Investigation into an adopted design procedure for raft foundations of light structures on expansive soils located in the Free State

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ABSTRACT: Raft foundations are characterized by their ability to distribute building loads and minimize differential movement. Raft foundation construction has become very popular in areas affected by expansive clay soils in South Africa. Expansive clays can cause heave when the suction potential exceeds the foundation's pressure, leading to visible cracks, jammed doors, damaged floors, and compromised structural integrity. Large parts of South Africa are affected by expansive soils, including the Karoo Supergroup and the Beaufort Group, found in South Africa's Gauteng Province, Free State Province, parts of the Western Cape Province, and certain areas in the Eastern Cape Province. These geological formations are associated with expansive clays, posing challenges for construction and engineering projects. The study highlights the critical importance of custom-made foundation solutions for the unique challenges expansive soils pose. This paper draws inspiration from Pidgeon's universal method (1988) and Bester et al.'s (2016) work on moisture variation underneath a raft foundation. Pidgeon's design approach provides a valuable outline for designing raft foundations on expansive clays based on edge heave and mound-shaped that will develop. However, the assumption of a centre-located dome-shape underneath a raft foundation is unrealistic since the previous studies did not consider the shadow cast by the structure. By applying this design approach to expansive soil conditions, this study suggests an improved approach and design to mitigate heave damages and ensure the long-term stability of structures built on expansive clay soils. This research explores raft foundation design in South Africa and suggests a new approach to mitigate structural damages of the challenges of expansive clays. By adopting this new approach, designers can enhance the service life of light-structured housing, ultimately contributing to the long-term sustainability of South African housing projects.

1 INTRODUCTION

Geotechnical engineers and engineering geologists across South Africa recognize the extent and influence of expansive clay. Expansive clay soils in South Africa pose huge challenges for structures, as highlighted by Netterburg (2019). These expansive clay soils have a notable shrink-swell potential for expanding clay minerals. During wet seasons, the higher moisture content in clay soils leads to expansion, while subsequent dry seasons cause shrinkage. This will result in movements and cracking in foundations. The heaving nature of clay soils can result in structural damage to buildings (Douglas and Noy, 2010). The swelling of clays results in substantial building damage due to heaving and millions of Rand losses (Williams, et al., 1985). Expansive soils, such as those from the Karoo Supergroup and the Beaufort Group, impact extensive regions of South Africa. Light structures are at risk due to their lightweight nature and the swelling pressures of expansive clay soils. A raft foundation is often used since it offers stable and evenly distributed support, making it a practical choice. These foundations are popular in regions affected by expansive soils, like much of the Free State and Northern Cape (Bester et al., 2016). Typically, a raft foundation helps limit the differential movements in the underlying soils to a level manageable by the superstructure (Day, 1991). The NHBRC recommends opting for a stiffened or cellular raft foundation when the projected total heave exceeds 15 mm (NHBRC, 1999).

Raft foundations should be designed to deal with unstable soils, such as active clay soils, that can cause differential movement and foundation instability (Williams & Pellissier, 1991). It has been observed that two noticeable heaving patterns could occur: centre doming or edge heave (Duncan, 1992). Raft foundation designers will often rely on the assumption of the shape and degree of these heaving patterns. The determination of the shape, location, and size of these heaving patterns underneath raft foundations is based on heave measurements conducted on simulated foundations and sheet covers such as by (Pidgeon, 1988) (Fityus, et al., 2004) (Miller, et al., 1995) & (Pidgeon & Pellissier, 1987). Therefore, designing raft foundations on expansive clay soils presents significant challenges since these design assumptions are based on simulated foundations that do not cast any shadows, influencing the pattern of heave that will develop. Bester *et al*., 2016 found that the moisture movement depends on temperature conditions influenced by solar radiation, which varies based on the architecture of the building. The researchers also suggested that currently accepted patterns of heave may not provide helpful guidance for foundation design. This is because the moisture concentration is typically found at the coldest side of the building, where the least amount of solar radiation will reach.

