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ORIGINAL ARTICLE

Geotechnical properties of Egyptian collapsible soils

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Abstract The risk of constructing structures on collapsible soils presents significant challenges to geotechnical engineers due to sudden reduction in volume upon wetting. Identifying collapsible soils when encountered in the field and taking the needed precautions should substantially reduce the risk of such problems usually reported in buildings and highways. Collapsible soils are those unsaturated soils that can withstand relatively high pressure without showing significant change in volume, however upon wetting; they are susceptible to a large and sudden reduction in volume. Collapsible soils cover significant areas around the world. In Egypt, collapsible soils were observed within the northern portion of the western desert including Borg El-Arab region, and around the city of Cairo in Six-of-October plateau, and Tenth-of-Ramadan city. Settlements associated with development on untreated collapsible soils usually lead to expensive repairs. One method for treating collapsible soils is to densify their structure by compaction. The ongoing study presents the effect of compaction on the geotechnical properties of the collapsible soils. Undisturbed block samples were recovered from test pits at four sites in Borg El-Arab district, located at about 20 km west of the city of Alexandria, Egypt. The samples were tested in both unsoaked and soaked conditions. Influence of water inundation on the geotechnical properties of collapsible soils was demonstrated. A comparative study between natural undisturbed and compacted samples of collapsible soils was performed. An attempt was made to relate the collapse potential to the initial moisture content. An empirical correlation between California Bearing Ratio of the compacted collapsible soils and liquid limit was adopted. The presented simple relationships should enable the geotechnical engineers to estimate the complex parameters of collapsible soils using simple laboratory tests with a reasonable accuracy.

1. Introduction

The increase of population in most urban areas in Egypt, such as Alexandria, resulted in development in the suburbs, which requires development of marginal land that may include deposits of natural collapsible soils. Collapsible soils may be defined as unsaturated soils that can sustain substantially high applied vertical stress without showing significant change in

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volume. When wetted, collapsible soils susceptible to large and sudden reduction in volume. In contrast to consolidation, where the reduction in void ratio is the result of the time-dependent expulsion of pore water, the settlement of a collapsing soil is more or less immediate and occurs upon the intake of moisture by the soil. Application of additional load is not required to cause such sudden volume decrease. Factors influence the collapse potential of soils include initial moisture content, initial dry density, soil composition, and confining pressure [2]. Jotisankasa et al. [12] presented a technique to investigate collapse behavior using a suction-monitored oedometer. Many collapsing soils may be residual soils resulted from weathering of parent rocks. The weathering process produces soils with a large range of particle-size distribution. Soluble and colloidal materials are leached out, resulting in loose honeycomb-type structure at a large void ratio and low dry unit weight. Majority of naturally occurring collapsible soils are aeolian wind-deposited sand and/or silts such as loess, aeolic beaches, and volcanic dust deposits. Loess deposits are found over 15–20% of Europe, over large parts of China, and large parts of the Midwestern and arid western United States [4]. Jefferson et al. [10] reported that collapsible soils cover about 10% of the world's landmass. In Egypt, collapsible soils were observed in northern portion of the western desert such as Borg El-Arab region, and around the city of Cairo such as Six-of-October plateau, and Tenth-of-Ramadan district [15]. The cohesion of collapsible soils may be the result of the presence of clay particles that serve merely as a binder coating around the soil particles, which attach them together in a rather stable condition in unsaturated state. The cohesion may also be imparted by precipitates of soluble compounds such as calcium carbonate, gypsum, or ferrous iron. Foundations that are constructed on collapsible soils may undergo large and sudden settlement when the soils become saturated from any unanticipated source of water such as damaged water pipelines, leaky sewers, drainage from reservoirs and/or swimming pools, and rise of groundwater table. When a collapsible soil becomes wetted, influx of water breaks down soil arrangement due to lose strength of clay binders and causes the soil to compress. Some structures have tilted markedly because surface waters were allowed to accumulate on one side [13,3].

