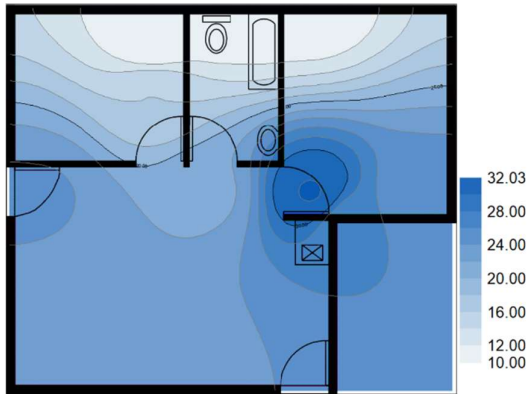
APPENDIX B - Figure 65: Botshabelo
GSH 2014 November 800mm MC:
25%-34%



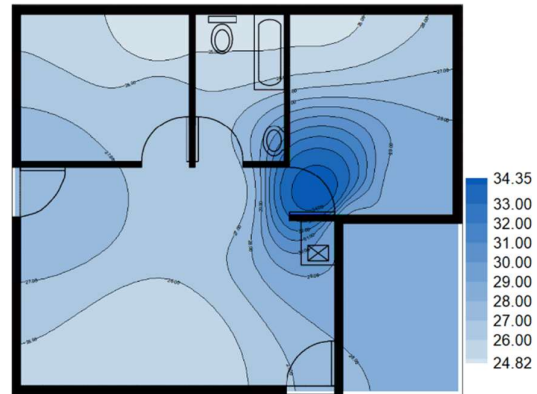
APPENDIX B - Figure 63: Botshabelo
GSH 2014 November 450mm MC:
24%-32%



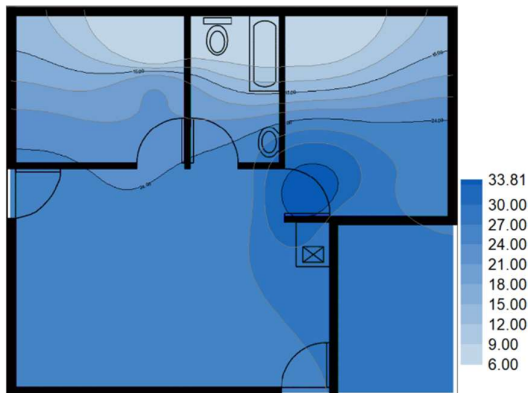
APPENDIX B - Figure 66: Botshabelo
GSH 2014 November 1,000mm MC:
24%-33%



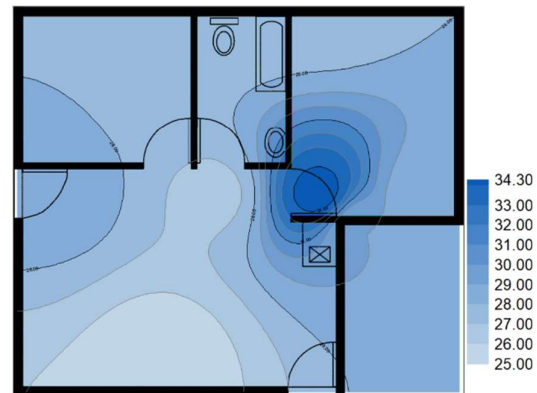
APPENDIX B - Figure 67: Botshabelo
GSH 2014 December 150mm MC:
10%-32%



APPENDIX B - Figure 70: Botshabelo
GSH 2014 December 600mm MC:
25%-34%



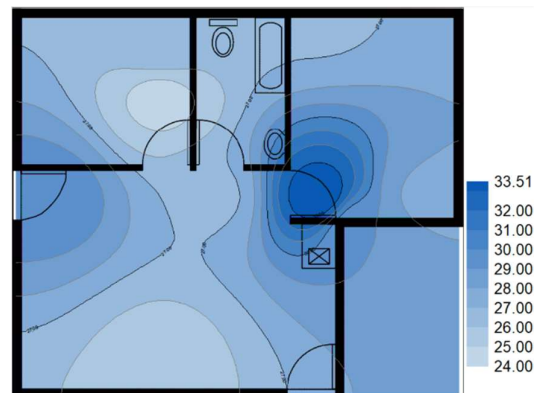
APPENDIX B - Figure 68: Botshabelo
GSH 2014 December 300mm MC:
6%-34%



APPENDIX B - Figure 71: Botshabelo
GSH 2014 December 800mm MC:
25%-34%



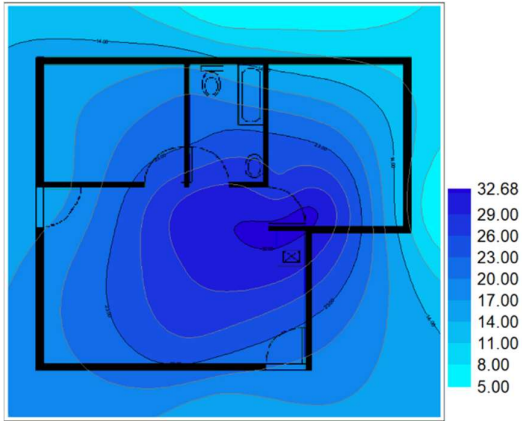
APPENDIX B - Figure 69: Botshabelo
GSH 2014 December 450mm MC:
24%-33%



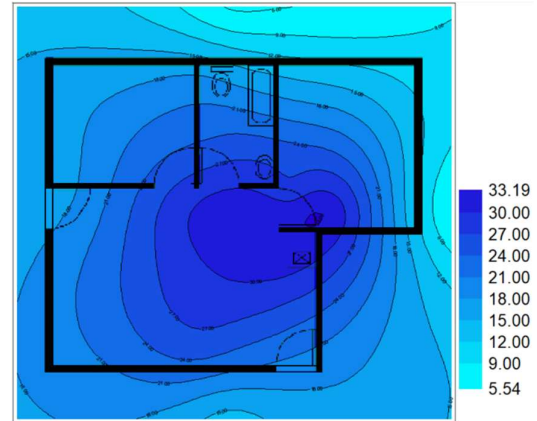
APPENDIX B - Figure 72: Botshabelo
GSH 2014 December 1,000mm MC:
24%-34%

APPENDIX C

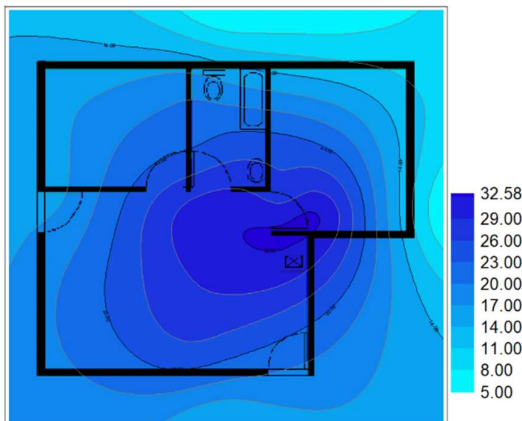
The variation in moisture of the SM raft foundation due to simulated seasonal changes using 3DField modelling



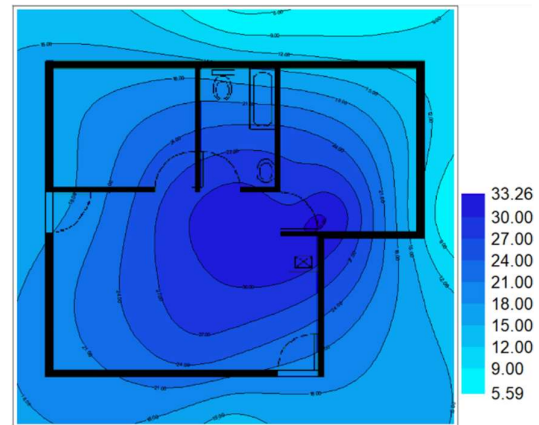
APPENDIX C - Figure 1: January Year 1 Moisture Content (%) for SM raft foundation



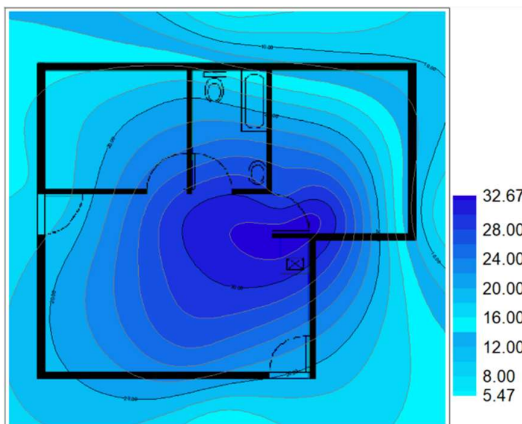
APPENDIX C - Figure 4: April Year 1 Moisture Content (%) for SM raft foundation



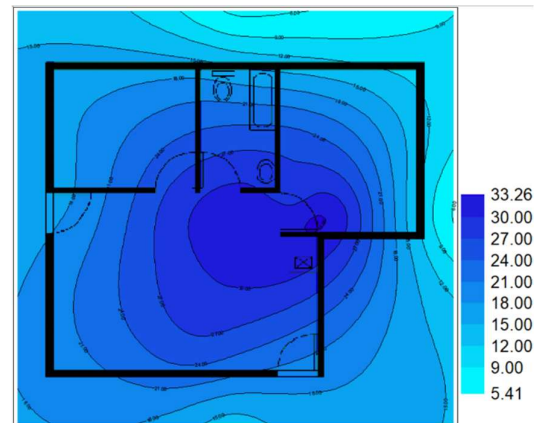
APPENDIX C - Figure 2: February Year 1 Moisture Content (%) for SM raft foundation



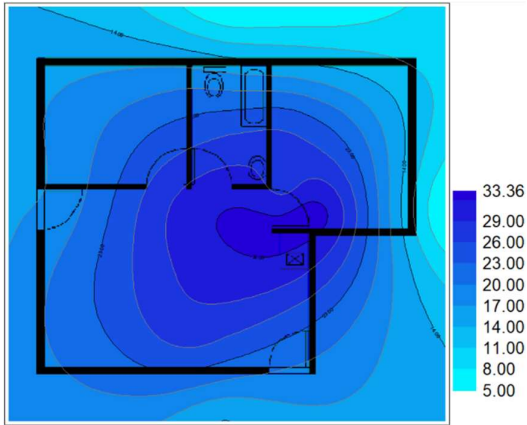
APPENDIX C - Figure 5: May Year 1 Moisture Content (%) for SM raft foundation



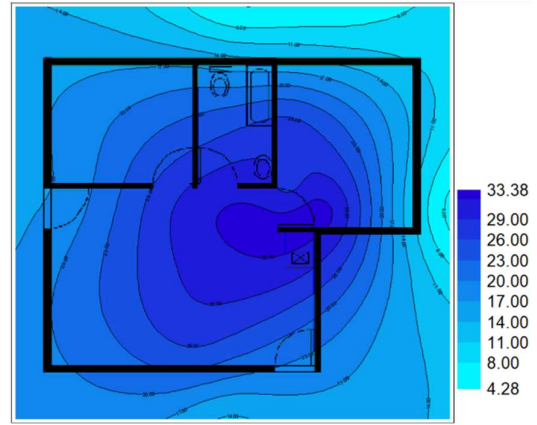
APPENDIX C - Figure 3: March Year 1 Moisture Content (%) for SM raft foundation



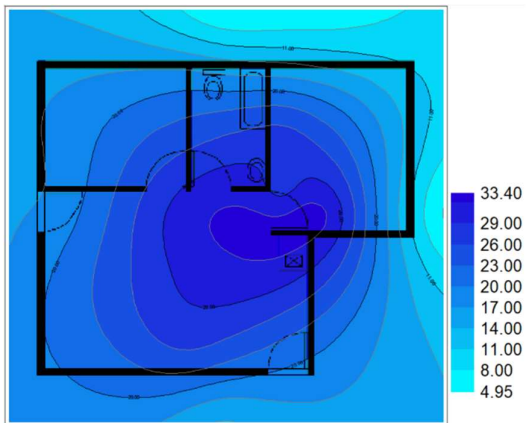
APPENDIX C - Figure 6: June Year 1 Moisture Content (%) for SM raft foundation



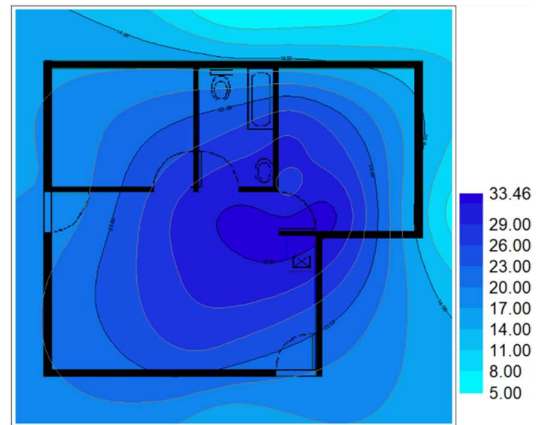
APPENDIX C - Figure 7: July Year 1 Moisture Content (%) for SM raft foundation



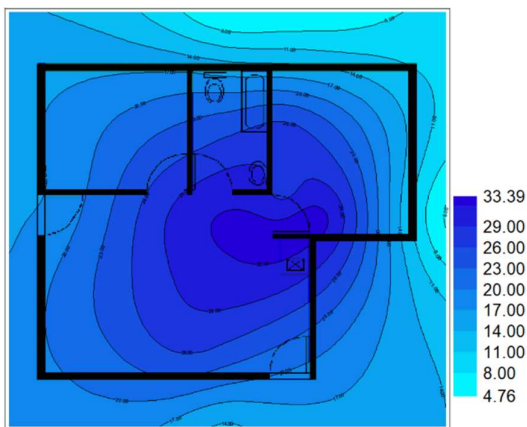
APPENDIX C - Figure 10: October Year 1 Moisture Content (%) for SM raft foundation



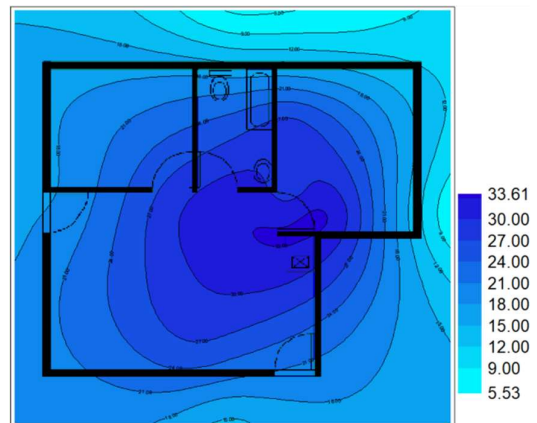
APPENDIX C - Figure 8: August Year 1 Moisture Content (%) for SM raft foundation



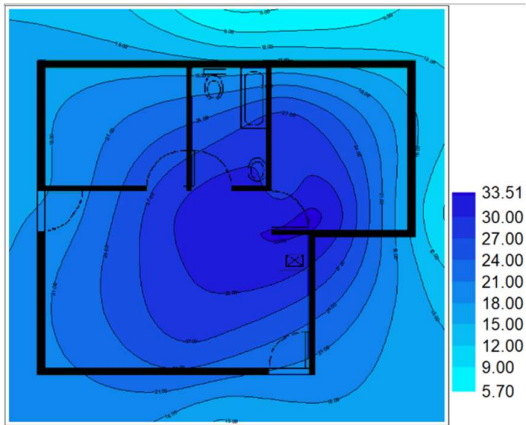
APPENDIX C - Figure 11: November Year 1 Moisture Content (%) for SM raft foundation



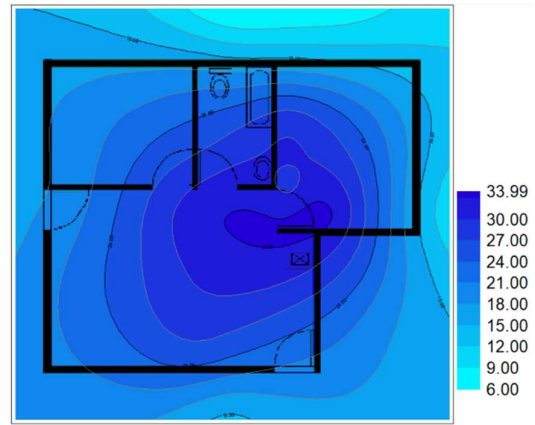
APPENDIX C - Figure 9: September Year 1 Moisture Content (%) for SM raft foundation



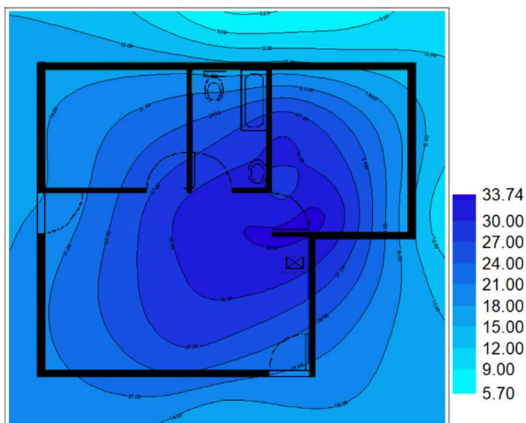
APPENDIX C - Figure 12: December Year 1 Moisture Content (%) for SM raft foundation



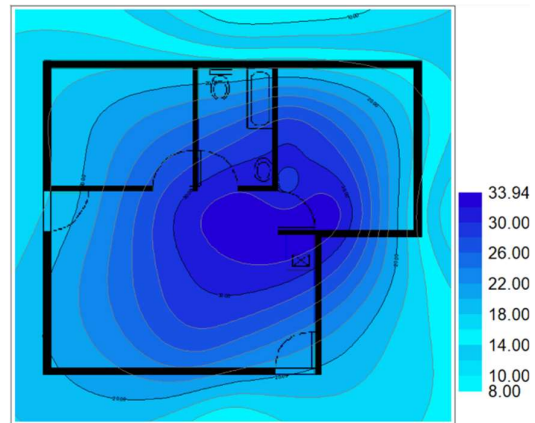
APPENDIX C - Figure 13: January Year 2 Moisture Content (%) for SM raft foundation



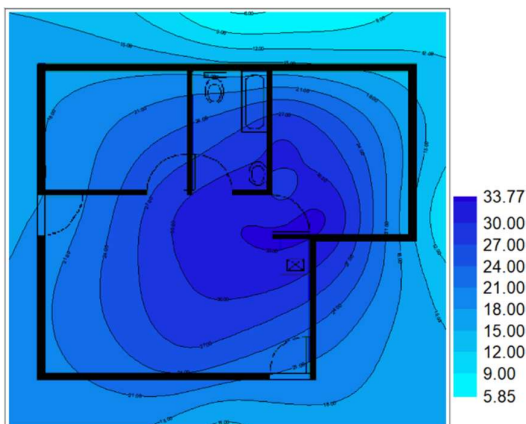
APPENDIX C - Figure 16: April Year 2 Moisture Content (%) for SM raft foundation



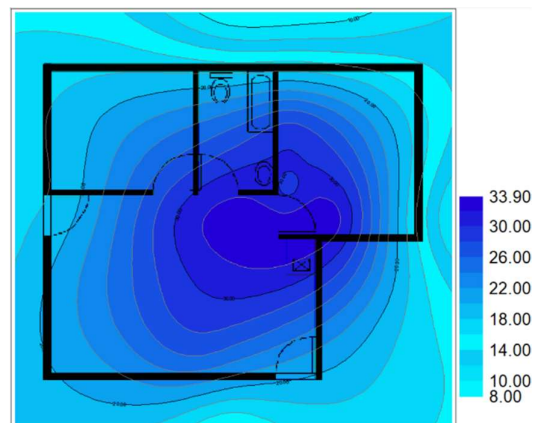
APPENDIX C - Figure 14: February Year 2 Moisture Content (%) for SM raft foundation



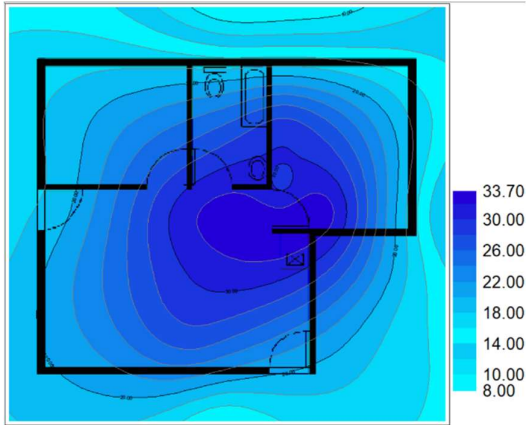
APPENDIX C - Figure 17: May Year 2 Moisture Content (%) for SM raft foundation



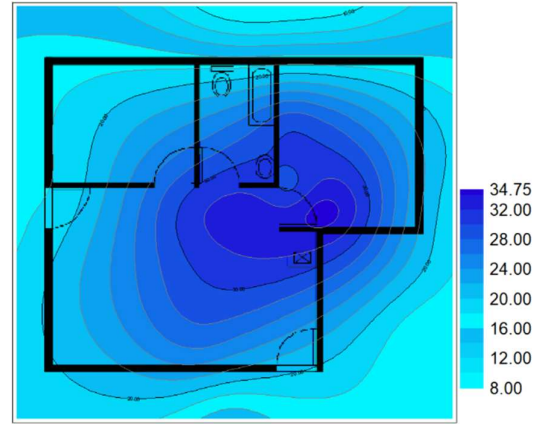
APPENDIX C - Figure 15: March Year 2 Moisture Content (%) for SM raft foundation



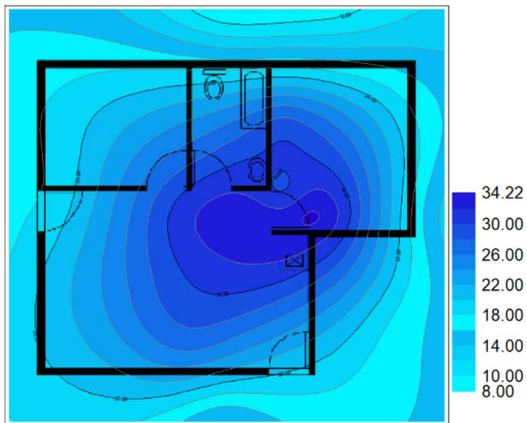
APPENDIX C - Figure 18: June Year 2 Moisture Content (%) for SM raft foundation



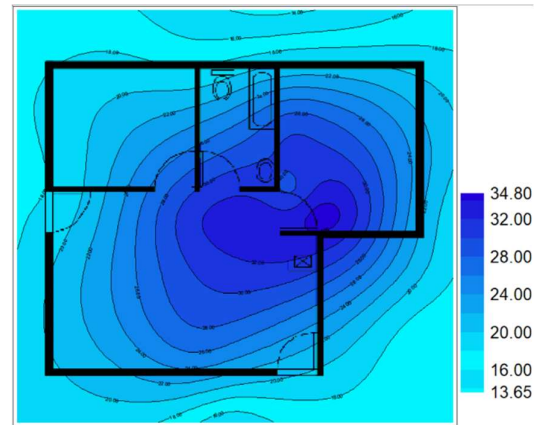
APPENDIX C - Figure 19: July Year 2 Moisture Content (%) for SM raft foundation



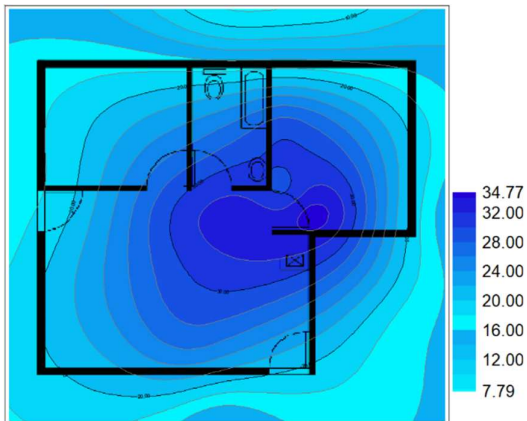
APPENDIX C - Figure 22: October Year 2 Moisture Content (%) for SM raft foundation



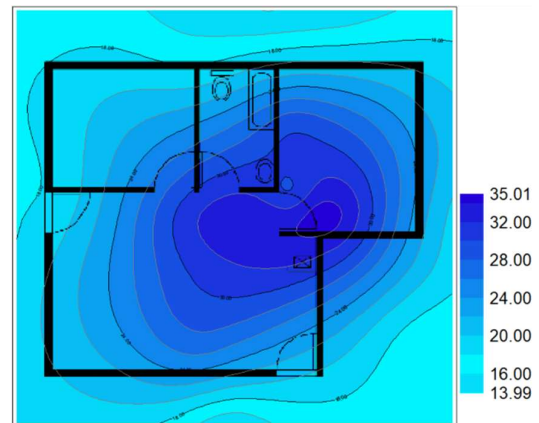
APPENDIX C - Figure 20: August Year 2 Moisture Content (%) for SM raft foundation



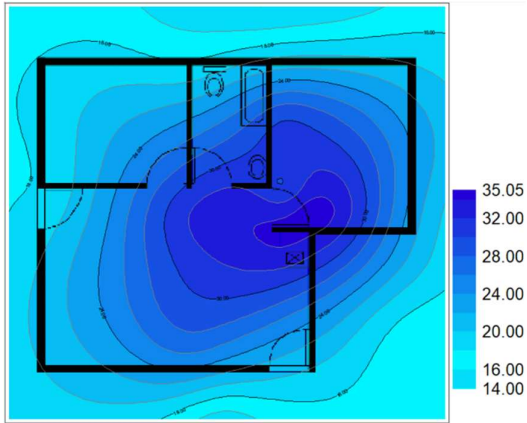
APPENDIX C - Figure 23: November Year 2 Moisture Content (%) for SM raft foundation



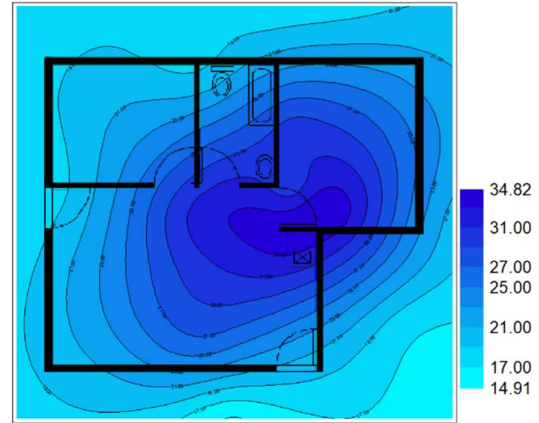
APPENDIX C - Figure 21: September Year 2 Moisture Content (%) for SM raft foundation



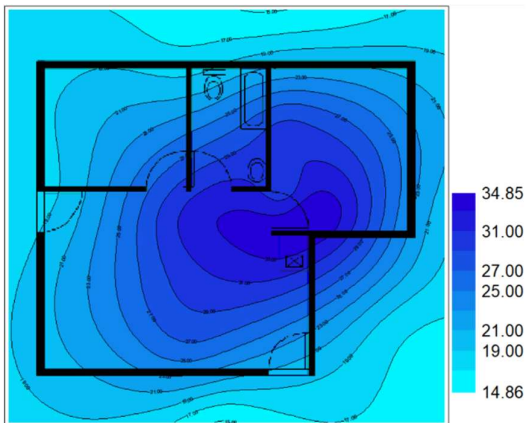
APPENDIX C - Figure 24: December Year 2 Moisture Content (%) for SM raft foundation



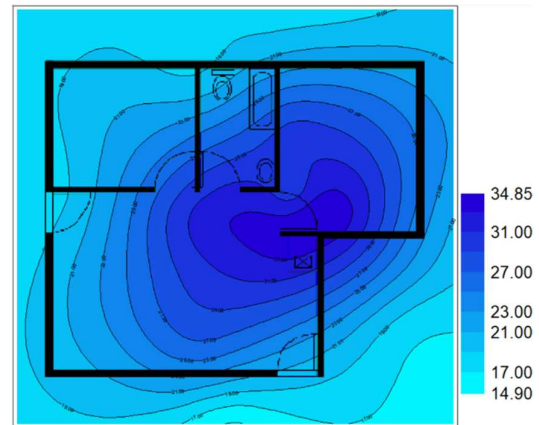
APPENDIX C - Figure 25: January Year 3 Moisture Content (%) for SM raft foundation



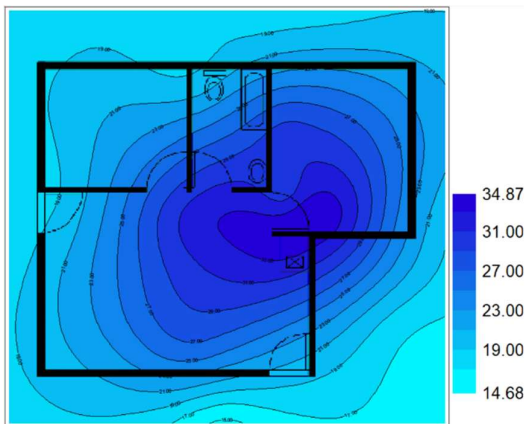
APPENDIX C - Figure 28: April Year 3 Moisture Content (%) for SM raft foundation



