

Laboratory Testing Regime for Quantifying Soil Collapsibility

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Abstract—Collapsible soils go through radical rearrangement of their particles when triggered by water, stress or/and vibration, causing loss of volume. This loss of volume in soil as seen in foundation failures has caused millions of dollars' worth of damages to public facilities and infrastructure and so has an adverse effect on the society and people. Despite these consequences and the several studies that are available, more research is still required in the study of soil collapsibility. Discerning the pedogenesis (formation) of soils and investigating the combined effects of the different geological soil properties is key to elucidating and quantifying soils collapsibility. This study presents a novel laboratory testing regime that would be undertaken on soil samples where the effects of soil type, compactive variables (moisture content, density, void ratio, degree of saturation) and loading are analyzed. It is anticipated that results obtained would be useful in mapping the trend of the combined effect thus the basis for evaluating soil collapsibility or collapse potentials encountered in construction with volume loss problems attributed to collapse.

Keywords—Collapsible soil, Geomorphological process, Soil Collapsibility properties, Soil test.

I. INTRODUCTION

COLLAPSIBLE soil, which cover naturally over 10% of the earth's surface, are a global problem [1], [2]. They are open unsaturated soils that collapse suddenly when wetted under loading. Collapse is induced by reduction in volume which causes differential settlement of buildings as seen in foundation failures costing millions of dollars' worth of damages to public facilities and infrastructure. Sinkholes and Seismic activities also can induce collapse.

A lot of past studies on collapsible soils have focused on understanding the existence, description, classification, structural make up and the state factors that influence the collapse mechanism of collapsible soils. However, lacking in knowledge among others is a model in the form of a 'guide' where the key geological parameters such as particle type (size, percentage and atterberg limits), dry density, moisture content, degree of saturation, overburden pressure, and stress-strain and the limit that make them collapsible are presented. A table guide would make geological behavioral identification of a collapsible soil simplified for sites. This paper intends to

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suggest a methodology on how this gap can be filled. To accomplish this, first the geomorphological processes (pedogenesis) of collapsible soils is studied, the effects of the different geological soil properties on collapsibility are investigated and finally a step by step methodology on how a geological model for identifying collapsible soil is proposed.

II. LITERATURE ON SOIL COLLAPSIBILITY

A. General

Collapsible soils are typically of silt and fine sand sizes with a small amount of clay; its pedogenesis is via dry alluvial (water) fan, colluviums (gravity) and aeolian (wind-blown) deposits. They are porous soil structures that show relatively high apparent strength (cohesion) in their dry state, have low density, and are susceptible to large settlement upon wetting. Severity of collapse is affected by the extent of wetting, depth of the collapsible soil deposit, the pressure from overburden weights (e.g. structure) and the collapse potential of the soil [1]–[7].

Some criteria for identifying collapsible soils have been described as having low density, high porosity (more than 40%) and low saturation (less than 60%); open partially unstable structure and unsaturated fabric; high silt content (more than 30% and sometimes more than 90%) and sand size with a small amount of clay [5], [8]–[14]. In addition, all fills are collapsible until proven otherwise [15]; local site geology, depositional processes and also climatological data show probability of collapsibility of the soil mass.

The collapse potential is affected by the nature and type of the soil particle and the sedimentation mechanism, which combine to produce collapsibility. Collapsible soils are seen as stable until there is a triggering event that turns them unstable causing collapse [9]; hence, they are best described as metastable structured soils. Soil collapsibility is brought about by changes in state parameter of the open structured soil into a densely structured soil.

Reference [16] states that the differential settlements are instigated by shear failure from pressures transcending the soil's critical pressure and also by hydro-collapse from soil inundation which impels loss of the soil's cementation bonds (clay bond or chemical bond) or loss of matric suction. This behavior can be of great challenge to the developer, designer and engineer in charge of such site, mostly when it has not been anticipated for at the design and construction stages. This makes it much more important that prior to construction, determination and identification of collapse potential of a soil is imperative.

Soil state parameters that affect the collapse intensity of the

soil are soil collapse potential, initial water content, initial dry density, pressure at wetting, extent of wetting and wetting front, atterberg limits, coefficient of uniformity, coefficient of curvature and depth of the deposit. [8], [12], [17]–[20].

B. Geomorphological Processes

Loess which is a wind deposit collapsible soil is the most widely distributed collapsible soil [2], [21], most encountered [22] and most researched; therefore loess formation would be used in the description of the geomorphological processes.

The origin of deposition formation of loess soils is from several different deposit formations which involve eluvial, proluvial, diluvial, alluvial and aeolian; but the worldwide paradigm theory is that of only aeolian deposition formation [23].

