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Construction Problems of Light Structures Founded on Expansive Soils in Sudan

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Abstract: ***Expansive soils in Sudan have been contributing to light structures failures and subsequently causing increased annual repair expenditure. The study aims to investigate the foundations problems associated with expansive soils and provides practical and economical solutions for construction on expansive soils in Sudan. The research is mainly concerned with field performance of expansive soils with emphasis on design criteria and construction precautions for structures founded on expansive soils. Some cases of existing light buildings and roads in different regions in Sudan, suffered from severe distresses and damages due to expansive soils, were studied. The results obtained clearly indicated that generation of high swelling pressure, which leads to differential heave of structures, is the main cause of failures. Finally, based on the case study investigation and the previous experiences recommended by researchers, proposed construction guidelines to assist the civil engineers to deal with expansive soils at design and construction stages of foundations is outlined and described.***

Keywords: expansive soils; foundations; structures; failures; construction.

1. Introduction

Expansive soil is one of the problematic soils that face many geotechnical engineers in the field (others include collapsible soil, quick clays, etc.). The problem of expansive soils was not recognized by engineers until the latter part of 1930. Expansive soil covers many areas in the world, especially the arid and semi-arid regions. In Sudan, there are several areas where this kind of problematic soil exists.

Expansive soils in many countries of the world pose a significant hazard to foundations for light Structures. Swelling clays experience significant volume change associated with changes in water contents. These volume changes can either be in the form of swell or shrinkage and this is why they are sometimes known as swell/shrink soils. Expansive clays can exert uplift pressures that cause significant damage to lightly loaded structures. Millions of dollars annually spend to repair buildings and other structures distressed by expansive soils. Various precautions have been considered by geotechnical engineers in order to minimize the risk of construction on expansive soils.

Recently, there is a world-wide interest in expansive clays. Researchers from many countries have contributed immensely to the knowledge and the proper foundation design for structures on expansive soils.

2. Literature Review

Expansive soil is a clay of smactite type which exhibits significant swelling when absorbs water. The three most important groups of clay minerals are montmorillonite, illite, and kaolinite. Such clay minerals are formed through a complicated process from an assortment of parent materials. Absorption of water by clays leads to expansion. The magnitude of expansion depends upon the kind and amount of clay minerals present. In general, montmorillonite clays swell when the moisture content is increased, while swelling is absent or limited in illite and kaolinite.

Potentially expansive soils can be recognized in the laboratory by their plastic properties. Clays of high plasticity, generally those with liquid limits exceeding 50 percent and plasticity index over 30, usually have high swelling potential. In the field, expansive clay soils can be easily recognized in the dry season by the deep cracks, in roughly polygonal patterns, in the ground surface (see Figure 1).

Figure 1: Expansive soil with polygonal patterns cracks

2.1. Expansive Soils in Sudan

Sudan is one of the countries with a wide distribution of expansive soils. Over one-third of Sudan's 1,886,068 square kilometers have expansive soils. Unfortunately, this area includes most of the nation's population centers and development projects. The frequent failure to recognize the potential problem has resulted in extensive damages. In some cases, the cost of repairs or replacement of damaged structures has exceeded the structure's initial value, [1].

Sudan has a tropical climate over most of the country. The climate ranges from a desert climate in the north having a short rainy season during the months of July-September, to an equatorial rainy zone in the southern border. In Khartoum, the capital of Sudan, temperatures of 32°C to 40°C are common throughout the year, with recorded extremes as high as 48°C in May.

In general, Sudan shows several soil types which have developed because of differences in climate and nature of parent rock. According to Charlie [2], desert sands occur in the north and west of Sudan, lateritic soils in the south and southwest areas and alluvial soils occur along the main Nile river and its branches. The expansive clay soils or black cotton soils are generally weathered sediment derived from the volcanic Ethiopian Highlands. This clay is commonly alkaline, containing calcium carbonate and gypsum, with the clay fraction composed largely of montmorillonite.

The wide range of climate and geology in Sudan produces a great variety of foundation problems. In general, central and eastern Sudan, including Khartoum, Gezira and Gedarif states, expansive clays problems are strongly evident. The soils in this region are generally desiccated. Also, in this area of Sudan, shallow foundations are commonly used. There have been very many cases where pressures of expansive clays have caused severe distresses and damages to buildings and other light structures.

2.2. Problems of Expansive Soils

Expansive soils are a worldwide problem, causing extensive damage to civil engineering structures. These soils pose the greatest hazard in regions with pronounced wet and dry seasons. Thus, the problems of expansive soil are the result of its changing in volume upon wetting and drying. The moisture change can be due to seasonal changes, garden watering, leaking underground water services, and deficient storm water drainage system.

