Controlling Collapsibility Potential by Partial Soil Replacement

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Abstract
At or near saturation, collapsible soils undergo a rearrangement of their grains and water
removes the cohesive (or cementing) material. In Borg El Arab, near Alexandria Egypt, soils
exhibit high susceptibility for collapse when saturated. In this paper, inundation stress has
been applied to investigate its effect on the collapse potential and permeability behavior of
Borg El Arab soil. Because of the collapse of soil when wetted low bearing capacity and rapid
substantial settlement are developed and makes it unsuitable as foundation soil or pavements
sub-base in their natural condition. The collapsible soil may be treated by remove and replace
method to improve strength. Experimental program was developed to explore the effect of
types of compacted replacement on collapsibility potential. A series of tests were carried out
to search for the most suitable types of partial replacement and the location of source of
surface wetting to evaluate their effects on the reduction of settlement of a footing on
collapsible soil when inundation occurs. The results show that inundation stress have strong
effect on collapse potential and permeability coefficient. The behavior of a shallow foundation
rests on compacted sand / crushed stone layers as partial replacement over treated collapsible
soil by pre-wetting and compaction is investigated.

Index terms—collapse; collapse potential; compressibility; improved; replacement soil.

1 I. Introduction and Literature Review
Problematic collapsible soils exist in many parts of the world, both naturally and as a result of manmade activity,
thus making their behavior a truly global problem. In general wetting induces volume changes, and leads to
changes in strength and stiffness. When significant amounts of water are introduced into the soil, the collapse
settlements are usually amplified. Man-made compacted fills, may also develop a collapsible or metastable
structure at low density. Collapsible soils are sensitive to changes of porosity and moisture content. Their
volume usually decreases with the increase of moisture content especially when much water reaches the soil
and sometimes under practically unchanged total vertical stress. Common causes of wetting are meanly human
activities in regions having collapsible soils so that which makes the hazards posed. Many researchers reported
that lack of knowledge in the construction industry with respect to identification, behavior and treatment of
collapsing soils led to many cases of foundation problems. [Houston, et al 2001], Ayadat, T. and Hanna, A.,2007;
2013, Hawraa, et al 2012]. In literature, little or no attempts were made to develop a rational soil classification
technique based on the most governing parameters of soil collapse behavior. Collapsible soils have been widely
studied for more than 70 years resulting in a broad wealth of literature. As their name indicates, these soils can
exhibit large volume change upon wetting, with or and sometimes without extra loading, thus posing significant
challenges to the geotechnical profession, [Houston, et al 2002]. Pereira et al. (2000) summarized the factors
that produce collapse as follows: "1. an open, partially unstable, unsaturated fabric, 2. a high enough net total
stress that will cause the structure to be metastable, 3. a bonding or cementing agent that stabilizes the soil in
the unsaturated condition, and 4. the addition of water to the soil, which causes the bonding or cementing agent
to be reduced and the inter granular contacts to fail in shear, resulting in reduction in total volume of the soil
mass.
In this study a series of experimental work was conducted to present the engineering techniques of Borg El Arab collapsible soils improvement by removal and partial replacement with thickness equal to foundation width, (Abdel-Mohsen, H.H., and Ali, A.N. 2014, 2015 and Ali, A.N. 2015), pre-wetting and pre-compression, which resulted in densification, and increase of bearing capacity reduction of its settlement. A series of experimental work was conducted on improved collapsible soil to study the performance of different types of partial replacement of cohesionless materials and their effect on the reduction of settlement when inundated. The problem of wetting inducing collapse involves many uncertainties related to soil variability, source of surface wetting and to the primary source of driving stress (overburden, structural, or both). A series of tests were carried out to search for most types of replacement and the location of wetting source to evaluate their effects on the reduction of settlement of a footing on collapsible soil when inundation occurs. The lack of knowledge in the construction industry about the identification, behavior and treatment of collapsing soils is believed to have had led to many cases of either foundation problems.

