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Controlling Collapsibility Potential by Partial Soil Replacement

By Naema.A. Ali

King Marrito Institute for Engineering, Egypt

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 inundationstress 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.

Keywords: collapse; collapse potential; compressibility; improved; replacement soil.

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Keywords: collapse; collapse potential; compressibility; improved; replacement soil.

I. Introduction and Literature Review

Problematic collapsible soils exist in many parts of the world, both naturally and as a result of man-made 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.

’’Numerous case histories pertaining to the problems caused by collapsible soils have been reported in the literature, (Rogers, et al 1994, Al-Rawas, A.A 2000, El Kholy, M.S. 2008 and Soliman, et al. 2010). In addition to the problems posed to buildings and embankments, challenges related primarily to differential settlements are encountered also in the construction of roads on collapsible soils.

Many studies are performed on geotechnical behavior of collapsible soil in different countries and reported that the problems induced by collapsible soils require consideration of the following four important issues: 1. identification and characterization of collapsible soils, 2. assessment of collapse potential and settlement; 3. estimation of the distribution and degree of wetting in the deposit; and 4. evaluation of design alternatives and mitigation strategies. While as the literature on collapsible soils is quite extensive, there

Author: Lecturer Civil Engineering Dpt., Higher Institute of Engineering & Technology, King-Marriot, Alex., Egypt.
e-mail: Dr_Naemaali1@yahoo.com

are significant voids that still need to be filled. An area that appears to require further work pertains to the (rapid) identification and characterization of these soils. Fundamentally, point of view, much investigation still is to be learned on the mechanisms responsible for the collapse. Finally, a more general approach for the selection of mitigation/ improvement methods to deal with these soils is also needed, (Telford, et al, 1990, Al-Rawas, A.A 2000 and Houston, et al 2001). During inundation, as the percentage of water in the pore spaces increases, matric suction decreases and the bond of matrix suction diminishes.

In Egypt, recent extensions of urban communities towards the desert, where collapsible soils may exist pose significant challenges to the geotechnical profession. Construction of foundations on collapsible soil is considered one of the outstanding problems in geotechnical engineering. The main geotechnical problem associated with collapsible soils is the significant loss of shear strength and volume reduction occurring when they are subjected to water from any source of water. Generally, collapsible soils are under partially saturated or dry conditions have negative pore pressure resulting in higher effective stress and high shear strength.

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.

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.

Table 1 : Index properties and collapsibility potential of undisturbed soil samples from Borg EL-Arab region

Soil properties	Sample 1	Sample 2
Initial Water Content (%)	6.3	6.8
Natural Unit Weight (kN/m^3)	13.8	14.6
Percentage of Sand	36.2	40.2
Percentage of Silt	58.4	53.6
Percentage of Clay	5.4	6.2
Collapsibility Potential C_p (%)	11.6	12.0

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).

An elevated water tank connected to a distribution device through a plastic tube was used to inundate the tested soil. Water was then placed in the tank and controlled to allow to seepage to the soil surface via flexible plastic pipes. The uniformity distribution of water on soil surface was ensured by equal length and diameter of flexible plastic pipes connecting the inlet and outlet nozzles, equal diameter of inlet nozzles attached to the tank's base and outlet nozzles attached to the water distributing steel grid in four columns and four rows. By adjusting the soil surface in a horizontal level, a uniform distribution of outlet nozzles on soil surface was guaranteed to drop the water around the footing model. It was noticed that there was no water head retained above the soil surface, figure 1.

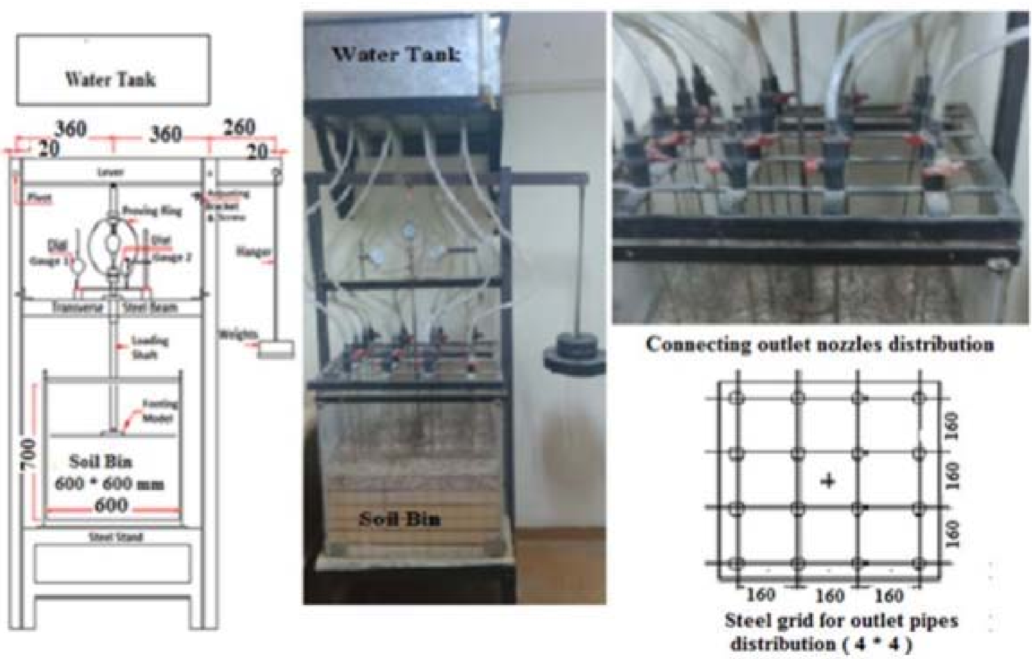

Figure 1 : Test Equipment

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.