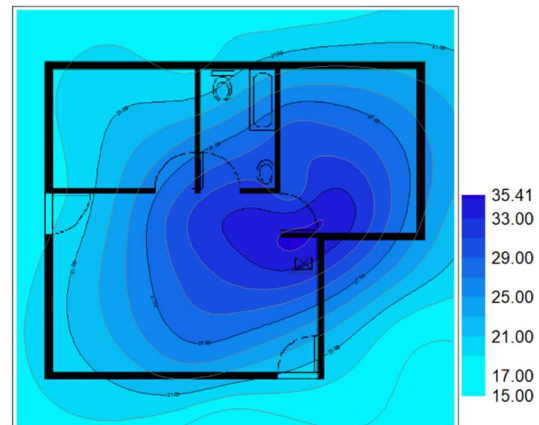
APPENDIX C - Figure 26: February Year 3 Moisture Content (%) for SM raft foundation



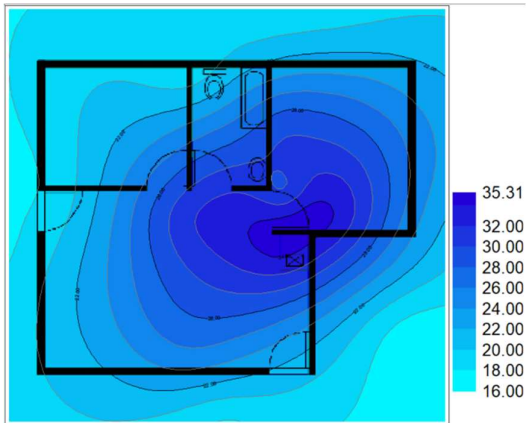
APPENDIX C - Figure 29: May Year 3 Moisture Content (%) for SM raft foundation



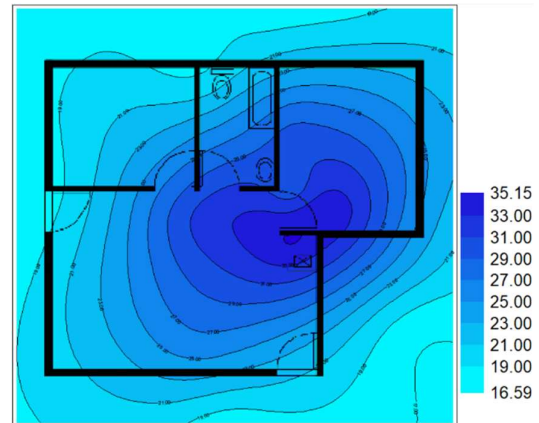
APPENDIX C - Figure 27: March Year 3 Moisture Content (%) for SM raft foundation



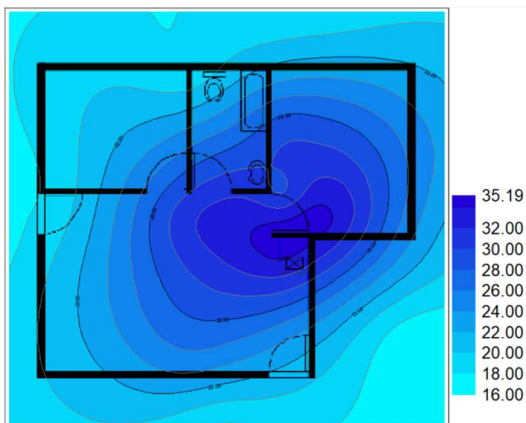
APPENDIX C - Figure 30: June Year 3 Moisture Content (%) for SM raft foundation



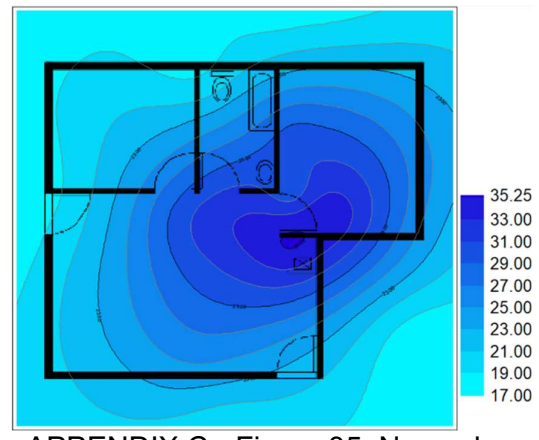
APPENDIX C - Figure 31: July Year 3 Moisture Content (%) for SM raft foundation



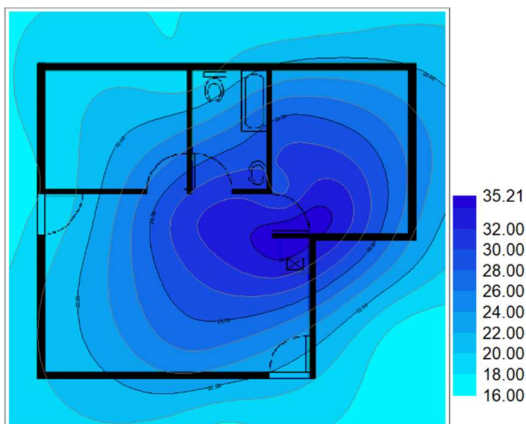
APPENDIX C - Figure 34: October Year 3 Moisture Content (%) for SM raft foundation



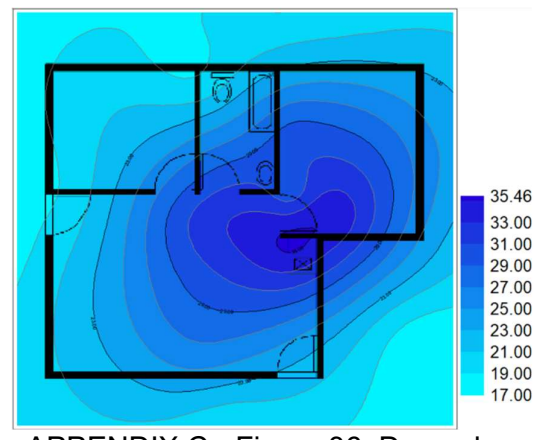
APPENDIX C - Figure 32: August Year 3 Moisture Content (%) for SM raft foundation



APPENDIX C - Figure 35: November Year 3 Moisture Content (%) for SM raft foundation



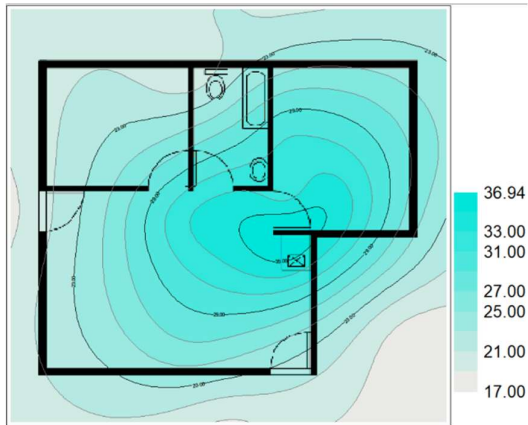
APPENDIX C - Figure 33: September Year 3 Moisture Content (%) for SM raft foundation



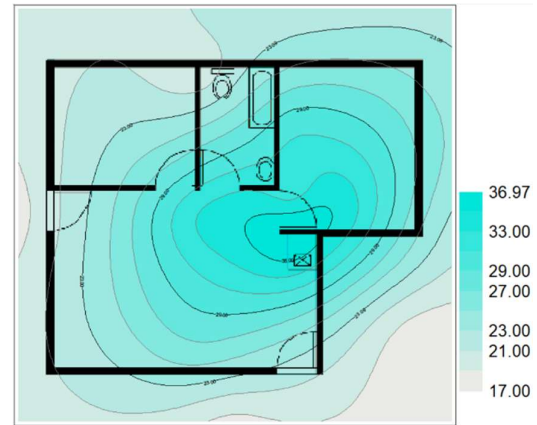
APPENDIX C - Figure 36: December Year 3 Moisture Content (%) for SM raft foundation

APPENDIX D

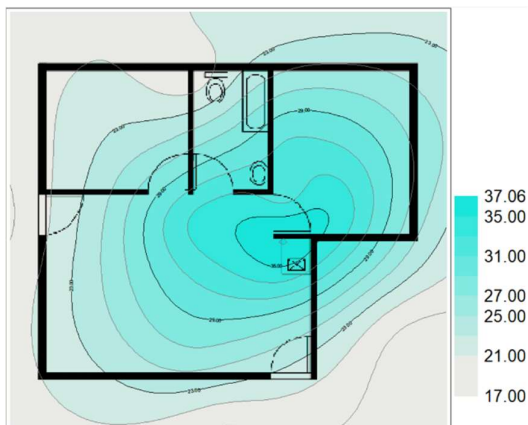
The variation in moisture of the SM cavity raft foundation due to simulated seasonal changes using 3DField modelling



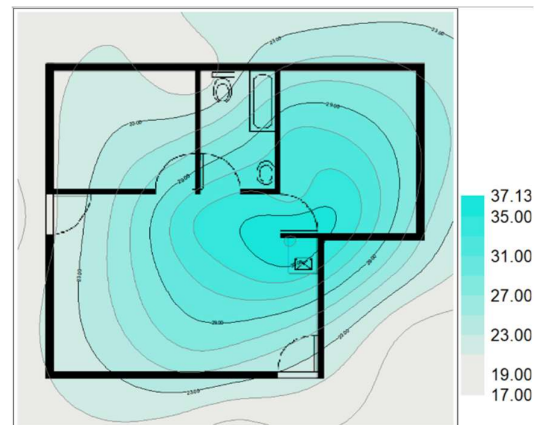
APPENDIX D - Figure 1: January Year 1 Moisture Content (%) for SM cavity raft foundation



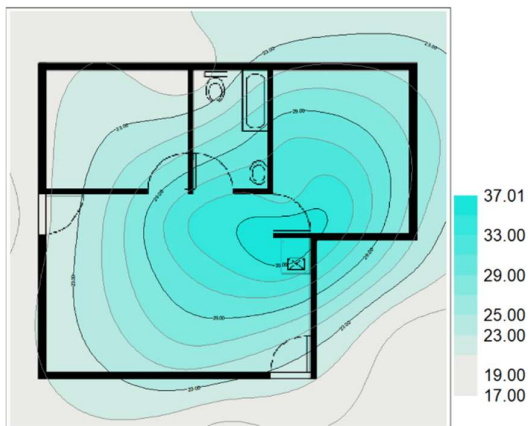
APPENDIX D - Figure 4: April Year 1 Moisture Content (%) for SM cavity raft foundation



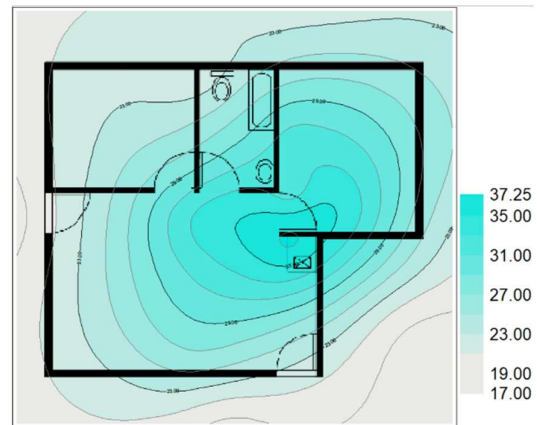
APPENDIX D - Figure 2: February Year 1 Moisture Content (%) for SM cavity raft foundation



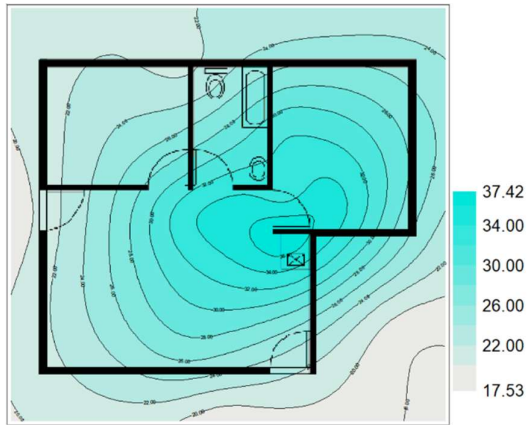
APPENDIX D - Figure 5: May Year 1 Moisture Content (%) for SM cavity raft foundation



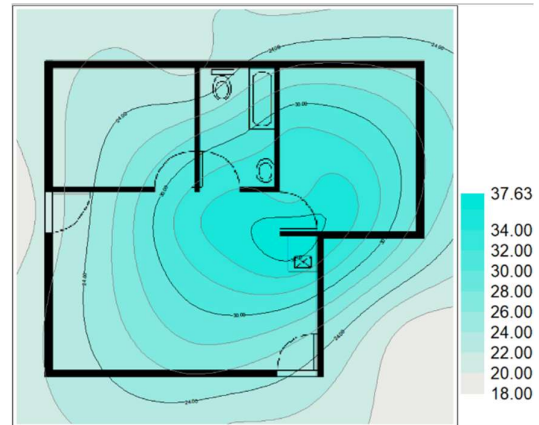
APPENDIX D - Figure 3: March Year 1 Moisture Content (%) for SM cavity raft foundation



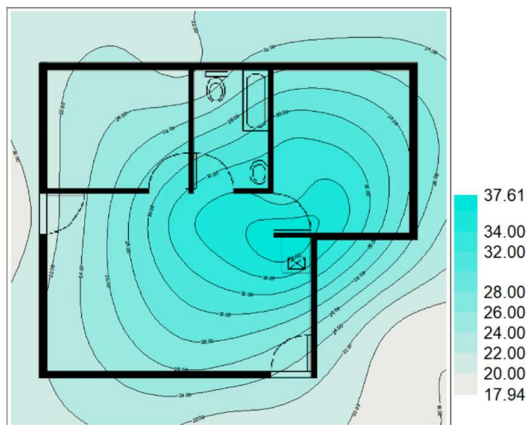
APPENDIX D - Figure 6: June Year 1 Moisture Content (%) for SM cavity raft foundation



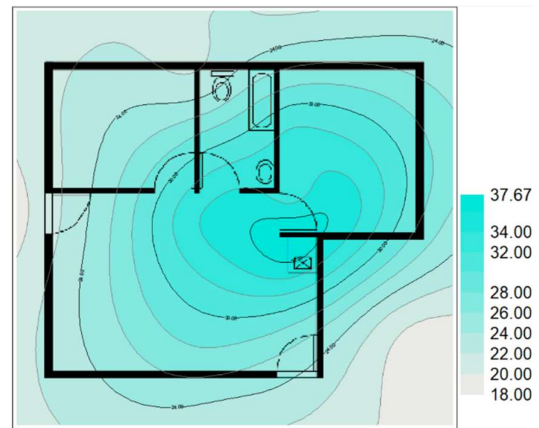
APPENDIX D - Figure 7: July Year 1 Moisture Content (%) for SM cavity raft foundation



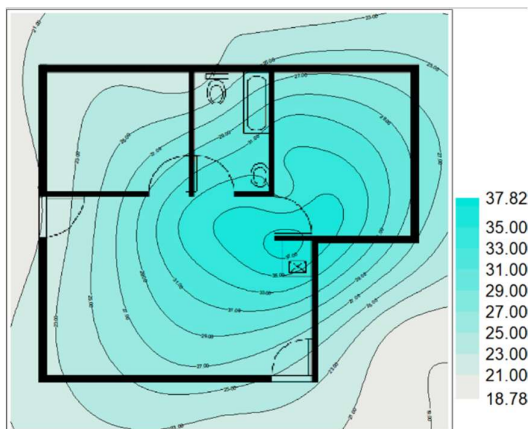
APPENDIX D - Figure 10: October Year 1 Moisture Content (%) for SM cavity raft foundation



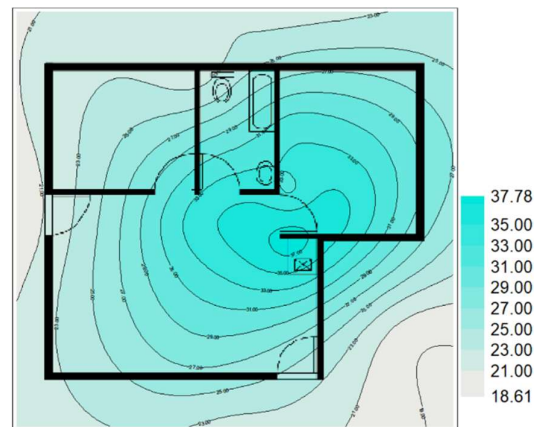
APPENDIX D - Figure 8: August Year 1 Moisture Content (%) for SM cavity raft foundation



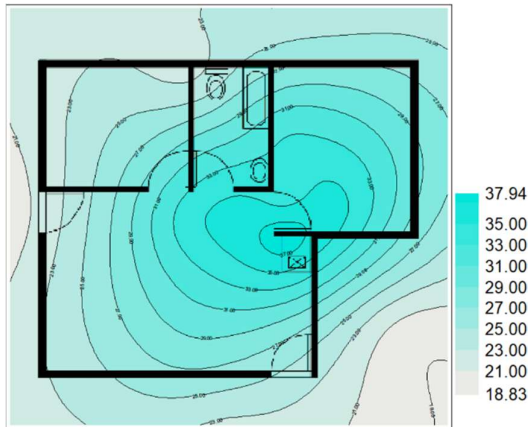
APPENDIX D - Figure 11: November Year 1 Moisture Content (%) for SM cavity raft foundation



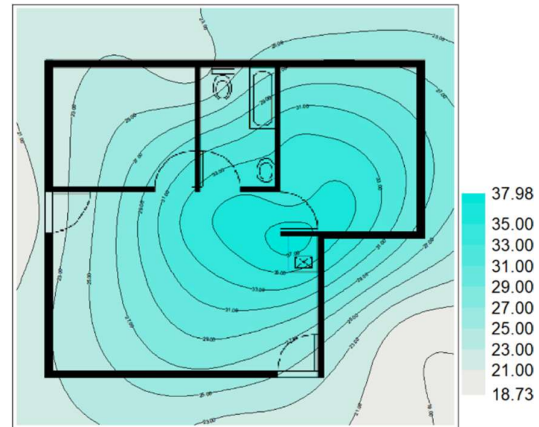
APPENDIX D - Figure 9: September Year 1 Moisture Content (%) for SM cavity raft foundation



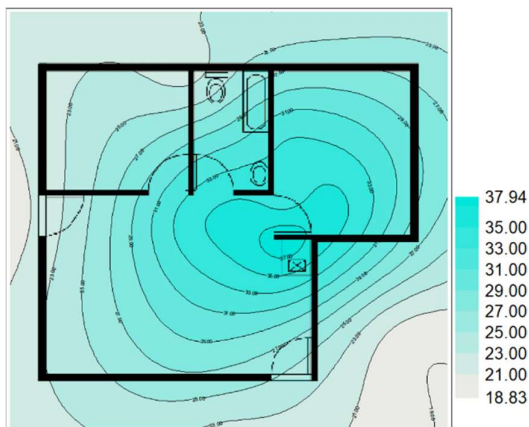
APPENDIX D - Figure 12: December Year 1 Moisture Content (%) for SM cavity raft foundation



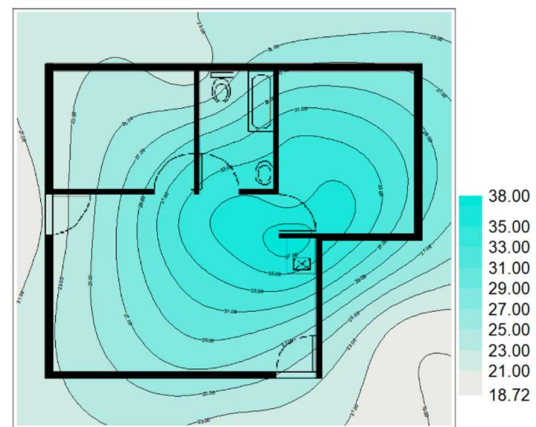
APPENDIX D - Figure 13: January Year 2 Moisture Content (%) for SM cavity raft foundation



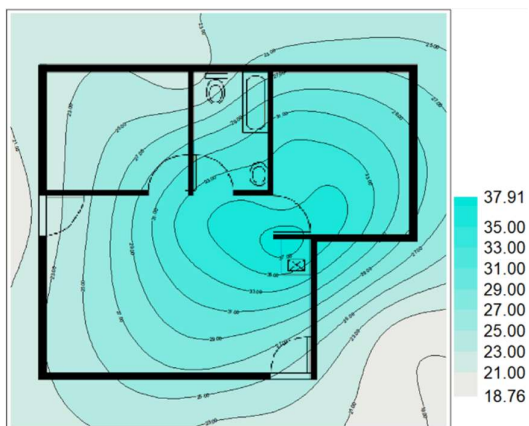
APPENDIX D - Figure 16: April Year 2 Moisture Content (%) for SM cavity raft foundation



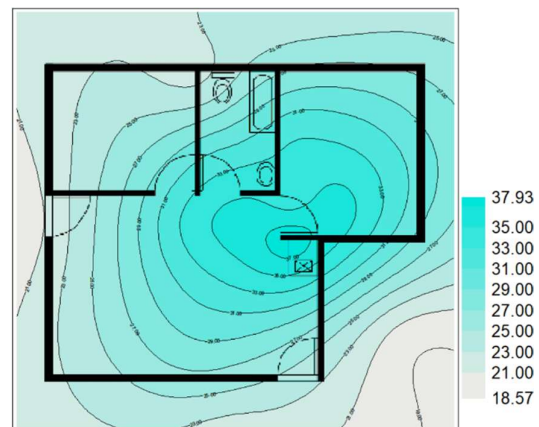
APPENDIX D - Figure 14: February Year 2 Moisture Content (%) for SM cavity raft foundation



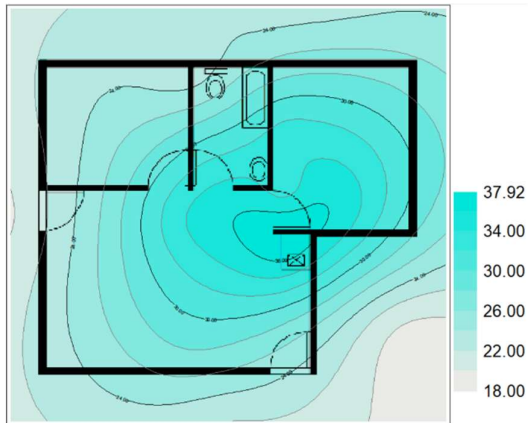
APPENDIX D - Figure 17: May Year 2 Moisture Content (%) for SM cavity raft foundation



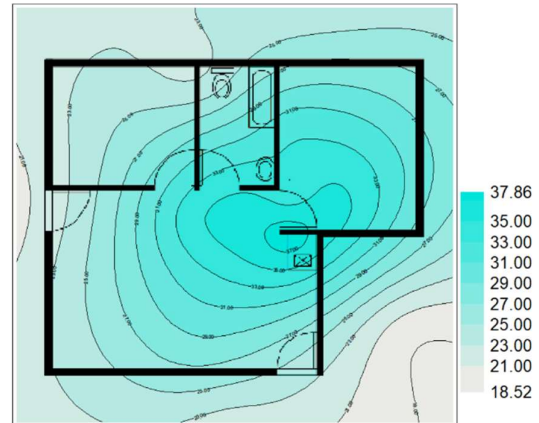
APPENDIX D - Figure 15: March Year 2 Moisture Content (%) for SM cavity raft foundation



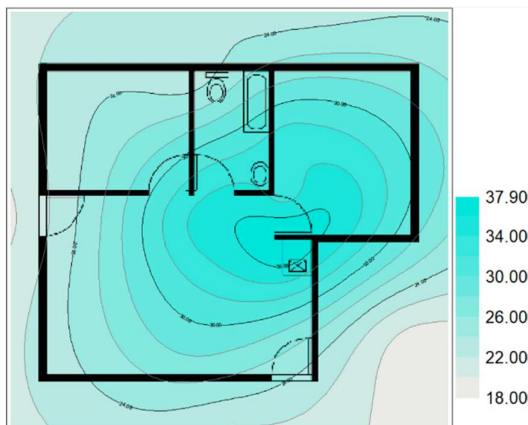
APPENDIX D - Figure 18: June Year 2 Moisture Content (%) for SM cavity raft foundation



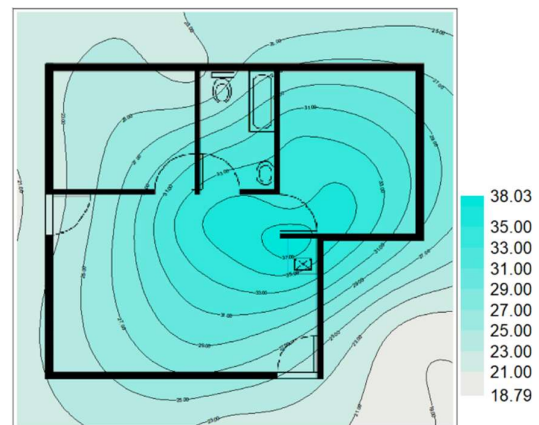
APPENDIX D - Figure 19: July Year 2 Moisture Content (%) for SM cavity raft foundation



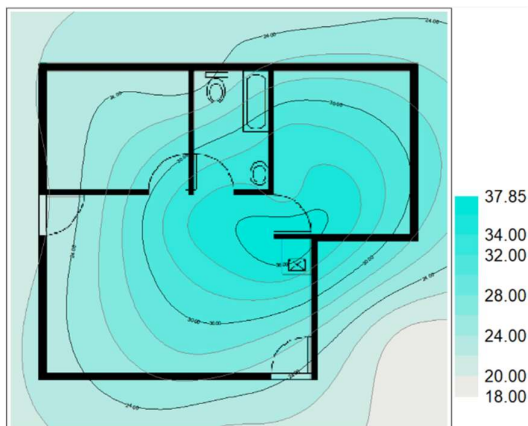
APPENDIX D - Figure 22: October Year 2 Moisture Content (%) for SM cavity raft foundation



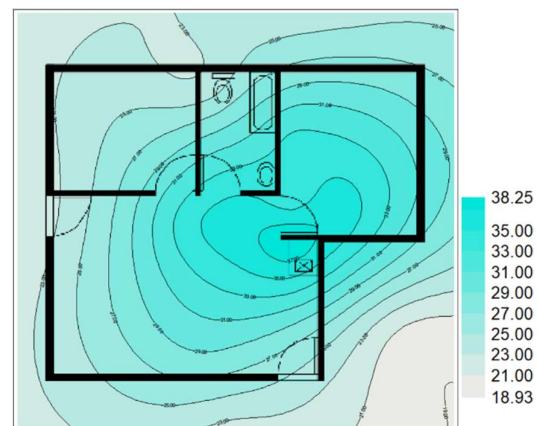
APPENDIX D - Figure 20: August Year 2 Moisture Content (%) for SM cavity raft foundation



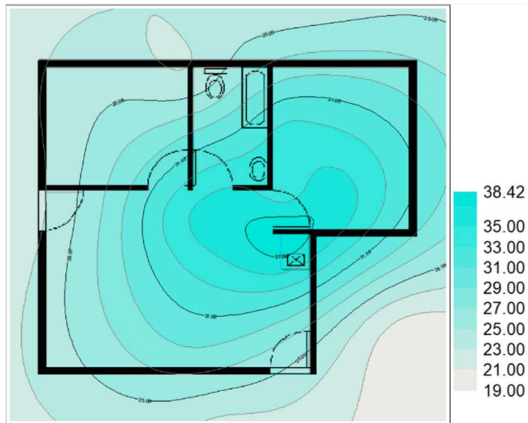
APPENDIX D - Figure 23: November Year 2 Moisture Content (%) for SM cavity raft foundation



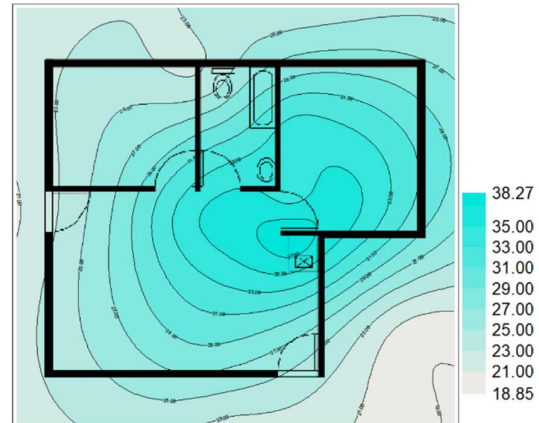
APPENDIX D - Figure 21: September Year 2 Moisture Content (%) for SM cavity raft foundation



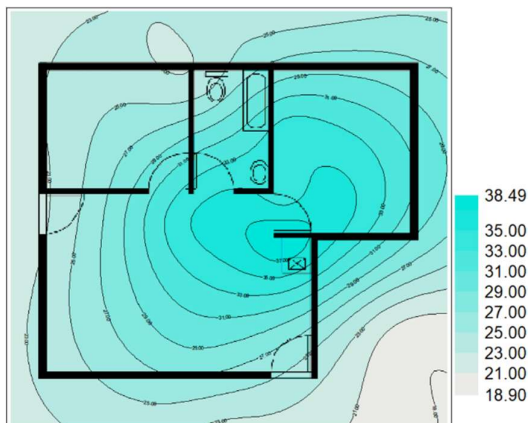
APPENDIX D - Figure 24: December Year 2 Moisture Content (%) for SM cavity raft foundation



