Expansive Clay Soil-Structure Interaction: A Case Study

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Abstract—**Expansive soils are problematic due to the extensive damages they may cause to structures and infrastructure. This paper presents results from a case study conducted in an area (Irbid, Jordan) that is characterized by a surficial formation of highly expansive soil. A school building suffering from damages that are attributed to the shrinkage of the soil layer under the foundation was investigated. The interaction between the expansive clay soil layer and the structure was studied through diagnostic investigation of the existing cracks, the properties of the foundation ground, and the climatic and other relevant stratigraphical factors. The results of this study indicated that the structural damages in building members (columns, beams and footings) were mainly due to the swelling gradient. Remedial measures were proposed to rehabilitate and strengthen the structure and prevent further damages.**

Index Terms—**expansive clay, soil-structure interaction, shrink-swell of clay**

I. Introduction

Expansive soils pose a severe threat to civil engineering infrastructure worldwide. Excessive cost of damages to infrastructure mainly due to expansive soils is reported each year. Expansive soil is typically characterized by its potential for significant volume change with varying water content. Expansive soils are especially abundant in arid zones [1]. The primary factors governing the behavior of expansive soil are grouped under three categories: i) geology, ii) soil index properties, and iii) environmental factors. Geology is important in determining the formation and presence of expansive clay minerals as well as the amount of aging. Soil index properties indicate the type and amount of clay particles, dry density and water content of the soil. The most relevant environmental factors are the presence of vegetation, as it affects the moisture content of the soil, and amount of precipitation and wetting-drying cycles as they can cause great variation in the moisture content. In addition to all these factors, when it comes to design of foundations on expansive soil, the surcharge pressure plays a significant role on the expansion potential and the interaction between the soil and structure. In general, light structures (i.e., low rise buildings) are very prone to damages resulting from expansive soil. This paper presents a case study from an area (Irbid, Jordan) characterized by a surficial formation of highly expansive soil. A low-rise school building with symptoms of distress and visible cracks was investigated to address the source and extent of damages and propose rehabilitation measures.

II. Site Description

A. Location, Climate and Stratigraphy

The site is located in Irbid, Jordan Fig. 1, which is a semi-arid area with a long rainy season (November through April), followed by a hot dry summer (May through September). The annual precipitation in the study area varies from 200 mm to 800 mm. The site is covered by a surfacial layer of expansive clay soil. The typical soil profile in the area consists of 2 - 3 m of dark grayish brown clay layer underlain by reddish brown clay layer down to a depth of 10 m. Then, weathered materials of large rounded boulders of basalt exist just above the clay/basalt interface [2].

Figure 1. Location map of the study site.

B. Current State of Structure

The structure of study is a reinforced concrete (RC) structure consisting of a "library building" and "main building" as shown in Figs. 2 and 3, respectively. The main building consists of ground, first, and second floors while library buildings are ground floor only. The visual inspection of the structure revealed evidence of cracking of external and internal walls of the western portion of the buildings. The structure had been subjected to cosmetic repair for cracks, however cracks have redeveloped and reappeared. Some photographs showing the current state of cracks/damages are presented in Fig. 4

III. Field Exploration and Laboratory Testing

A. Field Exploration

For field exploration purposes four test pits were excavated. The approximate locations of these test pits are marked in Figs. 2 and 3. The test pits reached to depths of 210 cm to 265 cm below ground surface. Disturbed soil samples were collected at various depths for laboratory testing. All sides and the bottom of each test pit, including foundations, were thoroughly examined. Soil strata and material recovered were described.

Existing cracks were spotted and monitored for a period of about 3 months by using thin glass till tales that were fixed across existing cracks at different locations at the interior face of the building walls.

B. Laboratory Testing

Laboratory tests were performed on selected samples from each test pit. The percentage of sand, silt, and clay for the studied soil were determined in accordance with ASTM procedure [3] and found to be (8-11) %, (52-54) % and (35-40) %, respectively. Atterberg limits were determined according to ASTM procedure [4]. The results showed that the soil samples have Liquid Limit (LL) of (58-63) %, Plastic Limit (PL) of (30-31) %, and Plasticity Index (PI) of (28-32) %. Based on Unified Soil Classification System (USCS), the soil was classified as high plasticity clay (CH). The degree of potential expansiveness was determined as *high expansiveness* according to the chart given by [5].

IV. Foundation Inspection

A. Test Pit 1(Library Building)

The RC foundation has dimensions of 100 x 130 x 30 cm and depth of 250 cm from the adjacent external sidewalk level. The foundation is underlain by a plain concrete layer with thickness of 15 cm and protrudes a distance of 15 cm from the external face of the footing. The foundation materials are composed of dark brown, very stiff to hard silty clay material with occasional gravels of chert and limestone.