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

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mm height inside the bin. Water was carefully mixed with the soil to the desired water content. Replacement cohesionless soil used in this study are, sand, mixture of crushed stone and sand, crushed stone and mixture of fine crushed stone and collapsible soil with different percentages. The artificially soil samples were prepared by mixing disturbed extracted samples with (20, 40 and 60)% of fine crushed stone. The soil is prepared outside the container and mixed thoroughly with 17% of water optimum moisture content. The mixture is poured into the container in two layers, each 40 mm. A static compaction method was applied to prepare sets of identical samples of unit weight 17.8 kN/m3 and relative compaction 95% of modified Proctor compaction. The replacement sample was directly compacted into the bin to reach a thickness of about 80 mm (equal to footing diameter D).

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 sample 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.

Table 1 : Test program

Effect of different types of partial replacement of cohesionless materials 1.0 D thickness on compacted improved collapsible soil	
Group A Types of replacement layer (Dry)	Sand Sand / crushed stone mixture 2:1 crushed stone
Group B The treatment of collapsible soil by mixing it with fine coarse graind soil	The mixtures prepared from a mix of excavated collapsible soil with fine crushed stone in different percent (20, 40, 60)%
Effect of inundation on treatment of soil	
Group C Inundated with 4000 cm^3 of water (rain fall)	Effect of inundations on different type of cohesionless
Group D Inundated with 4000 cm^3 of water with applied stress =150 kN/m^2	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.
Group E Inundated with 4000 cm^3 of water Soaked at different stresses 50, 100, 150 kN/m^2	Effect of inundations in sand replacement layer with thickness 1.0 D on compacted improved collapsible soil at stress =100 kN/m^2
Group F Inundated with 4000 cm^3 of water Soaked at different thickness of improvement collapsible soil at stress 100 kN/m^2	Effect of inundations on different thickness of compacted improved collapsible soil (4D≈350mm & 6D≈500mm) under replacement sand layer with thickness 1.0 D at stress =100 kN/m^2
Group G 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.	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.

V. Results and Discussion

Figure 2 shows the relationship between applied pressure and settlement of the collapsible soil improved by using partial replacement with different types of cohesionless soil with thicknesses equal to diameter of footing under concentric loaded footing, group A. It can be noticed that the bearing capacity increases with partially replacing collapsible soil with different cohesionless soils. The bearing capacity also increases with increasing the weight and stiffness from replacement sand to mixed sand and crushed stone to crushed stone. For the four cases under study the estimated ultimate bearing capacity values are 320, 575, 605 and 645 kN/m2 respectively for compacted collapsible soil, sand, Sand / crushed stone mixture 1:2 and crushed stone with thicknesses t=D, figure 2. Generally high strength subgrades materials are placed near surface on which load is applies because the intensity of stress under footing decreases with depth. The experimental work conducted for employed the mixture of removed collapsible soil with different percentages of fine crushed stone (20, 40, 60)%, as a partially replacement layer rest on improved collapsible soil by pre-wetting; test group B. Figure 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%.