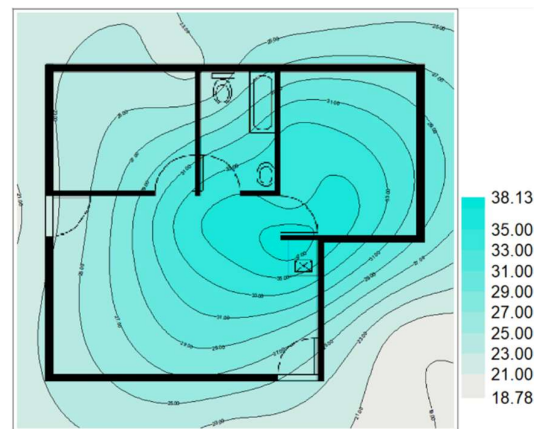
APPENDIX D - Figure 25: January Year 3 Moisture Content (%) for SM cavity raft foundation



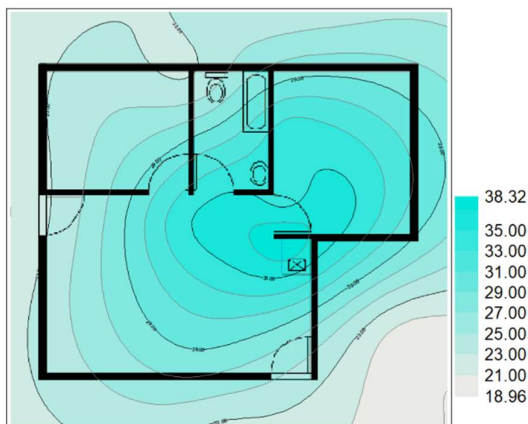
APPENDIX D - Figure 28: April Year 3 Moisture Content (%) for SM cavity raft foundation



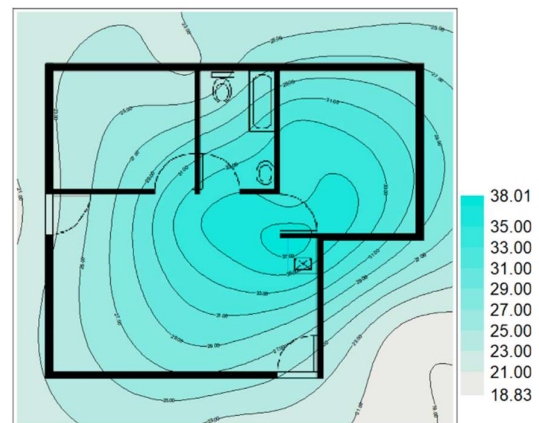
APPENDIX D - Figure 26: February Year 3 Moisture Content (%) for SM cavity raft foundation



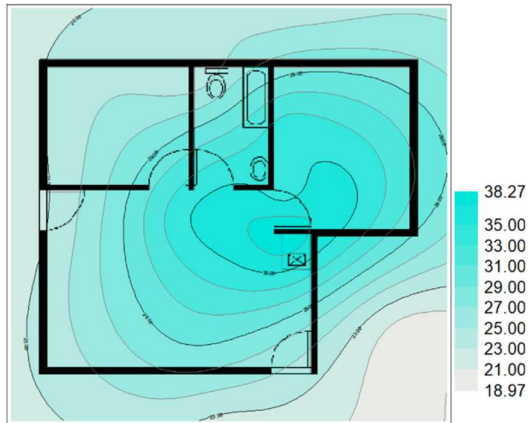
APPENDIX D - Figure 29: May Year 3 Moisture Content (%) for SM cavity raft foundation



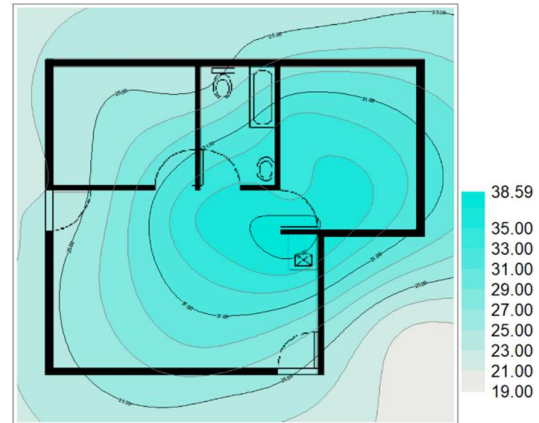
APPENDIX D - Figure 27: March Year 3 Moisture Content (%) for SM cavity raft foundation



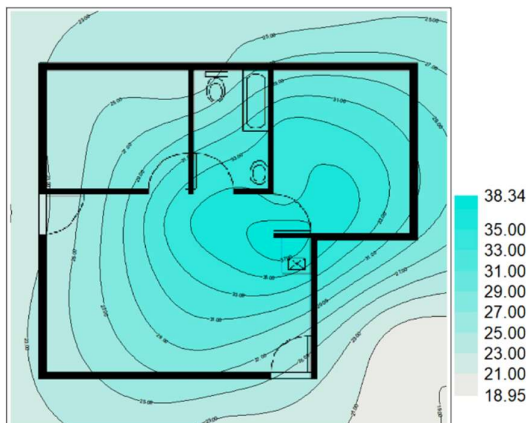
APPENDIX D - Figure 30: June Year 3 Moisture Content (%) for SM cavity raft foundation



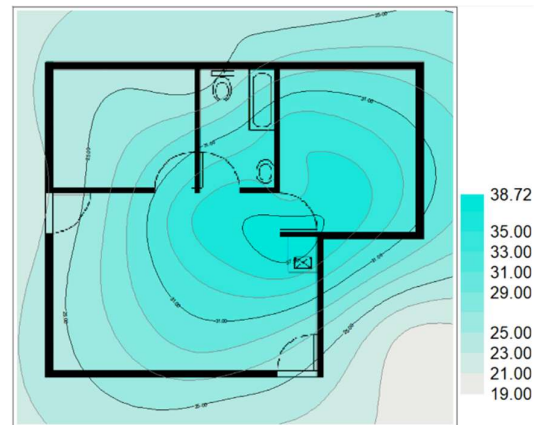
APPENDIX D - Figure 31: July Year 3 Moisture Content (%) for SM cavity raft foundation



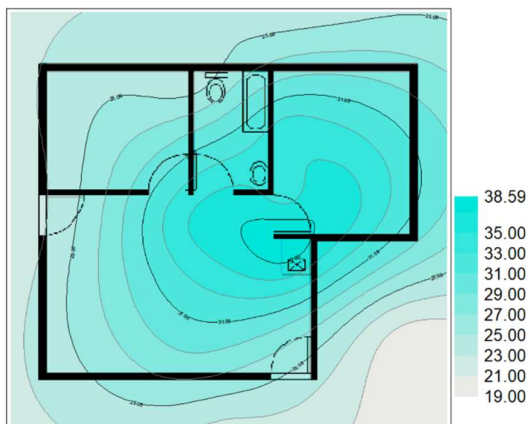
APPENDIX D - Figure 34: October Year 3 Moisture Content (%) for SM cavity raft foundation



APPENDIX D - Figure 32: August Year 3 Moisture Content (%) for SM cavity raft foundation



APPENDIX D - Figure 35: November Year 3 Moisture Content (%) for SM cavity raft foundation



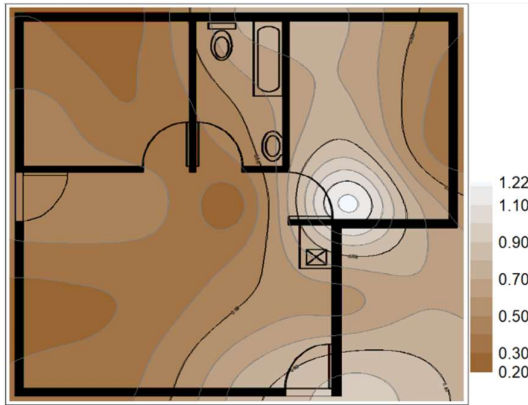
APPENDIX D - Figure 33: September Year 3 Moisture Content (%) for SM cavity raft foundation



APPENDIX D - Figure 36: December Year 3 Moisture Content (%) for SM cavity raft foundation

APPENDIX E

The movement of the SM raft foundation due to simulated seasonal changes using
3DField modelling



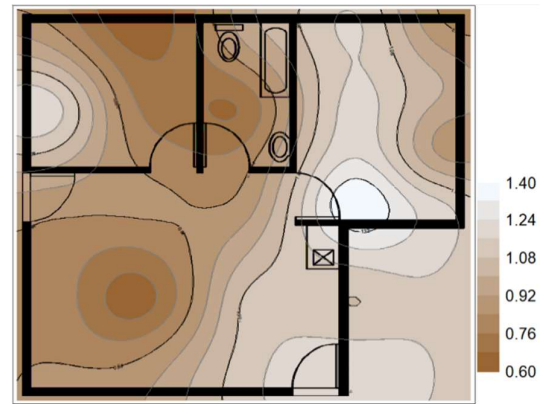
APPENDIX E - Figure 1: January Year 1 SM raft foundation movement in (mm)



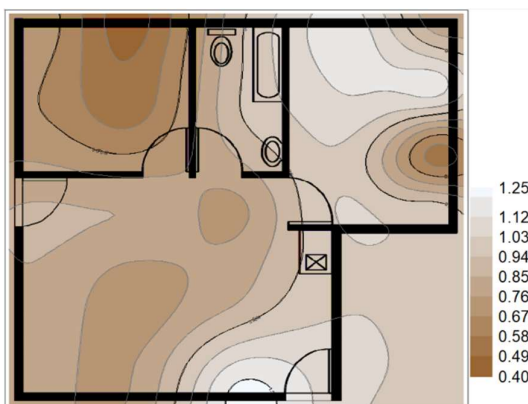
APPENDIX E - Figure 4: April Year 1 SM raft foundation movement in (mm)



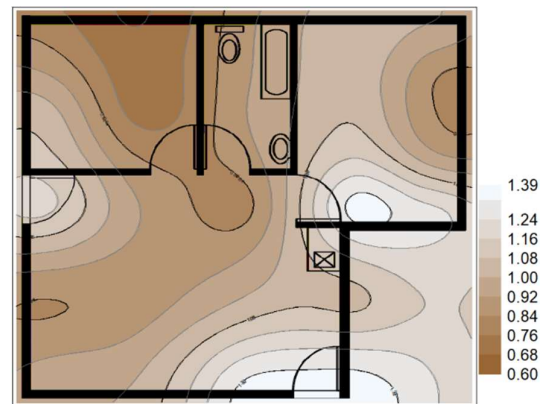
APPENDIX E - Figure 2: February Year 1 SM raft foundation movement in (mm)



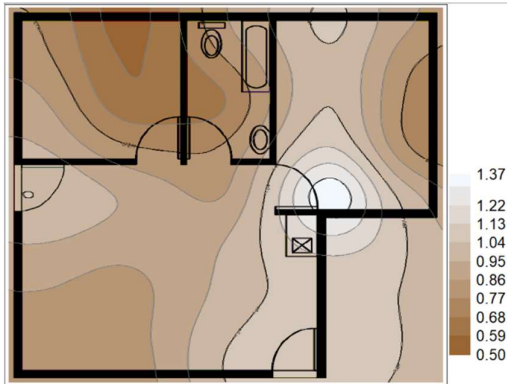
APPENDIX E - Figure 5: May Year 1 SM raft foundation movement in (mm)



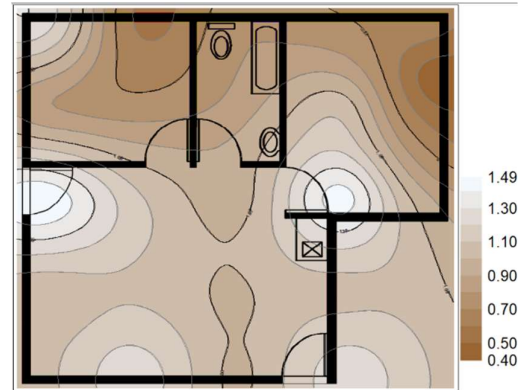
APPENDIX E - Figure 3: Year 1 March SM raft foundation movement in (mm)



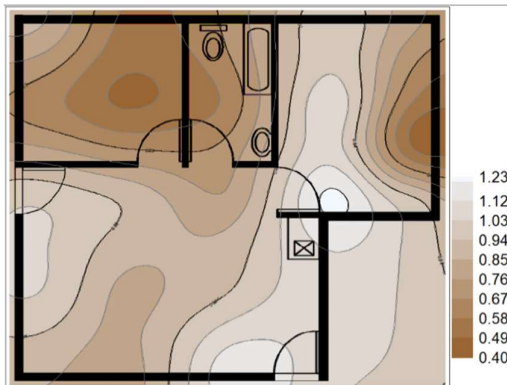
APPENDIX E - Figure 6: June Year 1 SM raft foundation movement in (mm)



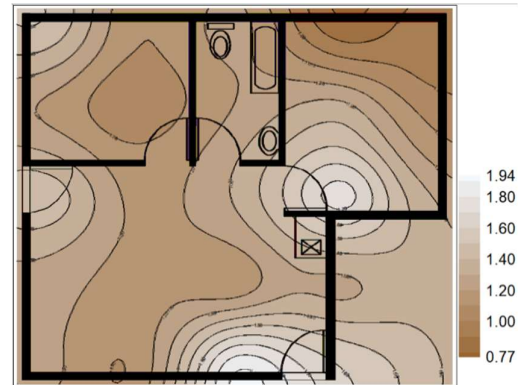
APPENDIX E - Figure 7: July Year 1 SM raft foundation movement in (mm)



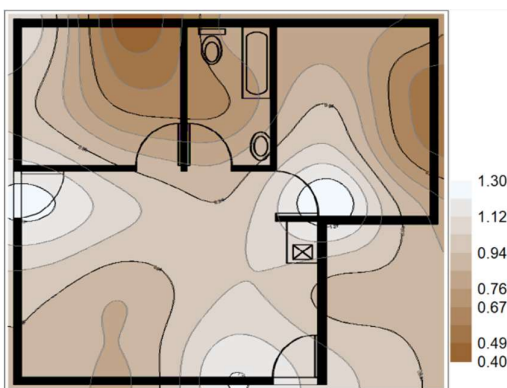
APPENDIX E - Figure 10: October Year 1 SM raft foundation movement in (mm)



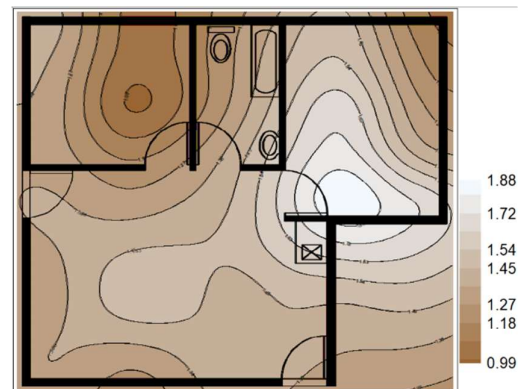
APPENDIX E - Figure 8: August Year 1 SM raft foundation movement in (mm)



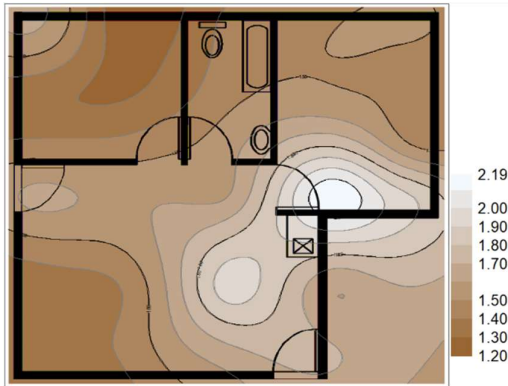
APPENDIX E - Figure 11: November Year 1 SM raft foundation movement in (mm)



APPENDIX E - Figure 9: September Year 1 SM raft foundation movement in (mm)



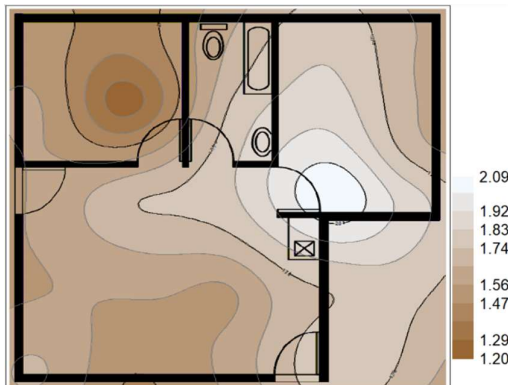
APPENDIX E - Figure 12: December Year 1 SM raft foundation movement in (mm)



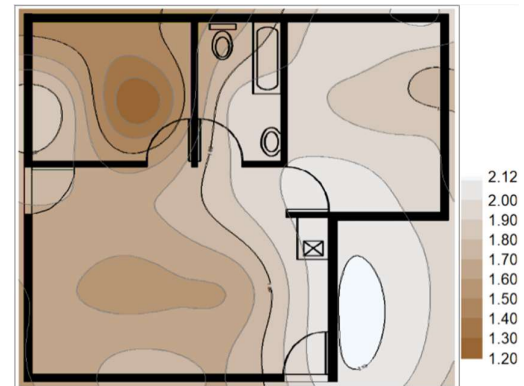
APPENDIX E - Figure 13: January Year 2 SM raft foundation movement in (mm)



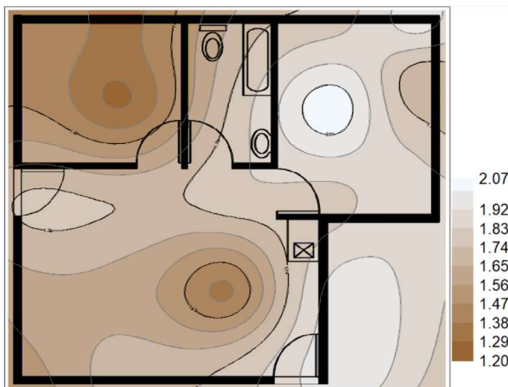
APPENDIX E - Figure 16: April Year 2 SM raft foundation movement in (mm)



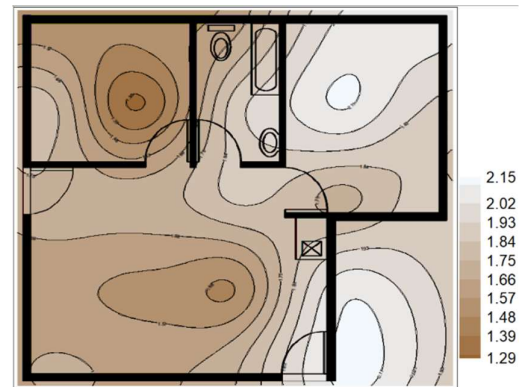
APPENDIX E - Figure 14: February Year 2 SM raft foundation movement in (mm)



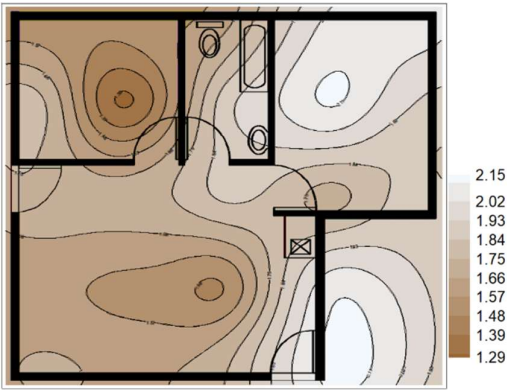
APPENDIX E - Figure 17: May Year 2 SM raft foundation movement in (mm)



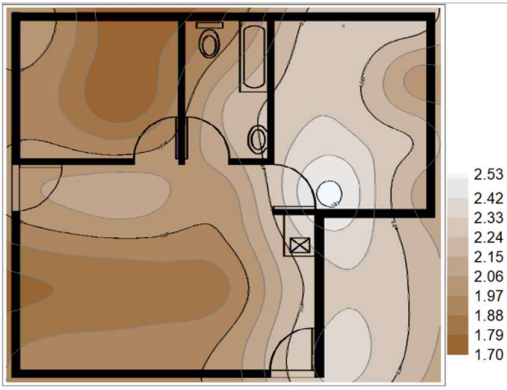
APPENDIX E - Figure 15: March Year 2 SM raft foundation movement in (mm)



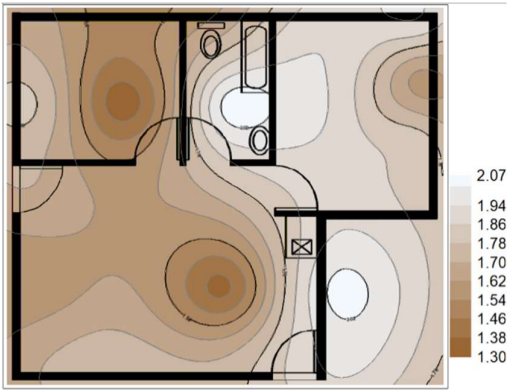
APPENDIX E - Figure 18: June Year 2 SM raft foundation movement in (mm)



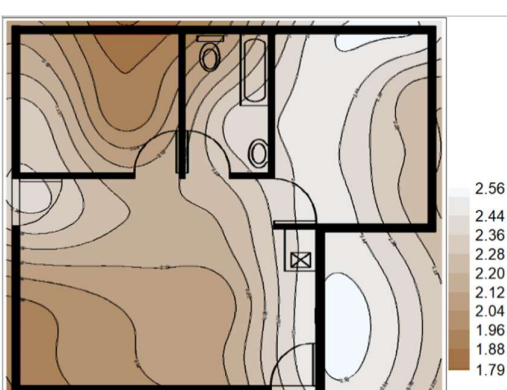
APPENDIX E - Figure 19: July Year 2 SM raft foundation movement in (mm)



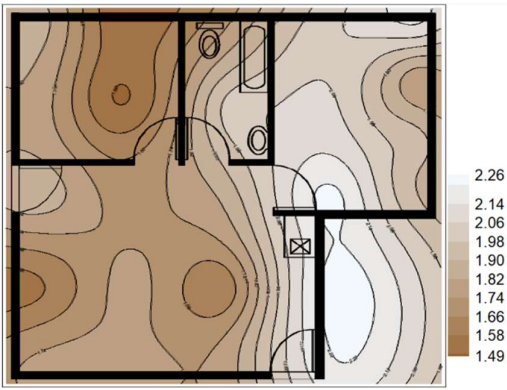
APPENDIX E - Figure 22: October Year 2 SM raft foundation movement in (mm)



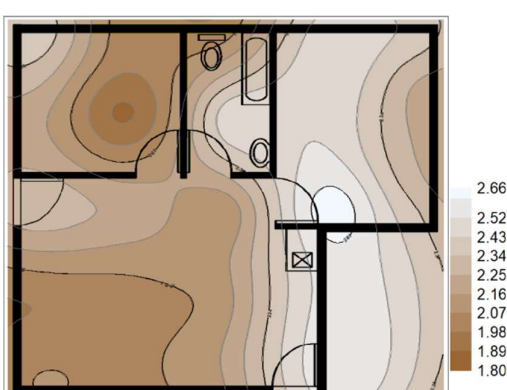
APPENDIX E - Figure 20: August Year 2 SM raft foundation movement in (mm)



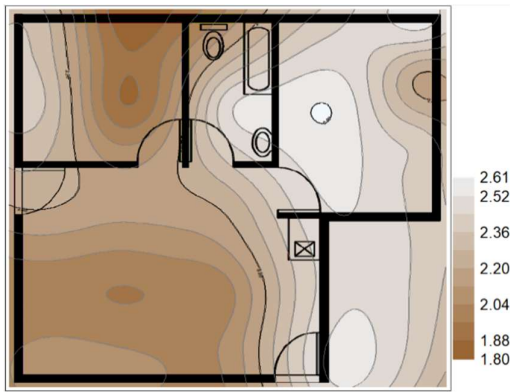
APPENDIX E - Figure 23: November Year 2 SM raft foundation movement in (mm)



APPENDIX E - Figure 21: September Year 2 SM raft foundation movement in (mm)



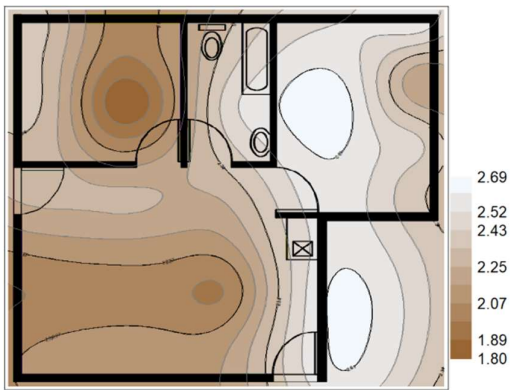
APPENDIX E - Figure 24: December Year 2 SM raft foundation movement in (mm)



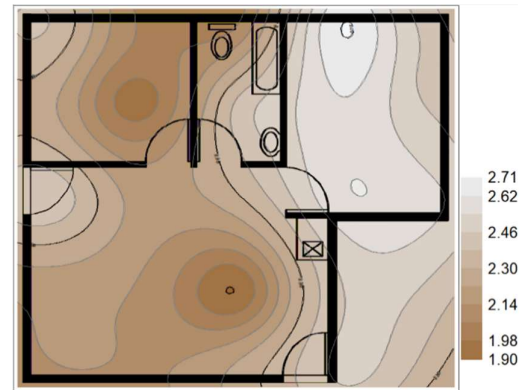
APPENDIX E - Figure 25: January Year 3 SM raft foundation movement in (mm)



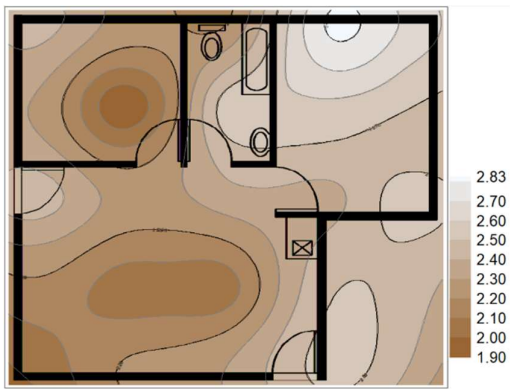
APPENDIX E - Figure 28: April Year 3 SM raft foundation movement in (mm)



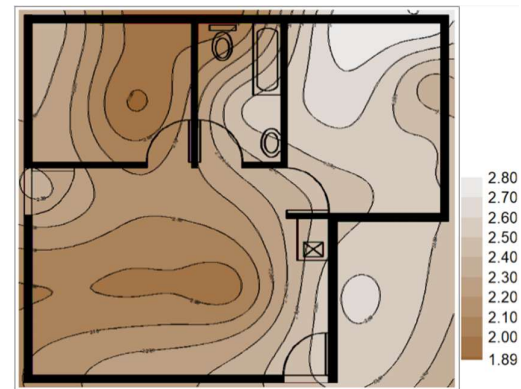
APPENDIX E - Figure 26: February Year 3 SM raft foundation movement in (mm)



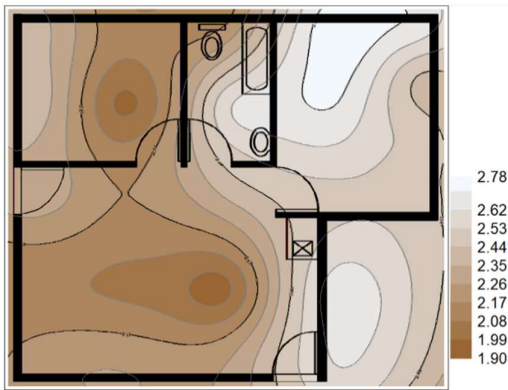
APPENDIX E - Figure 29: May Year 3 SM raft foundation movement in (mm)



APPENDIX E - Figure 27: March Year 3 SM raft foundation movement in (mm)



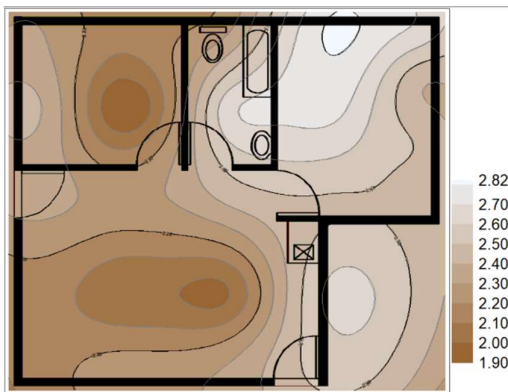
APPENDIX E - Figure 30: June Year 3 SM raft foundation movement in (mm)



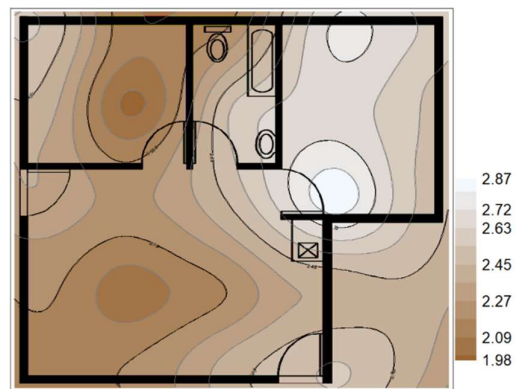
APPENDIX E - Figure 31: July Year 3 SM raft foundation movement in (mm)



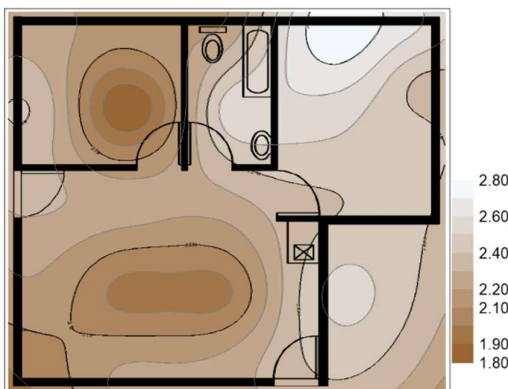
APPENDIX E - Figure 34: October Year 3 SM raft foundation movement in (mm)