Additionally, the north-facing side of the raft foundation will constantly show the greatest moisture changes because this area is most exposed to solar radiation. During dry periods, large cracks will develop in the clay soil at the north-facing side of the raft foundation. When rainfalls occur, these large cracks will allow water to penetrate fast and deep into the soils, allowing for substantial heave. Edge penetration distance determination also needs reconsideration, as there is no clear indication of the value of this parameter, which is commonly used to estimate the mound shape and required stiffness of the raft foundation. Therefore a centre dome is not recommended, as no clear evidence supports it (Bester, et al., 2017).

2 LITERATURE

2.1 *Raft foundations design methods commonly used*

Lytton's method for raft foundation design is well-suited for routine and basic designs. The method involves breaking down non-rectangular raft foundations into overlapping rectangles and analyzing each block individually (Day, 1991). Considerations for this method are the differential heave beneath the foundation, depth to the bottom of expansive layers, allowable deformation of the supporting structure, and the modulus of subgrade value. (Lytton, 1972). The general assumption of the method is that the heave will occur in the middle of the foundation, where Lytton expected the moisture concentration to be. The determination of the mound exponent, where heave occurs, is estimated based on field observations. Lytton (1972) examined various field studies and proposed a mound exponent value as $m = L/Z$, where L is the length of the shortest side of the foundation, and Z is the depth of the clay layer (Day, 1991).

Fraser and Wardle (1975) introduced the Swinburne method, which built upon the Lytton method (1972) soil-raft foundation interface method. The objective of the Swinburne method was to create a cost-effective design approach for raft foundations built on expansive clay soils. The method was developed based on multiple raft foundations constructed on different types of expansive clay soils. The raft foundations in this study were monitored for their movement over time to measure the field dome that occurred. The researchers utilized finite element modelling to represent the raft foundations and their stiffening beams, applying them as plates with beams resting on semi-infinite elastic soil layers. Two key parameters looked into were the maximum differential heave (Ym) and the edge moisture variation distance (e), also known as edge penetration distance (Frazer & Wardle, 1975).

Pidgeon (1980) found that raft foundation designs rely on constructing foundations on preexisting mounds or domes. Therefore, an estimate of the initial dome shape that would develop is needed (Pidgeon, 1980). Pidgeon believed raft foundations should be expected to be cast initially on level ground. Subsequently, with the construction of the raft foundation, an instant undrained surface settlement will occur. This will result in stress adjustments, strains, and suctions throughout the soil layers. Based on Pidgeon's findings, he developed the rational design procedure. Pidgeon (1987) suggests that raft foundation design should account for the worst-case scenario, which occurs when the soil underneath the centre of the raft foundation reaches its maximum moisture content or experiences swelling conditions.

The guide Pidgeon (1988) proposed for the rational design of stiffened raft foundations for small structures outlines a series of design steps. It offers a standardized method to design raft foundations. A foundation plan should be created. The plan should indicate the layout of stiffening beams, the position of wall loads, and determining dimensions such as the "base" rectangle, offset lengths for any "L" shapes, and the number of beams in each direction. Furthermore, a uniformly distributed load must be applied. Factors such as the long-term elastic modulus and Poisson's concrete ratio should also considered. Furthermore, the allowable deflection ratio for the intended superstructure is established, and the mound stiffness is assessed based on soil properties such as the equivalent elastic mound modulus and Poisson's ratio. Lastly, determine the mound shape, selecting between a flat-top mound with parabolic edges or a mound with no flat top, see Figure 1.