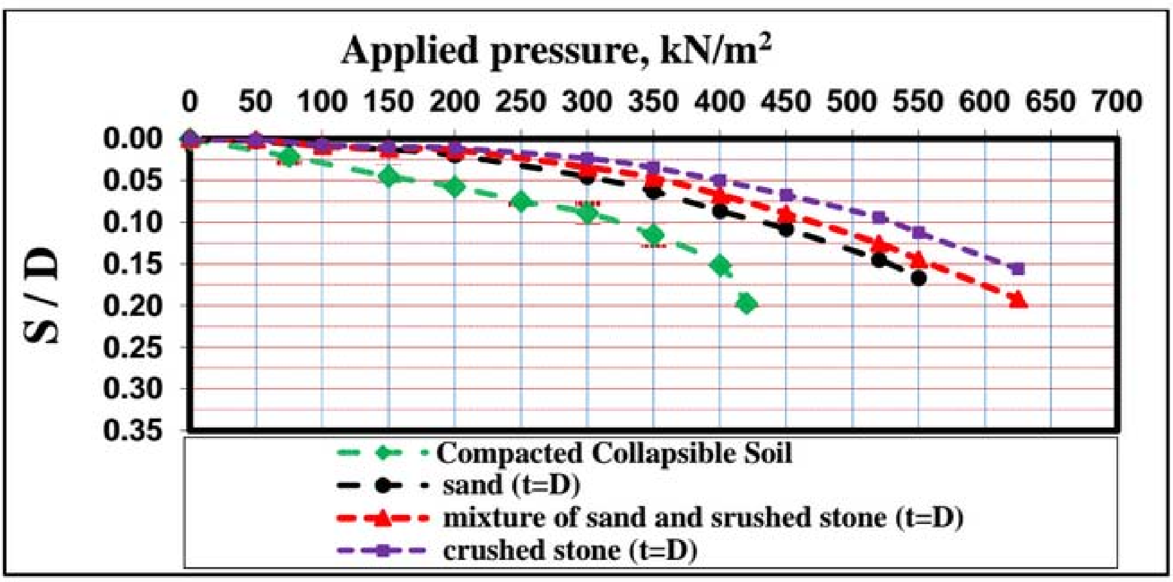

Figure 2 : Settlement versus applied vertical stress for different types of cohesion-less replacement soil before flooding

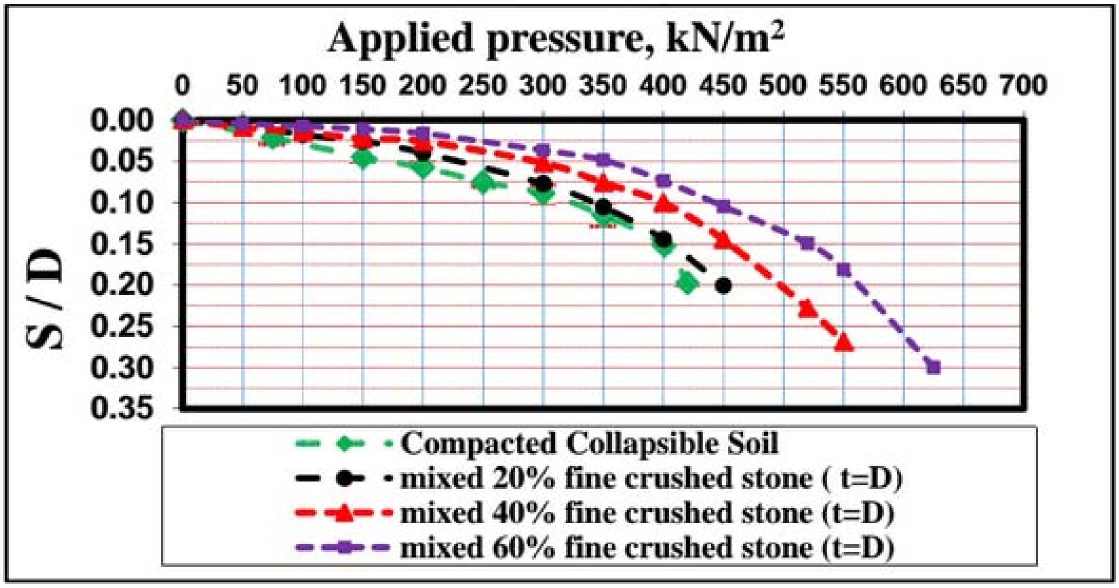

Figure 3 : Settlement versus applied vertical stress for different percentages of fine crushed stone added to collapse soil and using as layer of replacement soil before flooding

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 4 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 indicated 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.

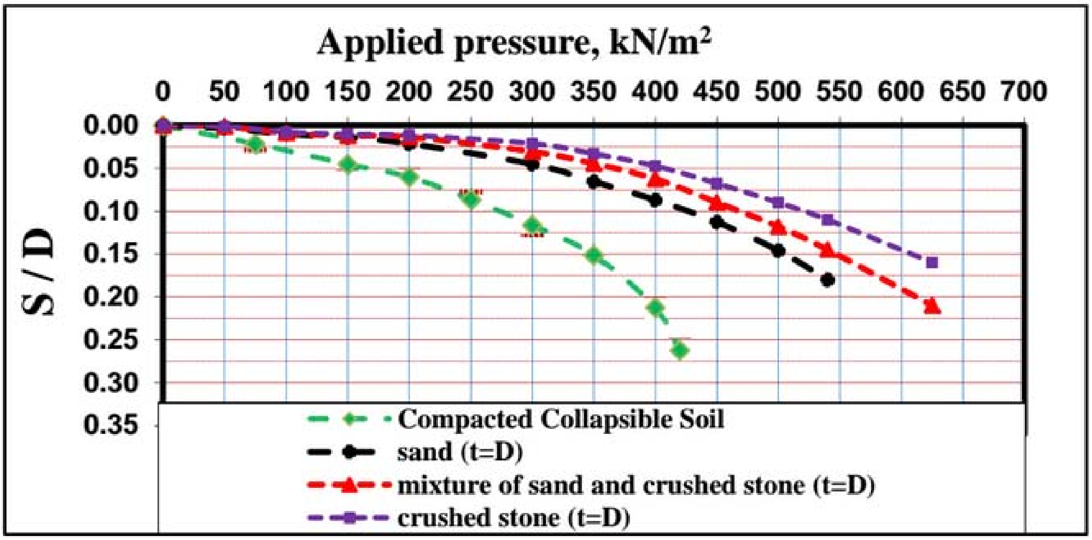

Figure 4 : Settlement versus applied vertical stress for different types of cohesionless replacement soil after flooding