If enough precautions were taken in field to prevent increasing moisture under structures, spread footings could have performed and much of the unpredicted settlement could have been avoided. If collapsible soils exist, continuous strip foundations perform better than isolated footings since strip foundations can withstand differential settlement and, hence, minimize damage to the structural framing system. If there is a possibility that shallow collapsible soils get wet during or after construction, collapsible soils need to be treated. There are many different methods available to treat collapsible soils and reduce potential for sudden volume decrease. Shallow deposit of natural collapsible soils may be moistened and compacted using rollers. Chemical stabilization may also be used and may be accomplished by flooding the foundations trenches with a solution of sodium silicate and calcium chloride. As these chemicals seep through collapsible soils, they react to create soft sandstone or siltstone capable of reducing collapse potential upon wetting. For deeper collapsible soils that might get wet, several techniques may be used to cause pre-collapse prior to construction. Flooding or pre-wetting the building footprint may be accomplished using dikes or wells. As the wetting front moves through the ground, the collapsible soils will densify and reach an equilibrium state. Care should be taken when using flooding of collapsible soils near existing buildings. Deep foundation system using piles or piers, which derive support from strata below the collapsible soils or the zone of possible wetting, can be used, however, the effect of negative skin friction that will be developed due to the collapsible soils should be considered. Other treatment techniques, such as soil–cement cushion, and stone columns have been also used successfully [8,5,6,14].

During this ongoing research, thirty block samples were extracted from the bottom of 30 test pits at four sites in Borg El-Arab region, located about 20 km west of the city of Alexandria, Egypt. Shear strength parameters, and collapse potential were measured for undisturbed samples as well as compacted samples in both unsoaked and soaked conditions. This was done to investigate some features of the behavior of collapsible soils in order to provide a useful support to geotechnical engineers when approaching the design of structures which are constructed on such soils and risk loss of serviceability as a consequence of large and sudden reduction in soil volume when wetting occurs. A comparative study for the soil parameters for both natural and treated samples was performed to show the effect of compaction for treating collapsible soils in terms of bearing capacity and collapse potential. Correlations between collapse potential and water content were developed. Moreover, California Bearing Ratio of the soil samples was estimated and related to the liquid limit of collapsible soils.

2. Soil sampling

In most soils, undisturbed sampling techniques provide high quality soil samples that better represent the natural soils. Collapsible soils include appreciable percentage of air in their voids. When sampled even by thin walled samplers, collapsible soils are likely to compress significantly leading to changes in soil properties as compared to in-place conditions [9]. It is critical not to use water or slurry mud to support the sides of the borehole during sampling collapsible soils. The extracted samples should be carefully sealed and handled. Given the above discussion, the author preferred to obtain block samples rather than Shelby tube samples. Thirty block samples were extracted from the bottom of 30 test pits that were dug at four sites in Borg El-Arab area near the city of Alexandria in north Egypt. The test pits were dug to a depth 1.50 m below ground surface using a backhoe. The block samples were obtained by carving an undisturbed soil from the bottom of each pit. The samples were waxed to preserve natural moisture, protected, and transferred to the laboratory for testing. For undisturbed soil specimens, the different water contents tested were really the natural in situ moisture content.

The primary goal for this ongoing research was to study the effect of compaction on the geotechnical properties of Egyptian collapsible soils. Compaction tests on the collected soil samples were carried out in accordance with modified Proctor procedure, ASTM D 1557. Maximum dry unit weights of compacted samples were found to be varied from 17.2 kN/m^3 to 19.4 kN/m^3, with an average of 18.4 kN/m^3. The corresponding optimum moisture content scattered from 12% to 16%, with a mean of 14.5%. Compacted samples were prepared at dry unit weight equal to 95% from its maximum

Table 1 Properties of soil.

Soil property	Lower bound	Upper bound	Mean value	Standard deviation
Percentage of sand (%)	15.00	41.00	30.10	7.44
Percentage of silt (%)	41.00	65.00	53.70	5.78
Percentage of clay (%)	5.00	33.00	16.50	6.31
Percentage of fines (%)	59.00	85.00	70.20	7.53
Uniformity coefficient	15.00	85.70	52.04	21.05
Coefficient of curvature	0.27	4.90	2.95	3.67
Natural moisture content (%)	6.00	15.00	11.00	2.00
Natural unit weight (kN/m^3)	14.10	16.10	15.38	0.45
Liquid limit (%)	23.00	33.00	28.50	2.52
Plastic limit (%)	11.00	17.00	13.60	1.52
Plasticity index (%)	10.00	19.00	14.90	2.42
Activity	0.45	1.71	0.95	0.34

