Indexed in
Scopus Compendex and Geobase Elsevier,
Geo-Ref Information Services-USA, List B of Scientific
Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 01

February 2016, P.P.204-210

Oedometer based Study on Collapse Potential of Cement Admixed Loess Soil

DARGA KUMARN AND RAVIKANT R SINGH
School of Building and Civil Engineering, CEST, Fiji National University, Fiji Islands
Email: *darga.nandyala@fnu.ac.fj*

Abstract: The large ground displacements caused by loess or collapsing soils can totally destroy roads and structures. In this study, a controlled Oedometer testing is carried out to understand the collapse potential (CP) of loess soil samples prepared at different dry unit weights and admixed with cement proportions 0%, 2%, 4%, 6%, 8% and 10%. When compared to the untreated soil, the reduction in CP is about 35% for the sample prepared at 11 kN/m^3 dry unit weight and 200 kPa stress level and for cement proportion of 8% and initial water content of 2%. But for the similar conditions and for cement proportion of 8% and initial water content of 4%, the reduction in collapse potential is observed about 95%. From the results, it can be revealed that CP of loess soil can be controlledwith the process of pretreatment.

Keywords: *Loess Soil, Void Ratio, Collapse Potential, Cement, Dry Unit Weight*

1. Introduction

Collapsible soils appear to be strong and stable in their natural dry state, but which rapidly consolidate under wetting, generating large unexpected settlements. This can lead to a total destruction of infrastructure built on such deposits. Such soils are often termed "collapsible" or "metastable" and the process of their collapsing is often called any of "hydro-consolidation", "hydro compression", or "hydro-collapse." Collapsible soil deposits share two main features: (i) they are loose, cemented deposits; and (ii) they are naturally quite dry. Loess soils consist primarily of silt sized particles loosely arranged in a cemented honeycombed structure. The loose structure is held together by small amounts of water softening or water-soluble cementing agents such as clay minerals and $CaCO_3$. The basic characteristics of collapsible soils are categorized as: high porosity (more than 40%), low saturation(less than 60%), high silt content (more than 30% and sometimes 90%), and rapid softening in the water (Rafie, 2008). The introduction of water dissolves or softens the bonds between the silt particles and allows them to take denser packing under any type of compressive loading. These soils possess high stiffness and shear strength at their dry and natural states. The sources of saturation or wetting of these soils can be either natural, such as rainfall and fluctuation in ground water table, or man-made, such as excessive irrigation and leakages from water and sewer lines. Collapse may be triggered by water alone or by wetting and loads acting together. The recent infrastructure developments accompanied by the use of large quantities of water and the associated construction problems warrant a comprehensive investigation of these soils. The collapse of soils due to wetting may result in settlements of 2 to 6 percent of their thickness. To control the collapse potential of these soils, the following initial treatment can be more appropriate: i. an open, partially unstable, partially saturated fabric, ii. a high enough total stress so that the structure is metastable, iii. a strong enough clay binder or other cementing agent to stabilize the structure when dry and iv. addition of water to the soil.

Clemence S P and Finbarr (1985) proposed criteria for collapsibility evaluation based on the soil dry density and stated that if the dry density of soil is less than 12.8 kN/m^3, there can be a soil collapse even after minor change in water content of soil. Lutenegger (1986) reported the effectiveness of dynamic compaction to stabilize a thick layer of friable loess before construction of a foundation. Tony Williams and Kyle Rollins (1991) studied how to identify the collapsible soils based on basic soils properties such as density, moisture content and liquid limit. Fredlund and Gan (1995) investigated the collapse mechanism of a soil subjected to one dimensional loading and wetting and reported that the collapse of an uncemented, dry collapsible soil is due to the loss in the normal stress between soil particles, leading to shear failure as a result of a reduction of metric suction from wetting.