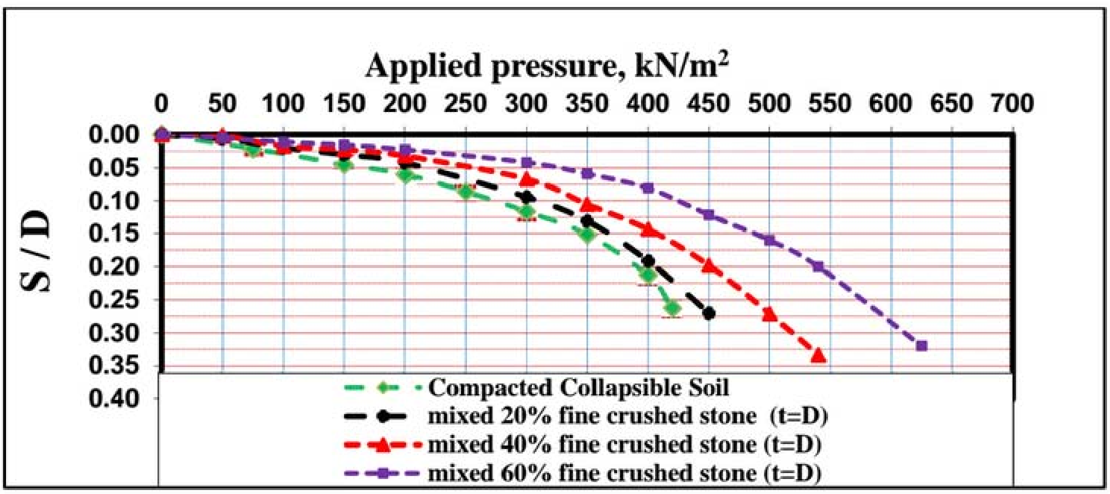

Figure 5 : Settlement versus applied vertical stress for different percentages of fine crushed stone added to collapsible soil and using as layer of replacement soil after flooding

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 potential. In tests of group E, during flooding the pressure was kept constant until collapse settlement has ceased. The results presented in figures 6 through 9 show the compressibility for the purpose of different improvements of collapsible soil. There are gradual decreases in volume with additional wetting which will led to an increase of water content of soil. Figures 6 through 8 show that using partial replacement cohesionless with higher value of stiffness reduced the collapse settlement of the footing and resulted in higher ability to resist higher value of applied stress than the compacted improved collapsible soil without partial replacement. Collapse potential was affected by applied stresses, the grater the applied stress the grater the collapse potential during wetting. Collapsing increased continuously with applied stress. Collapsing of treated soil with using partial replacement of cohesionless soil is less than that of partial replacement of mixed with 60% fine crushed stone treated soil with the same thickness at different stresses. Using fine crushed stone mixed with excavated collapse soil added more effect in reducing the collapse settlement of the footing and increased the bearing capacity.

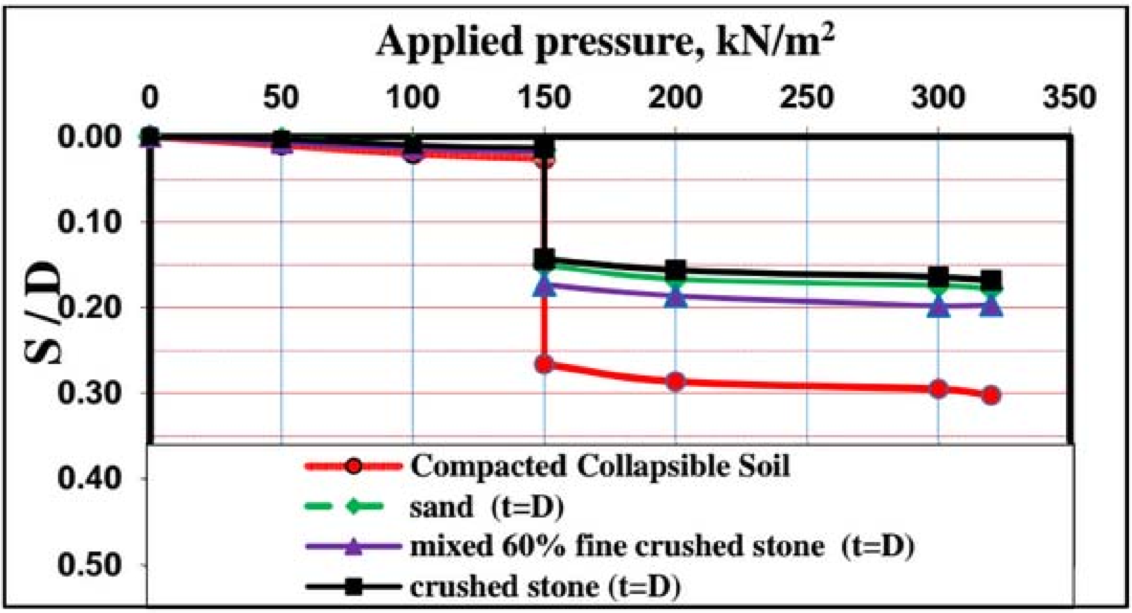

Figure 6 : Settlement versus applied vertical stress on the flooding at stress 150 kN/m2