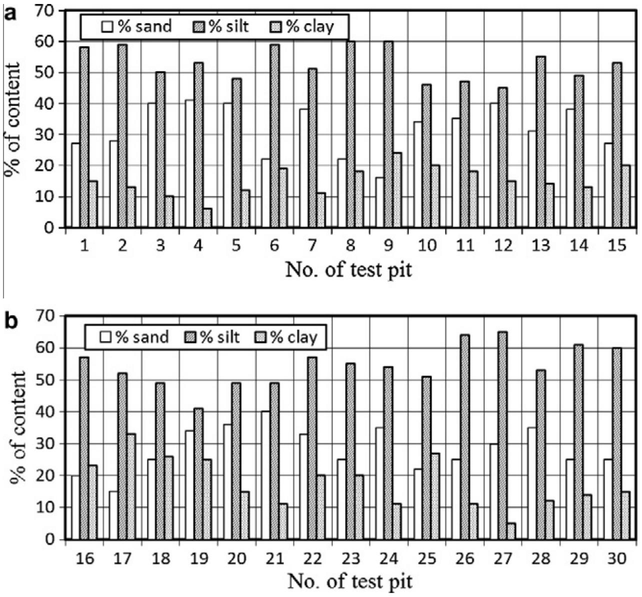

Figure 1 (a) Contents of soil samples, test pits from 1 to 15. (b) Contents of soil samples, test pits from 16 to 30.

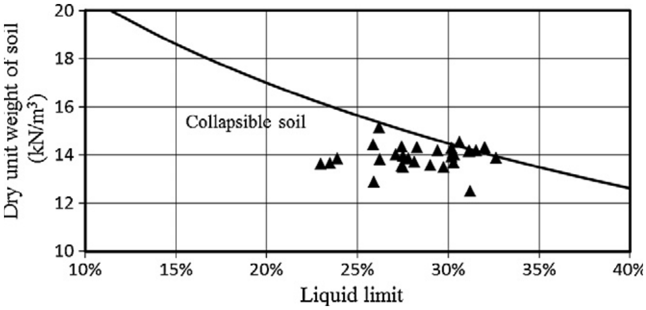

Figure 2 Dry unit weight of soil versus liquid limit.

dry unit weight as determined by the modified Proctor test. Relative compaction of 95% is often the lower limit of construction specification. To prepare a compacted soil sample, a part of the block sample from each test pit was air-dried. After the soil is completely dried, the soil pulverized and sieved on sieve No. 40. Water was carefully mixed into the soil to achieve the desired water content. Then the soil was compacted into the compaction mold in accordance with modified Proctor procedure to attain the required dry unit weight. The compacted soil was then extruded and trimmed to parts to be used in direct shear and oedometer tests.

3. Results and discussion

A laboratory testing program was conducted on the collected soil samples. Grain size analysis, natural unit weight, natural water content, and consistency limits were performed to estimate the mechanical properties of the soil. All tests were conducted in accordance with the relevant ASTM specifications [1]. Table 1 illustrates lower bound, upper bound, mean value and standard deviation of the achieved results. Fig. 1 shows the contents of soil samples for each test pit that were obtained using combined grain size analysis in accordance with ASTM D 422. Holtz and Hilf [7] suggested that a loessial soil that has a void ratio large enough to allow its moisture content to exceed its liquid limit upon saturation is susceptible to collapse. Fig. 2 shows a plot of the preceding limiting dry unit weights against the corresponding liquid limits. For any given soil, if the natural dry unit weight falls below the limiting line, the soil is likely to be collapse. It is evident that, all of the tested samples can be classified as collapsible soils, showing that Egyptian collapsible soils conform well to the proposal of Holtz and Hilf [7].

Shear strength parameters of collapsible soils are needed for bearing capacity, slope stability, and retaining wall design. Most soils, including collapsible soils, are subjected to natural cycles of drying and wetting due to climate conditions, hence both unsoaked and soaked shear strength parameters should be evaluated. Direct shear tests were conducted in accordance with ASTM D 3080 on both undisturbed and compacted samples in unsoaked and soaked conditions. The shear tests on unsoaked samples were carried out under constant water content conditions. On the other hand, soaked samples were tested in direct shear test apparatus under saturated conditions. In all cases, the shear rate was adopted to be 1.00 mm/min. The shear strength parameters, cohesion and angle of shearing resistance, were estimated for unsoaked and soaked conditions. To provide comparison basis, the shearing resistance of the soil at a depth of 1.50 m below the ground level was calculated. The depth of 1.50 m may be considered as the foundation depth of shallow foundations of most structures constructed in this area. Reduction factor in shearing

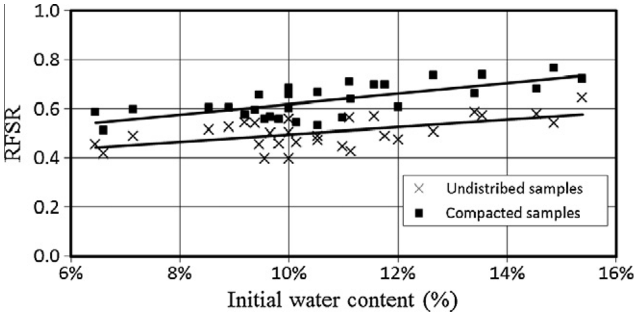

Figure 3 Reduction factor in shear strength at a depth of 1.50 m below ground level versus initial water content.