Amer Ali Al-Rawas (2000) studied the state-of-the-art review of collapsible soils, with special reference to: (a) the types of collapsible soils; (b) collapse mechanisms; (c) identification and classification; (d) laboratory and field tests; (e) stabilization techniques; and (f) foundation design and also studied the direct measurement of the collapse potential using one-dimensional oedometer test. Several treatment methods were proposed for minimizing the collapse of soils such as soil replacement, prewetting, compaction control and chemical stabilization or grouting. The choice of such methods depends on the ground conditions, type of structure to be constructed, practicality and economics of the method. Shallow foundations such as continuous strip footings and mat foundations are recommended when collapsing soil extends to shallow depth 1.5 to 2 m. In cases where collapsing soil extends to several meters, deeper than 3 to 5 m, deep foundations such as piles and drilled piers can be recommended.

Jose Pereira et al (2000) reported the volume change behavior of collapsible compacted gneiss soil using both conventional oedometer cell and triaxial permeameter system. The volume change induced by the collapse mainly depends on the initial void ratio and mean net stress under which the collapse takes place. Also reported that when imposed suction is decreased, large collapse takes place, in the samples compacted dry-of-optimum, while little collapse takes place, in the samples compacted wet-of-optimum. Prediction of footing settlements on collapsible soils gives a framework for calculating settlements of foundations on collapsible soils. Swelling potential was found to increase with the increase of dry density, whereas the collapse potential increases with the decrease of dry unit weight and in case of expansive soils, penetration values at the dry state increases with the increase of dry unit weight of the soil, whereas penetration values for wet condition increases very slightly with the increase of the dry unit weight. In case of collapsible soils, penetration values increases with the increase of dry unit weight. However, penetration values in case of wet condition are higher than the corresponding penetration value at dry unit weight state (Aboushook, 2005).

The collapse deformation of unsaturated compacted soil depends mainly upon the density and stress state under which the collapse occurs. Various criterion offer different judgment for soil collapsibility evaluation (Rafie, 2008). The collapse potential results of an artificially cemented collapsible soil obtained from single oedometer tests noticed to be higher than the one calculated from the double oedometer test for samples with the same initial conditions (Medero et al, 2009). Rachid and Brahim (2010) reported that for the soil with small percentage of fine particles, irrespective of nature of liquid used for wetting, the collapse potential decreased with the increased compaction energy and for soils with high percentage of fine particles, the collapse potential is increased. Also it has been reported that the high collapse potential was noticed in the sample that was wetted with water than the oil. It indicates that the collapse potential of soil is low if it is contaminated or mixed with oil. Due to oil wetting, the soil does not completely collapse and it can be attributed due to partly the links that can remains intact.

Kakoli (2011) studied the causes of immediate failure of foundations founded on collapsible soils based on the load -settlement curves. The void ratio and capillary force in soil are the important parameters to describe about the collapse potential and foundation failures on collapsible soils. Rezaei et al (2012) reported that collapse potential of soil can be reduced by increasing dry unit weight and liquid limit of soil. Collapsible soils have high porosity, during collapse test, bonds between soil particles destroy and soil particles will be re-arranged in a denser array, in a way, this process leads to soil collapse and sudden settlement. There are several methods to improve the collapsible soils, those can be used either single or combination of methods of treatment, depending on the project and site conditions. In most conditions, saturation of soils before construction can be helpful to stabilize collapsible soils. Best result can be achieved when wetting of soil and loading is done together.

Gaaver (2012) conducted studies on Egyptian collapsible soils. The bearing capacity of collapsible soils decreased to about 50% due to wetting process. Based on the above decrease in bearing capacity, it is recommended that a factor of safety 2 towards bearing capacity calculations in collapsible soils. The bearing capacity of collapsible soils when compacted to 95% showed 24 to 30% increase in bearing capacity as compared to the natural soil. It was further reported that in the undisturbed and compacted soil samples, as the initial water content increases the collapse potential of soil decreased. As the liquid limit of a collapsible soil increases, the value of California Bearing Ratio of the compacted samples decreased linearly. California Bearing Ratio of the compacted collapsible soils is correlated to the liquid limit. The study revealed that the use of compaction process to treat the collapsible soils prior to construction of foundations is very viable and controls the foundation failures on collapsible soils.