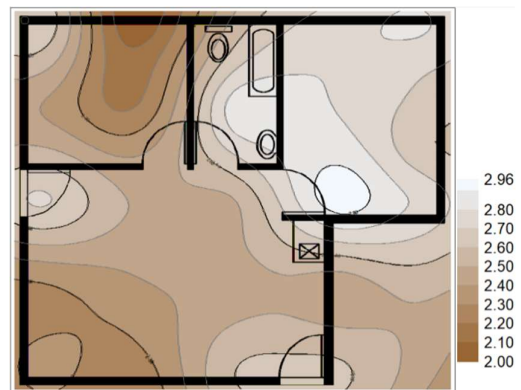
APPENDIX E - Figure 32: August Year 3 SM raft foundation movement in (mm)



APPENDIX E - Figure 35: November Year 3 SM raft foundation movement in (mm)



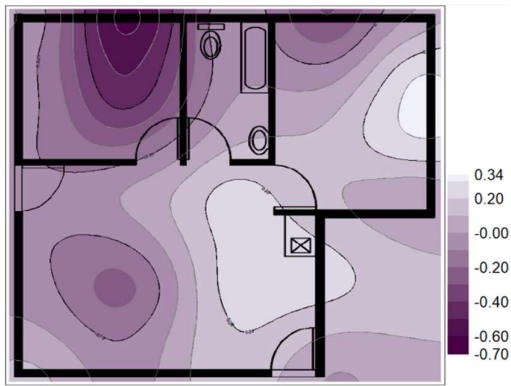
APPENDIX E - Figure 33: September Year 3 SM raft foundation movement in (mm)



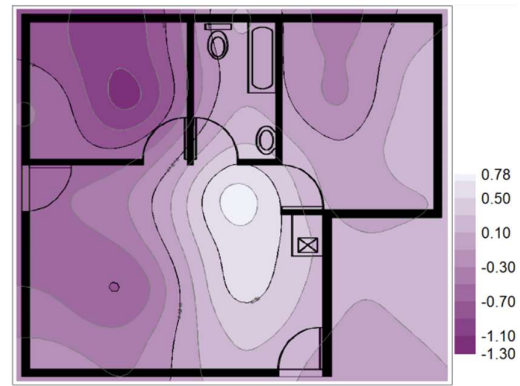
APPENDIX E - Figure 36: December Year 3 SM raft foundation movement in (mm)

APPENDIX F

The movement of the SM cavity raft foundation due to simulated seasonal changes using 3DField modelling



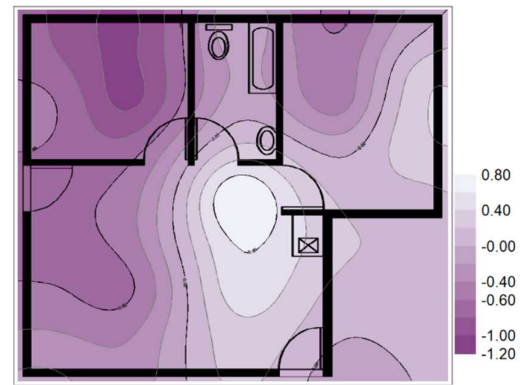
APPENDIX F - Figure 1: January Year 1 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 4: April Year 1 SM cavity raft foundation movement in (mm)



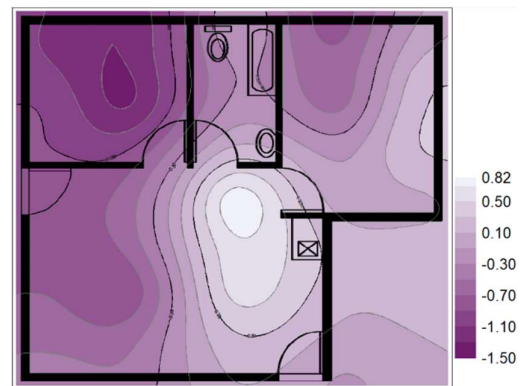
APPENDIX F - Figure 2: February Year 1 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 5: May Year 1 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 3: March Year 1 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 6: June Year 1 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 7: July Year 1
SM cavity raft foundation movement
in (mm)



APPENDIX F - Figure 10: October
Year 1 SM cavity raft foundation
movement in (mm)



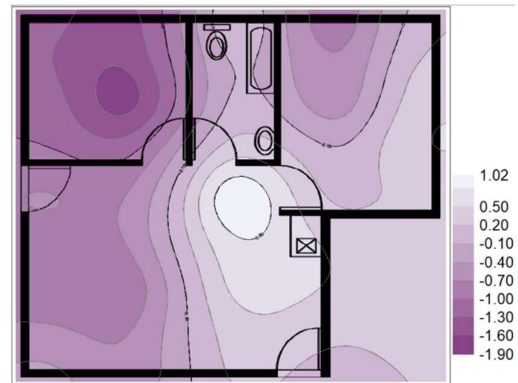
APPENDIX F - Figure 8: August Year 1
SM cavity raft foundation movement
in (mm)



APPENDIX F - Figure 11: November
Year 1 SM cavity raft foundation
movement in (mm)



APPENDIX F - Figure 9: September
Year 1 SM cavity raft foundation
movement in (mm)



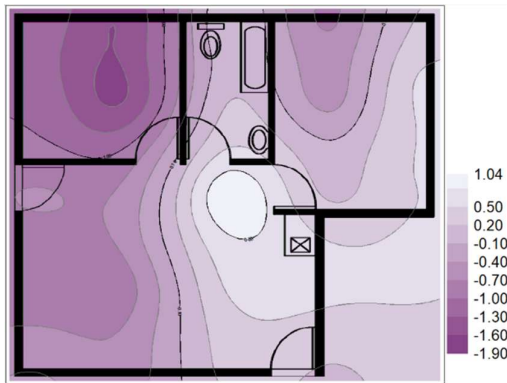
APPENDIX F - Figure 12: December
Year 1 SM cavity raft foundation
movement in (mm)



APPENDIX F - Figure 13: January Year 2 SM cavity raft foundation movement in (mm)



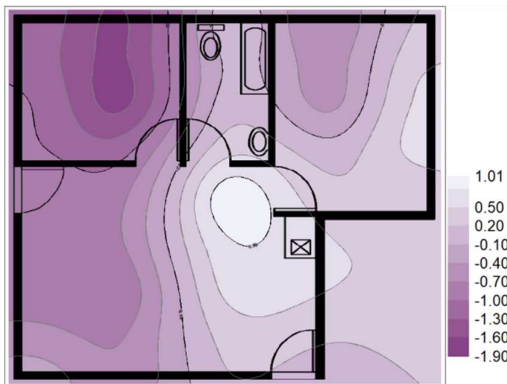
APPENDIX F - Figure 16: April Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 14: February Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 17: May Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 15: March Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 18: June Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 19: July Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 22: October Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 20: August Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 23: November Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 21: September Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 24: December Year 2 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 25: January Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 28: April Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 26: February Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 29: May Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 27: March Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 30: June Year 3 SM cavity raft foundation movement in (mm)



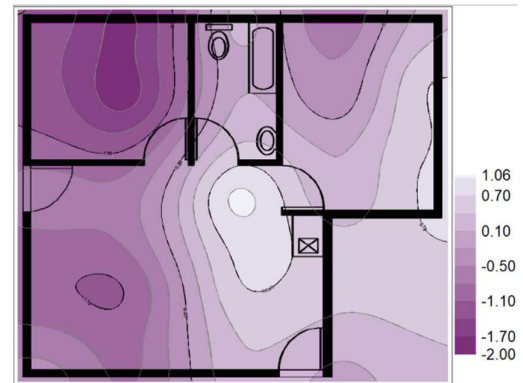
APPENDIX F - Figure 31: July Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 34: October Year 3 SM cavity raft foundation movement in (mm))



APPENDIX F - Figure 32: August Year 3 SM cavity raft foundation movement in (mm)



APPENDIX F - Figure 35: November Year 3 SM cavity raft foundation movement in (mm))



APPENDIX F - Figure 33: September Year 3 SM cavity raft foundation movement in (mm)

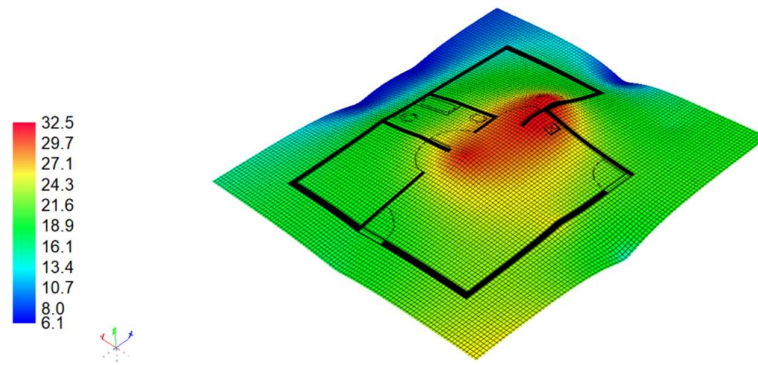


APPENDIX F - Figure 36: December Year 3 SM cavity raft foundation movement in (mm)

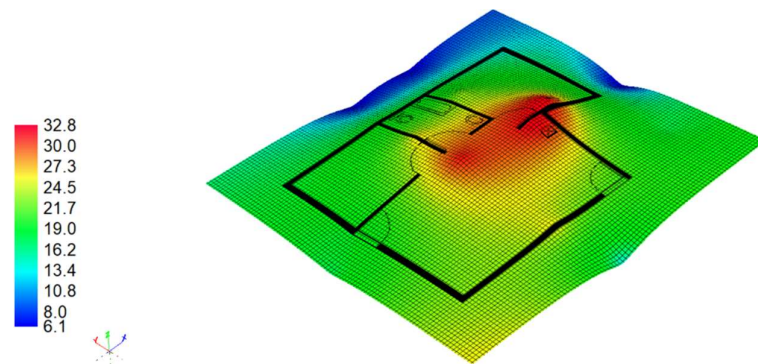
APPENDIX G

Heat Maps of Raft and Cavity Raft Foundations.

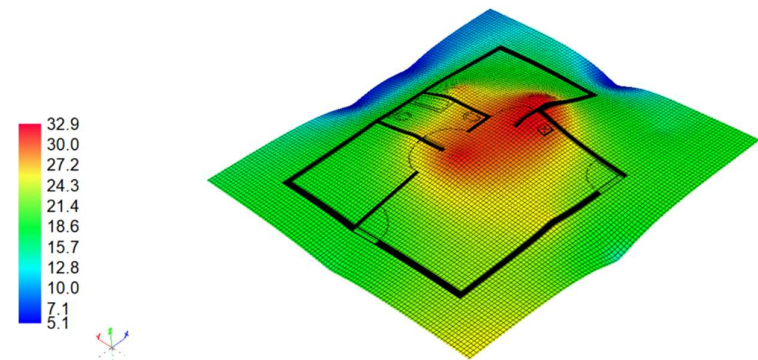
APPENDIX G includes 3D heat maps showing moisture content (MC%) and movement patterns for the SM Raft and SM Cavity Raft Foundations over three simulated years for the simulated months of March, June, September and December. Each map is oriented from the southwest corner, providing a visual reference for analysing seasonal and structural performance variations.



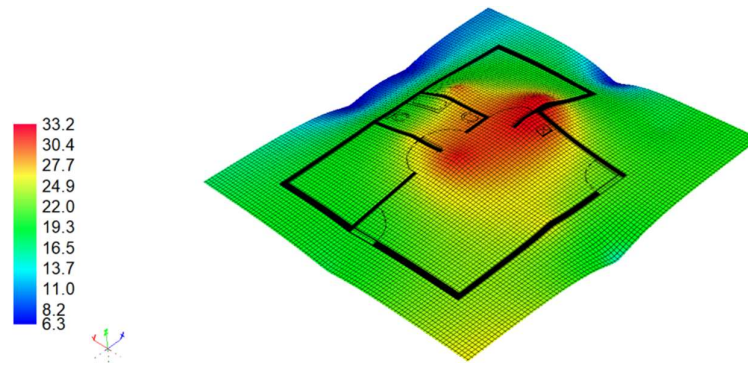
APPENDIX G: Year 1 – March: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



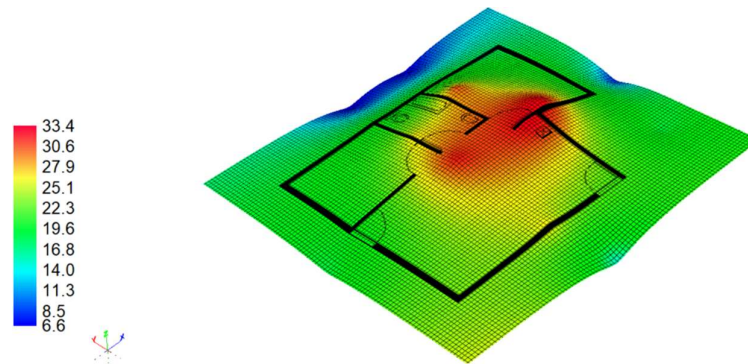
APPENDIX G: Year 1 – June: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



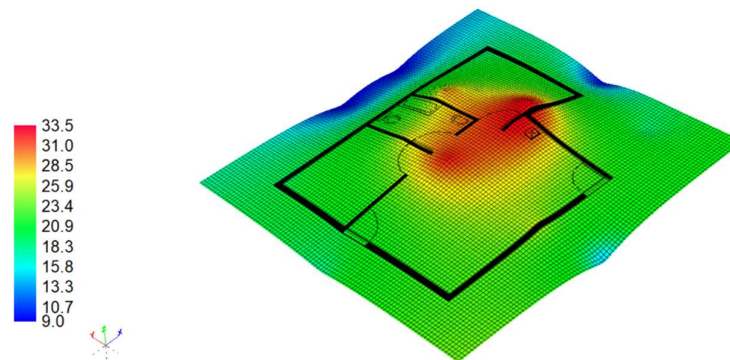
APPENDIX G: Year 1 – September: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



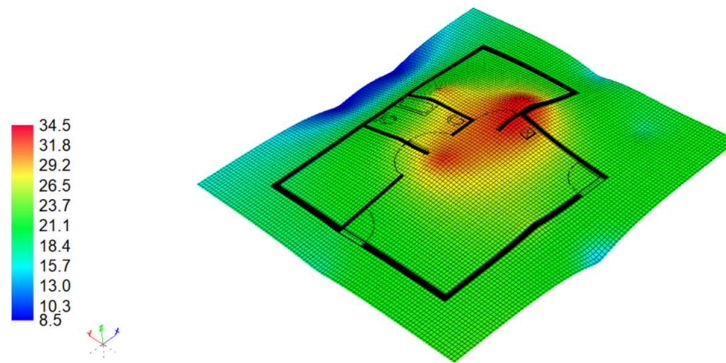
APPENDIX G: Year 1 – December: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



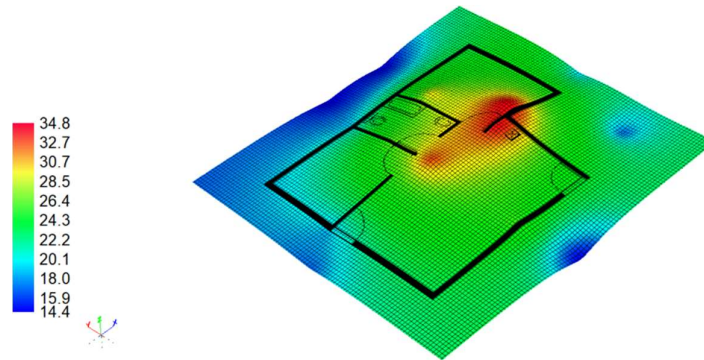
APPENDIX G: Year 2 – March: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



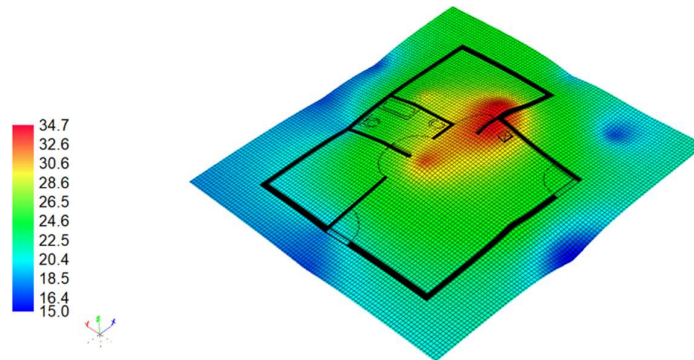
APPENDIX G: Year 2 – June: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



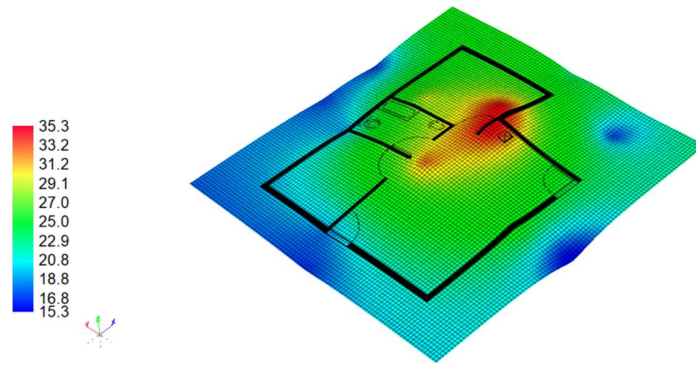
APPENDIX G: Year 2 – September: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



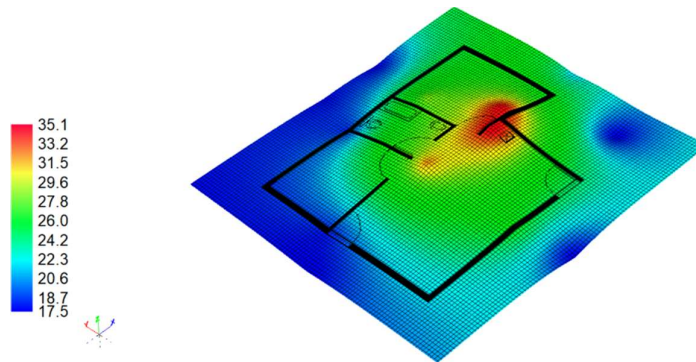
APPENDIX G: Year 2 – December: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



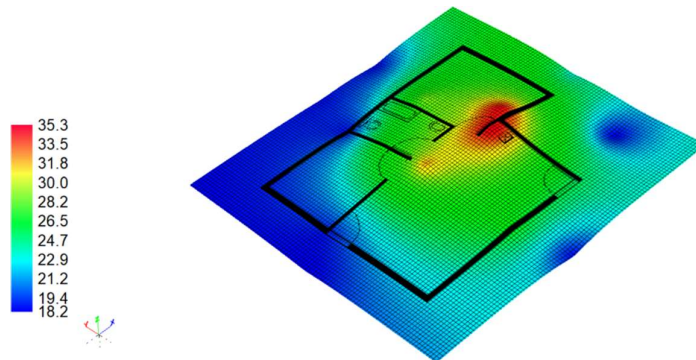
APPENDIX G: Year 3 – March: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



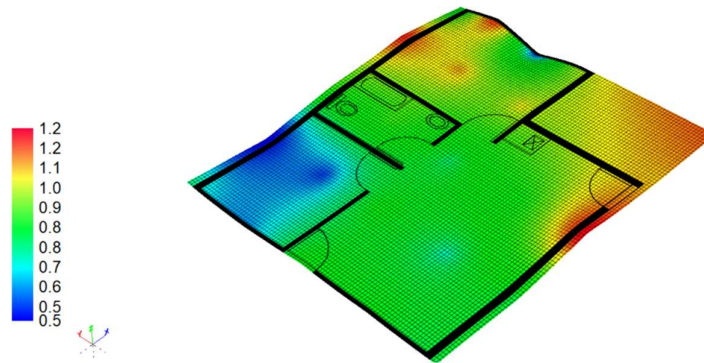
APPENDIX G: Year 3 – June: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



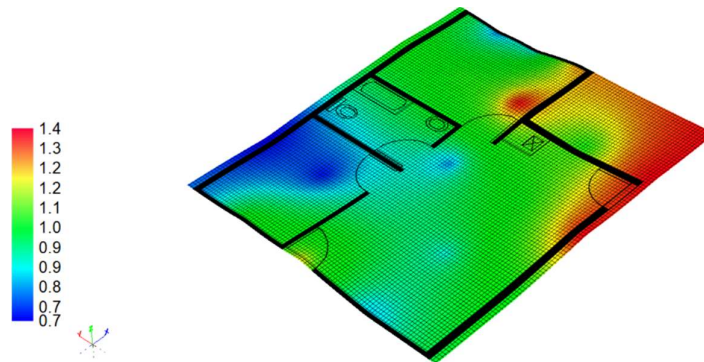
APPENDIX G: Year 3 – September: 3D moisture content (MC%) heat map of the Raft Foundation, orientation from the Southwest corner.



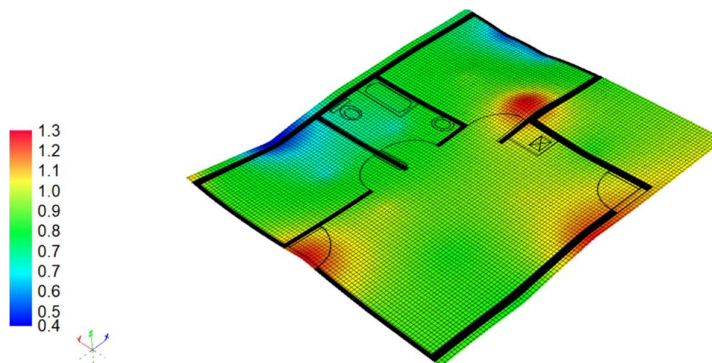
APPENDIX G: Year 3 – December: 3D moisture content (MC%) heat map of the SM Raft Foundation, orientation from the Southwest corner.



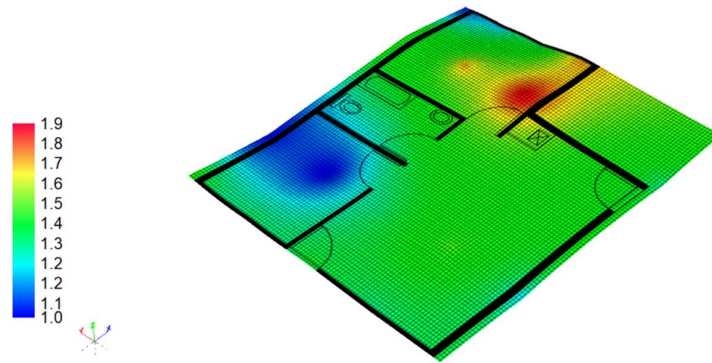
APPENDIX G: Year 1 – March: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



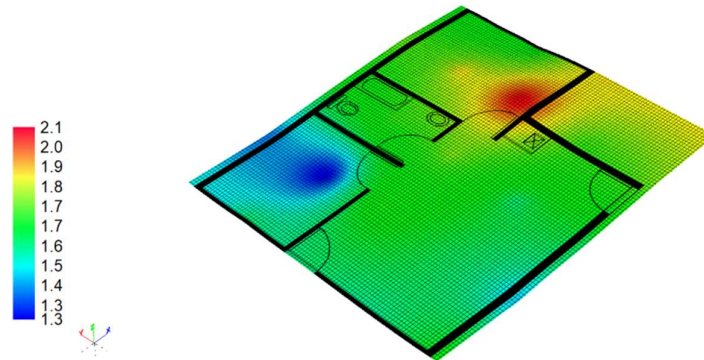
APPENDIX G: Year 1 – June: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



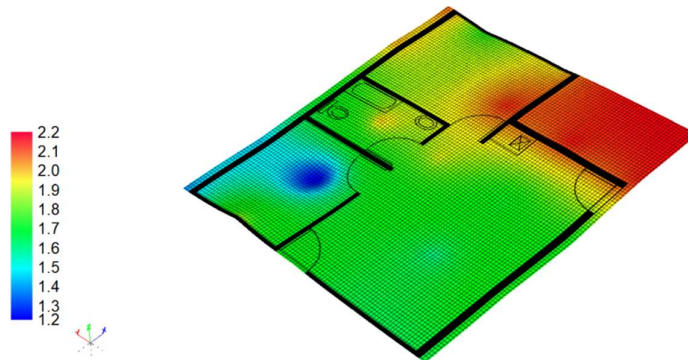
APPENDIX G: Year 1 – September: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



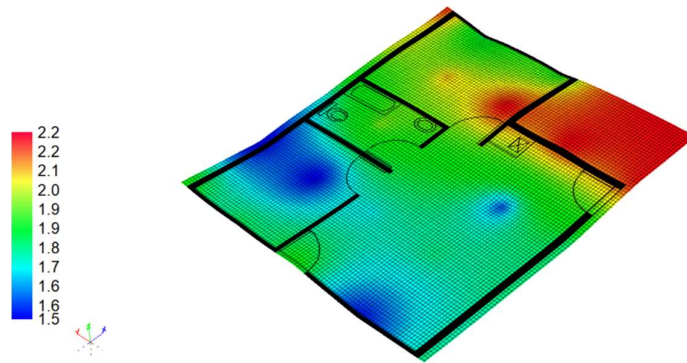
APPENDIX G: Year 1 – December: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



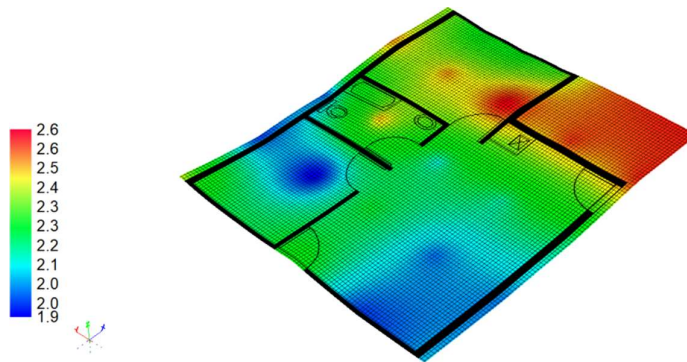
APPENDIX G: Year 2 – March: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



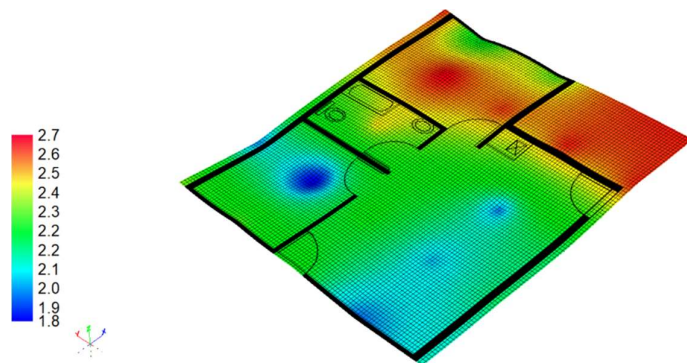
APPENDIX G: Year 2 – June: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



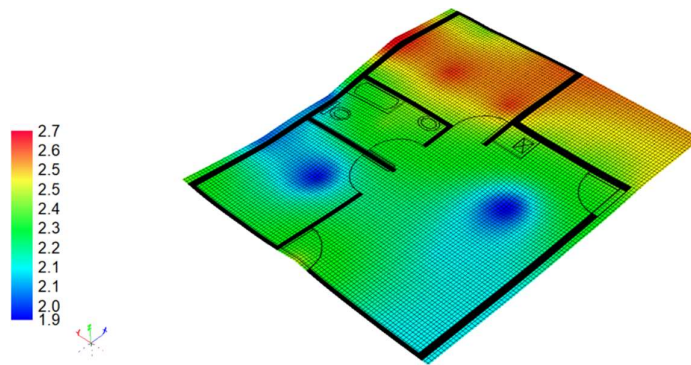
APPENDIX G: Year 2 – September: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



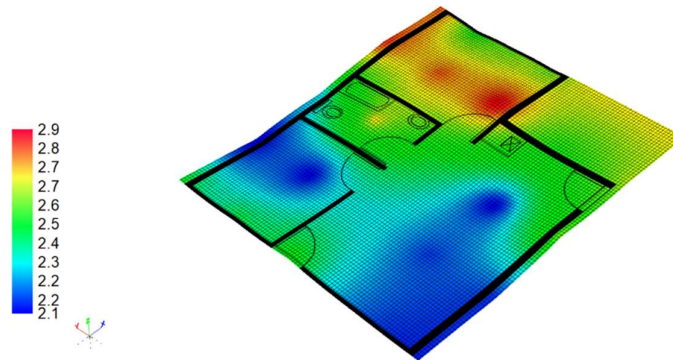
APPENDIX G: Year 2 – December: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



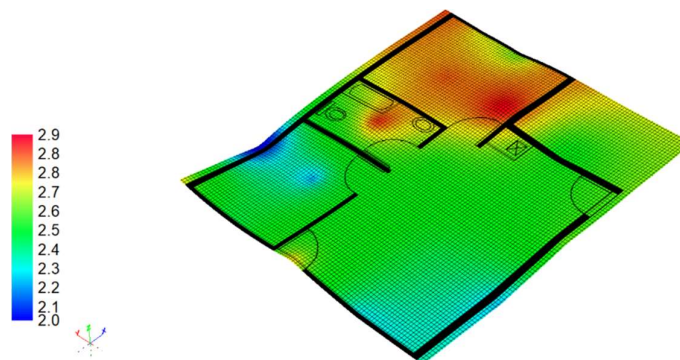
APPENDIX G: Year 3 – March: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



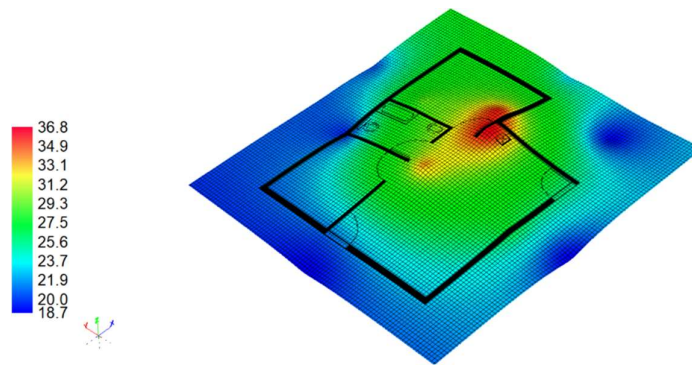
APPENDIX G: Year 3 – June: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



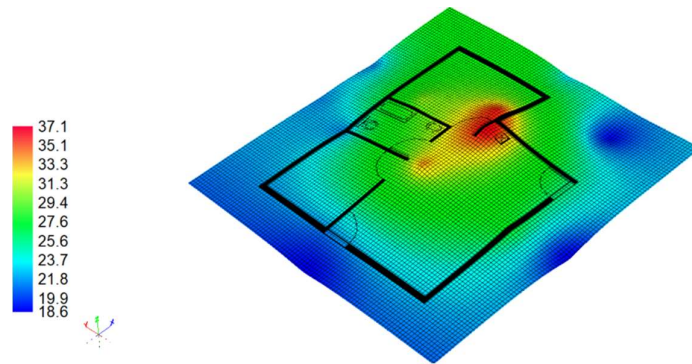
APPENDIX G: Year 3 – September: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



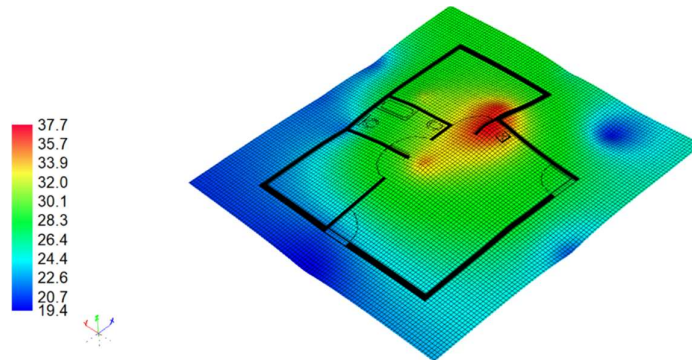
APPENDIX G: Year 3 – December: 3D movement heat map of the SM Raft Foundation, orientation from the Southwest corner.



