Construction and performance of an unloaded raft slab for a single storey building on expansive soil

M. Moneri, E.A. Burger & D.M. Bester
Department of Civil Engineering, Tshwane University of Technology, South Africa

ABSTRACT: Expansive soils pose significant challenges for residential construction in South Africa, often leading to foundation distress. This study evaluates the performance of raft slabs with no superstructure loads (unloaded raft slab) on expansive soils through field surveys, laboratory testing, and numerical simulations conducted in Gauteng, Ga-Rankuwa. The research simulates the effects of leaving a raft slab in place for an extended period before completing construction. Key parameters, including differential heave, strain distribution, and soil-structure interactions, were analysed to assess foundation behaviour. Findings indicate that moisture fluctuations, superstructure loads, and soil composition significantly impact raft slab performance. While SANS 10400 2012 provides standard design provisions, observed deflections under edge lift conditions suggest that current guidelines may require refinement. To enhance structural resilience, survey-informed design strategies, such as optimised reinforcement, effective drainage, and advanced geotechnical monitoring, should be integrated into construction practices. Key findings demonstrate the importance of regular field observations in validating design assumptions and enhancing the performance and safety of plain raft slabs.

1 INTRODUCTION

Expansive soils in South Africa pose significant challenges for residential structures, often resulting in foundation distress, such as cracks (Zumrawi et al. 2017). Differential heave, the uneven ground movement causing structural distortion (Kelm et al. 2008), is a crucial factor in the design of raft foundations. Accurate prediction of maximum heave governs the performance and durability of foundation systems (Rafael et al. 2018).

Field surveys play a critical role in assessing the performance of raft slabs on expansive soils, informing design improvements and construction practices (Sowers 1975, Dasgupta 2013). Raft foundations distribute loads evenly, minimising differential settlement and mitigating soil-induced structural strains (Williams et al. 1985). Their effectiveness depends on soil properties, climate conditions, and construction methodologies (Day 1994). Over time, design methods such as the Walsh approach have evolved to model soil-footing interactions better by integrating non-linear soil behaviour, numerical stimulations and geotechnical monitoring, improving foundation stability in expansive soils (Payne & Cameron 2014). Successful implementation of raft foundations has demonstrated their adaptability in diverse soil conditions worldwide (Hemsley 2000, Lee 1993).

Moisture migration under foundations significantly influences heave rates, necessitating predictive models for assessing movement patterns (Bester et al. 2024). While generalising solutions requires caution, correlations exist between soil movement types and climatic variations. The absence of predictive design data in South Africa highlights the need for refined approaches in raft foundation engineering. This paper examines the effectiveness of field surveys in evaluating raft slab behaviour and differential movements under varying environmental conditions. The objective includes:

- Assessing the structural performance of standard raft slabs under expansive soil conditions.

By analysing monitored data and case studies, this research highlights the role of field observations in mitigating structural risks, in return, reducing maintenance costs and optimising raft slab design. Given the widespread challenges of expansive soils in South Africa, this study aims to contribute to foundation engineering knowledge and offers practical insights for improving construction practices.

2 LITERATURE REVIEW

2.1 *Expansive Soils and Their Impact on Foundations*

Expansive soils undergo volume fluctuations due to moisture changes, which can significantly impact foundation stability (Sowers 1975). Heave potential is commonly assessed using empirical models, soil classification techniques, and field-based monitoring (Bester et al. 2024). These soils pose engineering challenges, as excessive movement can lead to structural damage if not properly managed.

In South Africa, a method to mitigate excessive clay movement involves pre-wetting the ground overnight before installing a damp-proof membrane (Bell & Maud 1995). This process induces initial soil expansion, reducing further movement within permissible limits. Since the damp-proof membrane is impermeable, moisture remains trapped beneath the foundation, preventing additional heave in the expanded clay layer (Williams et al. 1985). Jennings suggests continuing pre-wetting until 90% of the heave has occurred. Various mathematical models have simulated soil-structure interactions under different loading conditions (Jennings & Night 1957).

Ga-Rankuwa, despite being a well-developed peri-urban area suitable for low-cost housing, is underlain by expansive soil strata extending up to 2,0 metres deep, covering most of the developed land. Fine clays with moderate to high plasticity were discovered on-site and the surrounding area, described as class H2 (SANS 10400 2012).

2.2 *Raft Foundations on Expansive Soils*

Securing land with suitable geotechnical conditions for low-cost housing remains challenging in South Africa. However, comprehensive geotechnical surveys can be crucial in mitigating risks and guiding sustainable development.