2. Materials and Methods

2.1. Soil

The loess soil samples were collected at a depth of about 30 cm from the ground surface at construction site of Nizampet road area in Hyderabad, India and stored in airtight containers. Index test results of loess soils are presented in Table.1. The grain size distribution curve of the soil is shown in Fig.1.

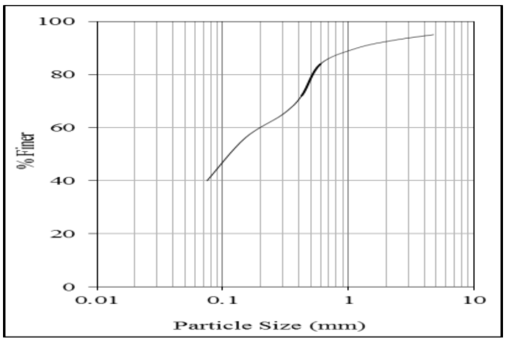

Figure 1.*Grain size distribution curve for soil*

Table 1 Basic Geotechnical Properties of Soil

S.No	Property	Value
1	Liquid limit (%)	34
2	Plastic limit (%)	25
3	Plasticity index (%)	9
4	% Gravel	2
5	% Coarse Sand	3
6	% Medium Sand	10
7	% Fine Sand	37
8	% Silt & Clay	48
9	Specific gravity	2.45
10	Free swell index (%)	45%
11	Soil Classification	SM
12	OMC	7.5%
13	MDD (kN/m^3)	14.5

2.2. Cement

The cement used in this study was Ordinary Portland Cement (OPC) of 43 Grade and was collected from the local market in Hyderabad. The cement sample collected was stored in air tight containers. The initial and final setting times of cement are 30 minutes and 600 minutes respectively. The soundness of cement is 10mm. The main chemical constituents in the cement are 62% CaO, 22% SiO_2 and 6% Al_2O_3. Its 28 days compressive strength is 43 MPa. The cement proportions adopted in the study by dry weight of soil are 0%, 2%, 4%, 6%, 8% and 10%.

2.3. Tests conducted on soil samples

The tests such as specific gravity (IS: 2720 -Part 3/Set I-1980), grain size analysis (IS: 2720- Part 4-1985), liquid limit and plastic limit (IS: 2720 -Part 5-1985), standard Proctors compaction test (IS: 2720-Part7-1980), Oedometer test (IS: 2720-Part 15-1968), free swell test (IS: 2720-Part 40-1977) were conducted in the laboratory.

2.4. Soil samples preparation

Soil samples were prepared at dry unit weights 11 kN/m^3, 13 kN/m^3 and 15 kN/m^3 in the consolidation ring by ramming gentle way with the small size wooden mallet. In some of the tests, the fraction of cement weighed by weight of dry soil was uniformly mixed with the soil and compacted at the same dry unit weights as that of pure dry soil. Similarly, the samples were prepared at natural state by adding initial moisture content of 2% and 4% to the soil cement mixture uniformly and compacted to achieve the dry unit weights such as 11 kN/m^3 and 13 kN/m^3.

2.5. Collapse potential

The collapse potential (CP) of a soil at a given stress can be estimated from the following equation 1.

$$CP = \frac{\Delta H}{H_0} = \frac{\Delta e_c}{(1+e_0)} \times 100 \quad \text{(Eq.1)}$$

Where ΔH is the change in height of the specimen upon flooding, H_o is the original height of the specimen, Δe_c is the change in void ratio of the specimen upon flooding and e_o is the void ratio before flooding. The collapse potential gives us an idea about soil severity in terms of collapse. The CP more than 5% is troublesome.

3. Results and Discussion

The test results are presented and discussed below. Fig. 2 shows void ratio-effective normal stress curves and also collapse at 100 kPa stress for soil samples prepared at dry unit weights 11 kN/m^3, 13 kN/m^{3}and 15 kN/m^3.