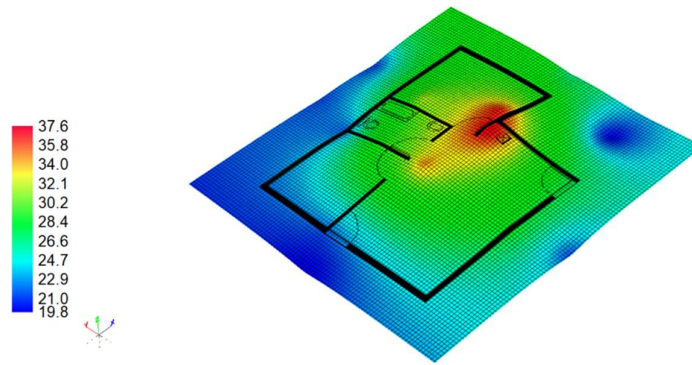
APPENDIX G: Year 1 – March: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



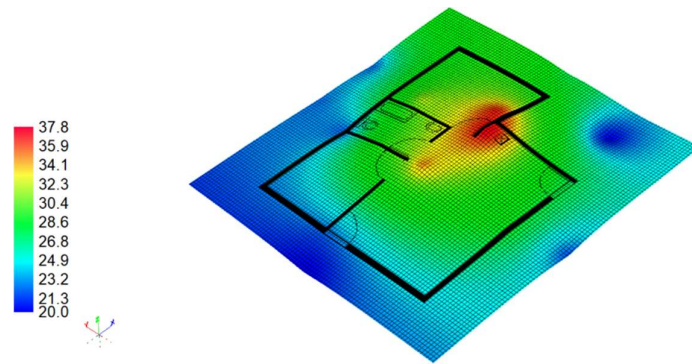
APPENDIX G: Year 1 – June: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



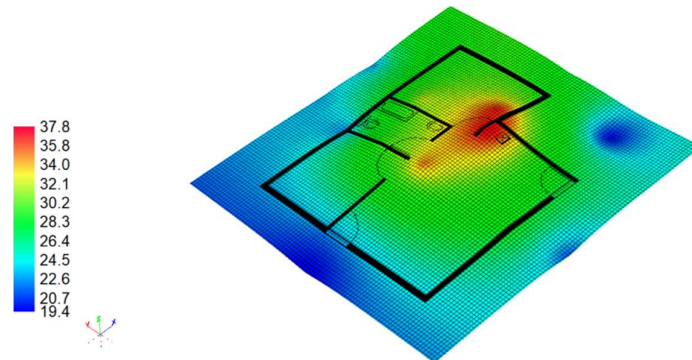
APPENDIX G: Year 1 – September: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



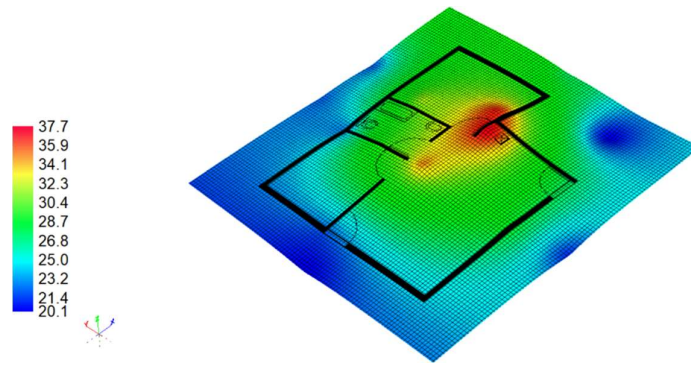
APPENDIX G: Year 1 – December: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



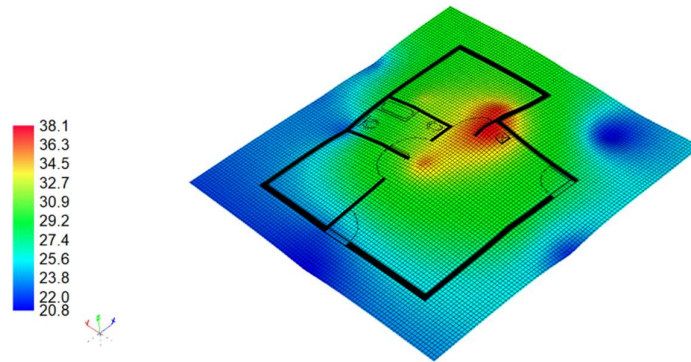
APPENDIX G: Year 2 – March: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



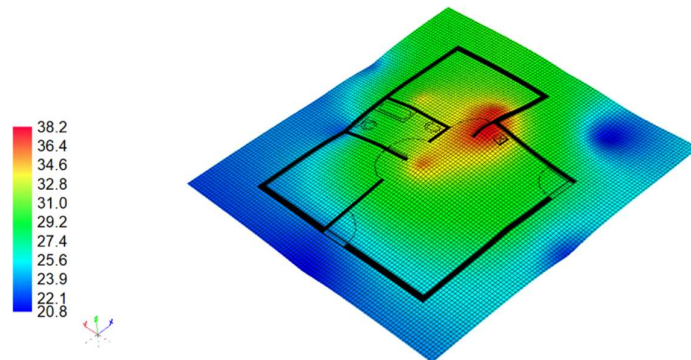
APPENDIX G: Year 2 – June: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



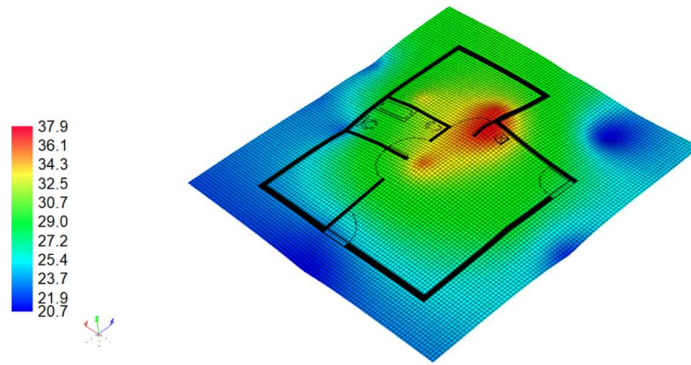
APPENDIX G: Year 2 – September: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



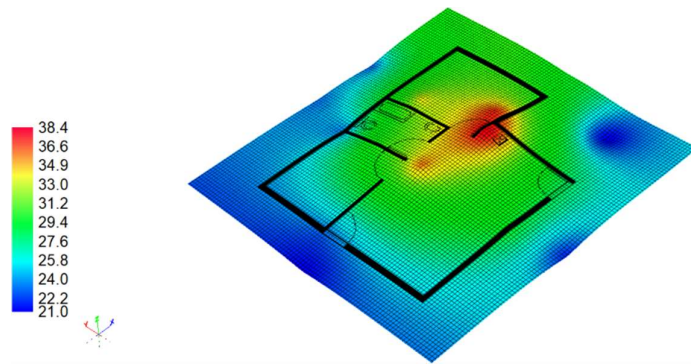
APPENDIX G: Year 2 – December: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



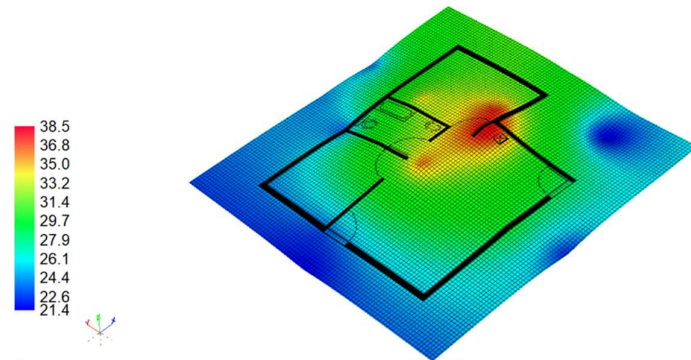
APPENDIX G: Year 3 – March: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



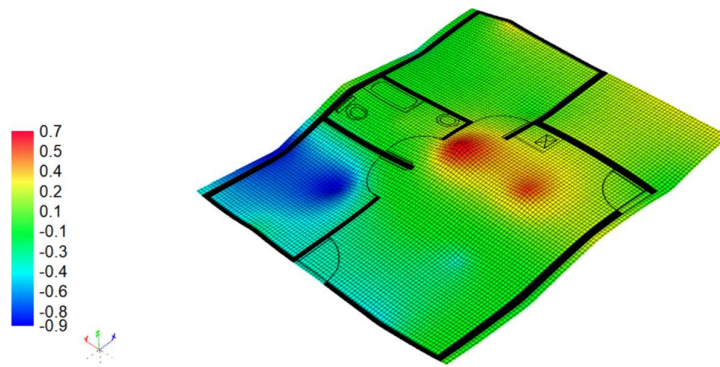
APPENDIX G: Year 3 – June: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



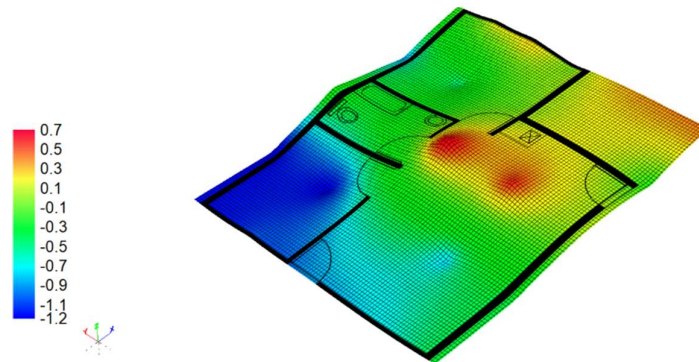
APPENDIX G: Year 3 – September: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



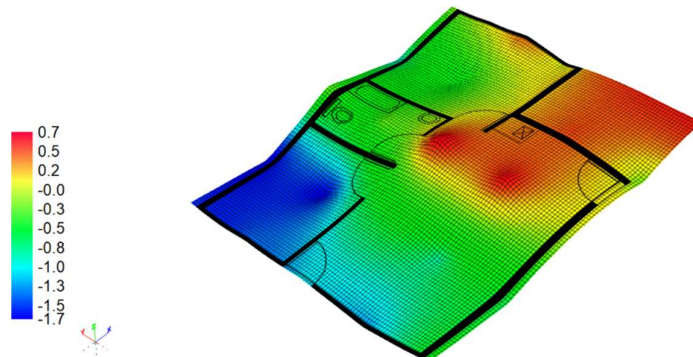
APPENDIX G: Year 3 – December: 3D moisture content (MC%) heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



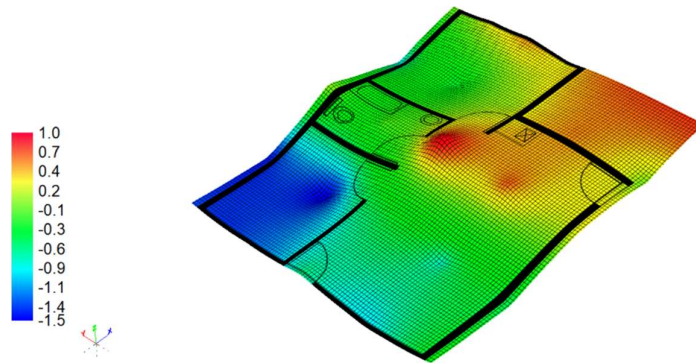
APPENDIX G: Year 1 – March: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



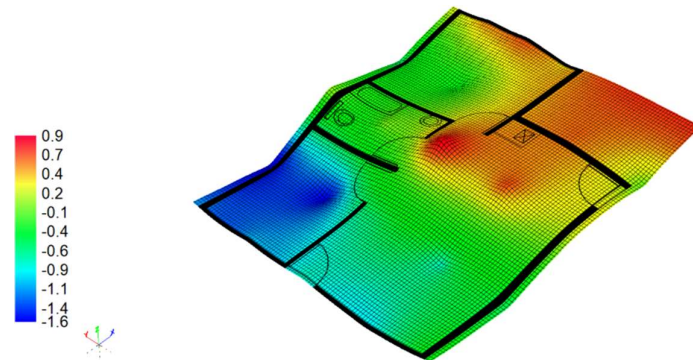
APPENDIX G: Year 1 – June: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



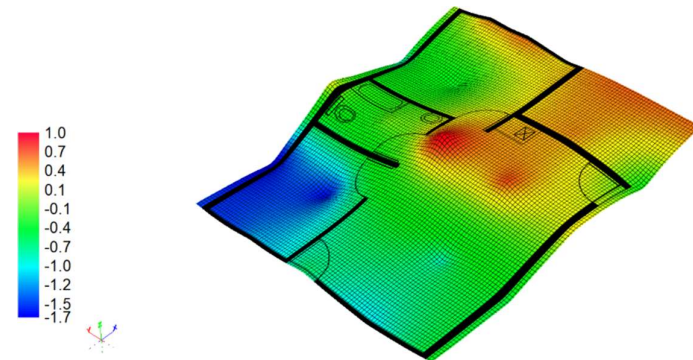
APPENDIX G: Year 1 – September: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



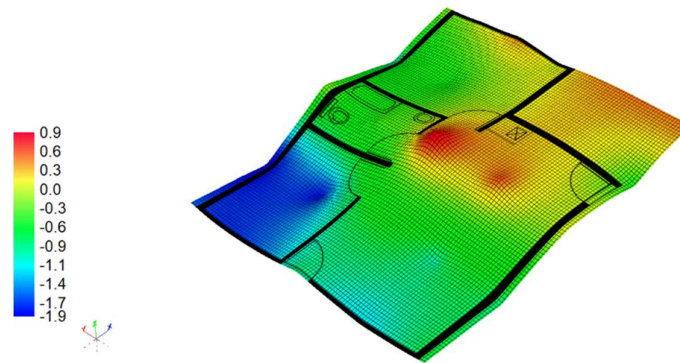
APPENDIX G: Year 1 – December: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



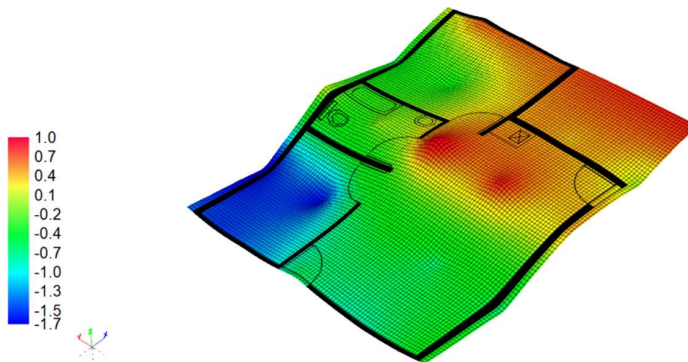
APPENDIX G: Year 2 – March: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



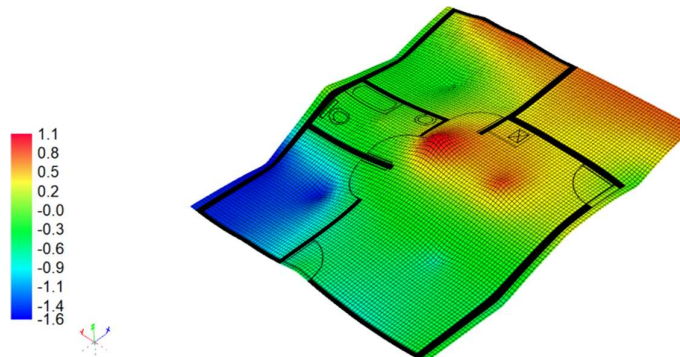
APPENDIX G: Year 2 – June: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



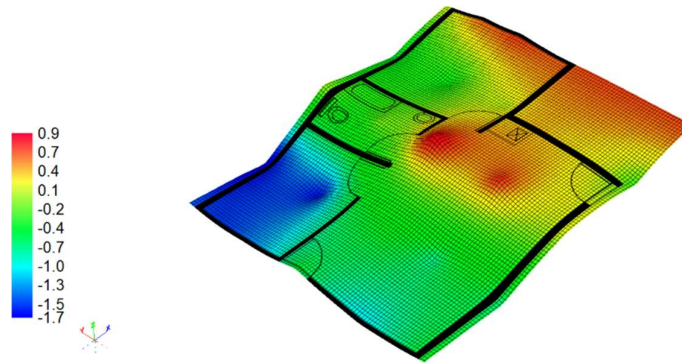
APPENDIX G: Year 2 – September: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



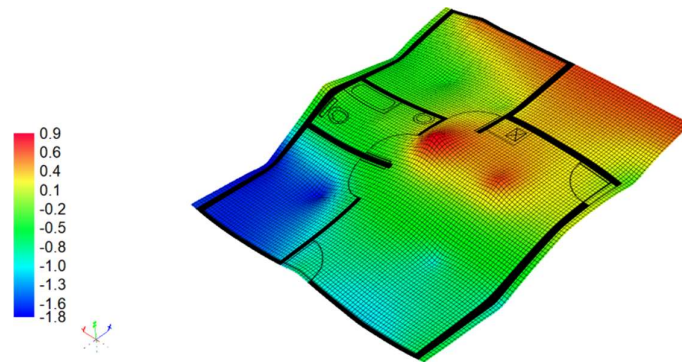
APPENDIX G: Year 2 – December: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



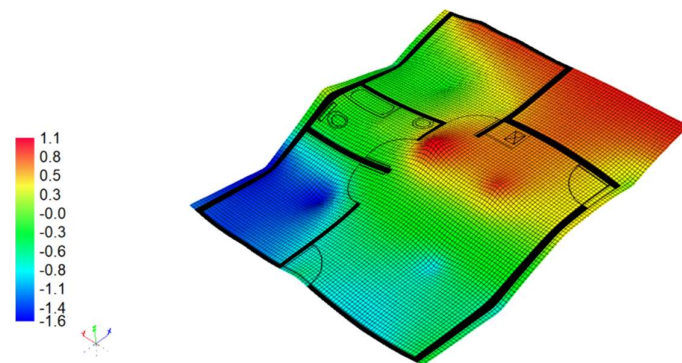
APPENDIX G: Year 3 – March: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



APPENDIX G: Year 3 – June: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



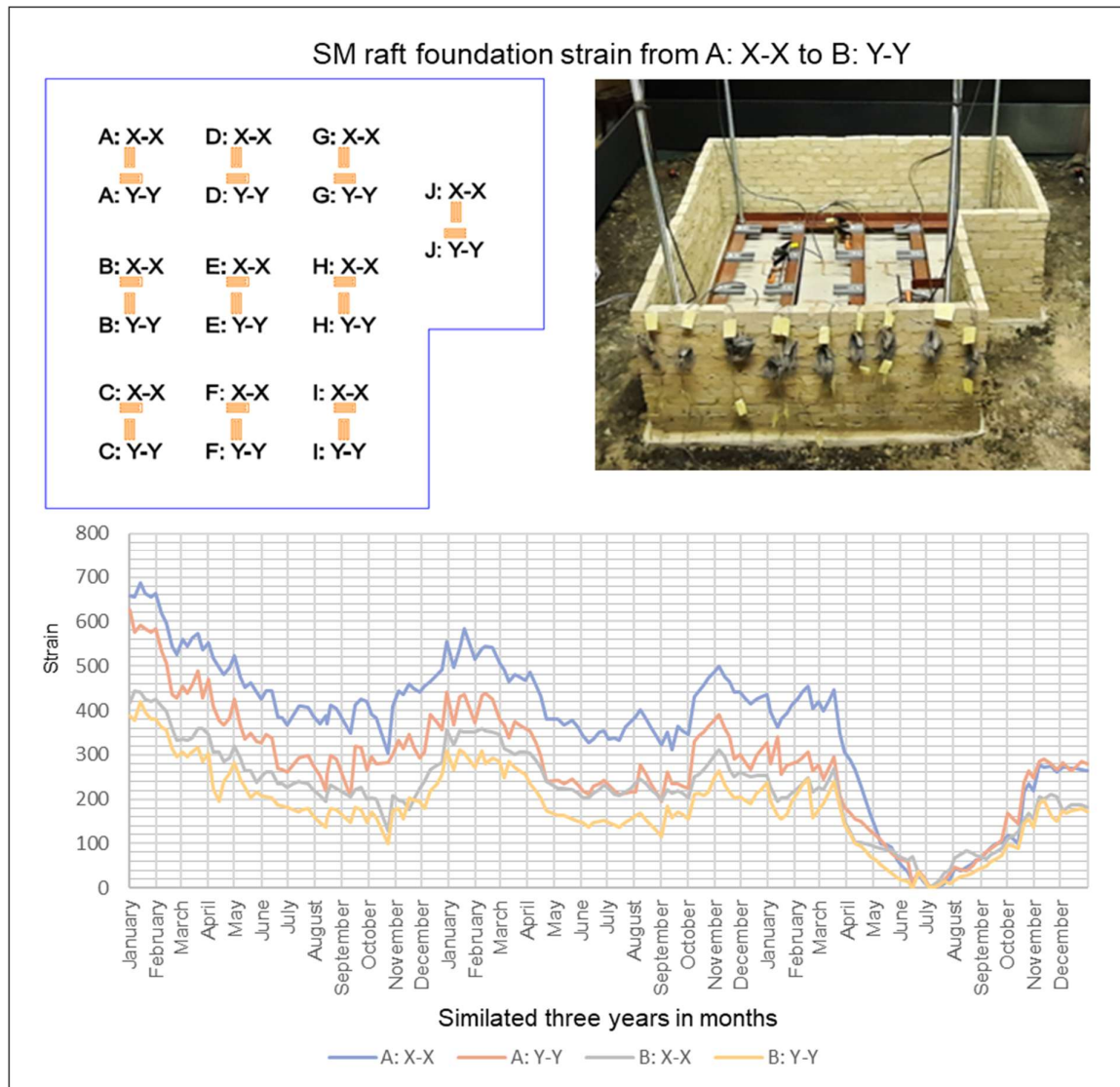
APPENDIX G: Year 3 – September: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.



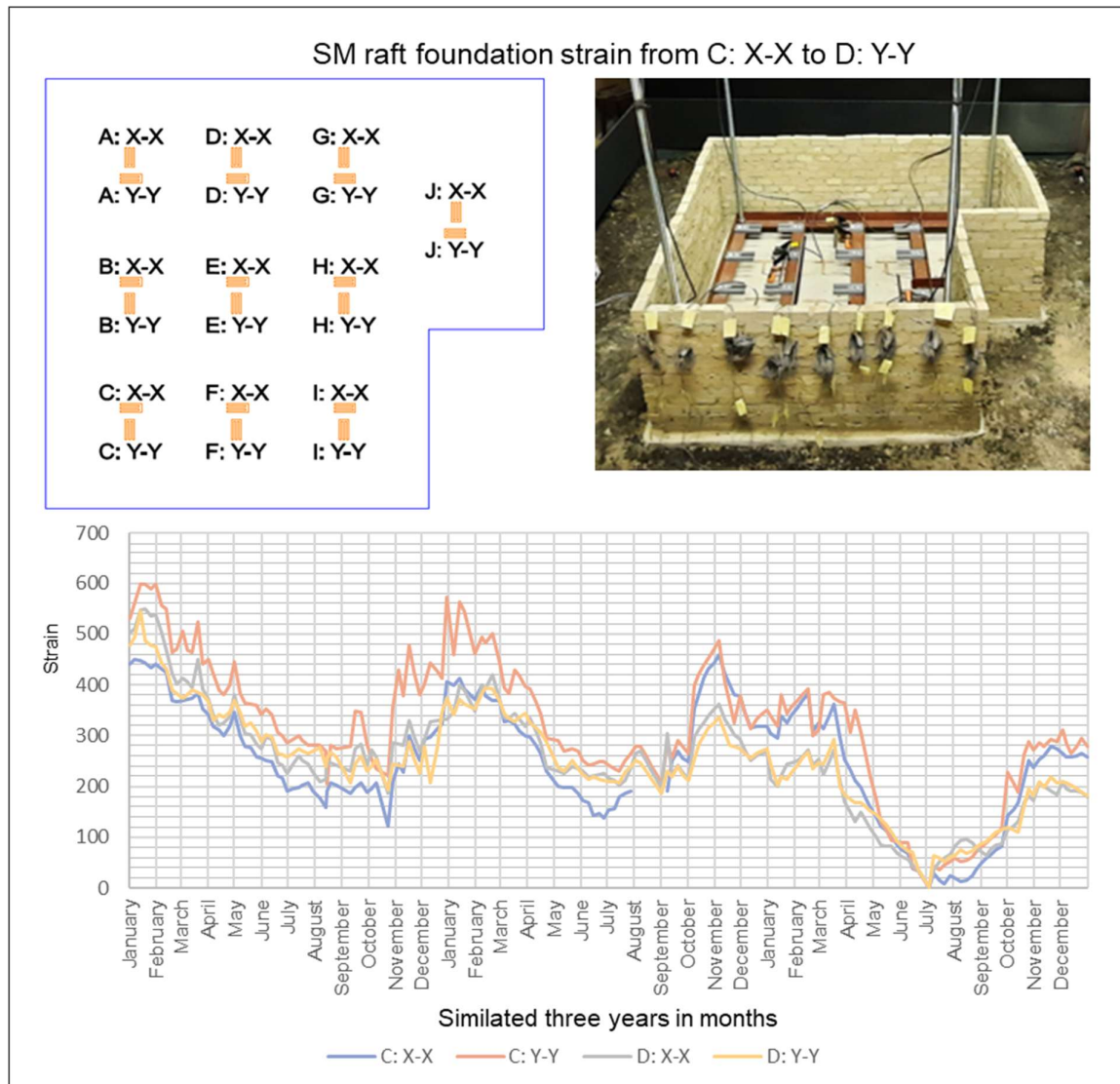
APPENDIX G: Year 3 – December: 3D movement heat map of the SM Cavity Raft Foundation, orientation from the Southwest corner.