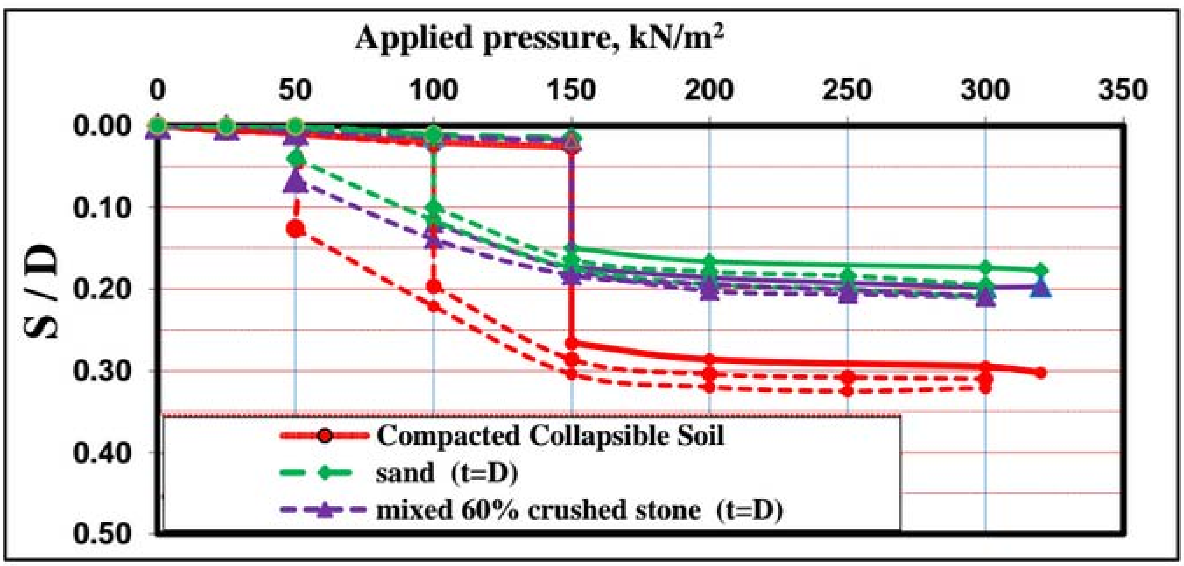

Figure 7 : Settlement versus applied vertical stress for different levels of inundation stresses

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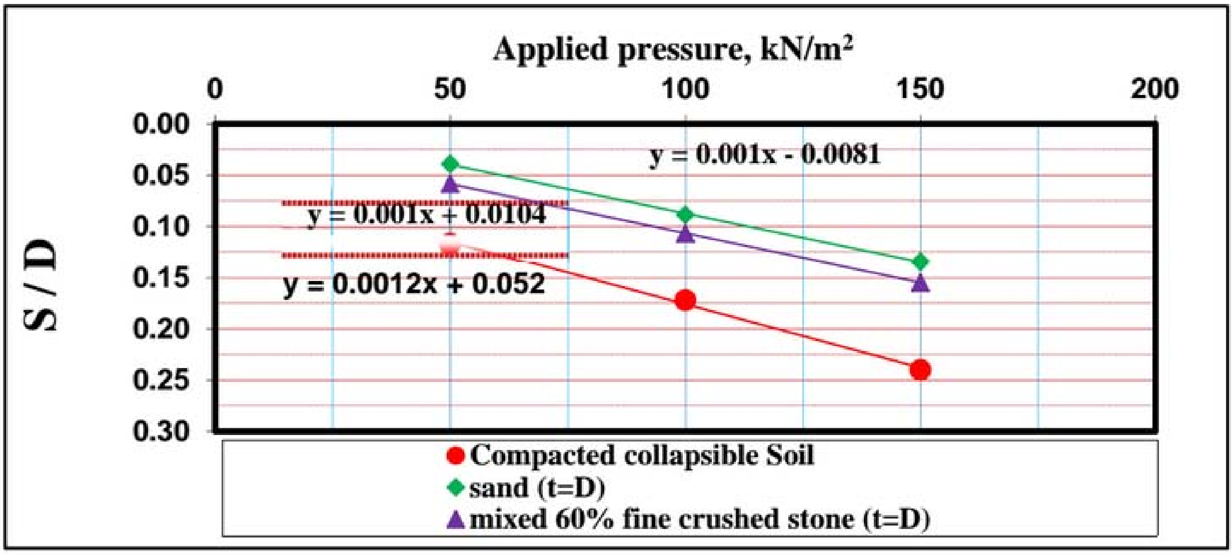

Figure 8 : Settlement versus applied vertical stress for different levels of inundation stresses