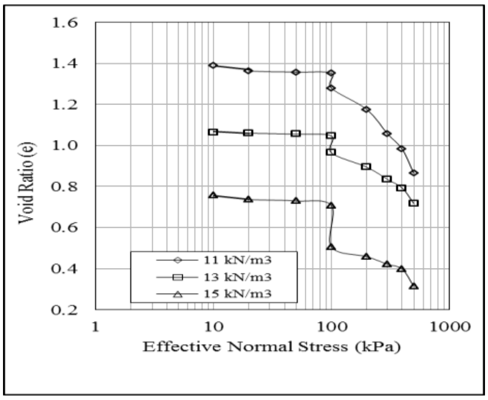

***Figure 2** Collapse behavior of initially dry samples at 100 kPa stress level*

From this figure, it is noticed that as the effective normal stress increases, the void ratio of soil samples is decreasing with the applied stress. This decrease in void ratio noticed is minimal in the dry state of compression of samples. Immediately after reaching 100kPa stress levels the sample is flooded with water for 24 hrs without changing the stress level. The decrease in void ratio is sudden in wet state as compared to dry state under the same stress levels.

It can be seen that the decrease in void ratio is more in case of samples prepared at a dry unit weights of 11 kN/m^3. The flooded samples in the Oedometer are further loaded with increased effective normal stress levels, and during this state, it is noticed that the decrease in void ratio is linear. This behavior can be attributed that the presence of water made the soil system as viscous and resulted in linear decrement in void ratio. From the Table 2, it can be seen that as the dry unit weight of soil sample increases, the CP is decreasing.

***Table 2** CP at 100 kPa stress level for initially dry sample*

Dry unit weight, kN/m^3	CP in %
11	11.29
13	4.14
15	3.97

It also can be seen that the CP is higher at soil dry unit weight 11 kN/m^3, whereas at dry unit weight 13 kN/m^3 the CP is very low. As per the limits of CP; if a soil possesses a CP of 5% and above can cause sudden reduction in volume upon wetting and in turn failure of foundations founded on these soils. Collapsible soils which are deposited at low dry unit weights can undergo sudden reduction in volume. From the CP values corresponding to 100 kPa stress levels, and for various dry unit weights given in Table 2, it is noticed that the CP of samples prepared at 11 kN/m^3 dry unit weightis 3.5 times than the CP of samples tested at dry unit weights 13 kN/m^3 and 15 kN/m^3.

Similarly the CP of soils corresponding to stress levels of 200 kPa and tested for dry unit weights 11 kN/m^3, 13 kN/m^3 and 15 kN/m^{3}are presented in Fig. 3 and Table 3. Fig.3 shows the sudden reduction in void ratio when samples are flooded at 200 kPa stress levels. From this figure, it is noticed that in dry state up to 200 kPa stress levels, the decrease in void ratio is very marginal and after flooding of samples and for further application of stress levels beyond 200 kPa caused slow rate and linear decrement in void ratio. It can be further observed that the void ratios are in the order of 1.3 to 1.4 before the sample is subjected to flooding. Under the same 200 kPa stress levels, the void ratios are noticed are varying from 1.18 to 1.0 upon flooding at the same stress levels. The decrease in void ratio at 200 kPa after flooding is noticed as 21%, 19% and 15 % respectively for soil samples tested corresponding to dry unit weights 11 kN/m^3, 13 kN/m^3 and 15 kN/m^3 respectively. The rate of decrease in void ratio is hardly 1 to 2 % when stressed for different normal stresses before and after flooding of samples. The CP of soil samples prepared at dry unit weights 11 kN/m^3, 13 kN/m^{3}and 15 kN/m^3 and corresponding to an effective normal stress of 200 kPa are presented in Table 3. From this table, it is observed that the CP is decreasing as the dry unit weight of samples increases. When compared to CP of sample tested at 11 kN/m^3 dry unit weight, the values are about 10% and 22% higher as that of soil samples tested at dry unit weights 13 kN/m^3 and 15 kN/m^3 respectively. There is a linear decrease in CP as the dry unit weight of soils increases.