APPENDIX H

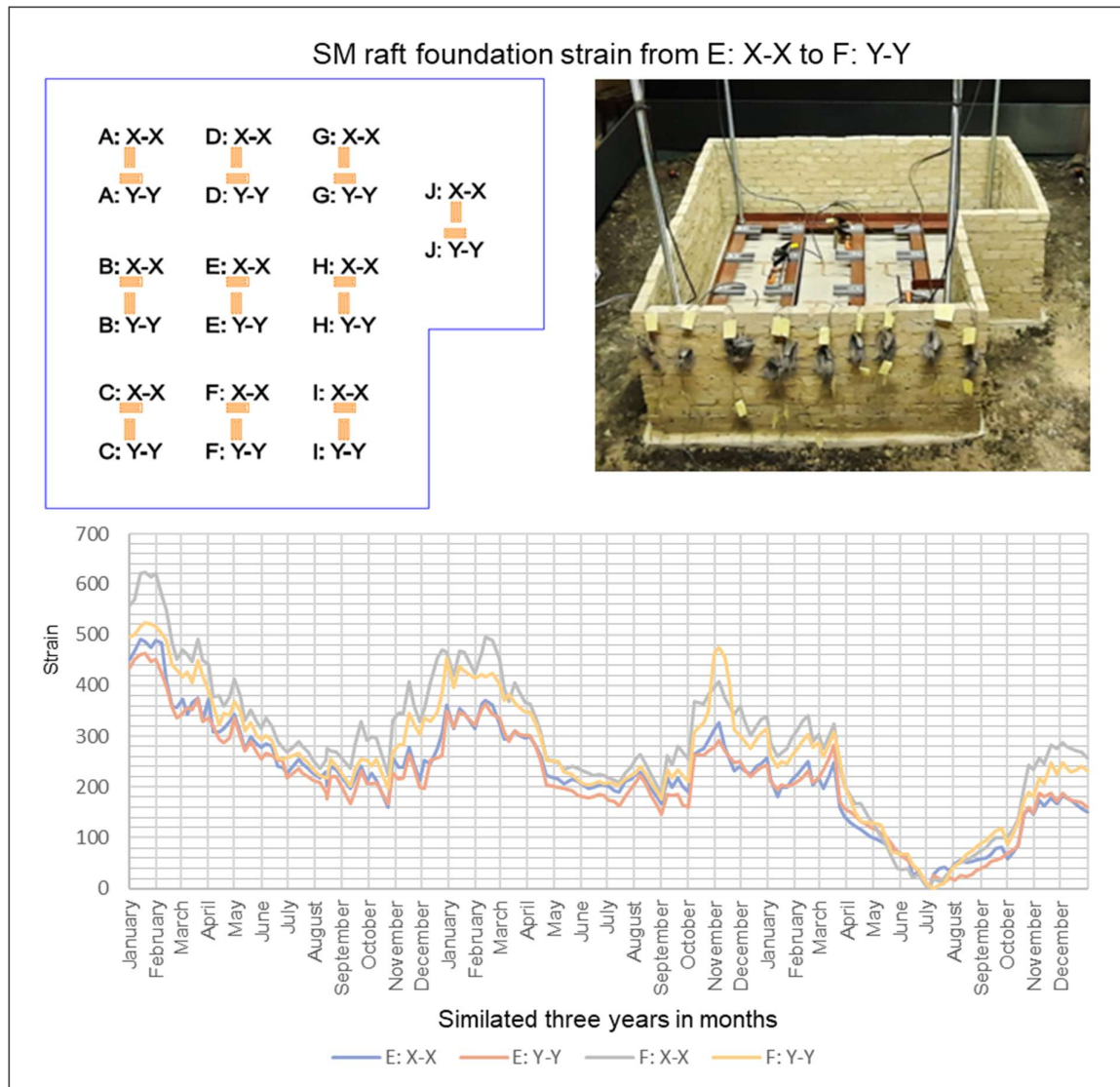
Simplified strain data for the SM raft foundation.



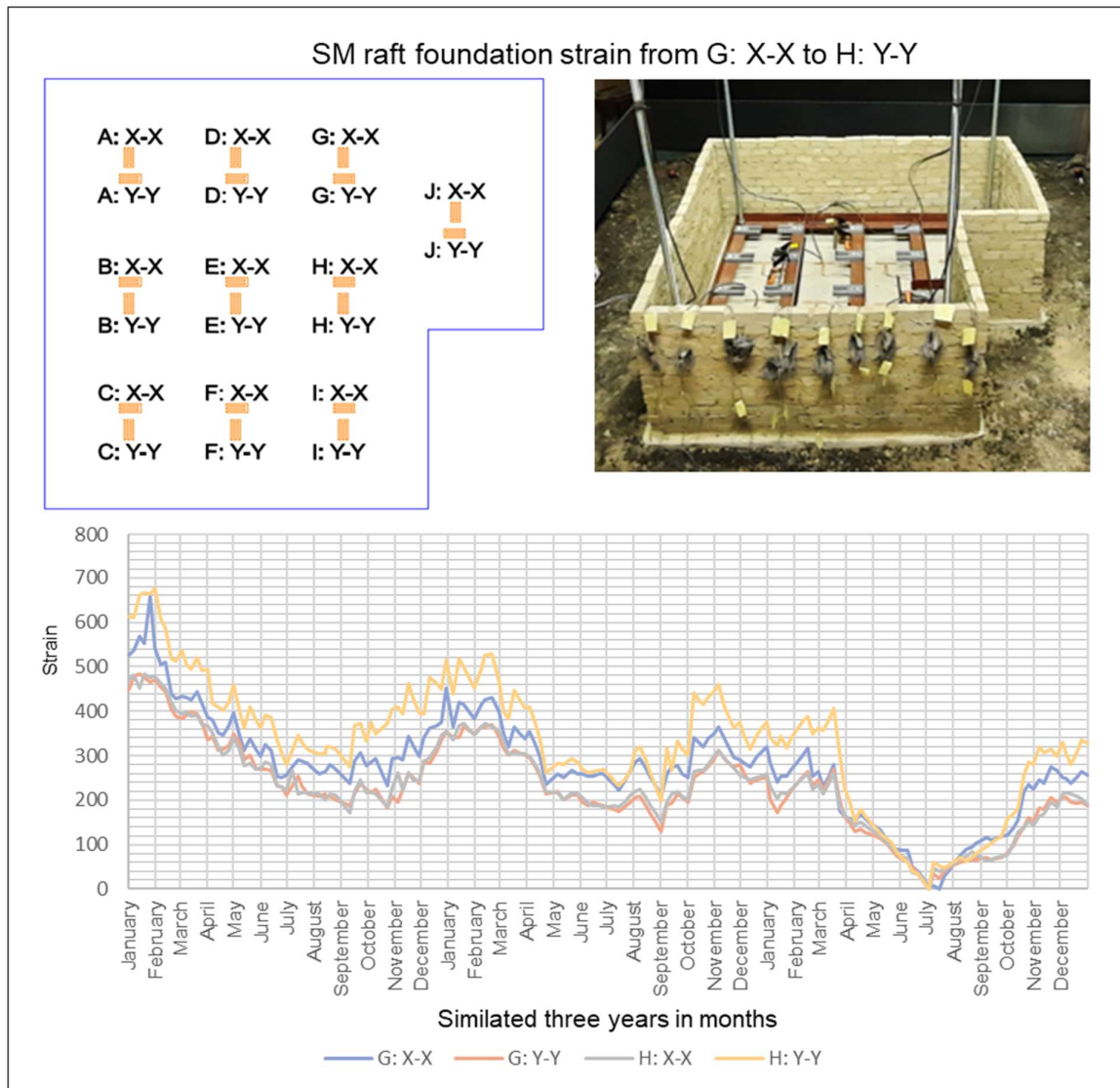
APPENDIX H - Figure 1: SM raft foundation strain from A: X-X to B: Y-Y



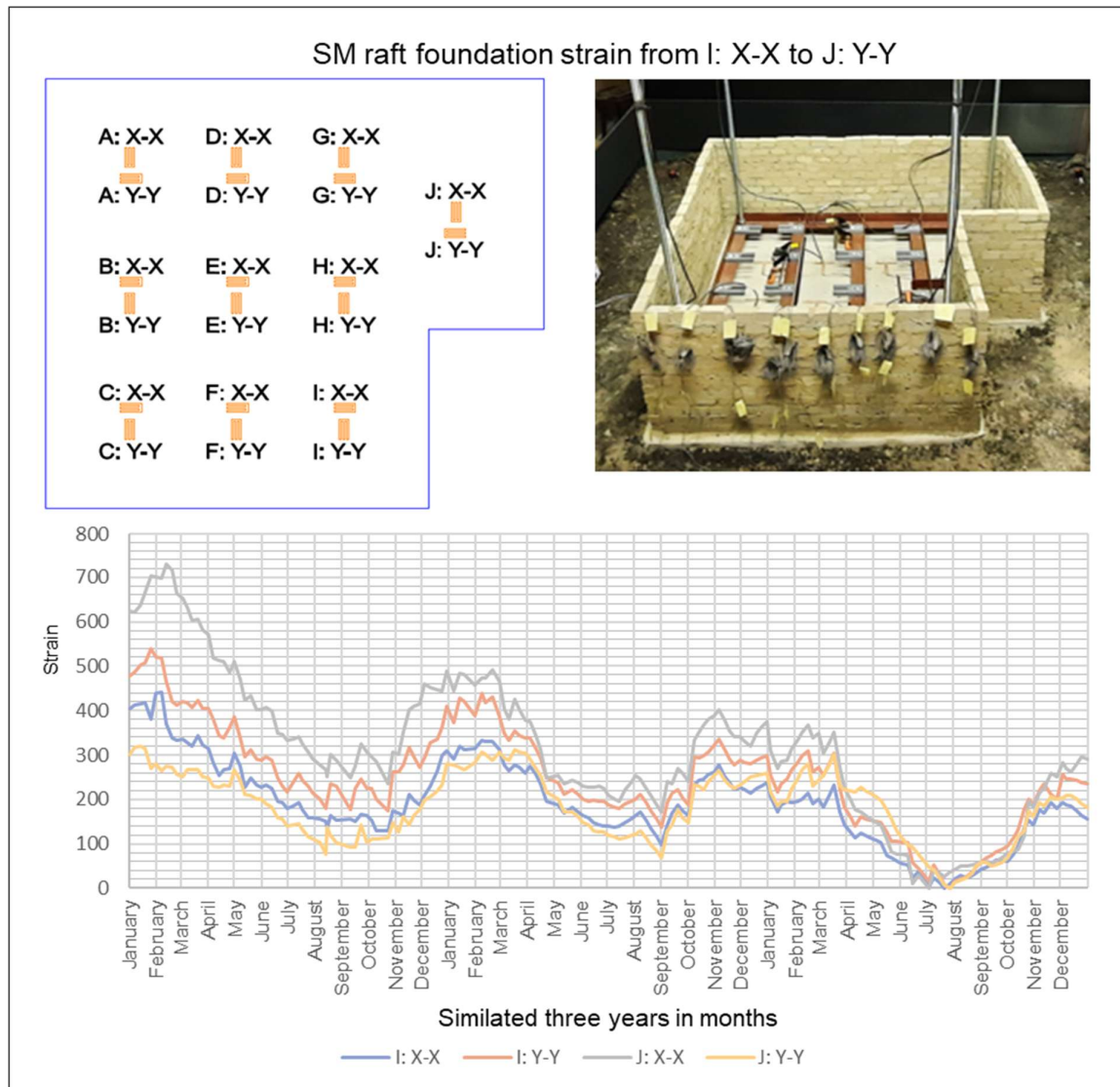
APPENDIX H - Figure 2: SM raft foundation strain from C: X-X to D: Y-Y



APPENDIX H - Figure 3: SM raft foundation strain from E: X-X to F: Y-Y



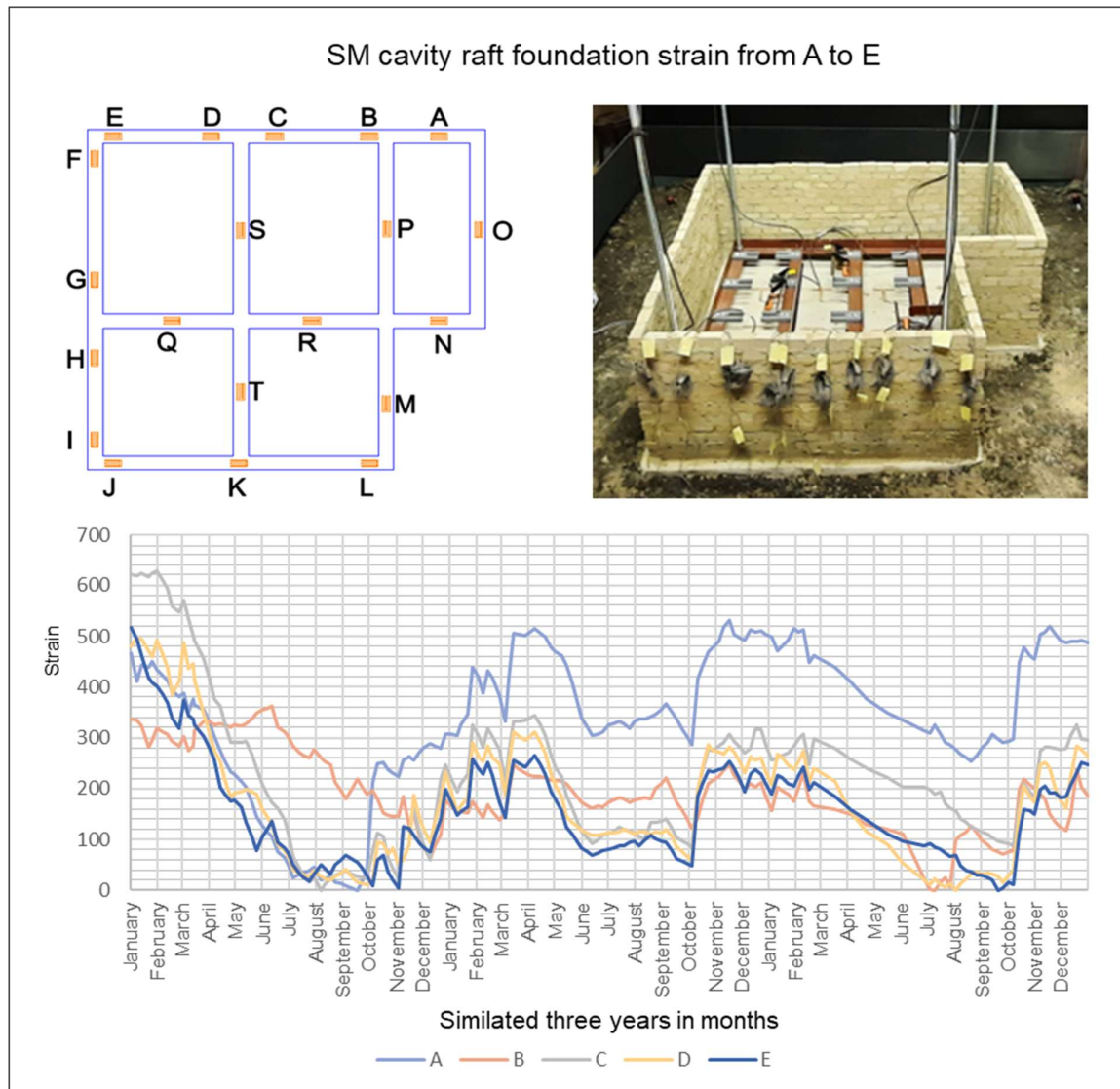
APPENDIX H - Figure 4: SM raft foundation strain from G: X-X to H: Y-Y



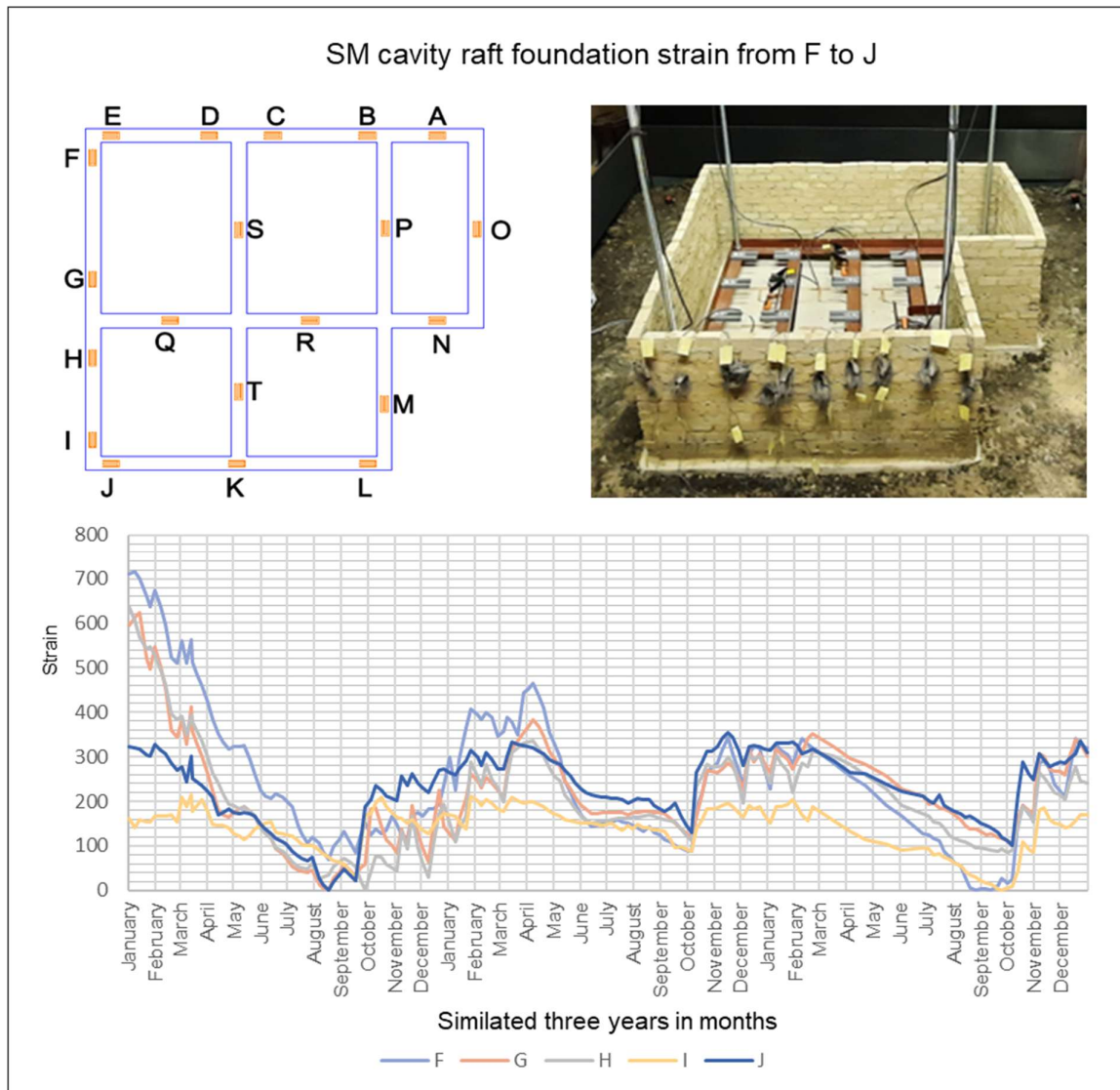
APPENDIX H - Figure 5: SM raft foundation strain from I: X-X to J: Y-Y

APPENDIX I

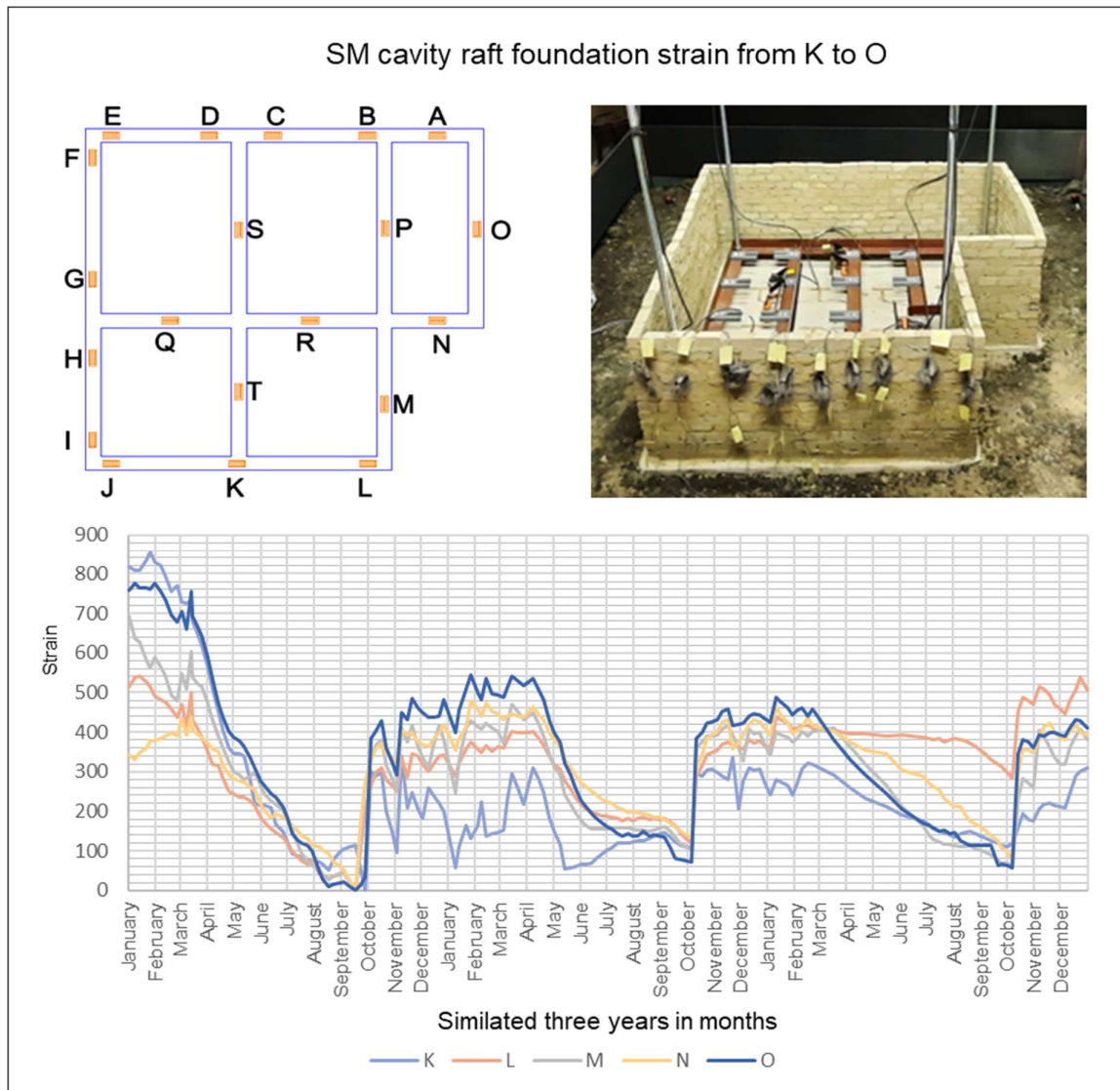
Simplified strain data for SM cavity raft foundation



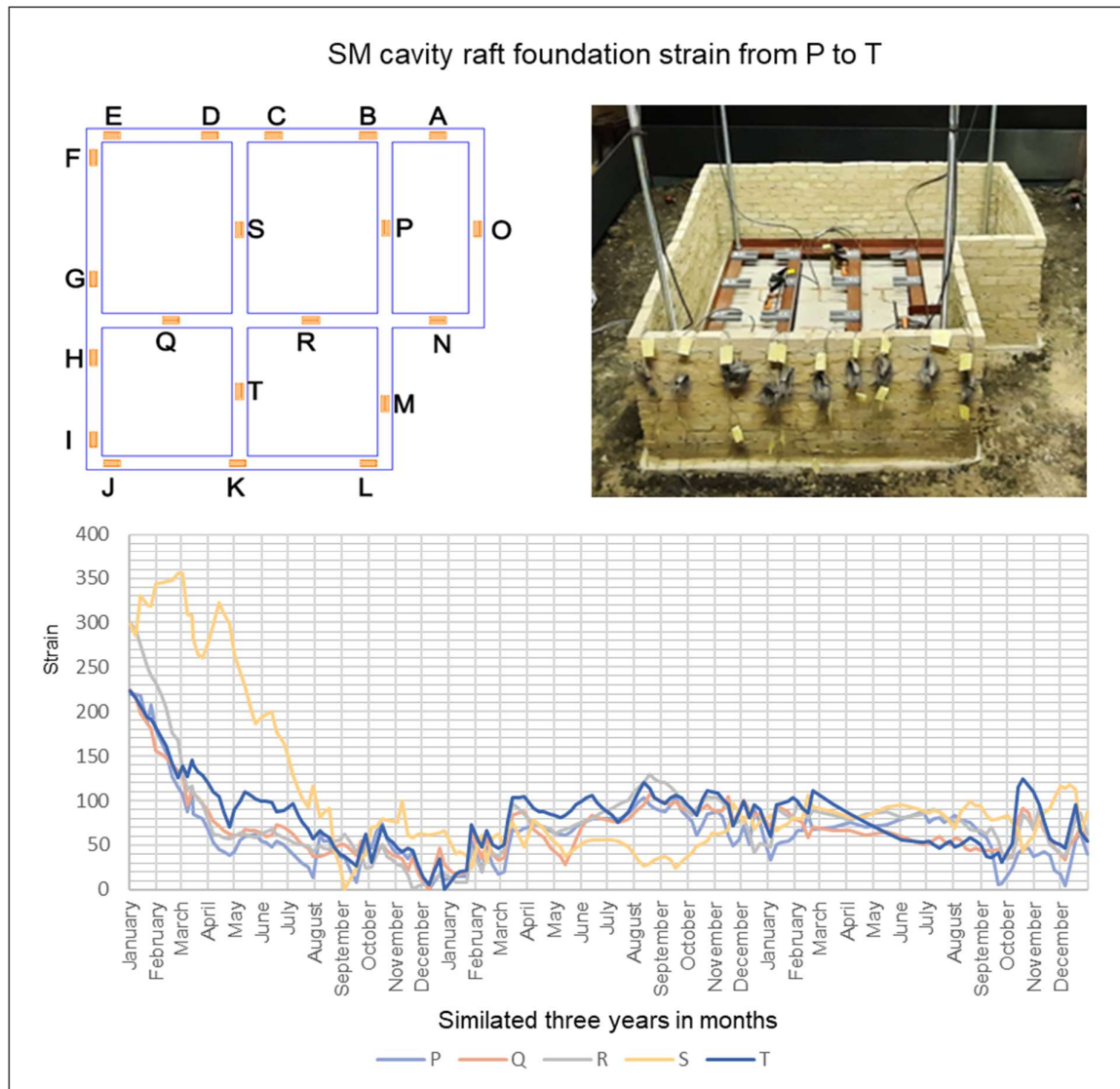
APPENDIX I - Figure 1: SM cavity raft foundation strain from A to E



APPENDIX I - Figure 2: SM cavity raft foundation strain from F to J



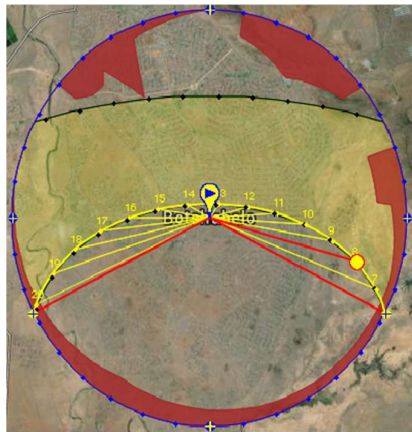
APPENDIX I - Figure 3: SM cavity raft foundation strain from K to O



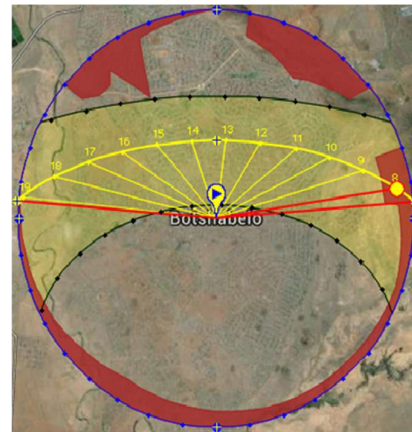
APPENDIX I - Figure 4: SM cavity raft foundation strain from P to T

APPENDIX J

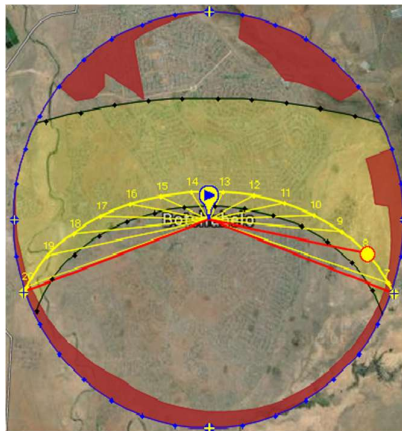
Orientation of the sun in Botshabelo



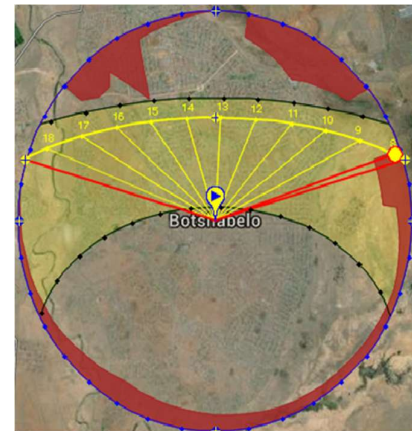
APPENDIX J - Figure 1: Orientation of the sun in January in Botshabelo



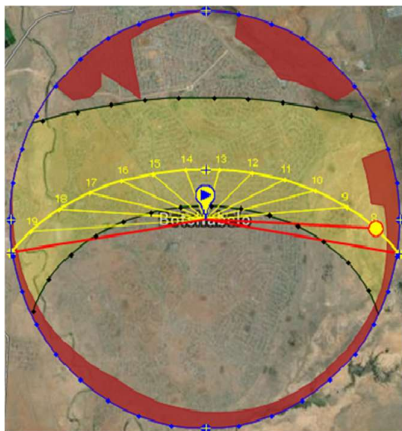
APPENDIX J - Figure 4: Orientation of the sun in April in Botshabelo