Figure 9 shows the settlement of the soil with time as it is related to penetrated water to depth of compacted improved collapsible soil under replacement layer. Collapse settlement increases due to an increase of soil collapse applied stress level on the foundation and decreases due to the increase of stiffness and elastic modulus of partial replacement layer under footing. The results showed the effect of the percentage of fines content in soil, coefficient of permeability and suction gradient. When saturated, collapsible soils undergo a rearrangement of their grains and the water removes the cementing material. Quick substantial settlement causes an increase in surface water infiltration. Higher conductivity of replacement layer allows great lateral movement of water which can result in wetting of the surface to considerable distance away from the source of wetting. The deeper wetting associated with lateral movement of water also suggests that any sources of water that is far laterally through the soil profile (either on-site or off-site) must be taken into consideration. This suggests that site drainage is an important factor to be considered during design and construction. If rainfall runoff ponds exist throughout a site with no sediment and runoff control, infiltration from water ponds may induce failure. Also, subsurface drains, top and interceptor drains shall be provided as a requirement in engineering standards. The structural stability of collapsible soils is related to suffuse process, which is a process of lateral and vertical removal of the fine soil particles by subsurface flow and often leads to settlement.

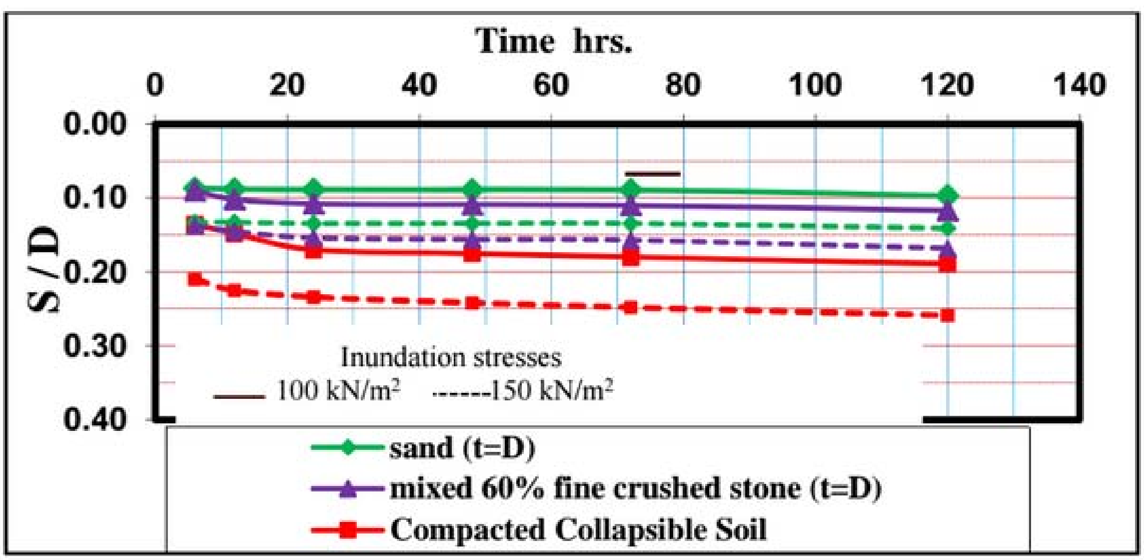

Figure 9 : Settlement – time at applied vertical stress on the flooding at stresses 100 / 150 kN/m2

A series of tests conducted involved different thickness of improved collapsible soil to study the effect of inundation on thickness of compacted improved collapsible soil (4D≈350mm & 6D≈500mm) under partially replaced sand layer with thickness 1.0 D at stress 100 kN/m2(tests group F). The change in soil moisture with depth guides the practicing engineers to design load on foundation. Figures 10 and 11 show the degree and depth of wetting during inundation. The results show the effect of the percentage of fines content in soil which lose their collapsible characteristic by compaction and assist in reducing the amount of water penetration into the subgrade, coefficient of permeability and suction gradient. There are gradual decrease in volume with additional wetting which leads to an increase of water content of soil. Collapse settlement was affected by the thickness of improved collapsible soil. The grater the depth of collapsible soil, the grater the collapse settlement, was observed. Naturally occurring routes of downward movement of soil loaded with water was observed. Another term for collapsible soils is "hydro-comp-active soils" because they compact after water is added. The amount of collapse depends on the thickness of the soil that becomes wetted. Thus these collapse soil require special consideration that is unique to regions where deep or thick layers of collapse soil are present.