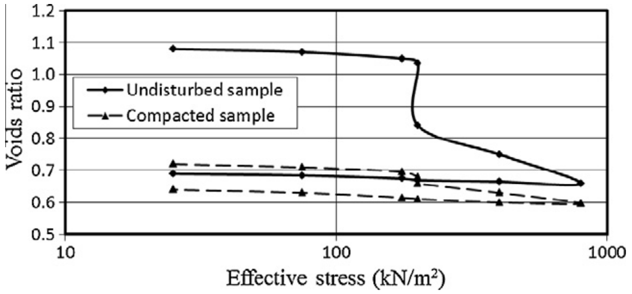

Figure 4 Voids ratio versus effective stress, test pit No. 19.

resistance (RFSR) was introduced and defined as the ratio between the shearing resistance of the soil in soaked condition to that in unsoaked condition. The determination of reduction factor is valuable as it represents the decrease in the bearing capacity of soil at foundation level due to soaking process. Fig. 3 shows the variation of reduction factor with the initial moisture content for both undisturbed and compacted samples. It is important to note that the initial moisture contents for undisturbed samples were really the natural in situ water contents while the initial moisture contents of compacted samples were the water contents of specimens prior to shear tests. Generally, as the initial water content increased, the reduction factor for both undisturbed and compacted samples increased. This behavior may be attributed to the increase in the degree of saturation due to the increase of initial water content. As the degree of saturation increases, the effect of soaking process decreases and thus the reduction factor increases. For natural collapsible soils, the reduction factor due to soaking process is between 0.43 and 0.58, with an average of 0.50. This means that the bearing capacity of natural collapsible soils may be decreased to about 50% due to soaking process, hence, it is recommended to use twice the factor of safety stated in different codes to account the soaking effect in collapsible soils. For 95% compacted samples, the reduction factor due to soaking process becomes between 0.53 and 0.75, with a mean of 0.64. In case of compacted collapsible soils, it is advised to use a value of 1.5 times the factor of safety recommended in different codes. For the same moisture content, the reduction factor for compacted samples is larger than for undisturbed samples by about 24–30%. The compaction contributes to an increase in the shear strength of collapsible soils. The scatter of results about the best-fit line in Fig. 3 may be attributed to the fact that interparticle forces in the collapsible soils are dependent on clay content and initial dry density as well as water content. The relationship between reduction factor in shearing resistance of soil due to soaking (RFSR) and initial water content (w_c) can be proposed as a best-fit line as shown in Eqs. (1) and (2) for values of ($6\% < w_c < 16\%$). These simple relationships enable the engineers to estimate the reduction in bearing capacity of soil due to socking process based on the natural moisture content.

$$\text{For undisturbed samples, RFSR} = 1.53(w_c) + 0.34 \tag{1}$$

$$\text{For 95\% compacted samples, RFSR} = 2.16(w_c) + 0.40 \tag{2}$$

The collapse potential was assessed using the procedure of Jennings and Knight [11] by placing soil sample at its natural moisture content in a consolidometer. Incremental loads were applied to the specimen up to stress level of 200 kN/m^2. Then, the soil specimen was inundated by distilled water for saturation and left for 24 h. The ratio between the change in height of the soil specimen and the initial height of soil specimen is a measure of its collapse potential (C_p). The foundation problems associated with collapsible soils have been correlated with the collapse potential [11]. Fig. 4 shows a representative relationship between void ratio of soil and effective stress for undisturbed and compacted samples. The loose structural arrangement of the particles for natural collapsible soils is a key element leading to the collapse phenomenon [8]. A portion of the fine-grained fraction of the soil exists as bonding material for the larger-grained particles. These bonds undergo local compression in the small gaps between adjacent grains. Therefore, these soils compress slightly at low moisture contents due to increase of pressures. When a collapsible soil is allowed to moisture, the fine binder that is providing the bonding mechanism between the large-grained particles will soften, weaken, and/or dissolve to some extent. Eventually, these bonding materials reach a stage where they can no longer resist the existing compressive stress and the soil structure collapse. It is important to mention that, the collapse potential is dependent on initial soil composition, fabric, water content as well as hydraulic and mechanical history of soil. In fact, the collapse potential of soil can vary with time. Fig. 5 illustrates the collapse potential versus the initial water content for both undisturbed and compacted samples. Generally, as the initial water content increases the collapse potential decreases. This means that peak value of collapse potential will be expected at dry case and as the voids between soil particles filled by water the tendency of collapse is decreased. This behavior can be attributed to the increase in the degree of saturation due to the increase of initial water content. As the degree of saturation increases, the volume of air filled the voids of soil decreases and thus the tendency of collapse decreases. The scatter of the results in Fig. 5 may be related to different clay contents and different initial dry densities in the tested samples. It was found that the collapse potential of undisturbed samples varied from 8.0% to 14.6%, with an average of 11.4%. Thus, the natural soil can be classified as trouble/severe trouble in accordance with [11]. When the soil compacted to 95% of its dry density, the collapse potential decreased to a value between 1.5% and 2.7%, with a mean of 2.1%. It is evident that the compaction process decreased the collapse potential of soil to about 0.15–0.23 of its original value. The classification of soil is also changed to be moderate trouble. Eqs. (3) and (4) are describing the best-fit lines for values of ($6\% < w_c$