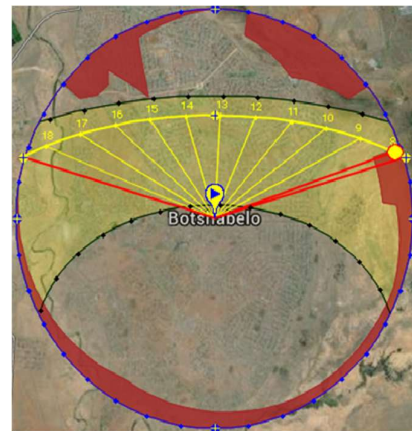
APPENDIX J - Figure 2: Orientation of the sun in February in Botshabelo



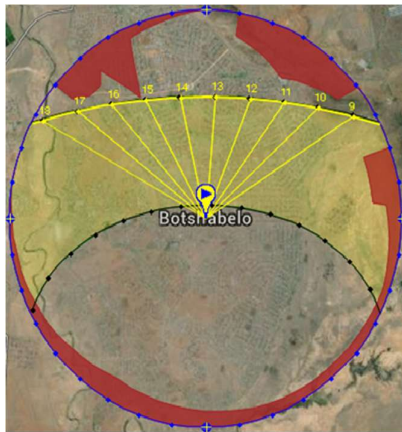
APPENDIX J - Figure 5: Orientation of the sun in May in Botshabelo



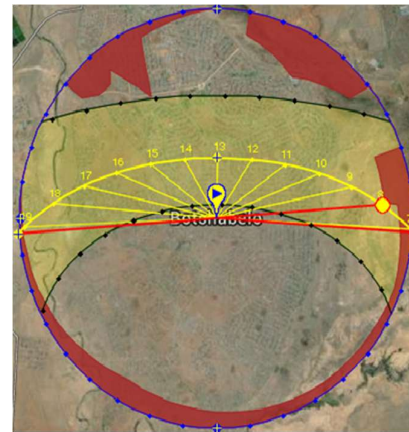
APPENDIX J - Figure 3: Orientation of the sun in March in Botshabelo



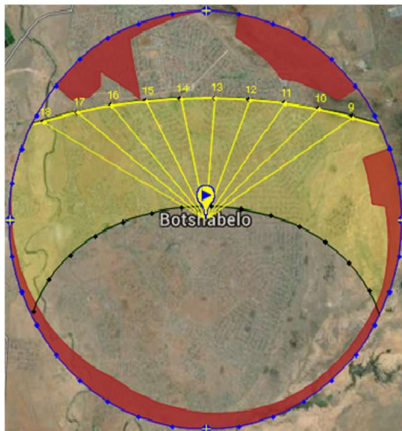
APPENDIX J - Figure 6: Orientation of the sun in June in Botshabelo



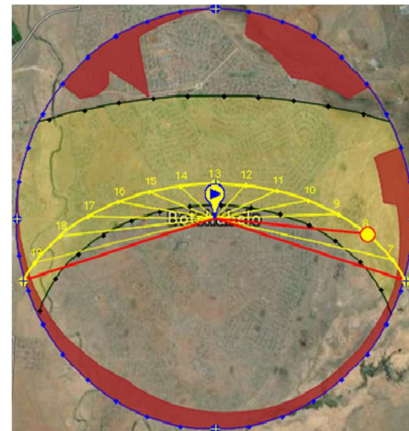
APPENDIX J - Figure 7: Orientation of the sun in July in Botshabelo



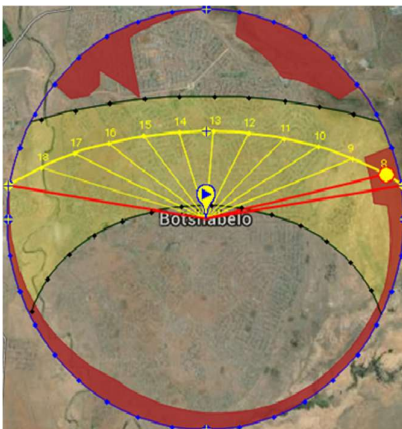
APPENDIX J - Figure 10: Orientation of the sun in October in Botshabelo



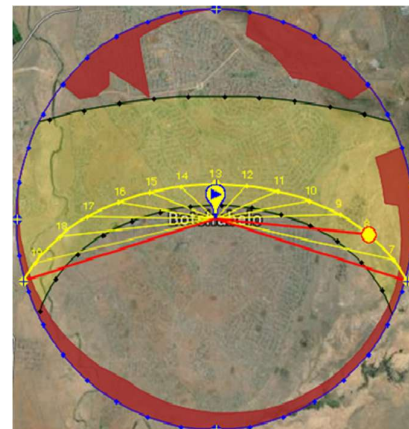
APPENDIX J - Figure 8: Orientation of the sun in August in Botshabelo



APPENDIX J - Figure 11: Orientation of the sun in November in Botshabelo



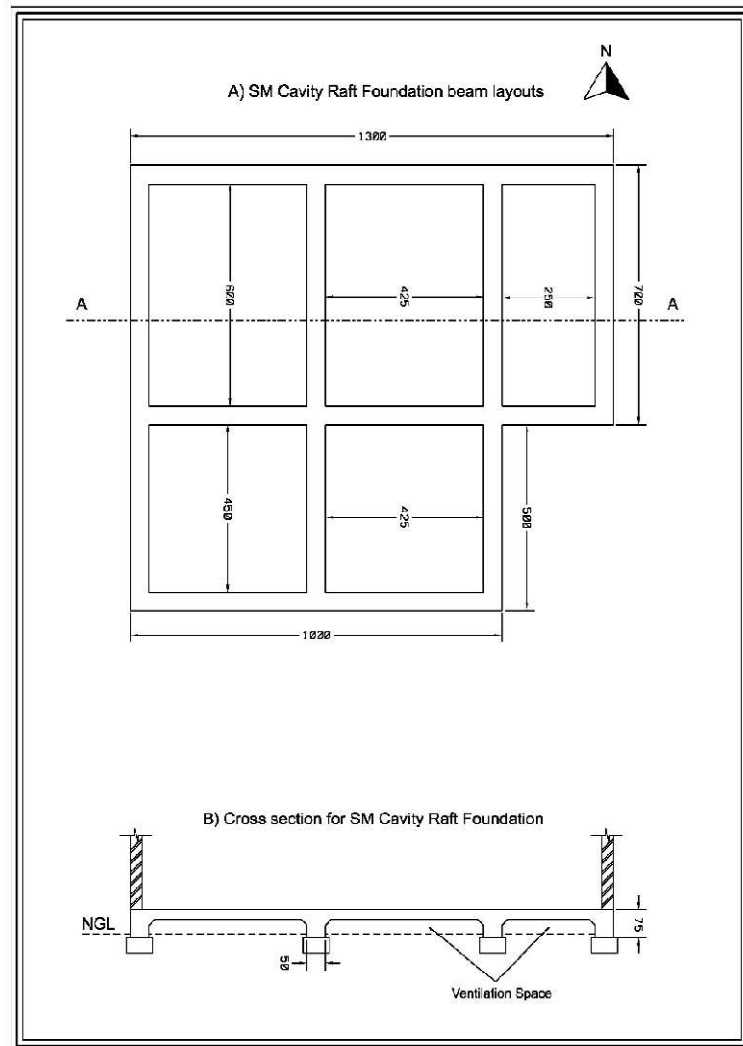
APPENDIX J - Figure 9: Orientation of the sun in September in Botshabelo



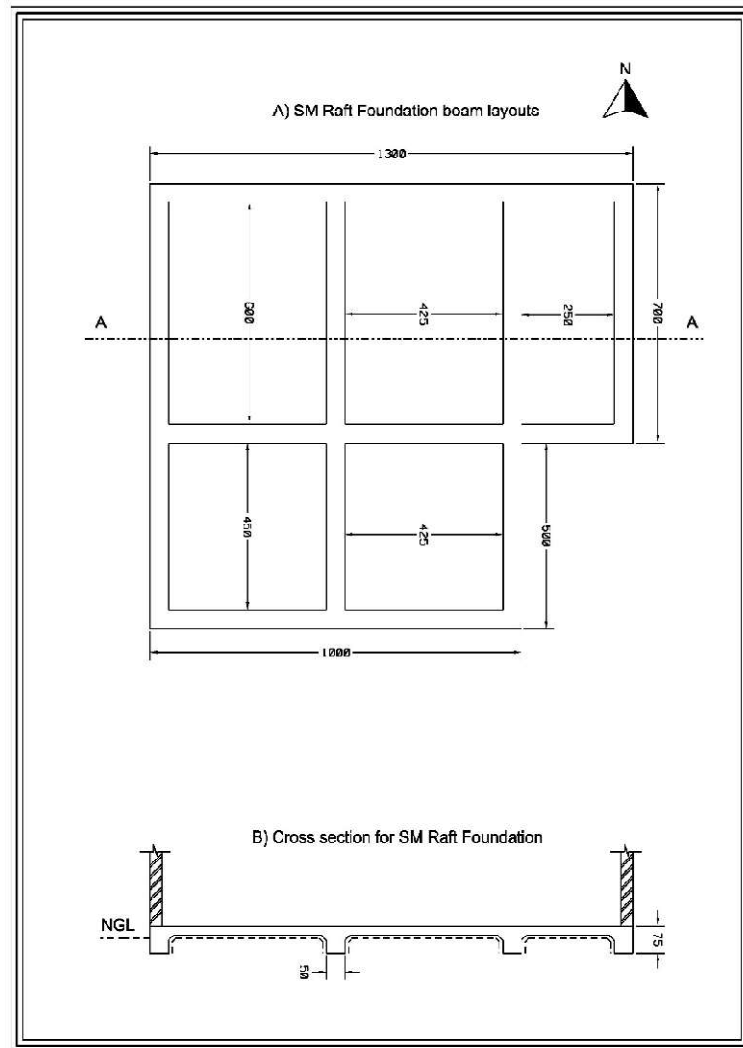
APPENDIX J - Figure 12: Orientation of the sun in December in Botshabelo

APPENDIX K

Drawings of the SM raft and cavity raft foundation



APPENDIX K: SM Cavity Raft Foundation: Section A-A



APPENDIX K: SM Raft Foundation: Section A-A

APPENDIX L

C# coding for the artificial sun inside the laboratory


```

... \Desktop\pCloud\6_CSharp\Dirk_Dashboard_v2_1\frmMain.cs 2
56
57     private List<Button> Lights = new List<Button>();
58
59     // Ratio of simulation
60     private int iRatio = 1;
61
62     // Web Camera
63     VideoCaptureDevice webCamera;
64     FilterInfoCollection fic;
65     List<String> wclist = new List<String>();
66
67     string SS_Path;
68
69     bool seqCompleted = false;
70
71     #endregion
72
73     public frmMain()
74     {
75         // Load user settings
76         settings.Reload();
77
78         // Build the form
79         InitializeComponent();
80
81         // Restore the users settings
82         InitializeControlValues();
83
84         // Enable/disable controls based on the current state
85         EnableControls();
86
87         SnapshotSetup();
88
89         comport.DataReceived += new SerialDataReceivedEventHandler
90             (comport_DataReceived);
91
92         // When data is recieved through the port, call this method
93         comport.DataReceived += new SerialDataReceivedEventHandler
94             (port_DataReceived);
95         comport.PinChanged += new SerialPinChangedEventHandler
96             (comport_PinChanged);
97
98         //Update DataGrids
99         UpdateDataGrids();
100
101         //Connect to SQLite database;
102         Logging = new DatabaseInterface("Log.db");
103
104         Lights.Add(btn_1);
105         Lights.Add(btn_2);
106         Lights.Add(btn_3);
107         Lights.Add(btn_4);
108         Lights.Add(btn_5);
109         Lights.Add(btn_6);
110         Lights.Add(btn_7);
111         Lights.Add(btn_8);

```

```

... \Desktop\pCloud\6_CSharp\Dirk_Dashboard_v2_1\frmMain.cs 3
109     Lights.Add(btn_9);
110     Lights.Add(btn_A);
111     Lights.Add(btn_B);
112     Lights.Add(btn_C);
113     Lights.Add(btn_D);
114     Lights.Add(btn_E);
115     Lights.Add(btn_F);
116     Lights.Add(btn_G);
117     Lights.Add(btn_H);
118     Lights.Add(btn_I);
119     Lights.Add(btn_J);
120     Lights.Add(btn_K);
121     Lights.Add(btn_L);
122     Lights.Add(btn_M);
123     Lights.Add(btn_N);
124     Lights.Add(btn_O);
125     Lights.Add(btn_P);
126     Lights.Add(btn_Q);
127     Lights.Add(btn_R);
128     Lights.Add(btn_S);
129     Lights.Add(btn_T);
130     Lights.Add(btn_U);
131
132     //Center Image in Picture Box;
133     pbWebCamera.SizeMode =
134         System.Windows.Forms.PictureBoxSizeMode.CenterImage;
135
136     StartCamera();
137
138     thSnapshot = new Thread(SnapCycle);
139
140 }
141
142 void comport_PinChanged(object sender, SerialPinChangedEventArgs e)
143 {
144     // Show the state of the pins
145     UpdatePinState();
146 }
147
148 private void comport_DataReceived(object sender,
149     SerialDataReceivedEventArgs e)
150 {
151     //Write the serial port data to the console.
152     SerialRead = comport.ReadExisting();
153 }
154
155 private void UpdatePinState()
156 {
157     this.Invoke(new ThreadStart(() =>
158     {
159         // Show the state of the pins
160         chkCD.Checked = comport.CDHolding;
161         chkCTS.Checked = comport.CtsHolding;
162         chkDSR.Checked = comport.DsrHolding;
163     }));
164 }

```



```

... \Desktop\pCloud\6_CSharp\Dirk_Dashboard_v2_1\frmMain.cs 4
163
164 private void port_DataReceived(object sender,
    SerialDataReceivedEventArgs e)
165 {
166     // If the com port has been closed, do nothing
167     if (!comport.IsOpen) return;
168
169     // This method will be called when there is data waiting in the
    port's buffer
170
171     // Determine which mode (string or binary) the user is in
172     if (CurrentDataMode == DataMode.Text)
173     {
174         // Read all the data waiting in the buffer
175         string data = comport.ReadExisting();
176
177         // Display the text to the user in the terminal
178         Log(LogMsgType.Incoming, data);
179     }
180     else
181     {
182         // Obtain the number of bytes waiting in the port's buffer
183         int bytes = comport.BytesToRead;
184
185         // Create a byte array buffer to hold the incoming data
186         byte[] buffer = new byte[bytes];
187
188         // Read the data from the port and store it in our buffer
189         comport.Read(buffer, 0, bytes);
190
191         // Show the user the incoming data in hex format
192         Log(LogMsgType.Incoming, ByteArrayToHexString(buffer));
193     }
194 }
195
196 #region GUI-Lights Buttons
197 private void btn_1_Click(object sender, EventArgs e)
198 {
199     Button b = (Button)sender;
200     changeStatus(b);
201 }
202
203 void changeStatus(Button _b, bool _s)
204 {
205     if (_s)
206     {
207         _b.BackColor = Color.OrangeRed;
208     }
209     else
210     {
211         _b.BackColor = Color.DimGray;
212     }
213 }
214
215 void changeStatus(Button _b)
216 {

```

```

... \Desktop\pCloud\6_CSharp\Dirk_Dashboard_v2_1\frmMain.cs 5
217 Color DefaultColor;
218 if (_b.Text.Contains("-1"))
219 {
220     DefaultColor = Color.Silver;
221 }
222 else
223 {
224     DefaultColor = Color.LightGray;
225 }
226
227 if (_b.BackColor == DefaultColor)
228 {
229     _b.BackColor = Color.OrangeRed;
230 }
231 else
232 {
233     _b.BackColor = DefaultColor;
234 }
235 }
236
237 private void btn_3_Click(object sender, EventArgs e)
238 {
239     Button b = (Button)sender;
240     changeStatus(b);
241 }
242
243 private void btn_2_Click(object sender, EventArgs e)
244 {
245     Button b = (Button)sender;
246     changeStatus(b);
247 }
248
249 private void btn_4_Click(object sender, EventArgs e)
250 {
251     Button b = (Button)sender;
252     changeStatus(b);
253 }
254
255 private void btn_5_Click(object sender, EventArgs e)
256 {
257     Button b = (Button)sender;
258     changeStatus(b);
259 }
260
261 private void btn_6_Click(object sender, EventArgs e)
262 {
263     Button b = (Button)sender;
264     changeStatus(b);
265 }
266
267 private void btn_7_Click(object sender, EventArgs e)
268 {
269     Button b = (Button)sender;
270     changeStatus(b);
271 }
272

```

```
...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 6
273 private void btn_8_Click(object sender, EventArgs e)
274 {
275     Button b = (Button)sender;
276     changeStatus(b);
277 }
278
279 private void btn_9_Click(object sender, EventArgs e)
280 {
281     Button b = (Button)sender;
282     changeStatus(b);
283 }
284
285 private void btn_A_Click(object sender, EventArgs e)
286 {
287     Button b = (Button)sender;
288     changeStatus(b);
289 }
290
291 private void btn_B_Click(object sender, EventArgs e)
292 {
293     Button b = (Button)sender;
294     changeStatus(b);
295 }
296
297 private void btn_C_Click(object sender, EventArgs e)
298 {
299     Button b = (Button)sender;
300     changeStatus(b);
301 }
302
303 private void btn_D_Click(object sender, EventArgs e)
304 {
305     Button b = (Button)sender;
306     changeStatus(b);
307 }
308
309 private void btn_E_Click(object sender, EventArgs e)
310 {
311     Button b = (Button)sender;
312     changeStatus(b);
313 }
314
315 private void btn_F_Click(object sender, EventArgs e)
316 {
317     Button b = (Button)sender;
318     changeStatus(b);
319 }
320
321 private void btn_G_Click(object sender, EventArgs e)
322 {
323     Button b = (Button)sender;
324     changeStatus(b);
325 }
326
327 private void btn_H_Click(object sender, EventArgs e)
328 {
```

```
...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 7
329     Button b = (Button)sender;
330     changeStatus(b);
331 }
332
333 private void btn_I_Click(object sender, EventArgs e)
334 {
335     Button b = (Button)sender;
336     changeStatus(b);
337 }
338
339 private void btn_J_Click(object sender, EventArgs e)
340 {
341     Button b = (Button)sender;
342     changeStatus(b);
343 }
344
345 private void btn_K_Click(object sender, EventArgs e)
346 {
347     Button b = (Button)sender;
348     changeStatus(b);
349 }
350
351 private void btn_L_Click(object sender, EventArgs e)
352 {
353     Button b = (Button)sender;
354     changeStatus(b);
355 }
356
357 private void btn_M_Click(object sender, EventArgs e)
358 {
359     Button b = (Button)sender;
360     changeStatus(b);
361 }
362
363 private void btn_N_Click(object sender, EventArgs e)
364 {
365     Button b = (Button)sender;
366     changeStatus(b);
367 }
368
369 private void btn_O_Click(object sender, EventArgs e)
370 {
371     Button b = (Button)sender;
372     changeStatus(b);
373 }
374
375 private void btn_P_Click(object sender, EventArgs e)
376 {
377     Button b = (Button)sender;
378     changeStatus(b);
379 }
380
381 private void btn_Q_Click(object sender, EventArgs e)
382 {
383     Button b = (Button)sender;
384     changeStatus(b);
```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 8
385     }
386
387     private void btn_R_Click(object sender, EventArgs e)
388     {
389         Button b = (Button)sender;
390         changeStatus(b);
391     }
392
393     private void btn_S_Click(object sender, EventArgs e)
394     {
395         Button b = (Button)sender;
396         changeStatus(b);
397
398         /*
399         foreach (Button z in panel1.Controls)
400         {
401             changeStatus(z);
402         }
403         */
404     }
405
406     private void btn_T_Click(object sender, EventArgs e)
407     {
408         Button b = (Button)sender;
409         changeStatus(b);
410     }
411
412     private void btn_U_Click(object sender, EventArgs e)
413     {
414         Button b = (Button)sender;
415         changeStatus(b);
416     }
417
418     #endregion
419
420     #region Local Properties
421     private DataMode CurrentDataMode
422     {
423         get
424         {
425             if (rbHex.Checked) return DataMode.Hex;
426             else return DataMode.Text;
427         }
428         set
429         {
430             if (value == DataMode.Text) rbText.Checked = true;
431             else rbHex.Checked = true;
432         }
433     }
434     #endregion
435
436     private void btnOpenPort_Click(object sender, EventArgs e)
437     {
438         bool error = false;
439
440         // If the port is open, close it.

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 9
441     if (comport.IsOpen) comport.Close();
442     else
443     {
444         // Set the port's settings
445         comport.BaudRate = int.Parse(cmbBaudRate.Text);
446         comport.DataBits = int.Parse(cmbDataBits.Text);
447         comport.StopBits = (StopBits)Enum.Parse(typeof(StopBits),
448             cmbStopBits.Text);
449         comport.Parity = (Parity)Enum.Parse(typeof(Parity),
450             cmbParity.Text);
451         comport.PortName = cmbPortName.Text;
452
453         try
454         {
455             // Open the port
456             comport.Open();
457
458             catch (UnauthorizedAccessException) { error = true; }
459             catch (IOException) { error = true; }
460             catch (ArgumentException) { error = true; }
461
462             if (error) MessageBox.Show(this, "Could not open the COM
463                 port. Most likely it is already in use, has been removed,
464                 or is unavailable.", "COM Port Unavailable",
465                 MessageBoxButtons.OK, MessageBoxIcon.Stop);
466             else
467             {
468                 // Show the initial pin states
469                 UpdatePinState();
470                 chkDTR.Checked = comport.DtrEnable;
471                 chkRTS.Checked = comport.RtsEnable;
472             }
473         }
474
475         // Change the state of the form's controls
476         EnableControls();
477
478         // If the port is open, send focus to the send data box
479         if (comport.IsOpen)
480         {
481             txtSendData.Focus();
482             if (chkClearOnOpen.Checked) ClearTerminal();
483         }
484     }
485
486     /// <summary> Log data to the terminal window. </summary>
487     /// <param name="msgtype"> The type of message to be written. </
488     param>
489     /// <param name="msg"> The string containing the message to be shown.
490     </param>
491     private void Log(LogMsgType msgtype, string msg)
492     {
493         rtfTerminal.Invoke(new EventHandler(delegate
494         {
495             rtfTerminal.SelectedText = string.Empty;
496             rtfTerminal.SelectionFont = new Font

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 10
    (rtfTerminal.SelectionFont, FontStyle.Bold);
490     rtfTerminal.SelectionColor = LogMsgTypeColor[(int)msgtype];
491     rtfTerminal.AppendText(msg);
492     rtfTerminal.ScrollToCaret();
493     }));
494 }
495
496 /// <summary> Enable/disable controls based on the app's current
497 state. </summary>
498 private void EnableControls()
499 {
500     // Enable/disable controls based on whether the port is open or
501     not
502     gbPortSettings.Enabled = !comport.IsOpen;
503     txtSendData.Enabled = btnSend.Enabled = comport.IsOpen;
504     //chkDTR.Enabled = chkRTS.Enabled = comport.IsOpen;
505
506     if (comport.IsOpen) btnOpenPort.Text = "&Close Port";
507     else btnOpenPort.Text = "&Open Port";
508 }
509 private void ClearTerminal()
510 {
511     rtfTerminal.Clear();
512 }
513
514 /// <summary> Converts an array of bytes into a formatted string of
515 hex digits (ex: E4 CA B2)</summary>
516 /// <param name="data"> The array of bytes to be translated into a
517 string of hex digits. </param>
518 /// <returns> Returns a well formatted string of hex digits with
519 spacing. </returns>
520 private string ByteArrayToHexString(byte[] data)
521 {
522     StringBuilder sb = new StringBuilder(data.Length * 3);
523     foreach (byte b in data)
524         sb.Append(Convert.ToString(b, 16).PadLeft(2, '0').PadRight(3, ' '));
525     return sb.ToString().ToUpper();
526 }
527
528 /// <summary> Convert a string of hex digits (ex: E4 CA B2) to a byte
529 array. </summary>
530 /// <param name="s"> The string containing the hex digits (with or
531 without spaces). </param>
532 /// <returns> Returns an array of bytes. </returns>
533 private byte[] HexStringToByteArray(string s)
534 {
535     s = s.Replace(" ", "");
536     byte[] buffer = new byte[s.Length / 2];
537     for (int i = 0; i < s.Length; i += 2)
538         buffer[i / 2] = (byte)Convert.ToByte(s.Substring(i, 2), 16);
539     return buffer;
540 }
541 private void btnClear_Click(object sender, EventArgs e)
542 {

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 11
537     ClearTerminal();
538 }
539
540 private void btnSend_Click(object sender, EventArgs e)
541 {
542     SendData();
543 }
544
545 /// <summary> Send the user's data currently entered in the 'send'
546 box.</summary>
547 private void SendData()
548 {
549     if (CurrentDataMode == DataMode.Text)
550     {
551         // Send the user's text straight out the port
552         comport.Write(txtSendData.Text);
553
554         // Show in the terminal window the user's text
555         Log(LogMsgType.Outgoing, txtSendData.Text + "\n");
556     }
557     else
558     {
559         try
560         {
561             // Convert the user's string of hex digits (ex: B4 CA E2)
562             to a byte array
563             byte[] data = HexStringToByteArray(txtSendData.Text);
564
565             // Send the binary data out the port
566             comport.Write(data, 0, data.Length);
567
568             // Show the hex digits on in the terminal window
569             Log(LogMsgType.Outgoing, ByteArrayToHexString(data) +
570 "\n");
571         }
572         catch (FormatException)
573         {
574             // Inform the user if the hex string was not properly
575             formatted
576             Log(LogMsgType.Error, "Not properly formatted hex string: "
577 + txtSendData.Text + "\n");
578         }
579     }
580     txtSendData.SelectAll();
581 }
582
583 private void SendData(string sCommand, string change, string
584 sPortName, string sPinno)
585 {
586     bool proceed = false;
587     bool hadToWait = false;
588
589     proceed = OpenPort(sPortName);
590     if (proceed)
591     {
592         SerialRead = "";

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 12
587     bool bInProgress = true;
588     int countLoops = 0;
589     while (bInProgress)
590     {
591         comport.Write(sCommand);
592         if (SerialRead.Contains("COMPLETED"))
593         {
594             SerialRead = "";
595             comport.Write("STATUS_" + sPinno);
596
597             for (int i = 0; i <= 10; i++)
598             {
599                 if (SerialRead != "")
600                 {
601                     if (SerialRead.Contains(change))
602                     {
603                         bInProgress = false;
604                         i = 11;
605                     }
606                     else
607                     {
608                         Thread.Sleep(200);
609                     }
610                 }
611             }
612         }
613         else
614         {
615             countLoops++;
616             Thread.Sleep(200);
617         }
618         if (countLoops > 50)
619         {
620             bInProgress = false;
621             MessageBox.Show("The following command was
        unsuccessful: " + sCommand);
622         }
623     }
624
625     // Send the user's text straight out the port
626     comport.Close();
627 }
628 }
629 }
630
631 /// <summary> Save the user's settings. </summary>
632 private void SaveSettings()
633 {
634     settings.BaudRate = int.Parse(cmbBaudRate.Text);
635     settings.DataBits = int.Parse(cmbDataBits.Text);
636     settings.DataMode = CurrentDataMode;
637     settings.Parity = (Parity)Enum.Parse(typeof(Parity),
        cmbParity.Text);
638     settings.StopBits = (StopBits)Enum.Parse(typeof(StopBits),
        cmbStopBits.Text);

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 13
639     settings.PortName = cmbPortName.Text;
640     settings.ClearOnOpen = chkClearOnOpen.Checked;
641     settings.ClearWithDTR = chkClearWithDTR.Checked;
642
643     settings.Save();
644 }
645
646 /// <summary> Populate the form's controls with default settings. </
        summary>
647 private void InitializeControlValues()
648 {
649     cmbParity.Items.Clear(); cmbParity.Items.AddRange(Enum.GetNames
        (typeof(Parity)));
650     cmbStopBits.Items.Clear(); cmbStopBits.Items.AddRange
        (Enum.GetNames(typeof(StopBits)));
651
652     cmbParity.Text = settings.Parity.ToString();
653     cmbStopBits.Text = settings.StopBits.ToString();
654     cmbDataBits.Text = settings.DataBits.ToString();
655     cmbParity.Text = settings.Parity.ToString();
656     cmbBaudRate.Text = settings.BaudRate.ToString();
657     CurrentDataMode = settings.DataMode;
658
659     RefreshComPortList();
660
661     chkClearOnOpen.Checked = settings.ClearOnOpen;
662     chkClearWithDTR.Checked = settings.ClearWithDTR;
663
664     // If it is still available, select the last com port used
665     if (cmbPortName.Items.Contains(settings.PortName))
666     {
667         cmbPortName.Text = settings.PortName;
668     }
669     else if (cmbPortName.Items.Count > 0) cmbPortName.SelectedIndex =
        cmbPortName.Items.Count - 1;
670     else
671     {
672         MessageBox.Show(this, "There are no COM Ports detected on
        this computer.\\nPlease install a COM Port and restart this
        app.", "No COM Ports Installed", MessageBoxButtons.OK,
        MessageBoxIcon.Error);
673         this.Close();
674     }
675 }
676
677 private void RefreshComPortList()
678 {
679     // Determain if the list of com port names has changed since last
        checked
680     string selected = RefreshComPortList
        (cmbPortName.Items.Cast<string>(), cmbPortName.SelectedItem as
        string, comport.IsOpen);
681
682     // If there was an update, then update the control showing the
        user the list of port names
683     if (!string.IsNullOrEmpty(selected))
684     {
685         cmbPortName.Items.Clear();

```