Raft foundations distribute loads over a broad surface area, reducing localized stress concentrations and minimizing differential settlement (Williams et al. 1985; Houston et al. 2011). Internationally, modifications such as piled rafts have been implemented to enhance stability in areas with extreme swelling potential (Hemsley 2000; Lee 1993). While these methods have proven effective in mitigating soil movement, their application in South Africa remains limited. This study evaluates the field performance of raft slabs in the local geotechnical context to address this gap context.

2.3 *Design Methods for Raft Slabs*

Raft slab design integrates empirical and analytical methods to improve soil-structure interaction models. Traditional approaches, such as the Walsh method, provide structured frameworks for estimating soil response under loading conditions (Payne & Cameron 2014). However, their accuracy depends on site-specific factors, including climate conditions, soil composition, and landscape influences (Day 1994). The lack of standardised predictive models for raft slabs on expansive soils in South Africa complicates the optimization of foundation materials and construction techniques. This study aims to enhance design reliability by capturing monitored field data.

2.4 *Field Surveys and Monitoring in Foundation Engineering*

Field Surveys are critical for assessing the real-world performance of raft slabs and correlating observed behavior with soil properties (Sowers 1975; Dasgupta 2013). Studies on differential movement, cracking patterns, and long-term stability have provided valuable insights into foundation design improvements (Houston et al. 2011). However, field-based research in South Africa remains limited, leading to a reliance on international findings that may not fully align with local conditions. Expanding field investigations, particularly within the Tshwane Metropolitan area, will support the development of more contextually appropriate construction guidelines.

2.5 *Knowledge Gaps and Research Justification*

Despite advancements in geotechnical engineering, key challenges remain in adapting raft slab designs for expansive soils in South Africa. These include:

- Limited field-based assessments of raft slab performance in local conditions.
- A lack of standardized predictive models for differential heave and soil-structure interaction.
- Insufficient integration of long-term monitoring data into foundation design practices.

Design procedures that are used by for structural analysis of raft slabs cannot produce rational approaches for modelling ground swell and shrinkages of soils. Overlapping approach for non-rectangular shape slab are assumed for analysing deformations and moment actions. This procedure is simply not realistic and overlooks stress, critical loads and boundary conditions.

The design approach follows two primary mound shapes:

- A convex mound (Plate-on-mound) is where the foundation is designed to rest on an expanded soil layer.
- Concave mound (Swell-Under-Load) where the soil swells beneath a flexible raft slab (Williams et al. 1985).

The Convex and concave cases are considered to derive most severe design cases, there are no combination methods to produce critical stresses.

This research addresses these gaps by conducting field surveys of raft slabs, analysing differential movements, and correlating structural performance with soil conditions. The findings will contribute to improved geotechnical engineering practices and enhance the reliability of raft foundations on expansive soils.

3 METHODOLOGY

The research methodology involved simulating the effects of leaving a raft slab in place for an extended period before completing construction. Field observations, laboratory testing, and current design procedures were used to evaluate the performance of raft slabs under expansive soil conditions.

3.1 *Field Observations*

Field observations were conducted on a raft slab for a residential building in the expansive soil region of Ga-Rankuwa. Peg points were marked visibly on the raft slab surface as shown on Figure 1(b), and movements were monitored weekly. Measurements included differential movement, and crack patterns across seasonal cycles. Advanced tools such as automatic level, and digital inclinometer were used to ensure accuracy.

3.2 *Method of Observation*

Readings were taken from the levelling staff, which was placed at marked points on the surface of the raft slab, using an automatic level with an accuracy of 0,1 mm. The levelling staff was fitted with a bubble level to ensure upright plumb during fieldwork. All level observations were referenced to a reliable benchmark structure in the yard. The tripod instrument was positioned midway between the benchmark and the raft slab, within 15 metre radii.

The raft slab movement profile, presented in Figure 3, was derived from a series of measurements taken at key intervals. Heave measurements proved to be easier to survey than initially anticipated, with the first set of readings taken on day 1 using a municipal sewer maintenance hole concrete surface as a benchmark. These baseline measurements were compared with readings taken 60 days later to assess movement trends.

3.3 *Laboratory Testing*

Soil samples were taken to a local soil laboratory for investigation of Atterberg limits and moisture content variation. The sample was described as a slightly moist silty grained sand transported layer followed by dark grey to blackish clay residual (black turf).