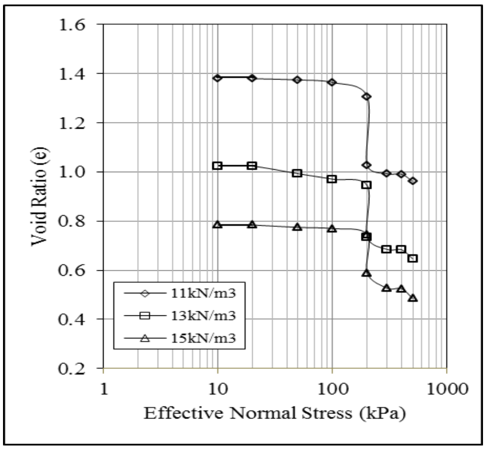

Figure 3 *Collapse behavior of initially dry samples at 200 kPa stress level*

Further, the collapse behavior of samples prepared at 11 kN/m^3, 13 kN/m^3& 15 kN/m^3 dry unit weights andsubjected to a stress level of 300 kPa are presented in Fig 4 and Table 4. From the figure, it can be seen that the CP of the soil samples tested at dry unit weights 11 kN/m^3, 13 kN/m^{3}and 15 kN/m^3 is found to be almost same and it is in the order of 7.5% to 7.0% respectively.

Table 3 *CP at 200 kPa stress level for initially dry sample*

Dry unit weight, kN/m^3	CP in %
11	11.48
13	10.15
15	8.85

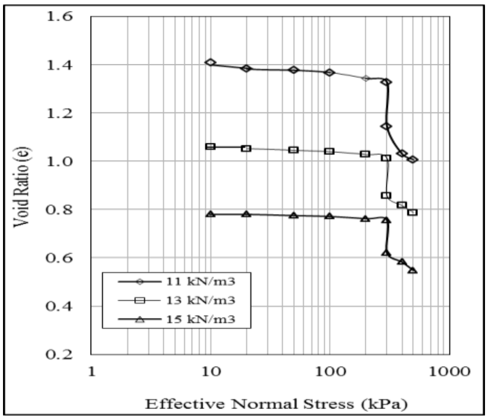

Figure 4.*Collapse behavior of initially dry samples at 300 kPa stress level*

Table 4 *CP at 300 kPa stress level for initially dry sample*

Dry unit weight, kN/m^3	CP in %
11	7.52
13	7.57
15	7.6

This indicates that the influence of dry unit weights of samples is nominal on CP at higher effective normal stress levels. From this, it can be further noticed that the higher effective normal stress causes immediate settlement of collapsible soil and hence there is a reduced CP as compared to CP observed corresponding to effective normal stress levels of 100 kPa and 200 kPa.

From Table 4, it can be seen that the influence of dry unit weight on CP estimated corresponding to an effective normal stress of 300kPa is very minimal. It is further observed that the CP is decreasing as the dry unit weights increases for the stress levels of 100 kPa and 200 kPa. Whereas at 300 kPa stress levels, not much change in CP is noticed irrespective of sample dry unit weights. Overall, it is noticed that the CP is very high corresponding to an effective normal stress of 200 kPa and it is in the order of 10% and above for soil samples tested at dry unit weights 11 kN/m^3, 13 kN/m^3 and 15 kN/m^3.

The CP 10% and above can be considered as trouble to the structures founded on the collapsible soils. To mitigate the collapse potential of soil, a study is carried out in the laboratory using cement as admixture. These results are pertinent to the samples which are prepared at different percentages of cement in dry state and those samples subjected to flooding at 200 kPa stress levels. Table 5 presents the CP of samples tested for dry state corresponding to 11 kN/m^3 dry unit weight and for different cement proportions varying from 0% to 10% at an increment of 2%. The CP is decreasing as the cement proportion increases. This decrease in CP marginal up to 4% cement and then onwards for 6%, 8% and 10% cements CP noticed is on an average 7% and this confirms about 40% decrease in CP when compared to untreated soil.