Loess was first formed when glaciers covered the earth; the warm temperatures melted the glaciers creating flows of water down into valleys or rivers. The fluvial transportation from the piedmont region and out into the desert exposed the mud; when dried, strong winds blew the exposed debris and gathered the finer materials from the flood plains into huge clouds of dust, which were deposited into banks forming higher piles of loess. With each individual glacier deposit and post-deposition a palaeosol of loess soil is produced [21], [23].

C. Geological Properties

Geological properties of soils give it the structural durability, mechanical ability and general stability. Collapsible soils particles are kept from forming closer packing naturally due to the geomorphological process forming clay bridge, carbonates and gypsums bonds [9]. These soils are unsaturated and of low degree of saturation. The soils are stable through these bonds acting with the strong matric suction between the particles. At a critical degree of saturation the bonds fail and the soil collapses [12], [24]. This process forms three mechanisms of collapse. See Table I:

TABLE I
STEPS OF COLLAPSE MECHANISM BY [3] CITED IN [7]

Phase	Collapse type	Degree of saturation	Matric suction	Volume deformation	Soil structure
1	Pre-collapse	Low (unsaturated)	High	Small	No particle slippage, intact structure
2	Collapse	Intermediate	Intermediate	Significant decrease	Altering structure, thus bond breakage
3	Post-collapse	High (> 85%) Approaching Saturated	No reduction in matric suction	No further decrease	Totally collapsed structure

D. Collapsibility Correlation

Several researchers have classified soil collapsibility; each one based their criteria on different parameters. The parameters can be looked at in four categories: atterberg with soil properties parameters; void ratios of the soil; numerical limits and graph presentation.

1) ‘Atterberg with Soil Properties Parameters’ Category, for Collapse

Equations (1)–(5) give the parameters in this category:

[25]
$$\frac{W_0}{L_L} * \frac{1}{Sr} > 1 \tag{1}$$

[26]
$$\frac{\gamma_w - \frac{1}{Gs}}{\gamma_d} < 1 \tag{2}$$

[27]
$$\frac{L_L - W_0}{L_L - P_L} < 0.5 \tag{3}$$

[28]
$$\frac{W_0 - P_L}{Sr_0 - P_L} > 0.85 \tag{4}$$

[29], [30]
$$\frac{W_{max}}{L_L} \geq 1 \tag{5}$$

where:

- W₀ – Initial moisture content
- W_{max} – Maximum moisture content
- L_L – Liquid limit
- P_L – Plastic limit
- Sr – Degree of saturation
- Sr₀ – Initial degree of saturation
- γ_w – Unit weight of water
- γ_d – Dry unit weight of water
- G_s – Specific gravity

2) Soil’s Void Ratios’ Category, for Collapse

Reference [31] used stress level of 300 kPa while, [32] recommended the use of 200 kPa [33] for testing the collapse potential of a soil. However [31], [32], [34] have (6):

[31], [32], [34]
$$\frac{\Delta e}{e_0 + 1} \% = C \tag{6}$$

for which C is 2%, 6% and 10% respectively. Others are [26], [35] seen in (7) and (8) respectively.

[26]
$$\frac{e_1}{e_0} < 1 \tag{7}$$

[35]
$$\frac{e_0 - e_1}{1 + e_0} > -0.1 \tag{8}$$

where:

- e₀ – Void ratio at initial moisture content
- e₁ – Void ratio at the liquid limit
- Δe – Void ratio reduction

3) ‘Numerical Limits’ Category

This category has the following:

- Dry density is less than 1.28Mg/m³, [36]
- Critical pressure is less than 0.15MPa, [37]
- Clay content is less than 16%, [30]

4) Graphs Presentation

References [29], [38] represent graph of dry density against liquid limit of which at 25% liquid limit, the soil is collapsible; defined a relationship in a graph of dry density against liquid limits show in Fig. 1.

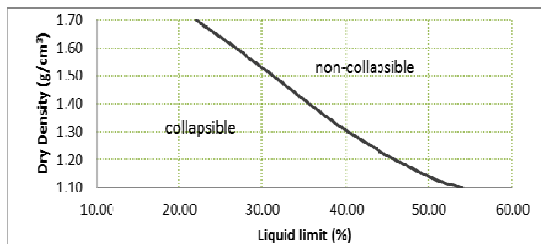


Fig. 1 Collapsibility according to [29] and [38]

III. ASSESSMENTS OF SOIL COLLAPSIBILITY

Several techniques are used to assess collapsibility of soils, they include: site reconnaissance, lithological (geology) sequencing, calibration with geotechnical collapse data (field and laboratory testing), and geophysical methods.

A. Reconnaissance

Reconnaissance process includes planning and procurement, description and classification of soils and rocks, the desk study and walk-over survey and basic field instrumentation for site investigation.