It was considered economical to investigate Atterberg limits and water content of the soil sample due the site's limited construction budget. The Atterberg limits test determined the soil's plasticity, with results indicating a liquid limit of 53%, a plastic limit of 25%, and a plasticity index of 25%, which suggests a highly plastic soil. These findings highlight the need for provision of foundation reinforcement due to the soil's high plasticity, swelling potential, and moisture sensitivity.

3.4 *Application*

3.4.1 *Building Model*

The South African codes of practice is fixed to a 450 mm overall beam depth, irrespective of the soil's surface heave (y) value. The permissible deflection requirement suggests 600 mm deep raft beam.

The predictive method based on design parameters for surface heave (y) between 15 mm and 30 mm, as outlined in SANS 10400 2012 deemed-to-satisfy provisions was adopted. With the site classification and material properties established, the predictive method calculated y/Δ, representing the required depth of raft beams for edge lift heave profile ranged at 310 mm.

The geometry of the raft slab was reduced into 150 mm deep L-shaped slab with 300 mm deep stiffening ground beams. The concrete configured with soil beneath were modelled on Oasys GSA 8.7 Analysis. The contact nodal stiff spring elements were adopted as soil support at 0,1 m increment. Figure 1 illustrates layout and cross-section properties.

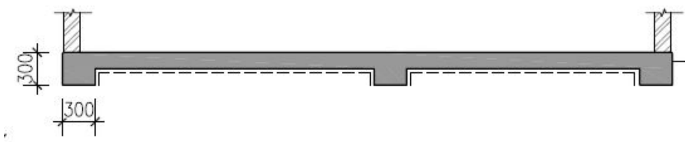

Figure 1. a) Typical cross-section of Raft slab

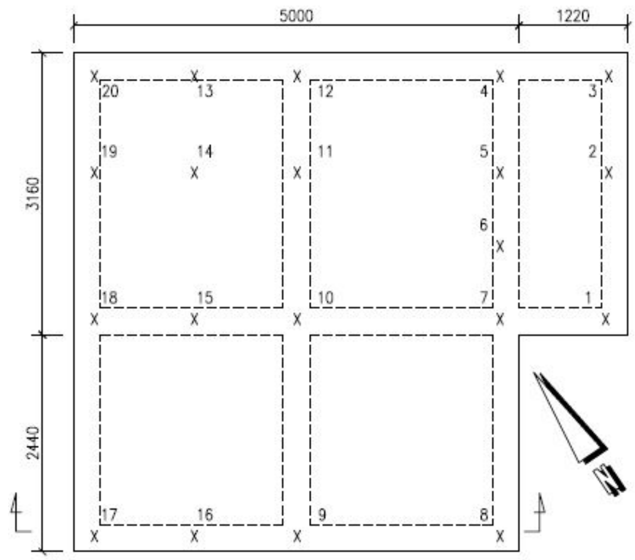

Figure 1. b) Raft Slab with Stiffened Beams

3.4.2 *Support Indices*

In configuring the raft foundation, a grid of ground beams was introduced to establish an inherent stiffness not available in a plain slab-on-ground. By virtue of their loading, these beams may resist future superstructure loads (permanent and variable) running around perimeter and safely transfer these loads to the supporting ground, loads of the order of 10,7 kN/m.

The approach for the design of stiffened raft slabs on expansive soils using Mitchell's method (Mitchell 1980), was followed, and the expression of soil heave reaction ρ, produced by its interaction with the structure, is expressed as follows:

$$\rho = k(y - \delta) \quad (1)$$

Where:
k = constant soil stiffness;
y = soil mound movement; and
δ = raft deflection or deformation due to soil movement.

The calculated soil heave ρ is then applied together with design loads/stresses. The bending moment and shear force are obtained using the corresponding EI. The soil mound at any point x from the heave mound centre, y, for the mound shapes can be reasonably defined by (Uzan & Lytton 1978):

$$y = \left(\frac{2x}{L}\right)^m y_m \quad (2)$$

Where:
y_m = surface heave;
m = mound exponent

3.4.3 *Foundation Deflection*

Assumptions are made to guarantee satisfactory maximum deflection ratios (Day 1985). This method does not specify whether the differential deflection is measured along the edge of the slab or across its centre. By inspection, the shorter dimension of the slab is taken as the effective span over which the deflection occurs. The foundation deflection δ can then be determined, including areas of lost contact with the soil, using $m = 3.66$ for permeable surface, as follows:

$$\delta = \left(\frac{2x}{L}\right)^m \Delta \quad (3)$$

4 RESULTS AND DISCUSSION

The field observations revealed significant variability in the raft slab's performance on expansive soils, particularly in terms of differential movement. This variability was influenced by layout configuration and fluctuations in soil moisture content. Such findings highlight the complexity of raft foundation behaviour on expansive soils and emphasise the need for precise design considerations. Figure 2 demonstrates surface movement of week 6 survey data.