Table 5 *CP at 200 kPa stress level for initially dry sample admixed with cement at dry unit weight 11 kN/m^3*

Cement (%)	CP in %
0	11.48
2	10.25
4	11.1
6	7.42
8	8.56
10	6.27

Table 6 presents the CP values of cement treated soils prepared at dry unit weight 13 kN/m^3 and flooded at stress levels 200 kPa. The CP is decreasing with the increased cement proportion. This decrease in CP is marginal up to 8% of cement and thereafter increases of cement proportion caused good reduction in CP value as 3.5% and this decrease is around 60% when compared to untreated soil.

Further to understand the effect of initial moisture content on CP, the soil is blended with cement at 2% and 4% moisture contents to simulate the natural state of soils. Corresponding to 2% initial moisture content, the CP measured at 200 kPa stress levels for cement proportions 4%, 6% and 8% are presented in Table 7 and graphically in Fig.5. It is clearly seen that as the percentage cement increases from 4% to 6% there is a decrease in CP. Similarly the CP results corresponding to 4% initial moisture contents are presented in Table.8 and graphically in Fig.6.

Table 6 *CP at 200 kPa stress level for initially dry sample admixed with cement at dry unit weight 13 kN/m^3*

Cement (%)	CP in %
0	10.15
2	12.45
4	12.08
6	10.41
8	2.98
10	4.34

Table 7 *CP at 200 kPa effective normal stress and at 11 kN/m^3 dry unit weight, 2% initial moisture content and for different proportions of cement.*

Cement (%)	CP in %
4	12.72
6	11.73
8	6.55

Table 8 *CP at 200 kPa normal stress and at 11 kN/m^3 dry density, 4% initial moisture content and for different proportions of cement.*

Cement (%)	CP in %
4	5.17
6	2.75
8	0.65

When compared to CP of soil samples blended at 2% initial moisture content, the CP of samples blended at 4% initial moisture content is very low. As compared to the dry samples the decrease in void ratio is more for the samples which are prepared at respective initial moisture contents 2% and 4%.

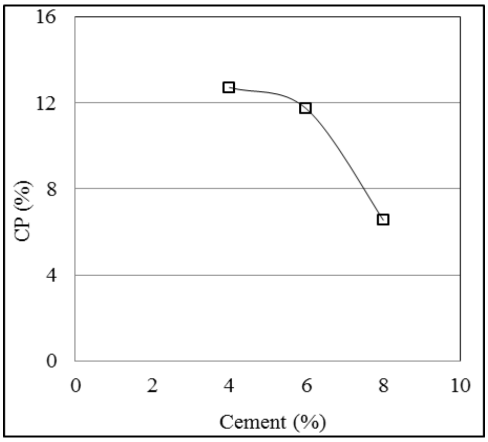

Figure.5 *CP variation at 200 kPa effective normal stress and at 11 kN/m^3 dry unit weight, 2% initial moisture content and for different proportions of cement.*

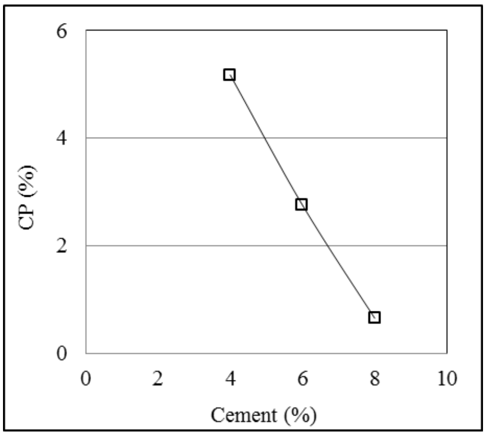

Figure.6 *Variation of CP at 200 kPa effective normal stress and at 11 kN/m^3 dry density, 4% initial moisture content and for different proportions of cement*