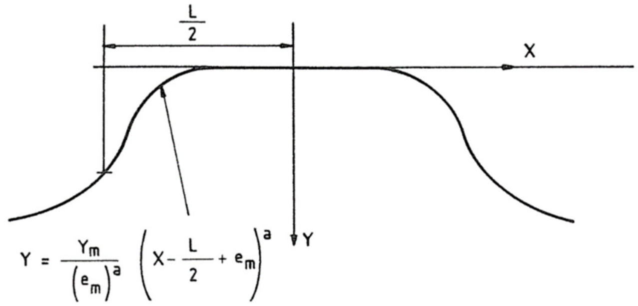

Figure 1. Unloaded mound with flat top and parabolic or cubic-shaped edges by Pidgeon (1987).

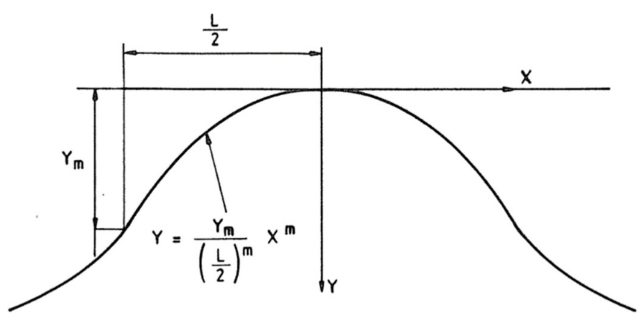

Figure 2. Unloaded mound with a shape defined by the mound exponent "m" by Pidgeon (1987).

2.2 *Raft foundation measurement of moisture variation in Botshabelo.*

In 2014, a study conducted in Botshabelo measured the moisture content under a light-structured house built on active clay soils (Bester et al., 2016). The study's findings indicated that doming tends to occur towards the re-entry corner of the raft foundation and not centrally as previously believed. The soil underneath the raft foundation mostly stays close to a fully expanded state, except on the northern-facing side, where it is most affected by solar radiation, where the water content in the upper layers may decrease to the shrinkage limit. The study indicates that conventional heave patterns may not provide foundation design guidance. The relevance of edge penetration also needs re-evaluation, as it does not indicate its value, which is typically used to estimate mound shape and required stiffness. The study advises against a centre dome as no evidence supports its effectiveness (Bester et al., 2017).

3 RESULTS FROM BOTSHABELO

The soil profile underneath the raft foundation in Botshabelo has a thin layer of dark brown clayey sand with a thickness of 150mm. This is underlain by a layer of black transported clay and a layer of olive residual clay. Both clays were assessed by Van der Merwe's method (Van der Merwe 1964) as having medium expansiveness. Rock is found at a depth of approximately 1.1 meters. The first clay layer is 150-900mm, and the second clay layer is 900–1100mm.

Figure 3 illustrates a 3D model of the moisture readings underneath the raft foundation in Botshabelo. The illustration shows that the moisture pattern is not a symmetrical dome. Therefore, utilizing a design procedure employing a mound, as suggested by Pidgeon, is not recommended. Various factors can influence the shape and position of the dome that will develop, such as the orientation of the building towards the sun, seasonal changes, the location of a re-entry corner and the landscaping of the surrounding areas.