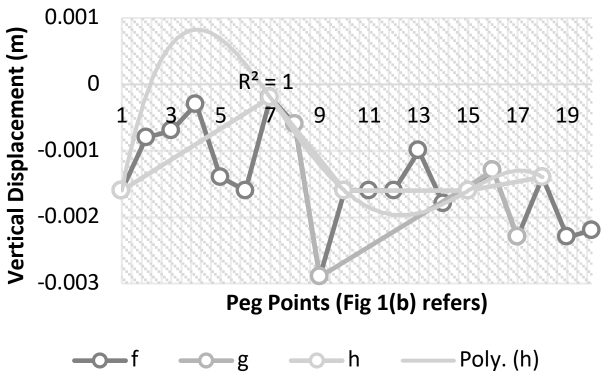

Figure 2. Observed differential movement along various beams

In this Figure 2, graph f illustrates the differential movement along all 20 pegs sequentially. Graph g illustrates the differential movement along edge beam (8-17). The movement solution set for centre beam (1-18) is presented on graph h. As peg positions increase gradually along centre beam, the continuous curve creates a trendline with points of vertical displacement values.

A flexural check in a logical application of the design code indicated an adequate design capacity, with permissible deflection exceeded by actuals, suggesting that adjustments to design parameters are required to optimise material usage. These parameters suggest that the deemed-to-satisfy provision may be overly conservative, particularly when site conditions approach the upper classification limits.

4.1 *Applied Soil Heave Profiles*

In this scenario, heave beneath the edge beams lifts only the edges, causing the raft slab to suspend between the raised beams. This phenomenon has led to structural instability and differential movement in houses, particularly because the soil in this region is very expansive. The expansive clay on site has a medium to high expansiveness (Van der Merwe 1964). This classification estimated the maximum edge lift at approximately 0,6×0,25 y to predict differential deflections in the area. Applying Equation (2), the maximum heave values of 2,25 mm for y = 15 mm and 4,5 mm for y = 30 mm were calculated, demonstrating the potential severity of edge lift movement.

4.1.1 *Edge Heave of Edge Beam*

The calculated values were used to plot displacement profile for edge beam 8 - 17, illustrated in Figure 3. The shape of the profile was kept constant and was only amplified up to the ultimate heave. The predictive slab deflection graphs are illustrated, and their shapes were processed with applied gravity loads.

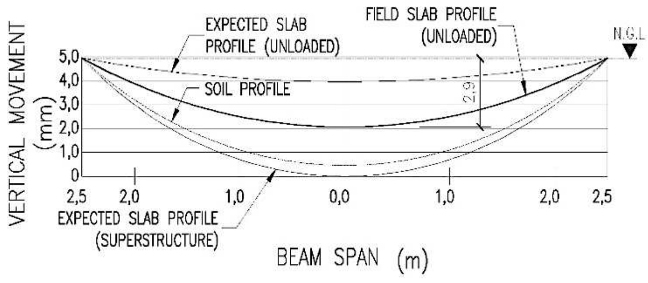

Figure 3. Edge lift heave profiles

From outset, the main problem to contend with on the structural design standpoint is large deflections. A maximum deflection in concrete, δ_c= 4,96 mm was calculated using the following equation:

$$\delta_c = \left(\frac{Wx(L-x)}{24EIL}\right)\left[L^2 + x(L-x)\right] \quad (4)$$

A deflection under service load of $l/1008$ was obtained and remains too flexible to span between the two edges as shown in Figure 3. Deflections are a linear function of inertia. By multiplying ratio of 2000 divided by deflection obtained, with current moment of inertia, suitable moment of inertia provides a new beam depth of 375 mm.

4.1.2 *Edge Heave of Building*

Figure 4, which represents the survey data from week 6, shows that the actual movement profile deviates from the expected mound curves. After several iterative analyses, the free surface sag shape was assessed. The sag does not necessarily lie at the centre of the raft slab in the longer span, while edge heave (hogging) is predominant in the eastern and southern sides of the house.

The maximum differential centre heave was found to be 2,9 mm at the centre of edge beam (8-17). This variation suggests that the assumed heave distribution may not fully account for localised soil behaviour, emphasising the need for further investigation in comparing the impact of seasonal climate influence and the ground water from greenfield site or excessive garden watering on raft slab movement in expansive soils.