From the results, it is clearly noticed that the samples which are blended at 4% moisture content and for the cement proportions of 6% and 8%, the decrease in CP is nearly about 4 and 17.5 times that of untreated soil. It indicates that a good control over the collapse potential of soil can be achieved when treated with 6% and 8% cement at 4% initial moisture content. From the results, it can be suggested that whenever a collapsible soil is found in-situ, it can be treated with 8% cement with initial moisture content 4%, it can be possible to achieve a good control over the CP of soil.

4. Conclusions

The influence of cement and the initial moisture content on reduction of CP is studied by conducting the laboratory controlled Oedometer test. Some of the observations from the findings are presented. The samples tested for collapse potential at 11 kN/m^3 dry unit weight showed higher collapse potential as compared to samples of dry unit weight 13 kN/m^3 and 15 kN/m^3. Higher collapse potential 10% and above is noticed corresponding to 200 kPa stress level and for sample dry unit weight 11 kN/m^3. At stress levels beyond 200 kPa, the collapse potential is not changing much irrespective of the dry unit weight. The collapse potential of samples admixed with cement and blended without initial moisture content showed still higher collapse potential when compared to the samples of similar conditions but blended with initial moisture contents. The sample mixed with 8% and 10% cement in dry state are showing the collapse potential in the order of 6.5 to 8.5% respectively at 200 kPa stress levels and for 11 kN/m^3 dry unit weight. The samples mixed with 8% cement and blended with 4% initial moisture content corresponding to 11 kN/m^3 dry unit weight at 200 kPa stress levels showed huge reduction in CP. The reduction in CPfor sample of 11 kN/m^3 dry unit weight and 200 kPa stress level, 8% cement proportion and blended at 4% initial moisture content is about 95% and it is almost representing a no collapse situation.

5. Future Scope of the Work

Collapsible soils are some of the most widely distributed and costly of geologic hazards in the form of land slide and land subsidence. Large scale filed studies can provide better correlations in terms index and engineering properties of these soils to mitigate anticipated local hazards. Also economically viable and technically feasible techniques can be studied with the help of laboratory tests, model and prototype tests.

References

[1] J. Lutenegger, Dynamic compaction in friable loess, *Journal of Geotechnical Engineering, ASCE*, 1986, 112: 663-667.

[2] Amer Ali Al-Rawas, The state-of-the-art review of collapsible soils, *Proceedings Science and Technology, Special Review, 2000,* 115-135, Sultan Qaboos University. Page: 1-21.

[3] ASTM 1993. Standard test method for measurement of collapse potential of soils, *D5333–92*. Annual Book of ASTM Standards, 4: 343-345.

[4] Apiniti Jotisankasa, Andrew Ridley and Matthew Coop, Collapse behavior of compacted silty clay in suction-monitored oedometer apparatus, *Proceedings journal of geotechnical and geoenvironmental engineering, ASCE / July 2007 / 867*. Page: 1-11.

[5] M. A. Rafie, Evaluation of soil collapsibility potential and he did a case study on semnan railway station, *Proceedings EJGE*, 2008, Vol. 13, Bund. G. 1-7.

[6] D. G. Fredlund. and J. K. M Gan, The collapse mechanism of a soil subjected to one dimensional loading and wetting, *Proceedings E. Derbyshire et al. (eds), Genesis and Properties of Collapsible soils*, 1995, 173-205, Kluwer Academic Publishers.

[7] G. Medero, M, F. Schnaid and W. Y. Y. Gehling, Oedometer behavior of an artificial cemented highly collapsible soil, *Proceedings 840/Journal of Geitechnical and Geoenvironmental Engineering, ASCE*, 2009, 1-4.

[8] H. F. Jose. Pereira and G. Delwyn. Fredlund, Volume change behavior of collapsible compacted gneiss soil. *Proceedings journal of geotechnical and geoenvironmental engineering/*October 2000/907, 1-10.