2 II. Soil Characteristics

The odometer test (ASTM D5333-03) was used to study the soil collapse potential. The influence of the particle size distribution, void ratio and density on the soil collapsibility was also, studied using (ASTM) standard procedures on the undisturbed soil samples. These samples have been collected from different locations located in Borg El-Arab area near Alexandria city, north of Egypt to determine their geotechnical properties. Table 1 shows geotechnical properties based on results of a laboratory testing program on undisturbed soil samples recovered from test sites.

3 III. Laboratory Model and Experimental Procedures

Assembly of test equipment is shown in Figure 1. A soil bin used to contain the soil is a square tank 600mm × 600mm internal dimensions and 700 mm high. The four sides of the tank are transparent plastic (Perspex) plates with 12 mm thickness braced with steel angles to prevent lateral movements of tank sides during placing and compacting the soil and loading. The base of the bin is a square steel plate with 40 mm thickness. The loading system consists of rigid steel frame supporting a steel lever with 1020 mm length connected to steel columns by a pivot, Figure 1. Steel shaft is attached with a proving ring to transmit the load by the lever. Proving ring has 2 KN maximum capacity and 2N accuracy. The loads were applied incrementally via the loading lever using standard dead weights. Circular model footings 80 mm diameter and 30 mm thickness were used. The vertical settlement of the loaded footing was measured by mechanical dial gauges of 0.01 mm accuracy which were fixed rigidly to dial gauge holders, (Abdel-Mohsen, H.H., and Ali, A.N., 2015).
4 Figure 1: Test Equipment

The study is a part of detailed investigation program designed to examine the collapsibility potential of Borg EL-Arab collapsible soils and to search for a suitable method to mitigate their potential risk upon wetting. In the current laboratory study, a footing model was loaded up to failure on partially replacement cohesionless materials on improved subgrade using pre-wetting and compaction.

Basic laboratory tests were carried out on undisturbed soil samples representing the collapsible soil which were collected from different locations to determine geotechnical and physical properties. Improved compacted samples have maximum dry unit weights which varied between 16.8 kN/m³ and 17.8 kN/m³ with corresponding optimum water content varying between 16.2% and 17.3%. Compacted samples were prepared at dry unit weight of 98% of the maximum dry unit weight determined by Modified Proctor Test.

5 IV. Sample Preparation

Dry soil is mixed with a certain percentage of water and placed in the bin in relatively thin layers, each 50 mm thick up to a predetermined height, which is 400 Year 2016 Circular footing of steel 80 mm diameter and 30 mm thickness was used and centered on top of the replacement layer. Vertical loads were applied incrementally via loading lever, for each and load, settlement was recorded with time till it ceased, after which next increment was applied. The problem of induced collapse due to wetting involves many uncertainties related not only to the soil variability, but also to the source of wetting and to the primary source of driving stress. To study the wetting / inundation effect, soil was inundated with 4000 cm³ of water which was allowed to seep on the soil surface via flexible plastic pipes, to simulate inundation in field due to rain fall or excessive irrigation and/or leakage from water and / or sewer lines. Soaking stage of soil was found to take one day wetting the soil from top to bottom. To simulate inundation in field due to access of water from different sources water was allowed to seep on the soil surface via one or two rows of flexible plastic pipes through controlled tubes at distances D and 3D where D is the footing diameter. For each test, the water was allowed to seep through the soil to a specified elapsed time of 1 hr., 6 hrs., 12 hrs., 24 hrs., 48 hrs. and 72 hrs. to study differential soil collapse and localized collapse of foundation nearest to leakage. In these tests the penetrated water in compacted improved collapsible soil was measured, and soil specimens to determine their water content were taken at different depths through the horizontal soil surface at many locations. The depths of soil specimens were measured using scale of 1.0 mm accuracy.

Seven groups of tests were designed to study the effect of different types of partial replacement of cohesionless materials with thickness equal to diameter of footing placed on top of improved compacted collapsible soil layer upon inundation and different imposed stresses. The designed testing program is summarized in Table 1. 3 shows that by adding the fine crushed stone to collapsible soil has significantly influenced the allowable applied pressure and reduced settlements that is at the same applied pressure the settlement is lower. The largest reduction in settlement was achieved with the increase of percentage of added crushed stone. The settlement decreased with the increase of percentages of fine crushed stone mixed with the collapse soil. From three cases under study the estimated ultimate bearing capacity values are 320, 360, 460 and 520 kN/m² respectively with the different percentage of fine crushed stone mixed. As shown in fig.