A great deal of structural movement has been unduly blamed on expansive soils. Many floor slabs constructed in an expansive soil area crack and sometimes heave due to improperly designed concrete. It is a well known fact that improper curing of concrete, in addition to the lack of expansion joints, will cause cracking. Curing of concrete slabs has a strong resemblance to heaving floors caused by swelling soils. This is especially true for large warehouse floors where proper curing and design is essential.

In expansive soil areas, the soils are generally stiff, and the chance of lightly loaded structures cracking due to settlement is rather remote. At the same time, there are a large number of instances where heavy cracks have appeared in the basement walls that were not caused by foundation heaving but by earth pressure exerted on the wall, generally compounded by seepage pressure. In most cases where vertical or horizontal cracks developed in the basement wall, earth pressure problems are suspect. Diagonal cracks that develop below windows and above doors are a strong indication of swelling movement.

Expansive soils are oftentimes blamed for arching of a wall when actually improper reinforcement and restraint is the real problem. Backfill should not be placed against the wall until the wall has been properly restrained at top and bottom. Failure may result horizontal swelling pressure being exerted against the wall. While it is possible that a large amount of swelling pressure can be exerted horizontally against a wall, generally backfill is so loosely compacted that distress caused by lateral expansion of backfill is very uncommon.

Structural defects are sometimes mistaken for distress caused by swelling soils. Split level houses are generally constructed with grade beams placed at different levels. Such grade beams, if not properly tied together with reinforcement, can result in cracks and movement.

While it is true that swelling soils are probably responsible for most of the cracking and movement of lightly loaded structures, other aspects of foundation movement should not be ignored.

The losses due to extensive damage to structures founded on expansive soils are estimated to be in billions of dollars all over the world. In the United States alone, Nuhfer [3] reported that annual losses due to expansive soils are between $6 billion and $11 billion in damages annually to buildings, roads, airports, pipelines, and other facilities. In Sudan, the estimated cost of buildings and light structures swell related damage exceed $6 million, [2].

2.3. Soil Improvement

Many researchers have been trying to investigate the proper techniques of soil improvement that could be used to reduce the expected structural damages due to the swelling behavior of expansive soils. It is well known as stated by Ramanujam [4] that the purpose of using the most common techniques of soil improvement are to prevent or limit moisture ingress, change properties of the soil and suppress movement with overburden.

Marei [5] conducted an experimental study to investigate the effect of using different techniques on the behavior of expansive soils. They found that using the method of removal and replacement by non-swelling soils significantly reduced the swelling characteristics. The treatment by sand-lime mix caused the largest reduction in swelling potential and swelling pressure compared to other treatments (sand or clayey silt), which was attributed to the effect of the chemical action of lime. Marei [5] concluded that the sand-lime mix also caused a slower rate of swelling and considerable improvement in the shear strength properties of the expansive soil. Chen [6] conducted a research using various stabilizers including calcium lime, Portland Cement and lime/cement mixtures to conclude that lime shows the greatest improvement to compressibility, CBR and swelling. Byer [7] recommended using a compacted expansive soil-lime mixture (4% by weight of quicklime) to overcome the cracking and sliding of the side slopes lining of Friant-Kern canal in California, USA.

Sorochan [8] recommended adopting soil replacement for the beds and side slopes of waterways constructed in expansive soil deposits. He reported that the materials used consist of loams, sandy loams, non-expansive clays, and sands or sand-gravel mixes. Sorochan [8] found that this treatment technique reduced the non-uniform heave of expansive soil. Katti [9] showed that using a cohesive non-expansive soil, of adequate thickness on top of the expansive soil layer, underneath the foundation, is effective in improving the strength and reducing the swelling characteristics of expansive soil.

Recently, geosynthetics including geotextiles, geogrids, and geomembranes are materials used to improve soil conditions. Geotextiles play a role in separating materials, reinforcing, filtering, draining and/or providing a moisture barrier, [10]. As stated by Zornberg and Gupta [11] that geotextiles reinforce the subgrade of expansive soil by providing lateral restraint, tensile membrane support and increasing the bearing capacity.

The soil improvement experiences reviewed have been practiced with varying degrees of success. However, these techniques may suffer from certain limitations with respect to their adaptability, like longer time periods required for pre-wetting the highly plastic clays [12], difficulties in constructing the ideal moisture barriers [10], pulverization and mixing problems in case of lime stabilization [6], high cost for geogrids reinforcement and geosynthetic reinforcement, [11].