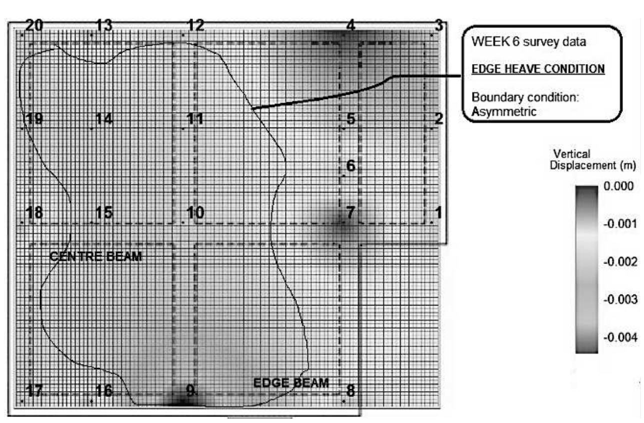

Figure 4. Movement profile during field observation (in metres)

Relative movement of the slab can be inferred from these colour schemes assuming the slab was poured with a level surface. A total of 20 measurements were taken per week across the raft slab surface. colour schemes showing relative vertical movement on an approximately 0,1 m grid are plotted. The grid colour scheme plot indicated that a severe edge heave occurred in the long span.

4.1.3 *Edge beam model*

Due to level inconsistencies observed on the movement profile in Figure 4, the spring supports under the slab were assumed not to have heaved, allowing the raft slab to have heaved on edge beams only. A real case scenario was assumed where an edge lift profile was increased linearly to produce differential heave up to 4,5 mm. The midspan of the slab was analysed unrested on the middle portion of soil. The results illustrated the middle of the slab rested on the soil as shown on Figure 5, indicating that the slab does not satisfy the deflection criteria of the soil profile as is too flexible to span between the edge supports.

Figure 5. Depressed slab on predicted soil profile

4.2 *In Pursuit of Breaking Grounds*

The selection of the most suitable raft slab was based on structural engineering principles and ease of construction for emerging contractors. From a structural perspective, the raft slab needed to:

- Resist bending forces caused by differential heave.
- Provide sufficient stiffness to prevent visible distortion in the superstructure.

These criteria were addressed by incorporating adequate reinforcement and adjusting slab depth. The 150 mm-thick raft slab contained 6,5 cubic meters of concrete and 175 kg of reinforcement steel, ensuring structural integrity under expected loading conditions.

4.2.1 *Key Structural Considerations*

Three primary factors were analysed in detail:

- Contact pressure distribution beneath the raft.
- Raft design based on applied loads and soil conditions.
- Nominal reinforcement to mitigate shrinkage stresses.

The raft slab configuration was designed to allow manual excavation, making it accessible for local contractors. The following construction parameters were established:

- Monitoring of emerging contractors for key activities such as setting-out, excavation, damp-proof

membrane installation, steel fixing, and concrete pouring.
- Ground beams measuring 300mm × 300mm to provide stability.
- Standardised rebar detailing for all ground beams, using Y12 bars (top and bottom) with R8 stirrups at 200mm spacing.
- Fabric mesh reinforcement (Ref. 245) for floor slabs.

4.2.2 *Performance and Site Considerations*

The site class designation was assumed to remain unchanged for the building's lifespan. Generally, raft slabs on expansive soils experience minimal damage, ranging from category 0 (negligible damage) to category 2 (minor cracking). Only fine cracks were visible on slab surface, which are temperature induced. However, field observations indicate that houses in the study area exhibit significant structural damage, suggesting that current design approaches may not fully mitigate expansive soil movements. This highlights the need for further investigation into long-term raft slab performance under local conditions. A maximum deflection check was carried out in accordance to principles set out in the (SANS 10100 2000), concrete code. The ability of a typical perimeter ground beam supported on peg points 8 and 17 in Figure 4 has given a theoretical value of 6,04 mm. A competitive value of 5 mm was measured during field observation and is demarcated in blue on Figure 4.

5 DISCUSSION AND CONCLUSION

The behaviour and stability of the unloaded raft slab on expansive soil has been investigated. Theoretical predictions using potential edge heave criteria and design approaches were compared with raft slab field-based movement profiles in order to study the influence of expansive soil interaction in local condition. This work included design and construction of full-scale field experimental raft slab and field Surveys of real-world differential movement performance.