```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 14
683 cmbPortName.Items.AddRange(OrderedPortNames());
684 cmbPortName.SelectedItem = selected;
685 }
686 }
687 }
688
689 private string[] OrderedPortNames()
690 {
691     // Just a placeholder for a successful parsing of a string to an
692     // integer
693     int num;
694     // Order the serial port names in numeric order (if possible)
695     return SerialPort.GetPortNames().OrderBy(a => a.Length > 3 &&
696         int.TryParse(a.Substring(3), out num) ? num : 0).ToArray();
697 }
698 private string RefreshComPortList(IEnumerable<string>
699     PreviousPortNames, string CurrentSelection, bool PortOpen)
700 {
701     // Create a new return report to populate
702     string selected = null;
703
704     // Retrieve the list of ports currently mounted by the operating
705     // system (sorted by name)
706     string[] ports = SerialPort.GetPortNames();
707
708     // First determine if there was a change (any additions or
709     // removals)
710     bool updated = PreviousPortNames.Except(ports).Count() > 0 ||
711         ports.Except(PreviousPortNames).Count() > 0;
712
713     // If there was a change, then select an appropriate default port
714     if (updated)
715     {
716         // Use the correctly ordered set of port names
717         ports = OrderedPortNames();
718
719         // Find newest port if one or more were added
720         string newest = SerialPort.GetPortNames().Except(
721             PreviousPortNames).OrderBy(a => a).LastOrDefault();
722
723         // If the port was already open... (see logic notes and
724         // reasoning in Notes.txt)
725         if (PortOpen)
726         {
727             if (ports.Contains(CurrentSelection)) selected =
728                 CurrentSelection;
729             else if (!string.IsNullOrEmpty(newest)) selected =
730                 newest;
731             else selected = ports.LastOrDefault();
732         }
733         else
734         {
735             if (!string.IsNullOrEmpty(newest)) selected = newest;
736             else if (ports.Contains(CurrentSelection)) selected =

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 15
729 CurrentSelection;
730     else selected = ports.LastOrDefault();
731 }
732 }
733
734 // If there was a change to the port list, return the recommended
735 // default selection
736 return selected;
737 }
738
739 void UpdateDataGrids()
740 {
741     string filePath = string.Empty;
742     string fileExt = string.Empty;
743     //OpenFileDialog file = new OpenFileDialog(); //open dialog to
744     //choose file
745     //filePath = "C:\\Users\\Bulls123\\Desktop\\pCloud\\6_CSharp\\
746     //Dirk_Dashboard_v1\\bin\\Debug\\Duration.csv";
747     filePath = "Duration.csv";
748
749     //if (file.ShowDialog() ==
750     //    System.Windows.Forms.DialogResult.OK) //if there is a file
751     //    chosen by the user
752     //{
753     //    filePath = file.FileName; //get the path of the file
754     //    fileExt = Path.GetExtension(filePath); //get the file extension
755
756     try
757     {
758         LoadCSVOnDataGridView(filePath, dgvDuration);
759     }
760     catch (Exception ex)
761     {
762         MessageBox.Show(ex.Message.ToString());
763     }
764
765     //}
766
767     filePath = string.Empty;
768     fileExt = string.Empty;
769
770     //filePath = "C:\\Users\\Bulls123\\Desktop\\pCloud\\6_CSharp\\
771     //Dirk_Dashboard_v1\\bin\\Debug\\Repetition.csv";
772     filePath = "Repetition.csv";
773
774     //file = new OpenFileDialog(); //open dialog to choose file
775     //if (file.ShowDialog() ==
776     //    System.Windows.Forms.DialogResult.OK) //if there is a file
777     //    chosen by the user
778     //{
779     //    filePath = file.FileName; //get the path of the file
780     //    fileExt = Path.GetExtension(filePath); //get the file extension
781
782     try
783     {

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 16
774 LoadCSVOnDataGridView(filePath, dgvRepetition);
775 }
776 catch (Exception ex)
777 {
778     MessageBox.Show(ex.Message.ToString());
779 }
780 //}
781 }
782 }
783
784 private void LoadCSVOnDataGridView(string fileName, DataGridView dgv)
785 {
786     try
787     {
788         ReadCSV csv = new ReadCSV(fileName);
789
790         try
791         {
792             dgv.DataSource = csv.readCSV;
793         }
794         catch (Exception ex)
795         {
796             throw new Exception(ex.Message);
797         }
798     }
799     catch (Exception ex)
800     {
801         throw new Exception(ex.Message);
802     }
803 }
804
805 private void button1_Click(object sender, EventArgs e)
806 {
807     dgvLog.DataSource = Logging.SqlReturnData("SELECT * FROM
808     Sequence");
809 }
810
811 private void btnSimulate_Click(object sender, EventArgs e)
812 {
813     //Thread seqView = new Thread(StartCounting);
814     thSimulation = new Thread(StartCounting);
815     thSimulation.IsBackground = true;
816     iStateOfThread = 2;
817     thSimulation.Start();
818     btnSimulate.Enabled = false;
819 }
820
821 private void ManageThreads()
822 {
823     //Main Simulation
824     Thread simThread = new Thread(frmMain.StartSim);
825 }
826
827 public static void StartSim()
828 {
829     /*for (int i = 0; i < 3; i++)

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 17
829 {
830     MessageBox.Show("Let's go! " + Convert.ToString(i) + " of
831     3");
832     Thread.Sleep(2000);
833 }*/
834 }
835
836 private void frmMain_FormClosed(object sender, FormClosedEventArgs e)
837 {
838     //simThread.Abort();
839     StopCamera();
840 }
841
842 private delegate void LightSeqDelegate(int i);
843
844 public void StartCounting()
845 {
846     string lightid1;
847     string lightid2;
848     string light1;
849     string light2;
850     string base_name = "btn_";
851
852     string simMonth;
853     string sToLabel;
854     string sCommand1;
855     string sCommand2;
856     string sArduino1;
857     string sArduino2;
858     string sPortName1;
859     string sPortName2;
860     string sPinno1;
861     string sPinno2;
862     int iNightTime;
863     int iDelayTime;
864     int iOnTime;
865
866
867     if (txtSimRat.Text != "")
868     {
869         iRatio = Convert.ToInt32(txtSimRat.Text);
870     }
871     else
872     {
873         iRatio = 1;
874     }
875
876     //thSnapShot.Start();
877     pbYear.Invoke(new UpdateProgressYear(ProgressYear), 0);
878
879     // Simulate from Jan to Dec
880     for (var month = 0; month < dgvRepetition.RowCount - 1; month++)
881     {
882         if (iStateOfThread != 2) break;
883     }

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 18
884     simMonth = Convert.ToString(dgvRepetition[0, month].Value);
885
886
887
888     pbDay.Invoke(new UpdateProgressDay(ProgressDay), 0);
889     pbDay.Invoke(new UpdateProgressSeqMax(ProgressDayMax),
890         Convert.ToInt32(dgvRepetition[1, month].Value));
891
892     //Repeat each day of the Month
893     for (var day = 0; day < Convert.ToInt32(dgvRepetition[1,
894         month].Value); day++)
895     {
896         pbYear.Invoke(new UpdateProgressYear(ProgressYear), 1);
897         pbDay.Invoke(new UpdateProgressDay(ProgressDay), 1);
898
899         if (iStateOfThread != 2) break;
900         sToLabel = Convert.ToString(day + 1) + " " + simMonth;
901         lblSimDateVal1.Invoke(new UpdateLabelText
902             (UpdateSimDateLabel), sToLabel);
903
904         //iDelayTime = Convert.ToInt32(dgvRepetition[3,
905             month].Value) / iRatio;
906         iDelayTime = 3000;
907         iNightTime = Convert.ToInt32(dgvRepetition[2,
908             month].Value) / iRatio;
909         //UPDATE to more efficient way;
910         int TotalSeq = 0;
911         for (var i = 0; i < dgvDuration.RowCount - 1; i++)
912         {
913             if (simMonth.ToUpper() == Convert.ToString
914                 (dgvDuration[4, i].Value).ToUpper())
915             {
916                 TotalSeq++;
917             }
918         }
919
920         pbSeq.Invoke(new UpdateProgressSeq(ProgressSeq), 0);
921         pbSeq.Invoke(new UpdateProgressSeqMax(ProgressSeqMax),
922             TotalSeq);
923
924         string simuldat = "";
925         //Simulate sequence of each Day
926         for (var i = 0; i < dgvDuration.RowCount - 1; i++)
927         {
928             if (iStateOfThread != 2) break;
929             if (simMonth.ToUpper() == Convert.ToString
930                 (dgvDuration[4, i].Value).ToUpper())
931             {
932                 pbSeq.Invoke(new UpdateProgressSeq(ProgressSeq),
933                     1);
934                 iOnTime = Convert.ToInt32(dgvDuration[11,
935                     i].Value) / iRatio;
936                 sToLabel = simMonth + " - " + Convert.ToString
937                     (dgvDuration[6, i].Value);
938                 lblSeq.Invoke(new UpdateLabelText
939                     (UpdateSeqLabel), sToLabel);

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2 1\\frmMain.cs 19
928         lightid1 = Convert.ToString(dgvDuration[1,
929             i].Value);
930         light1 = base_name + lightid1;
931         //txtSimRat.Invoke(new LightSeqDelegate
932             (DisplayCount), i);
933
934         sArduino1 = Convert.ToString(dgvDuration[3,
935             i].Value);
936         sArduino2 = Convert.ToString(dgvDuration[10,
937             i].Value);
938
939         if (sArduino1 == "UNO") sPortName1 = txtUNO.Text;
940         else if (sArduino1 == "NANO") sPortName1 =
941             txtNANO.Text;
942         else sPortName1 = "";
943
944         if (sArduino2 == "UNO") sPortName2 = txtUNO.Text;
945         else if (sArduino2 == "NANO") sPortName2 =
946             txtNANO.Text;
947         else sPortName2 = "";
948
949         Button one = findButton(light1);
950
951         one.Invoke(new ClickButtonDelegate(ClickButton),
952             light1);
953
954         lightid2 = Convert.ToString(dgvDuration[8,
955             i].Value);
956         light2 = base_name + lightid2;
957         sPinno2 = Convert.ToString(dgvDuration[9,
958             i].Value);
959         Button two = findButton(light2);
960
961         sPinno1 = Convert.ToString(dgvDuration[2,
962             i].Value);
963         sCommand1 = sArduino1 + "_ON_" + sPinno1;
964         SendData(sCommand1, "_ON_", sPortName1, sPinno1);
965         simuldat = simMonth + " - " + Convert.ToString(day
966             + 1);
967         logData(GetCurrentTime(), simuldat, "UPDATE",
968             sCommand1, sPortName1, Convert.ToString(iOnTime));
969
970         if (lightid2 != "")
971         {
972             two.Invoke(new ClickButtonDelegate
973                 (ClickButton), light2);
974             sCommand2 = sArduino2 + "_ON_" + sPinno2;
975             SendData(sCommand2, "_ON_", sPortName2,
976                 sPinno2);
977             logData(GetCurrentTime(), simuldat, "UPDATE",
978                 sCommand2, sPortName2, Convert.ToString(iOnTime));
979         }
980         Thread.Sleep(iOnTime);
981         one.Invoke(new ClickButtonDelegate(ClickButton),
982             light1);

```



```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2_1\\frmMain.cs 20
968 sCommand1 = sArduino1 + "_OFF_" + sPinno1;
969 SendData(sCommand1, "_OFF_", sPortName1,
    sPinno1);
970 logData(GetCurrentTime(), simuldat, "UPDATE",
    sCommand1, sPortName1, Convert.ToString(iOnTime));
971 if (lightid2 != "")
972 {
973     two.Invoke(new ClickButtonDelegate
    (ClickButton), light2);
974     sCommand2 = sArduino2 + "_OFF_" + sPinno2;
975     SendData(sCommand2, "_OFF_", sPortName2,
    sPinno2);
976     logData(GetCurrentTime(), simuldat, "UPDATE",
    sCommand2, sPortName2, Convert.ToString(iOnTime));
977     Thread.Sleep(iDelayTime);
978 }
979 }
980 sToLabel = "NIGHT TIME";
981 lblSeq.Invoke(new UpdateLabelText(UpdateSeqLabel),
    sToLabel);
982
983 if (!seqCompleted) simuldat += "_INCOMPLETED";
984 logData(GetCurrentTime(), simuldat, "NIGHT TIME", "N/A",
    "N/A", Convert.ToString(iDelayTime));
985 Thread.Sleep(iNightTime);
986 }
987
988 btnSimulate.Invoke(new EnableButtonDelegate(EnableButton));
989
990 }
991
992 }
993
994
995
996
997 private Button findButton(string sNameofButton)
998 {
999     foreach (Button b in Lights)
1000     {
1001         if (b.Name == sNameofButton)
1002         {
1003             return b;
1004         }
1005     }
1006     return null;
1007 }
1008
1009 private void DisplayCount(int i)
1010 {
1011     txtSimRat.Text = i.ToString();
1012 }
1013
1014
1015 private delegate void EnableButtonDelegate();

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2_1\\frmMain.cs 21
1016 private void EnableButton()
1017 {
1018     btnSimulate.Enabled = true;
1019 }
1020
1021 private delegate void UpdateProgressYear(int value);
1022 private void ProgressYear(int value)
1023 {
1024     if (value == 0) pbYear.Value = 0;
1025     else pbYear.Value = pbYear.Value + value;
1026 }
1027
1028 private delegate void UpdateProgressDay(int value);
1029 private void ProgressDay(int value)
1030 {
1031     if (value == 0) pbDay.Value = 0;
1032     else pbDay.Value = pbDay.Value + value;
1033 }
1034
1035 private delegate void UpdateProgressDayMax(int max);
1036 private void ProgressDayMax(int max)
1037 {
1038     pbDay.Maximum = max;
1039 }
1040
1041 private delegate void UpdateProgressSeqMax(int max);
1042 private void ProgressSeqMax(int max)
1043 {
1044     pbSeq.Maximum = max;
1045 }
1046
1047 private delegate void UpdateProgressSeq(int value);
1048 private void ProgressSeq(int value)
1049 {
1050     if (value == 0) pbSeq.Value = 0;
1051     else pbSeq.Value = pbSeq.Value + value;
1052 }
1053
1054 private delegate void ClickButtonDelegate(string s);
1055 private void ClickButton(string name)
1056 {
1057     findButton(name).PerformClick();
1058 }
1059
1060 private void btnSimulate_EnabledChanged(object sender, EventArgs e)
1061 {
1062     if (btnSimulate.Enabled)
1063     {
1064         btnSimulate.BackColor = Color.DarkGray;
1065     }
1066     else
1067     {
1068         btnSimulate.BackColor = Color.White;
1069     }
1070 }
1071
1072 private delegate void UpdateLabelText(string labelVal);

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2_1\\frmMain.cs 22
1072 private void UpdateSimDateLabel(string labelVal)
1073 {
1074     lblSimDateVal.Text = labelVal;
1075 }
1076 private void UpdateSeqLabel(string labelVal)
1077 {
1078     lblSeq.Text = labelVal;
1079 }
1080
1081 private void btnPause_Click(object sender, EventArgs e)
1082 {
1083     Pause();
1084 }
1085
1086 private void OpenPort(int iBaudRate, int iDataBits, StopBits
1087 vStopBits, Parity vParity, string sPortName)
1088 {
1089     bool error = false;
1090
1091     // If the port is open, close it.
1092     if (comport.IsOpen) comport.Close();
1093
1094     // Set the port's settings
1095     comport.BaudRate = iBaudRate;
1096     comport.DataBits = iDataBits;
1097     comport.StopBits = vStopBits;
1098     comport.Parity = vParity;
1099     comport.PortName = sPortName;
1100
1101     try
1102     {
1103         // Open the port
1104         comport.Open();
1105     }
1106     catch (UnauthorizedAccessException) { error = true; }
1107     catch (IOException) { error = true; }
1108     catch (ArgumentException) { error = true; }
1109
1110     if (error) MessageBox.Show(this, "Could not open the COM port.
1111     Most likely it is already in use, has been removed, or is
1112     unavailable.", "COM Port Unavailable", MessageBoxButtons.OK,
1113     MessageBoxIcon.Stop);
1114
1115     private bool OpenPort(string sPortName)
1116     {
1117         bool stillbusy = true;
1118         bool greenlight = false;
1119         int counter = 0;
1120         string errorMessage = "";
1121
1122         do
1123         {
1124             bool error = false;

```

```

...\\Desktop\\pCloud\\6 CSharp\\Dirk_Dashboard v2_1\\frmMain.cs 23
1124
1125     // If the port is open, close it.
1126     if (comport.IsOpen) comport.Close();
1127
1128     // Set the port's settings
1129     comport.BaudRate = 14400;
1130     comport.DataBits = 8;
1131     comport.StopBits = StopBits.One;
1132     comport.Parity = Parity.None;
1133     comport.PortName = sPortName;
1134
1135     try
1136     {
1137         // Open the port
1138         comport.Open();
1139     }
1140     catch (UnauthorizedAccessException e) { error = true;
1141     errorMessage += e.Message + "\\n"; }
1142     catch (IOException e) { error = true; errorMessage +=
1143     e.Message + "\\n"; }
1144     catch (ArgumentException e) { error = true; errorMessage +=
1145     e.Message + "\\n"; }
1146
1147     if (!error)
1148     {
1149         stillbusy = false;
1150         greenlight = true;
1151     }
1152     else
1153     {
1154         counter++;
1155         Thread.Sleep(10000);
1156     }
1157
1158     if (counter >= 20)
1159     {
1160         stillbusy = false;
1161         SendEmailToDirk();
1162         MessageBox.Show("Could not open the COM port. Most
1163         likely it is already in use, has been removed, or is
1164         unavailable.", "COM Port Unavailable",
1165         MessageBoxButtons.OK, MessageBoxIcon.Stop);
1166         MessageBox.Show(errorMessage, "Exceptions",
1167         MessageBoxButtons.OK, MessageBoxIcon.Stop);
1168     }
1169
1170     } while (stillbusy);
1171
1172     return greenlight;
1173 }
1174
1175 void SendEmailToDirk()
1176 {
1177     var mailMessage = new MailMessage();
1178     mailMessage.From.Add(new MailboxAddress("Foundation Dashboard",

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 24
1173     "iemand@doendit.net");
1174     mailMessage.To.Add(new MailboxAddress("Dirk",
1175     "besterdn@tut.ac.za"));
1176     mailMessage.Cc.Add(new MailboxAddress("Japie",
1177     "jansevr@gmail.com"));
1178     mailMessage.Subject = "Open Port Error";
1179     mailMessage.Body = new TextPart("plain")
1180     {
1181         Text = "The Error couldn't be solved by waiting for more than 100 iterations."
1182     };
1183     using (var smtp = new SmtpClient())
1184     {
1185         smtp.Connect("mail.privateemail.com", 465, true);
1186         Thread.Sleep(200);
1187         smtp.Authenticate("ruiterand@doendit.net",
1188         "hwz*van0CEW3cvc.phv");
1189         Thread.Sleep(200);
1190         smtp.Send(mailMessage);
1191         Thread.Sleep(200);
1192         smtp.Disconnect(true);
1193     }
1194     #region Thread Management
1195     public void Pause()
1196     {
1197         thSnapshot.Abort();
1198         iStateOfThread = 1;
1199     }
1200
1201     public void Resume()
1202     {
1203         _pauseEvent.Set();
1204     }
1205
1206     public void Stop()
1207     {
1208         // Signal the shutdown event
1209         _shutdownEvent.Set();
1210
1211         // Make sure to resume any paused threads
1212         _pauseEvent.Set();
1213
1214         // Wait for the thread to exit
1215         thSimulation.Join();
1216     }
1217
1218     #endregion
1219     //Email Test
1220     /*
1221     private void button2_Click(object sender, EventArgs e)
1222     {
1223

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 25
1224     var mailMessage = new MimeMessage();
1225     mailMessage.From.Add(new MailboxAddress("Dirk die bo-baas Blou
1226     Bul", "iemand@doendit.net"));
1227     mailMessage.To.Add(new MailboxAddress("Dirk",
1228     "besterdn@tut.ac.za"));
1229     mailMessage.Cc.Add(new MailboxAddress("Japie",
1230     "jansevr@gmail.com"));
1231     mailMessage.Subject = "Kom ons handloop die toets";
1232     mailMessage.Body = new TextPart("plain")
1233     {
1234         Text = "Aweh, my vriend. Eendag sal ons verstaan hoekom ons
1235         so sukkel."
1236     };
1237     using (var smtp = new SmtpClient())
1238     {
1239         smtp.Connect("mail.privateemail.com", 465, true);
1240         Thread.Sleep(200);
1241         smtp.Authenticate("ruiterand@doendit.net",
1242         "hwz*van0CEW3cvc.phv");
1243         Thread.Sleep(200);
1244         smtp.Send(mailMessage);
1245         Thread.Sleep(200);
1246         smtp.Disconnect(true);
1247     }
1248
1249     try
1250     {
1251         /*
1252         MailMessage message = new MailMessage();
1253         SmtClient smtp = new SmtpClient();
1254         message.From = new MailAddress("iemand@doendit.net");
1255         message.To.Add(new MailAddress("jansevr@gmail.com"));
1256         message.Subject = "Test";
1257         message.Body = "Test";
1258         smtp.Port = 465;
1259         smtp.Host = "mail.privateemail.com";
1260         smtp.EnableSsl = true;
1261         smtp.UseDefaultCredentials = false;
1262         smtp.Credentials = new System.Net.NetworkCredential();
1263         smtp.DeliveryMethod = SmtpDeliveryMethod.Network;
1264
1265         /*
1266         MailMessage message = new MailMessage();
1267         SmtClient smtp = new SmtpClient();
1268         message.From = new MailAddress("iot@jansevr.com");
1269         message.To.Add(new MailAddress("jansevr@gmail.com"));
1270         message.Subject = "Test";
1271         message.Body = "Test";
1272         smtp.Port = 465;
1273         smtp.Host = "mail.privateemail.com";
1274         smtp.EnableSsl = true;
1275         smtp.UseDefaultCredentials = false;

```

```

... \Desktop\pCloud\6 CSharp\Dirk_Dashboard_v2_1\frmMain.cs 26
1275 smtp.Credentials = new System.Net.NetworkCredential
1276 ("japie@jansevr.com", "UWtG_gWjkeT1sH8ZU6");
1277 smtp.DeliveryMethod = SmtDeliveryMethod.Network;*/
1278
1279 //smtp.Send(message);
1280
1281 /*
1282     }
1283     catch(Exception)
1284     {
1285     }
1286 }
1287
1288 MessageBox.Show("Completed");
1289
1290 *//
1291
1292 private void button3_Click(object sender, EventArgs e)
1293 {
1294     Bitmap bitmap = new Bitmap(Screen.PrimaryScreen.Bounds.Width,
1295                               Screen.PrimaryScreen.Bounds.Height);
1296     Graphics graphics = Graphics.FromImage(bitmap as Image);
1297     graphics.CopyFromScreen(0, 0, 0, 0, bitmap.Size);
1298     string curtime = DateTime.Now.ToString().Replace(':',
1299     '-').Replace(' ', '-');
1300     bitmap.Save("Screenshot" + curtime + ".jpeg", ImageFormat.Jpeg);
1301 }
1302
1303 void StartCamera()
1304 {
1305     fic = new FilterInfoCollection(FilterCategory.VideoInputDevice);
1306     foreach (FilterInfo filterInfo in fic)
1307     {
1308         wclist.Add(filterInfo.Name);
1309         webCamera = new VideoCaptureDevice(fic[0].MonikerString);
1310         webCamera.NewFrame += webCamera_NewFrame;
1311         webCamera.Start();
1312     }
1313
1314 private void webCamera_NewFrame(object sender, NewFrameEventArgs
1315     eventArgs)
1316 {
1317     pbWebCamera.Image = (Bitmap)eventArgs.Frame.Clone();
1318 }
1319
1320 void StopCamera()
1321 {
1322     try
1323     {
1324         if (webCamera.IsRunning) webCamera.Stop();
1325     }
1326     catch (NullReferenceException) {
1327         MessageBox.Show("You first need to start the web camera
1328         before you may stop it",
1329         "Can't stop", MessageBoxButtons.OK, MessageBoxIcon.Information);
1330     }
1331 }

```

```

... \Desktop\pCloud\6 CSharp\Dirk_Dashboard_v2_1\frmMain.cs 27
1326 }
1327
1328
1329
1330 void Snapshot()
1331 {
1332     Rectangle rect = new Rectangle(0, 0, this.Bounds.Width,
1333     this.Bounds.Height);
1334
1335     using (Bitmap bmpScreenshot = new Bitmap(Bounds.Width,
1336     Bounds.Height, PixelFormat.Format32bppArgb))
1337     {
1338         this.Invoke(new DrawFrmBitmap(), bmpScreenshot,
1339         rect);
1340         string fileName = "DashBoard_" + GetCurrentTime() + ".jpg";
1341         // Build the filename
1342         string myFilepath = SaveFileNameCheck(SS_Path, fileName);
1343         bmpScreenshot.Save(myFilepath, ImageFormat.Jpeg);
1344     }
1345 }
1346
1347 void SnapshotSetup()
1348 {
1349     SS_Path = Environment.GetFolderPath(
1350     System.Environment.SpecialFolder.DesktopDirectory) + "\
1351     \ScreenShots\\";
1352
1353     if (!Directory.Exists(SS_Path))
1354     {
1355         Directory.CreateDirectory(SS_Path);
1356     }
1357
1358     /*string sDesktopPath = Environment.GetFolderPath(
1359     System.Environment.SpecialFolder.DesktopDirectory) + "\
1360     \ScreenShots\\";
1361
1362     if (!Directory.Exists(sDesktopPath))
1363     {
1364         Directory.CreateDirectory(sDesktopPath);
1365     }*/
1366
1367     //SS_Path = sDesktopPath + "\\" + GetCurrentTime() + "\\";
1368     //Directory.CreateDirectory(sDesktopPath);
1369 }
1370
1371 void SnapCycle()
1372 {
1373     int sleepTimer;
1374     if (iRatio < 500)
1375     {
1376         sleepTimer = 3600000 / iRatio;
1377     }
1378     else
1379     {
1380         sleepTimer = 5000;
1381     }
1382 }

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 28
1377
1378     do
1379     {
1380
1381         Snapshot();
1382
1383         Thread.Sleep(sleepTimer);
1384     } while (iStateOfThread == 2);
1385 }
1386
1387 string SaveFileNameCheck(string path, string filename)
1388 {
1389     if (!Directory.Exists(path)) return "";
1390     string filenamewoext = Path.GetFileNameWithoutExtension
1391         (filename);
1392     string extension = Path.GetExtension(filename);
1393     int count = 1;
1394     while (File.Exists(path + filename))
1395     {
1396         filename = filenamewoext + "(" + count.ToString() + ")" +
1397             extension;
1398         count++;
1399     }
1400     return path + filename;
1401 }
1402
1403 void logData(string time, string sim_date, string sequence, string
1404 command, string portname, string duration)
1405 {
1406     string sql_cmd =
1407         "INSERT INTO Sequence (time, sim_date, sequence, command,
1408         portname, duration)\n" +
1409         "VALUES\n" +
1410         "(" + time + "\", \"" + sim_date + "\", \"" + sequence + "\",
1411         \"" + command + "\", \"" + portname + "\", \"" + duration +
1412         "\"";
1413     Logging.SqlCommandNQ(sql_cmd);
1414 }
1415
1416 private void tpLog_Enter(object sender, EventArgs e)
1417 {
1418     RefreshLog();
1419 }
1420
1421 void RefreshLog()
1422 {
1423     dgvLog.Invoke(new UpdateLog(UpdateLogCommand), "SELECT * FROM
1424     Sequence");
1425 }
1426
1427 private delegate void UpdateLog(string updateCommand);
1428 private void UpdateLogCommand(string sqlCommand)
1429 {
1430     dgvLog.DataSource = Logging.SqlReturnData(sqlCommand);
1431 }

```

```

...\\Desktop\\pCloud\\6_CSharp\\Dirk_Dashboard_v2_1\\frmMain.cs 29
1426 //DrawToBitmap
1427 private delegate void DrawBitmap(Bitmap bmps, Rectangle r);
1428 private void DrawFrmBitmap(Bitmap bmpS, Rectangle r)
1429 {
1430     this.DrawToBitmap(bmpS, r);
1431 }
1432
1433 string GetCurrentTime()
1434 {
1435     string currentTime = DateTime.Now.ToString();
1436     currentTime = currentTime.Replace(" ", "_").Replace(":",
1437         "_").Replace("/", "_");
1438     return currentTime;
1439 }
1440
1441 private void btn_Copy_Click(object sender, EventArgs e)
1442 {
1443     //DateTime dt = DateTime.Now;
1444     //string dbName = "DB" + Convert.ToString(dt.Ticks);
1445     string dbName = "DB_" + GetCurrentTime();
1446     Logging.SqlCommandNQ("CREATE TABLE " + dbName + " AS SELECT *
1447     FROM Sequence");
1448     Logging.SqlCommandNQ("DELETE FROM Sequence");
1449     RefreshLog();
1450 }
1451 }
1452
1453

```