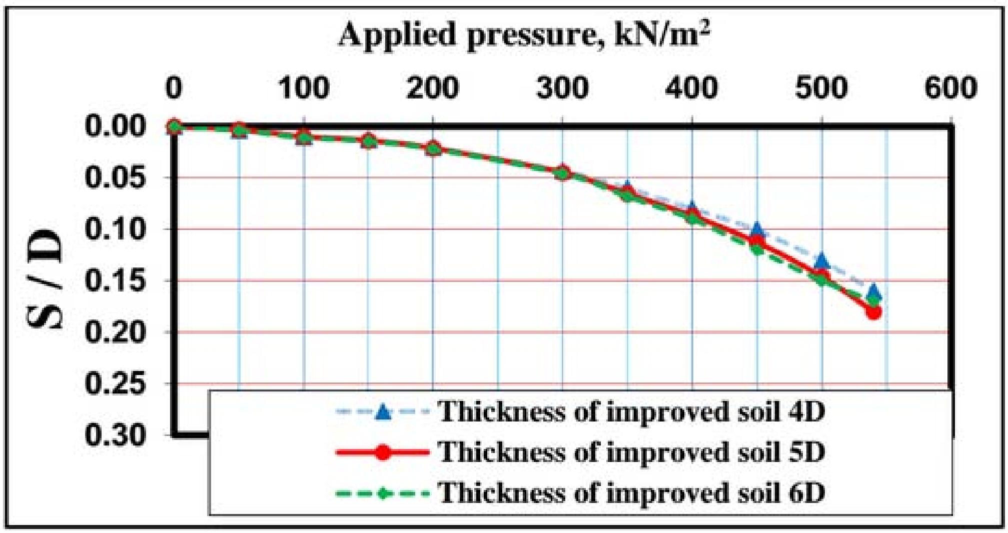

Figure 10 : Settlement versus applied vertical stress after flooding

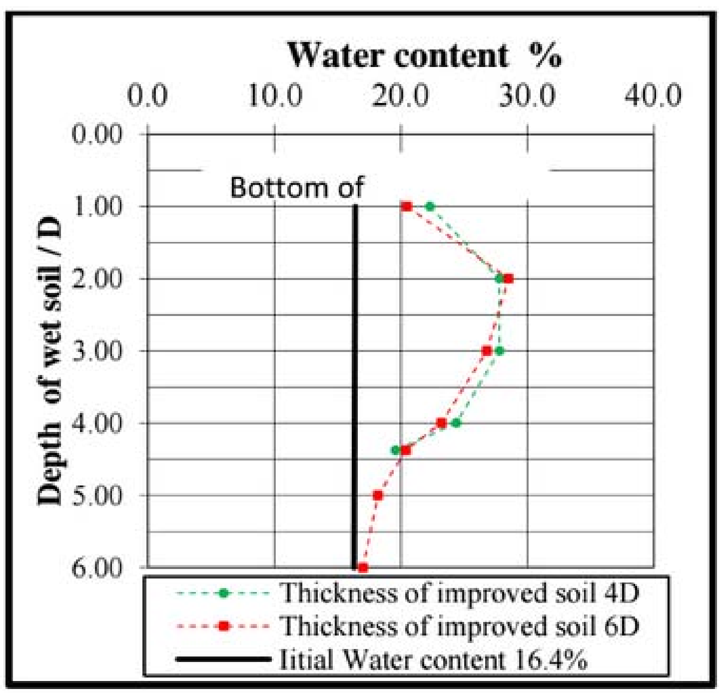

Figure 11: Variation of water content with depth in improved soil

Foundation movement problems are mostly associated with water existence and therefore, it is imperative that the investigation of the sources of water be the first order of distress investigation. Thus a series of tests conducted involved different sources of inundation, thickness of improved collapsible soil under replacement equal to 6D (tests of group G). Inundated soil with 4000 cm3 from water pipes at distance D and 3D from footing on both sides of footing under a stress during inundation =100 kN/m2 to simulate water leaking from a broken water / sewer lines or utility line leakage.

Figures 12 through 14 shows that wetting may reduce or soften bond or cementation between soil particles leading to their rearrangement near the water source causing differential soil collapse. Figures show that the total amount of collapse potential depends on the environmental conditions, such as the extent and duration of wetting, and the pattern of moisture migration.

Figure 13 and 14 indicate that compressibility of improved soil before inundation is low and increase gradually during inundation with time. After seven days the increase in collapse settlement under foundation resulting from nearest source of water is greater than that of the second source at the same time; although the inundation in the two cases uses the same amount of water (4000 cm3). This result may be due to amplified collapse settlement supplemented by consolidation settlement induced by the significant increase in soil unit weight resulting from the addition of water. Thus providing a minimum of ten percent surface slope outwards from foundation may be considered as prudent a suitable protective measure.

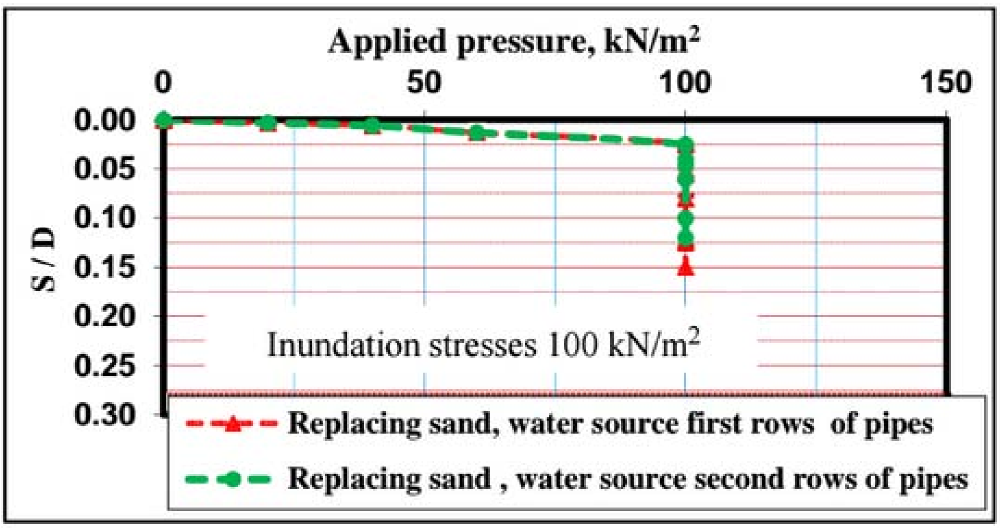

Figure 12 : Settlement versus applied vertical stress on inundation at stress 100 kN/m2