(3), an increase in the percentage of fine crushed stone mixed with collapsible soil from 0% to 60% reduced the footing settlement and increased the estimated ultimate bearing capacity, with increase of 0.125, 0.43 and 0.62 respectively. The largest increase in bearing capacity was achieved at the largest percentage of added fine crushed stone which is 60%. Causes of immediate/ sudden foundation failure due to inundation of collapsible soil are identified based on pressure-settlement curves. The demonstration of pressure-settlement response of collapsible soil, in relation to the change in soil moisture, guides the practicing engineers to obtain a safe design load on foundation and its type. Figures 1 and 5 present relationships between applied pressure and settlement of the footing collapsible soil after inundation (test groups C and D). After soaking, the bin is left for 24 hours to ensure that all soil was completely soaked. The load was then applied to failure, which was indicated by the increase of settlement rate at a nearly constant load intensity. From figures, it is quite clear that replacement on top of improved collapsible soil presents better footing performance in terms of settlement against applied stress.

Due to inundation, the estimated ultimate bearing capacity values decreases to 290, 425, 460 and 520 kN/m² for the four cited combinations respectively with reduction of 0.10, 0.26, 0.24 and 0.19 respectively. The results indicate that the wetting of compacted soil significantly increases the expected footing settlement under the effect of load, and this settlement decrease when the material under footing has a high elastic modulus.

Figure 5, indicates that the estimated ultimate bearing capacity values decreases by flooding to 290, 320, 410 and 480 kN/m² respectively with reduction of 0.10, 0.11and 0.077 respectively. The non-collapsibility nature of compacted fine crushed stone, may counteract the process of collapsibility through surface friction among soil particles. It is noticed that the increase of fine crushed stone percent to collapsible soil reduced its collapse to one half. As shown in figures, the influence of soil wetting on foundation settlement decreases abruptly when replacement material has a high stiffness and high elastic modulus. With such replacement, collapse due to wetting was greatly reduced or eliminated, irrespective of the compaction water content. The problem of wetting inducing collapse involves many uncertainties related not only to the soil variability, but also to the source of wetting and to the primary source of driving stress (overburden, structural, or both). A series of conducted tests involved loading to stress levels representative of the overburden stresses and expected field load to study the collapsibility
VI. CONCLUSION

Based on the results, conducted investigation and analyses the following conclusions can be advanced:

1. Removal of some thickness of collapsible soil and replacing it by cohesionless soil and altering surface and subsurface drainage patterns of water on collapsible soil improve the stability of collapsible soil formation. The soil partially replaced with compacted cohesionless soil in this study reduces the foundation settlement by about 50% and increased bearing capacity by about (80-100%).
2. Adding fine crushed stone to collapsible soil has significantly influenced the results concerning applied pressure and settlement relationships; at the same applied pressure the settlement is significantly lower. The largest reduction was achieved at the largest percentage of added fine crushed stone (60%). The settlement decreased with the increase of the crushed stone percentages mixed with the collapse soil.
3. An increase in the percentage of fine crushed stone mixed with collapsible soil from 0% to 60% reduced the footing settlement and increases the monitored ultimate bearing capacity by increase of 0.125, 0.43 and 0.62 for the three mixed respectively. The largest increase in bearing capacity was achieved at

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the largest percentage of added fine crushed stone 60%. Collapse potential of treated collapsible soil by using partial replacement of cohesionless soil decreases with the increase of stiffness of replacement material and with increase of high elastic modulus near the footing load.