B. Test Pit 2 (Library Building)

The RC foundation has dimensions of 120 x 150 x 35 cm and depth of 265 cm from the adjacent internal ground level. Similar to the formation of Test Pit 1, the soil beneath the foundation is dark brown, very stiff to hard silty clay with occasional gravel of chert and limestone.

C. Test Pit 3(Main Building)

The RC strip foundation has width of 180 cm and thickness of 30 cm. The foundation is placed 215 cm below the adjacent external sidewalk level. The soil formation underlain the foundation is consistent with that of previous test pits (i.e., Test Pits 1 and 2), revealing dark brown, very stiff to hard silty clay with occasional gravels of chert and limestone.

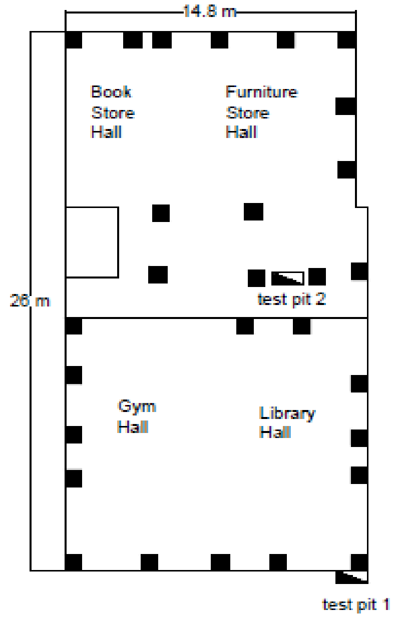

Figure 2. General layout of library building and test pits

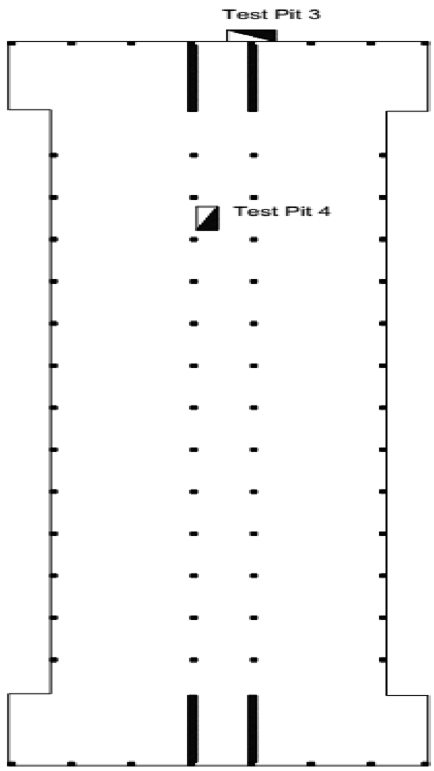

Figure 3. General layout of main building and location of test pits.

D. Test Pit 4 (Main Building)

The RC strip foundation has width of 190 cm and thickness of 30 cm. Depth of foundation is 210 cm from the adjacent internal ground level. The soil beneath the foundation was found to be the same as that discovered in the other test pits; dark brown, very stiff to hard silty clay material with occasional gravels of chert and limestone. Location of test pits in the library and main buildings are shown in Figs. 2 and 3, respectively. Fig. 5 shows cross section of the foundation in the main building Test Pit 4.