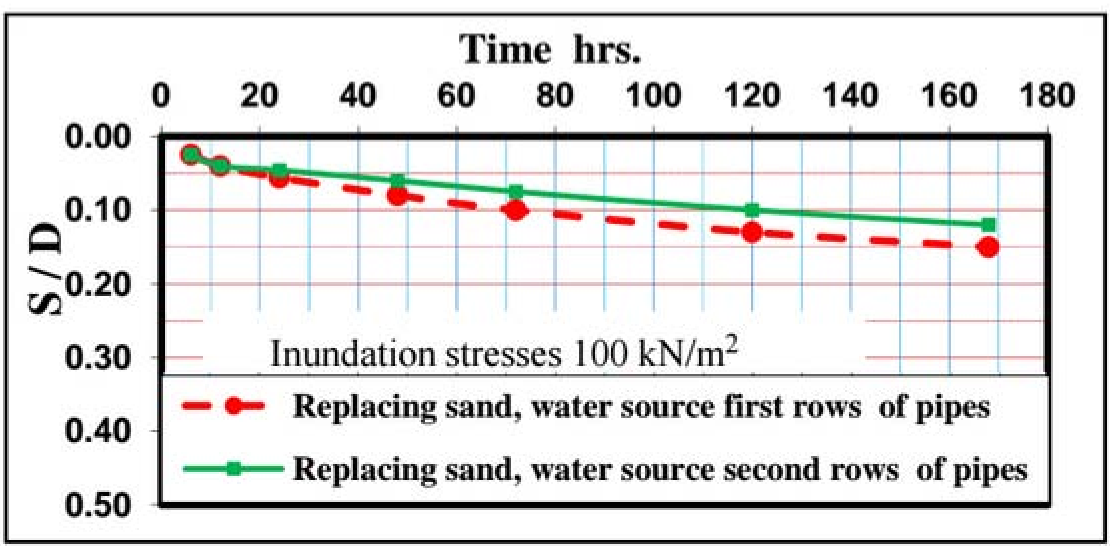

Figure 13 : Settlement versus time at applied vertical stress on the flooding at stress 100 kN/m2

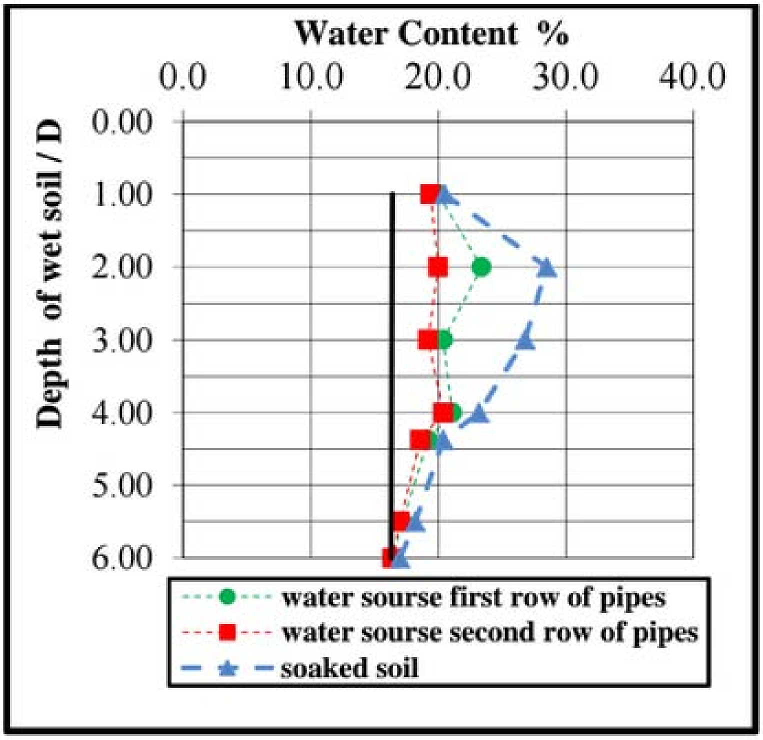

Figure 14 : Water content along improved soil depth

Figure 14 shows the variation of water content before and after wetting with depth under footing which explained an increase in the collapse settlement with time. For this study case, water penetration reached as far as 5.5 footing diameter.

VI. Conclusion

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

- 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%).
- 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.
- 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 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

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sudden settlement when exposed to wetting, and provide remediation for design and construction oversight.

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