The collapse of compacted improved soil is more than of the cases using partial replacement of cohesionless soil. Collapse potential was affected by the applied stress, the greater the applied pressure, the greater the collapse caused during wetting, collapse increased continuously with the increase of applied stress. The severity of the collapse depends on the extent of wetting, depth of the deposit and load from the overburden and structure. Predicting settlements due to collapsible soil is difficult due to several factors including sample disturbance problems, variability of the subsoils, extent of wetting and variable loading conditions. Settlement estimates are generally made by considering the collapse over the potential depth of wetting. The settlements typically occur along the perimeter of the structure and are differential. Relatively severe settlements and building distress have been experienced where the collapsible soil depth is greater. Results proved that improvement of collapsible soils is possible to mitigate their risk potentials against...
<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Water Content (%)</td>
<td>6.3</td>
<td>6.8</td>
</tr>
<tr>
<td>Natural Unit Weight (kN/m³)</td>
<td>13.8</td>
<td>14.6</td>
</tr>
<tr>
<td>Percentage of Sand</td>
<td>36.2</td>
<td>40.2</td>
</tr>
<tr>
<td>Percentage of Silt</td>
<td>58.4</td>
<td>53.6</td>
</tr>
<tr>
<td>Percentage of Clay</td>
<td>5.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Collapsibility Potential $C_p$ (%)</td>
<td>11.6</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Figure 2: Table 1:

Figure 3:
### Effect of different types of partial replacement of cohesionless materials 1.0 D thickness on compacted improved collapsible soil

<table>
<thead>
<tr>
<th>Group A</th>
<th>Types of replacement layer (Dry)</th>
<th>Sand / crushed stone mixture 2:1 crushed stone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Group B</td>
<td>The treatment of collapsible soil by mixing it with fine coarse grained soil</td>
<td>The mixtures prepared from a mix of excavated collapsible soil with fine crushed stone in different percent (20, 40, 60)%</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>Group C</td>
<td>Inundated with 4000 cm$^3$ of water (rain fail)</td>
<td>Effect of inundations on different type of cohesionless</td>
</tr>
</tbody>
</table>

**Figure 4:**

<table>
<thead>
<tr>
<th>Group D</th>
<th>Inundated with 4000 cm$^3$ of water with applied stress =150 kN/m$^2$</th>
<th>replacement layer and mixtures of collapsible soil with fine crushed stone in percentages of 60% with thickness 1.0 D placed on compacted improved collapsible soil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group E</td>
<td>Inundated with 4000 cm$^3$ of water Soaked at different stresses 50, 100, 150 kN/m$^2$</td>
<td>Effect of inundations in sand replacement layer with thickness 1.0 D on compacted improved collapsible soil at stress =100 kN/m$^2$</td>
</tr>
<tr>
<td>Group F</td>
<td>Inundated with 4000 cm$^3$ of water Soaked at different thickness of improvement collapsible soil at stress 100 kN/m$^2$</td>
<td>Effect of inundations on different thickness of compacted improved collapsible soil (4D=350mm &amp; 6D=500mm) under replacement sand layer with thickness 1.0 D at stress =100 kN/m$^2$</td>
</tr>
<tr>
<td>Group G</td>
<td>Inundated with 4000 cm$^3$ of water pipes at distance D and 3D from footing in both sides. Footing stress during inundation =100 kN/m$^2$.</td>
<td>Effect of inundations form different sources of water on replacement layer with thickness 1.0 D on compacted improved collapsible soil at stress =100 kN/m$^2$ to simulate water leaking from broken water lines or utility line leakage.</td>
</tr>
</tbody>
</table>

**Figure 5:** Figure 2:

**Figure 6:** Figure 3:
Figure 7:

Figure 8: Figure 4 :

Figure 9: Figure 5 :
Figure 10: Figure 6:

Figure 11: Figure 7:
VI. CONCLUSION

Figure 12: Figure 8:

Figure 13: Figure 9:
Figure 17: Figure 14:

Figure 18:
Figure 19:

![Figure 19: Water content vs. depth of wet soil for different water sources.](image)

Figure 20: Table 1:

<table>
<thead>
<tr>
<th>Table 1: Water Content vs. Depth of Wet Soil</th>
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</thead>
<tbody>
<tr>
<td>Water Source First Row of Pipes</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>4.0</td>
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