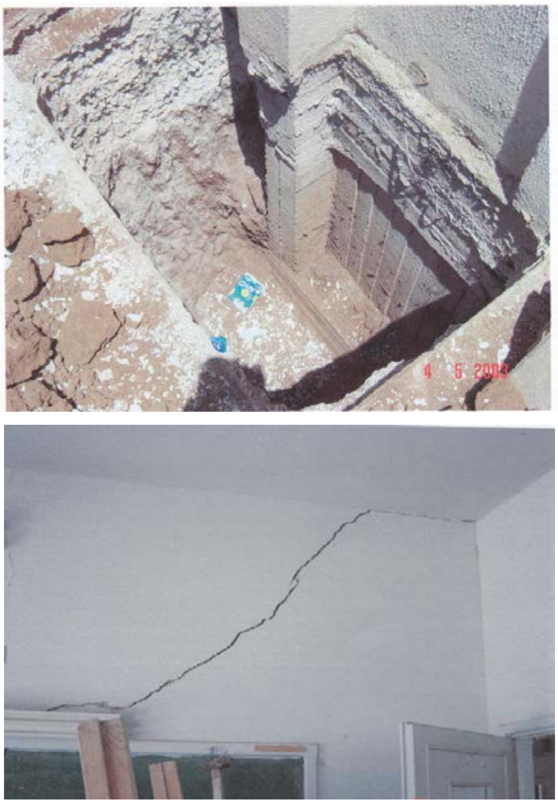

Figure 4. Test pit 3 and state of cracks in main building

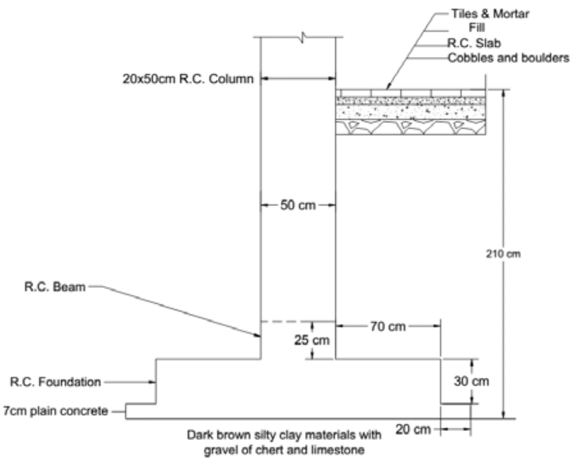

Figure 5. Elevation view of foundation at test pit 4 in the main building

V. Analysis of the Laboratory And Field test Results

The expansive clay layer is the focus of this study. To understand the interaction between the soil and the structure, it is important to quantify the swell/shrink potential and bearing capacity of this founding clay layer. The average value of the measured corrected standard penetration test blows/ft, N_{60} at the depth of foundation was 17. The undrained compressive strength may be found through empirical correlations employing N_{60} value and PI [6]. Using such correlation, the unconfined compressive strength of the stiff clay was estimated as 200 kN/m^2. The allowable bearing capacity of the foundation was calculated based on [7]: $q_{ult} = S_u N_c / FS = 100 \times 5.14/3 = 171$ kN/m^2. The dead load and live load on the slab were computed as 7 kN/m^2 and 4 kN/m^2 respectively. The calculated bearing pressure was 156 kN/m^2 which is less than the allowable bearing capacity of the soil.

VI. Description and Classification of Cracks

A. Cracks in the Library Building

Most of the cracks took place at the western portion of the building, and particularly at the southern west and northern west corners of the building. Diagonal, vertical and horizontal cracks were observed at internal and external walls, particularly at the library room and in the furniture store room.

B. Cracks in the Main Building

Most of the cracks in the Main Building were found to be at the external and internal walls of the western staircase of the building, at the ground and first floors. Two diagonal cracks were observed at internal partitions, and columns located in the ground and first floors.

Based on the cracks classification given by [8] the observed cracks classification ranged from *negligible* to *moderate*.

VII. Swelling Pressur and Swell Potential

The relationship between the swell potential and plasticity index can be expressed as follows [9]

$$S_p = Be^{A(I_p)} \quad (1)$$

Where, A = 0.0838, B = 0.2558 and I_p = plasticity index. Using Eq. (1) the swell potential of the clay can be calculated as 3.7 %. In the present study the depth of the expansive clay layer was found to be 8 m below the ground surface. The depth of foundation was found to be on average about 2.0 m in the main building as shown in Fig.6, and 2.5 m in the library building. The depth of the active zone extends down to 3.5 m. Thus, the thickness of clay layer beneath foundation that is susceptible to heave due to moisture content variation is 1.5 m in the main building and 1.0 m in the library building.

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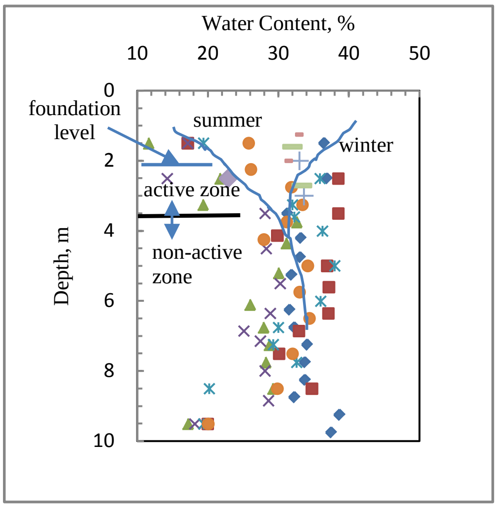

Figure 6. Seasonal variation of water content with depth for Irbid soil. [12].