The current design methods have been in existence for a half a century, but there are no validated methods to check raft slab on expansive soil interactions for various geographical areas. There are a lot of underperforming foundations that are derived by these methods and causing homeowners a fortune to repair their houses. Despite these insights, specific limitations exist, including shortcomings that are not realistic and are based on assumption of overlapping shapes for non-rectangular raft slabs. The results from the analysis suggest that the raft slab deflection does not satisfy edge heave condition. The current design methods that are adopted by geotechnical engineers have significant shortcomings that are not rational.

The findings highlight that survey-informed design intervention, such as optimised actual movement profile can significantly enhance raft slab designs.

ACKNOWLEDGEMENTS

The authors would like to thank Ms Mosime for allocating land at the Thusanong Day Centre to accommodate the donated research building. I am deeply grateful to my supervisors for their invaluable encouragement throughout this research, and to Muhi Peiso for their unwavering support.

REFERENCES

Bester, D.M., Theoren, E., Stott, P.R. & Snyman, J. 2024. A comparative study of real-world vs. small-scale mat foundations on expansive clay soils for low-cost housing. *Horizon Research Publishing* 5(20 May 2024): 12.

Bell, F.G. & Maud, R.R. 1995. Expansive clays and construction, especially of low-rise structures: a viewpoint from Natal, South Africa. *Environmental & Engineering Geoscience* 1(1): 41-59.

Dasgupta, T. 2013. *Geotechnical aspects of buildings on expansive soils*. [Publisher details needed].

Day, P.W. 1985. Design of raft foundations for expansive clay using Lytton's method. Structural Division. Course on Design of Foundations to Suit Various Soil Conditions, pp.1-15.

Day, R.W. 1994. Performance of slab-on-grade foundations on expansive soil. *Journal of Performance of Constructed Facilities* 8(2): 129-138.

Hemsley, J.A. (ed.). 2000. *Design applications of raft foundations*. London: Thomas Telford.

Houston, S.L., Dye, H.B., Zapata, C.E., Walsh, K.D. & Houston, W.N. 2011. Study of expansive soils and residential foundations on expansive soils in Arizona. *Journal of Performance of Constructed Facilities* 25(1): 31-44.

Kelm, R., Wylie, N., Inc., F.E. & TX, H. 2008. Which way is it moving? Guidelines for diagnosing heave, subsidence and settlement. Foundation Performance Association. [Online] Available at: https://www.foundationperformance.org/pastpresentations/Kelm_Pres_Doc-9Apr08.pdf [Accessed 24 December 2024].

Lee, I.K. 1993. *Analysis and performance of raft and raft-pile systems*. [Publisher details needed].

Payne, D.C. & Cameron, D.A. 2014. The Walsh method of beam-on-mound design from inception to current practice. *Australian Journal of Structural Engineering* 15(2): 177-188.

Pidgeon, J.T 1980. A comparison of existing methods for the design of stiffened raft foundations on expansive soils. Pretoria: National Building Research Institute.

Pidgeon, T. 1980. The interaction of expansive soils and stiffened raft foundations. *National Building Research Institute* 12(Dec 1980).

Rafael, A., Daniel, T. & Susana, M. 2018. *Structural analysis of historical constructions*. 2nd ed. Springer International Publishing.

Sowers, G.F. 1975. Review of expansive soils. *Journal of Geotechnical and Geoenvironmental Engineering* 101: 1-15. Available at: https://api.semanticscholar.org/CorpusID:127263055 [Accessed 3 February 2025].

Uzan, J. & Lytton, R.L. 1978. Measurement of flow properties of expansive clays. *International Journal for Numerical and Analytical Methods in Geomechanics*: 73-86.

Williams, A.A.B., Pidgeon, J.T. & Day, P.W. 1985. Expansive soils: problem soils in South Africa—state of the art. *Civil Engineer in South Africa* 27(7): 367-401.

Zumrawi, M.M.E., Abdelmarouf, A.O. & Gameil, D.A.E.A. 2017. Damages of buildings on expansive soils: diagnosis and avoidance. [Online] Available at: https://www.researchgate.net/publication/317032307_Damages_of_Buildings_on_Expansive_Soils_Diagnosis_and_Avoidance [Accessed 27 December 2024].

Van der Merwe, D.H. 1964. The prediction of heave from the plasticity index and percentage clay fraction of soils. *Civil Engineer in South Africa* 6: 103-107.

SANS 10100-1. 2000. The structural use of concrete – Part 1: Design.

SANS 10400-H 2012. The application of the national building regulations – Part H: Foundations.