3. Case Study

A detail investigation into distresses and damages to buildings of single or two storey and light structures were undertaken through visual inspection. Due to some constrains in terms of length of paper, only few examples of the damaged structures are presented here, as described in the following sections.

3.1 Khartoum

Khartoum is the capital and largest city of Sudan. Soil properties vary throughout the city with expansive soils occurring east of the Nile and White Nile. Expansive soil damages have occurred to projects of light buildings, roads, and water and sewer pipes located in various parts of the city, especially the southern parts where the surface is underlain by a thick layer of expansive soils.
Many one and two storey buildings utilizing shallow foundations have been extensively damaged. It is observed that severe cracks and uplifting of floors are common distresses of most houses throughout the city. Figure 2 shows damage to the room wall on the ground floor. It can be observed from Figure 2 that the wall has developed a severe diagonal crack. It is observed also, most of the damaged walls in the front face of the structure. This is because of plants in the front garden which is subjected to considerable watering continuously throughout the year. Therefore, the subsequent swelling of the soils has exerted an uplift force on the wall resulting in the development of a crack.

Figure 2: Typical severe diagonal deep crack in the wall

Some major roads in Khartoum state such as Obeid Khatim, Alazhari and Alarda roads suffered from severe distresses and damages, [13]. He found that the main causes of these failures due to expansive subgrade soils and poor drainage, leading to severe cracking and heave on road surface. Although these roads were maintained several times during the last 10 years but still suffered from failures (Figure 3).

Figure 3: Severe distresses of heave on Alarda road, [13]

3.2 Gezira University

This case study is typical of what happens when foundations are placed on expansive soil without considering uplift forces. In this instance the study involves many buildings of the university were constructed without benefit of adequate design. The university is situated in Wad Medani in Gezira state, 250km south of Khartoum. Many buildings of the faculty of medicine in Nishaishiba area greatly suffered from expansion. The site is underlain by a 5m thick expansive soil layer. The single and two storey buildings supported by isolated footings, placed at a depth of 2m has experienced significant damages near bathroom areas. Visual inspection by the author indicates that most of the buildings suffered from severe cracking and uplifting of ground floors by soil expansion as shown in Figure 4. As stated in the records of the university that the repairs of these buildings amounted to more than 6% of their initial cost.

Figure 4: A severe cracks of ground floor and inside walls

3.3 Asalaya Sugar Factory

The factory is situated on the east bank of the White Nile about 280km south of Khartoum. The site is underlain by a 6m thick layer of clay having a high swelling potential. The factory was poorly sited since an outcrop of non-expansive soils having good natural drainage lie within a few kilometers of the site. Because of the expansive soil, the factory was founded on bored piles 6.5m long. Floors were placed on grade and not designed to resist upheaval forces. To reduce uplift forces on the piles, the upper 3m were cased with plastic pipe. In addition, the factory was underlain by polyethylene sheeting intended to prevent process water from seeping through the floor and into the soil. In spite of these precautions, the soil has swelled heavily and the factory has experienced significant movement of floors and uplift of piles forcing suspension of process operations. Investigations of the damage indicate that rain water, factory process water spills, and water leaking from water and sewage pipes and external drains are the source of moisture increase in the soil and thus the cause of the swell. As stated in the records of the factory that the estimated remedial and maintenance costs related to the expansive soils will exceed the original construction costs, possibly by a factor of three.

3.4 Rahad Irrigation Project

This is a large irrigated farm project which situated 300km southeast of Khartoum. Deep deposits of highly expansive soils, known as Black Cotton Soils, exist throughout the project. Damages caused by expansive soils occurred to most of the buildings constructed within the project. The single story staff housing and administrative buildings founded on short column or short piles showed severe cracks because of soil upheaval movement. A severe damage to the staff housing is shown in Figure 5 and consists of wide cracks in the exterior walls and roof has been observed in kitchen and bathroom areas, probably due to leaky service lines. Initial damage occurred following heavy rains which flooded the site shortly after construction. The flooding was caused by road embankments hindering rapid runoff. It is stated in the technical reports of the factory that maintenance and repair of such damages cost more than 5% of their initial costs.

Figure 5: Severe wide cracks in walls and roof

4. Construction Guidelines

The main objective of this study is to derive practical and economical construction guidelines to eliminate or minimize the swelling damages to light loaded civil structures. This may be achieved by justifying some improvements to the current design and construction practices to suit Sudan.