Based on the calculated percent heave, the total surface heave is estimated to be 5.6 cm under the main building and 3.7 cm under the library building. These values of heaving result in significant angular distortion; 1/135 and 1/90 for the library building and main building, respectively. Such large values of angular distortion are immediate cause for cracking in the structure, as they exceed the allowable limit of 1/500 for single and multistory structures [10]. The variation of swelling pressure in the area with natural moisture content may be calculated from Eq (2) [11]. The results of this equation coincides well with measured values of Irbid clay [12].

$$log p_s = -2.0 + 0.02LL + 0.001\rho_d - 0.04w_n \quad (2)$$

Where p_s = swelling pressure in kg/cm^2
LL = liquid limit (%)
w_n = natural moisture content (%)
ρ_d = dry density of soil in kg/m^3

The variation of swelling pressure with the moisture content variation is plotted in Fig. 7 as predicted by Eq. (2).

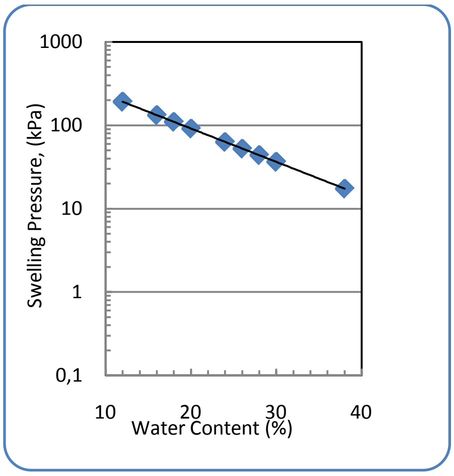

Figure 7. Variation of swelling pressure with the moisture content for the studied soil.

VIII. Causes Of Cracks

Based on the field observation and Laboratory tests conducted in this study the following factors were found to contribute to foundation movement observed cracks.

A. *Depth of Foundation*

The foundation is located within the active zone i.e. the zone of the seasonal moisture variation. Depth of foundation ranges from 215 to 265 cm below the adjacent external sidewalk level while the depth of the active zone is 300 cm.

B. *Foundation soil*

The foundation soil was found to bee highly plastic with high swelling potential. Thus, the soil is susceptible to movement by swelling and shrinkage as a result of moisture content variation.

C. *Moisture Content Variation*

The main cause of foundation movement either upward or downward is the change in soil moisture content. This change is resulted from changes in the field environment from natural conditions. For the library building, the moisture content at the time of the investigation (April) was found to be 25.1 % at the base of the foundation outside the building (Test Pit 1) while it was found to be 12.9 % under the footprint of the building (Test Pit 2). Such discrepancy between the values of moisture content inside and outside the building may be explained by the presence of plants and tress surrounding the perimeter of the building. Further, the footprint area of the building is covered by the structure itself that limits the exposure, thus is likely to experience less variation in the moisture content when compared to the outer perimeter which is open with direct exposure. The difference in moisture content between inner and outer perimeters leads to dish-shape heaving as shown in Fig. 8. This may explain the cracks in the exterior walls of the library building.

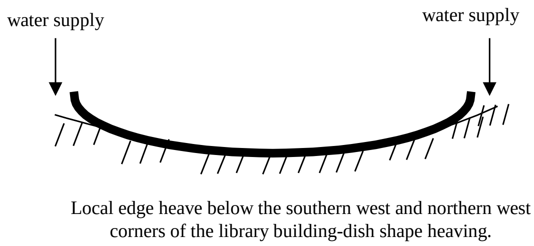

Figure 8. Local edge heave below the southern west and northern west corners of the library building-dish shape heaving

The moisture content for the main building at the time of the investigation was found to be 17.3 % in the soil of uncovered area and 19.2 % in the soil of covered area at the base of the foundation. The high value of moisture content in the covered area is due to the migration of water vapor from higher temperature uncovered area to the cooler inside covered area to equalize the thermal energy of the two areas. The construction of the main building was started in the summer where the moisture content was low. However, the moisture content has

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increased with time.. It is important to pint out that the moisture content in the uncovered area starts a decreasing trend towards the summer, and especially because of the plants and tress nearby. Such decrease in the uncovered will result in what is called doming heave as shown in Fig. 9.