[9] IS: 2720-Part 15-1968, Methods of tests for soils, Part 15, Consolidation characteristics of soil.

[10] IS: 2720-Part 40-1977, Methods of tests for soils, Part 40, Free swell test of soils.

[11] IS: 2720 (Part 3/Set I)-1980, Methods of test for soils: Part 3 Determination of specific gravity, Section I Fine grained soils.

[12] IS: 2720-Part7-1980, Methods of tests for soils, Part 7, Standard Proctors compaction.

[13] IS: 2720 (Part 4)-1985, Methods of test for soils, Part 4 Grain size analysis.

[14] IS: 2720 (Part 5)-1985, Methods of test for soils, Part 5 Determination of liquid and plastic limit.

[15] Noorany, Discussion: stress ratio effects on collapse of compacted clayey sand, Lawton, Gragaszy, and Hard casle. *Journal of Geotechnical Engineering, ASCE*, 1992, 188: 1472-1473.

[16] Khaled E. Gaaver, Geotechnical properties of Egyptian collapsible soils, *Alexandria Engineering Journal*, 2012, www.elsevier.com/locate/aej; www.sciencedirect.com.

[17] M. Aboushook., Correlation and prediction for problematic soils with field measurements, *Proceedings of International Conference on Problematic Soils, Famagusta, Cyprus, Geoprob 2005*. Page 1-7.

[18] Mohsen Rezaei, Rasoul Ajalloeian, Mohammad Ghafoori, Geotechnical Properties of Problematic Soils Emphasis on Collapsible Cases, *Proceedings International Journal of Geosciences,* 2012, 3, 105-110 Doi:10.4236/ijg.2012.31012.

[19] N. F. Ismael. A. Jeragh, M. A. Mollah and O. Khalidi, Factors affecting the collapse potential of calcareous desert sands, *Proceedings of the 9th Southeast Asian Geotechnical Conference, Bangkok, Thailand*, December 7-11, 1987, No. 5, 147-158.

[20] Roberto Nova, Prediction of footing settlements on collapsible soils. *Proceedings First Euro Mediterranean in Advances on Geomaterials and Structures – Hammamet* , 2004, 3-5.

[21] Rachid Benkadja and Brahim Belouahri, Influence of oil on the magnitude and rate of collapsible soils, *Proceedings Journal of Civil Engineering Research and Practice*, Vol. 7 No.1, 2010, 1 – 12.

[22] S. P. Clemence, and A. O. Finbarr, Design considerations for collapsible soils. *Journal of the Geotechnical Engineering Division, ASCE*, 1985, 107: GT3, 305-317.

[23] S. L. Houston. W.N. Houston. and D. J. Spadola, Prediction of field collapse of soils due to wetting, *Journal of Geotechnical Engineering, American Society of Civil Engineers, ASCE, 1998,* 114: 40-58.

[24] S.T.N. Kakoli, Causes of foundation failure and sudden volume reduction of collapsible soil during inundation. *Proceedings 4th Annual Paper Meet and 1st Civil Engineering Congress*, December 22-24, 2011, Dhaka, Bangladesh, 1-8.

[25] Tony Williams and Kyle M. Rollins, *Proceedings Report 91-10, Utah geological survey a division of Utah department of natural resources*, 1991, 1-44.

[26] W. Zhang, and Zhang, Development of loess engineering properties research in China. *Unsaturated Soils*, *Proceedings of the First International Conference on Saturated Soils*, 1995, Sept. 6-8, Paris, E.E. Alonso and P. Delage, eds., Belkema Press.

[27] Y. M. Reznik, Determination of deformation properties of collapsible soils. *Geotechnical Testing Journal, ASTM,* 1992, 15: 248-255.

[28] Z.G. Lin, S. J. Wang, Collapsibility and deformation characteristics of deep-seated loess in China. *Engineering Geology*, 1988, 25 pp: 271-282.