The suggested construction guidelines are based on previous studies recommendations and experiences, ([14], [15] and others). As with any foundation the main aim is to minimize effects of movement, principally differential, and two strategies are used when dealing with expansive soils:

- Isolate structure from soil movements
- Design a foundation stiff enough to resist movements

4.1 Foundation design

For proper design of foundations on expansive soils, the following criteria are to be considered:

- Sufficient dead load pressure is exerted on the foundation
- The structure is rigid enough so that differential heaving will not cause cracking
- The swelling potential of the foundation soils can be eliminated or reduced.

The recommended foundation alternatives when dealing with potentially expansive soils include:

1) Strip or continuous footings

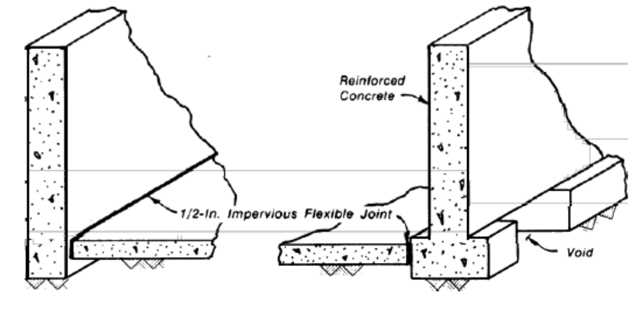
This is the most common type of foundation used for lightly loaded structures. The use of strip footing should be limited to expansive soils at shallow depths not more than 2m and with low degree of expansion less than 1 percent and a swelling pressure of less than 40 kpa.

To use the strip foundations on expansive soils, the following modifications are to be considered:

- Basement walls of reinforced concrete can be constructed directly on the foundation soil without footings, provided foundation pressures are less than the allowable bearing capacity (Figure 6a).
- To concentrate sufficient dead load pressure on expansive soils, the width of the footing should be as narrow as

possible. Voids can also be spaced at intervals beneath the walls to increase loading pressures on the foundation soil and to minimize flexing of the walls (Figure 6b).

- Joints should be provided if slab-on-ground is used. The slab should be isolated from the walls with a flexible impervious joint (Figure 6a and 6b).



a. Wall Without Footing b. Wall with Footing and Void Space

Figure 6: Basement walls with slab-on-grade

2) Pad footings

The pad foundation can only be used in those areas where the expansive soils possess only a medium degree of expansion with volume change of 1 to 5 percent and a swelling pressure in the range of 40 to 60 kpa. When pad footings are used, some modification should be applied to minimize the effects of swelling and shrinkage. Modifications include:

- Narrowing footing width
- Provide void spaces within support footing to concentrate loads at isolated points
- Increase perimeter reinforcement.

3) Raft foundations

Raft foundation, sometimes referred to as slab-on-grade or reinforced and stiffened slab, is often suitable for small and lightly loaded structures, particularly if the expansive soil extends from the ground surface to deep depths. This raft is suitable for resisting subsoil heave. A thick, reinforced raft is suitable for large and heavy structures. The rigidity of thick rafts minimizes distortion of the superstructure from both horizontal and vertical movements of the foundation soil.

Concrete slabs without internal stiffening beams are much more susceptible to distortion from heaving soil. Stiffening beams and the action of the superstructure with the raft as an indeterminate structure increase foundation stiffness and reduce differential movement. Edge stiffening beams beneath reinforced concrete slabs can also lessen soil moisture loss and reduce differential movement beneath the slab. Stiffened slabs may be either conventionally reinforced or post-tensioned. The raft may be inverted (stiffening beams on top of the slab) in cases where bearing capacity of the surface soil is inadequate or a supported first floor is required. Design procedures consist of determining bending moments, shear and deflections associated with structural and swell pressure loads. The general layout used is illustrated in Figure 7.

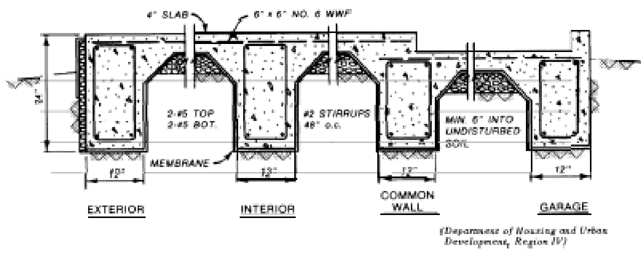


Figure 7: Typical detail of a stiffened raft, 14

4) Pier/Pile and beam foundations

These foundations consist of a ground beam used to support structural loads, transferring the load to the piers or piles. Between the pier/pile and ground beam a void is provided to isolate the structure and prevent uplift from swelling. Floors are then constructed as floating slabs.