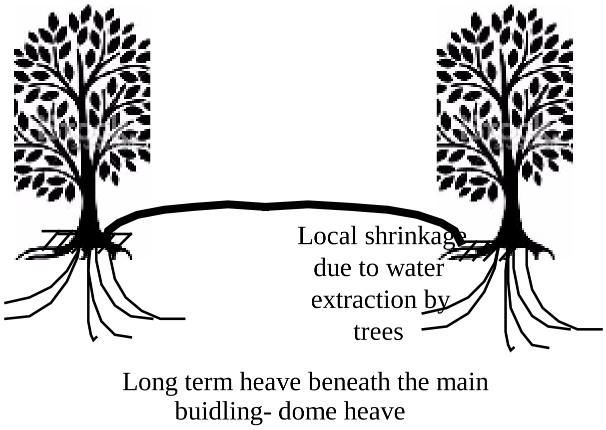

Figure 9. Long term heave beneath the main building- dome heave

D. Surrounding pavement

It was observed that the library building is surrounded by a pavement of width of 1 m from the south and north sides of the building. The pavement showed sagging, settlement and cracks and separation from the adjacent walls. Thus water from rainfall and surface water is allowed to drain towards the foundation causing moisture content variation.

E. Effect of Trees

At the site, trees and various plants of dense population were found to surround the building. The extraction of water from soil due to the existence of trees and plants is expected to be substantial.

Building damage can be noticed as trees height becomes approximately equal to their distance away from the building. In nearly every such case damage has subsequently increased in severity as the trees have grown higher heights. In most cases the crack patterns have indicated relative downward movement of the part of the building nearest to trees. This fact can be taken as circumstantial evidence that the building damage has been caused by moisture extraction from the ground associated with tree growth and root spread. The main cause of water removal and replenishment is the weather; shrinkage of the ground occurs due to evaporation in the hot dry season, and swelling occurs due to rainfall infiltration in the cool wet winter season. The ability of the climate to remove water from ground is greatly increased by the pumping action of plants which transpire moisture through their leaves into the atmosphere; the moisture is taken from the ground by fine roots.

IX. Building repair and Remedial measures

The type of building repair and any remedial measures undertaken on a damaged building will depend on three factors: the extent and scale of the damage, the nature of the movement causing the damage and the cost of the repairs and remedy in relation to the value of building. In the current study the following remedial measures and building repair types were recommended:

A. Environmental Control

1. Sloping the ground down and away from the buildings so that any water run-off flows away from it.
2. Ensuring that water supply pipes and sewer pipes are all not damaged and not leaking and sufficiently flexible, or are flexible connected, to accommodate movements.

3. Ducting all rainwater falling onto roofs well away from the foundations to the adjacent streets or areas.

4. Cutting all trees around the buildings particularly, the tress located at the northern side of the library building, and the western side of the main building.

5. For library building. It is recommended to reconstruct the pavement (approximately 2 m wide) at the northern and southern sides of the building. The pavement in general shall be slopping outwards at 2.5 % in order to protect the soil near the building from surface water. The pavement should not be connected to the building though dwells instead it should be separated from the building by sealed vertical slip joint. Suggested typical details for the pavement are shown in Fig. 10.

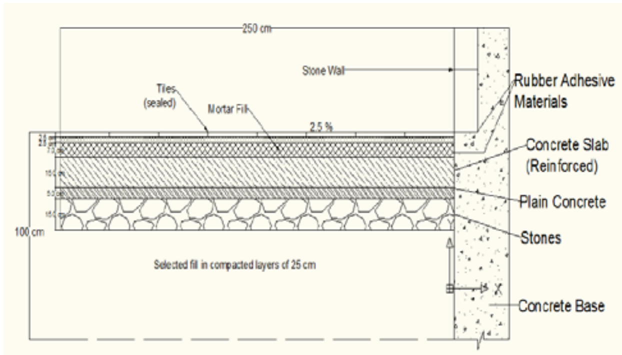

Figure 10. Pavement Details

B. Building Repair

It is expected that the implementation of the remedial technical and environmental measures specified in (A) will restrict the problem and swelling and shrinkage of the foundation soil appreciably. Continuous monitoring of crack progression is recommended and in case there is any underpinning to the foundation in away to increase the depth of the foundation below the active zone region (3 m depth) below the ground surface. If no further movement is detected at least six months after the implementing of the remedial measures, crack repair may proceed.

X. Conclusion

A damaged RC building due to an expansive soil was investigated in the form of a case study. Diagnostic analyses of the damage were conducted through reconnaissance measurements. The investigation showed that the foundation soil is highly plastic and has high expansiveness potential. The field and laboratory measurements showed that the main reason for building cracking was the swell/shrink movement of the foundation soil and consequently the building foundation. Calculated angular distortion was found to exceed by far the allowable limit for typical residential buildings. This finding was significant in identifying the causes of differential movement of foundation and eventual cracking of the walls of the building. Remedial measures were prescribed in the current study. The proposed remedial measures focused on isolating the foundation of the building from the water so, there will be no change in moisture content over the year which will substantially reduce the swell/shrink movement of the foundation and ceasing the building movement.

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