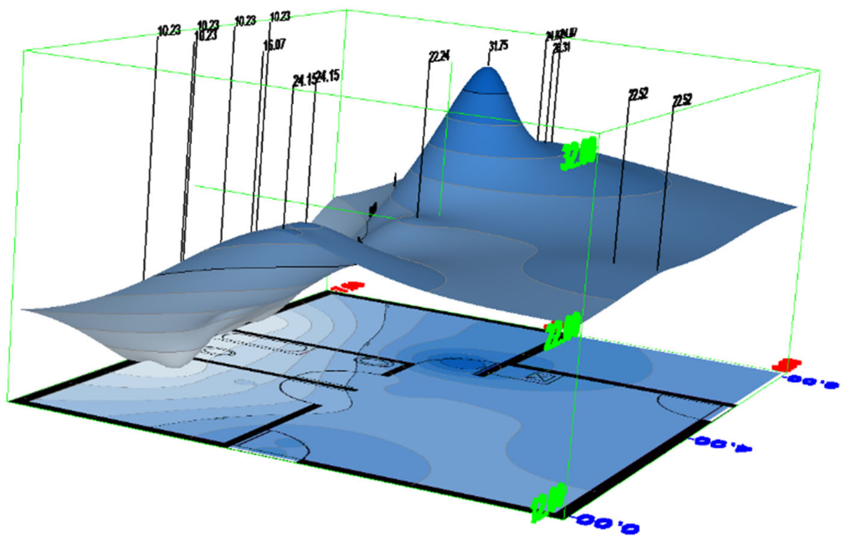

Figure 3. 3D visualization from the southwest corner of November 2014 moisture readings in Botshabelo at 150mm depth.

4 DESIGN CONSIDERATIONS AND RECOMMENDATIONS TO BE EMPLOYED

In many cases, stiffened raft foundations are the most cost-effective way to erect light structures on possibly expanding soil profiles. Although raft design techniques have been created in the past, their empirical nature suggests that their applicability is limited to specific soil and climate circumstances. Pidgeon (1988) devised a technique that applied to South African circumstances and presented an alternative design approach. Many distinct approaches or methods exist for designing stiffened raft foundations on expanding soils. Pidgeon (1980) compared these, and Pidgeon (1986) reviewed them critically. Only seven of these techniques are thorough, logical, and precise enough to be considered for application. Before formulating a method, this approach necessitates defining multiple elements: the type of soil model, the geometry of the soil mound, the soil/structure interaction model, the structure's loading representation, the foundation's shape and representation, and the concrete section analysis form. However, in most cases, a "swell-under-load" strategy makes more sense (Pidgeon 1980). However, based on Pidgeon's methodologies, either Figure 1 or 2 is recommended for the mould shape. It could result in a raft foundation design, which can fail due to not considering the extent and complexity of the moisture variation underneath. Based on the findings of the Botshabelo study, assuming a symmetrical dome could be problematic. Therefore, a modified design for raft foundations on expansive clay soils is recommended.

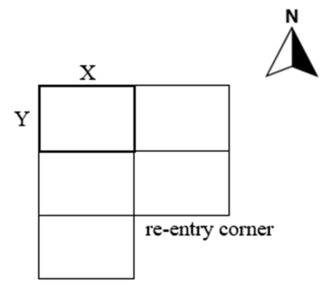

Figure 4. Design where the re-entry corner is considered based on the structure's orientation to the sun.

It is important to conduct a comprehensive site assessment before beginning any computations. The designer should recognize the orientation of the building to the sun, understanding the expected moisture variation conditions and soil profile. The design approach is to design the worst-case scenario pod of the raft foundation. Depending on the building's orientation, moisture concentration will move to the re-entry corner on the south side, as seen in Figure 4 in the southern hemisphere. Therefore, the pod furthest away is the northwest location. This location would be most prone to moisture changes to occur. Assume the pod is unsupported and fixed to one end. Design the pod so that the deflection of the pod should be within 1 in 3,500 for solid brickwork with no joints, and for brickwork with joints not exceeding 4m, it should be 1 in 1,000. The slab thickness, beam depth and width obtained by designing for the worst case should be adopted throughout the raft foundation.

Careful attention should be paid to the depth and width of the raft foundation beams. Figure 5 shows the NHBRC commonly used raft foundation design. This design is not recommended as the beams are not deep enough to control the moisture variation underneath the foundation adequately. Therefore, it is recommended that a design similar to Figure 6 be adopted on expansive soils, where the beams extend to a depth of 600 to 900 mm, depending on the soil condition. The more expansive the soil condition, the deeper the raft foundation beams should be located.

Additionally, the number of beams can be increased to increase the strength of the inner core of the raft foundation to prevent lifting of the inner floor slab in all weather conditions. Finally, it is good practice to provide an apron around the raft foundation which slopes away from it. This will help prevent additional moisture from migrating underneath the raft foundation.