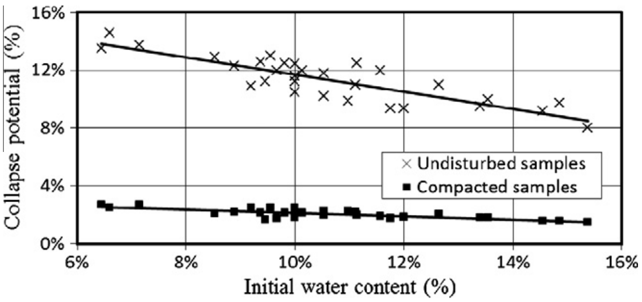

Figure 5 Collapse potential versus initial water content.

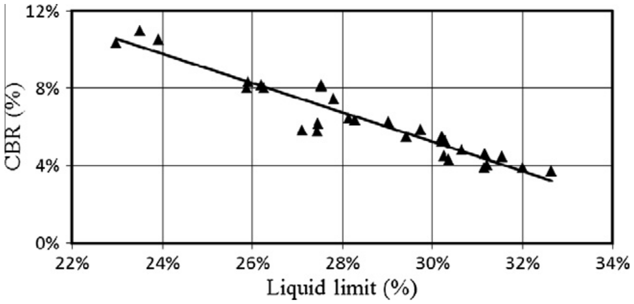

Figure 6 CBR versus liquid limit.

< 16%). These simple relationships enable the engineers to obtain the collapse potential of soil based on the initial water content.

$$\text{For undisturbed samples, } C_p = 0.177 - 0.59(w_c) \tag{3}$$

$$\text{For 95\% compacted samples, } C_p = 0.033 - 0.11(w_c) \tag{4}$$

The values of California Bearing Ratio, CBR, for the compacted samples were determined in accordance with ASTM D 1883. Fig. 6 shows the values of CBR versus liquid limit of soil, LL. As the liquid limit increases, CBR decreases linearly. This means that as the clay content of soil increases, the value of CBR decreases. Eq. (5) describes the best-fit line for values of (22% < LL < 34%).

$$\mathrm{CBR} = 0.28 - 0.76(\mathrm{LL}) \tag{5}$$

The above results support the use of compaction to treat collapsible soils as an easy and economical method. However, the procedure requires close control of water contents which can prove difficulties in collapsible soils with relatively low plasticity. The compaction energy per unit volume of collapsible soils may be higher than for noncollapsible soils because collapsible soils are usually loose but have high strength in their initial state.

4. Conclusions

The laboratory results presented in this paper showed that Egyptian collapsible soils conform well to the proposal of Holtz and Hilf [7]. The bearing capacity of collapsible soils decreased to about 50% due to soaking process, hence, the author recommends using twice the factor of safety stated in different codes to account the soaking effect in collapsible soils. The bearing capacity of collapsible soils when compacted to 95% of its dry density is larger than that of natural soil by about 24–30%. For both undisturbed and compacted soil samples, as the initial water content increases the collapse potential of soil decreases. When a collapsible soil is compacted to 95% of its dry density, the collapse potential decreased to be about 0.15–0.23 from its original value for natural soil, which changed the classification of natural soil from trouble/severe trouble to moderate trouble. As the liquid limit of a collapsible soil increases, the value of California Bearing Ratio of the compacted samples decreases linearly. Simple relationships that enable the engineers to estimate collapse potential of both undisturbed and compacted collapsible soils based on initial water content were presented. Also, California Bearing Ratio of the compacted collapsible soils was correlated to the liquid limit. Finally, the study supports the use of compaction to treat the collapsible soils prior to construction the foundations.

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