The piers/piles are reinforced (with reinforcement taken over whole length to avoid tensile failures) concrete shafts with or without belled bottoms, steel piles driven or pushed, or helical pile whose aim is to transfer loads to stable strata. Under-reamed bottoms and helical piers/piles can be effective in soils with high swell potential overcoming the impractical length that would otherwise be required with straight shaft piers/piles, or where there is a possibility of a loss of skin friction due to rising groundwater levels. If a stable non-expansive stratum occurs near surface pier/pile can be designed as rigid anchoring members. If however, the depth of potential swell is high, piers/piles should be designed as an elastic member in an elastic medium. Figure 8 illustrates a typical pier and beam foundation.

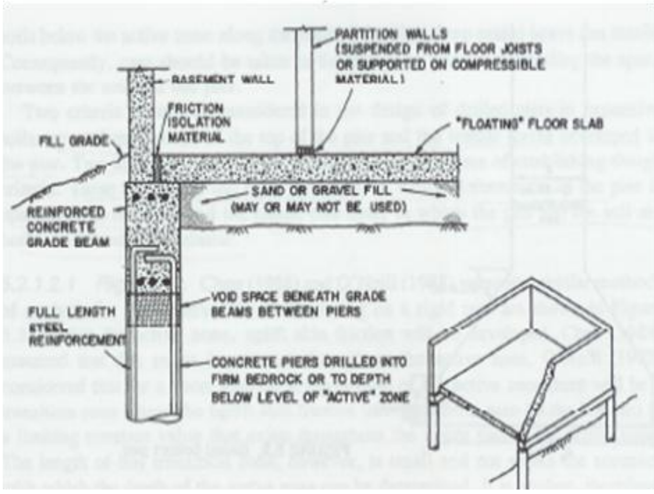


Figure 8: Illustration of a Pier and beam foundations, 15

4.2 Minimization of foundation movement

For proper and effective foundation design on expansive soils, it is essential to minimize the foundation movement. This is achieved by different techniques as described below..

1) Removal and replacement

Removal of about 1.2 to 2.4m of surface swelling soil and replacement with nonexpansive, low permeable backfill will reduce heave on foundation. This depth depends on the overburden pressure to counteract the swelling of soil. Backfills adjacent to foundation walls should also be non-swelling, low permeable material. Non-swelling material minimizes the forces exerted on foundations, while low permeable backfill minimizes infiltration of surface water through the backfill into the foundation soil. If only pervious, non-expansive (granular) backfill is available, a subsurface drain at the bottom of the backfill is necessary to carry off in filtrated water and to minimize seepage of water into deeper desiccated foundation expansive soils. In general, the backfills of selected materials should be compacted to 95 percent of standard maximum density and should be wet of optimum water content. As an alternative, backfills of lime-treated natural soil compacted to 95 percent standard maximum density at optimum water content may be satisfactory if the soil is sufficiently reactive to the lime.

2) Moisture barriers

The purpose of moisture barriers is to prevent or minimize the movement of water beneath the foundation through the membrane and thus reducing cyclic edge movement. These barriers consist of horizontal and vertical plastic and asphalt membranes and granular materials. Concrete is an ineffective moisture barrier. The horizontal moisture barriers are used around the perimeter of the structure to reduce lateral variations in moisture content and differential heave in the foundation soil. Plastic or other thin membranes around the perimeter should be protected by a 15 to 30 cm thick layer of earth. The vertical barrier should extend to the depth of the active zone and should be placed a minimum of 1m from the foundation to simplify construction and to avoid disturbance of the foundation soil.

3) Adequate drainage

Drainage is provided by surface grading and subsurface drains. The most commonly used technique is grading of a positive slope away from the structure. The slope should be adequate to promote rapid runoff and to avoid collecting, near the structure, ponded water, which could migrate down the foundation soil. These slopes should be, greater than 1 percent and preferably 5 percent. Covered drains can be provided to discharge away the surface runoff water. Subsurface drains may be used to control a rising water table, groundwater and underground streams, and surface water penetrating through pervious soil. Subsurface drains or perforated pipes, 15 cm diameter can help control the water table before it rises but may not be successful in lowering the water table in expansive soil.

5. Conclusion

From the results of this study, the following conclusions may be drawn:

- The governing factors which contribute to the problems and damages to light structures include: the type and amount of clay minerals, initial moisture content, ingress of surface water into ground, foundation design and the soil investigation, prior to the construction.
- It was found that the damage to light structures was due to generated uplift forces resulting from heave caused by the swelling of soils in response to increase in moisture content. The repairs and maintenance of such damages cost more than the initial construction costs.
- Based on recommendations and experiences of previous researches, practical and economical construction guidelines are recommended to be used in Sudan.

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