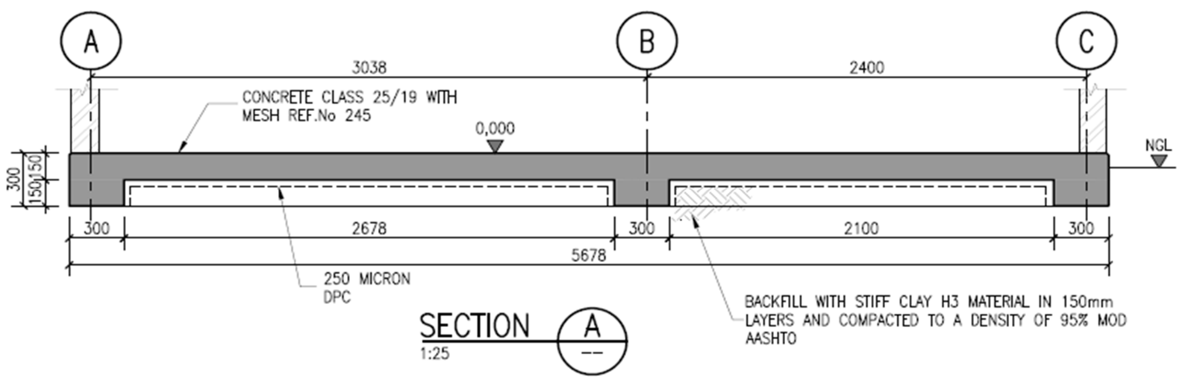

Figure 5. Commonly used raft foundation design used by the NHRBC (1999)

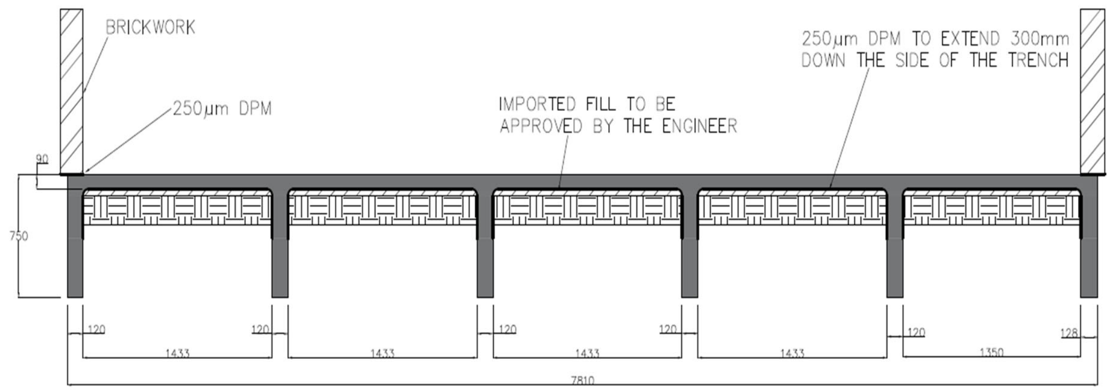

Figure 6. Proposed raft foundation design with deeper beams.

5 CONCLUSION

The moisture content measurements under a raft foundation built on expansive clay soil suggest that accepted heave patterns may not be reliable for foundation design. A new robust design procedure is recommended to account for the unpredictable characteristics of the moisture variation underneath raft foundations constructed on expansive clay soils. This approach should enable a more reliable design of a wide range of raft foundations, reducing the likelihood of failures. Designing on the worst-case scenario based on a cantilever furthest away from the expected moisture concentration would be located would provide the most robust design approach for a raft foundation design. Additionally, including beams as deep as possible in the design will limit the moisture variation changes due to the additional distance the moisture will have to travel underneath the raft foundation. Providing deep beams as part of the design will be a labour-intensive process which requires careful calculation, analysis, and construction supervision. Engineers can design a foundation that offers long-term durability for the supported superstructure by thoroughly grasping the soil conditions, location of the moisture concentration, and structural features such as the shape of the building.

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