B. Field Testing

Field testing is approached using two methods of geotechnical and geophysical [2].

C. Laboratory Testing

Laboratory testing of the soil obtained from the field is done to gather geotechnical data that instigate the stability factors of the soil. Tests done include: soil classification, oedometer and triaxial.

1) Soil Classification

This plays an important role in identifying the properties of the soil. The tests involved are moisture determination, sieve analysis, atterberg limits and compaction.

2) Oedometer Test

This is the most used method of laboratory testing of collapse potentials of soil. References [2], [24], [31], [33], and [39] have used this method and found it most effective.

3) Triaxial Test

This test can be independently controlled to find results for the collapse potential of soils. Reference [40] carried out triaxial test to check the stress-strain effect of the sample; [3] used the triaxial test to observe the effects of matric suction against void ratio and net confining stress; and [41] test showed the effect of drying and wetting path of same sample.

D. Soil Synthesis Method

The study of collapsible soils from undisturbed samples is difficult to retrieve since the open metastable fabric is disturbed during the sampling process. To overcome these shortcomings, artificial cemented specimens were used in [42] study.

The laboratory scheme focuses on defining the mechanical behavior of the residual soil at dry-of-optimum moisture

content condition and at low dry density. This condition forms a structure which is capable of further densification, resulting in a collapsible soil [3], [43].

IV. METHODOLOGY

To overcome the challenges of sampling undisturbed soils, metastable structured soil are synthesized in the lab and tested to simulate the behavioral properties of the field collapsible soils.

Factors that affect the collapse intensity of a soil would be studied; which include the soil's fabric (size and nature of the soil's grains), compactive variable (such as density, matric suction, degree of saturation, void ratio, water content) and loading. These factors would be observed to understand the role each plays in the stability of the soil structure concerning the mechanism of collapse.

The relationship between soil fabric and state-parameters that make the soil metastable would be incorporated in the preparation, observation and study of collapsible soils. The result is then used in identifying the controlling effects collapsibility has on a soil structure. Fig. 2 shows the methodology summary.

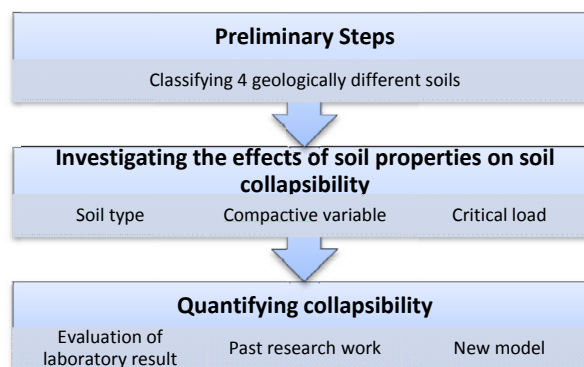


Fig. 2 Methodology summary

A. Preliminary Steps

'Preliminary steps' comprises of testing the soils for their geological properties such as soil fabrics, maximum dry density (MDD), optimum moisture content (OMC) and degree of saturation (S_r) at the MDD, to note their effect on the soil's collapse potential when the structural properties are reconditioned.

1) Soil Classification and Property Identification

Several acquired soils from different sites are tested to identify and classify their properties. Laboratory tests carried out to identify the state parameters of the soil structure are: Sieve analysis and sedimentation test to identify the soil's fabric makeup and Atterberg and compaction for classification.

Soil Preparation: The obtained samples are dried in the oven for at least 24 hours and then fines are grinded to their original particle sizes.

Identification tests: Dry sieve analysis and sedimentary test are executed on the soil samples to identify the particle size

distribution. Atterberg limit test is conducted to specify the characteristics of the fines and obtain values for liquid limit and plastic limits of the soils.

Finally, *mechanical properties* of the different soils are tested for the MDD and OMC using the standard proctor compaction test.

The aim of these tests ultimately is to find the critical point at which the key parameters that make the soil stable lose their strength.

2) Metastable Soils

The acquired soils are tested and retested to get the suitable properties required for the purpose of collapsibility, hence the problem of liquefaction cannot be studied herein since continuous wetting and drying will have removed any chemicals the soil would have to cause such effect. The plan is to prepare specimens for testing and analysis of their physical and mechanical properties, from which to ascertain their collapse potential as a structure. The plasticity indexes of the soils are particularly important in the fabric bonding of the soil particles and stability of the soil structure.

B. Effect of Soil Properties on Soil Collapsibility

At this stage the optimum performances of each soil would have been identified. The next step is to vary and change the soils' geological structure to note their effect on the collapse potential of the soil. To achieve this, specimens are prepared and tested to acquire a metastable structured soil by observing the following factors: Soil fabric: Particle size distribution (PSD) and plasticity of the soil; Compactive Variable: Initial moisture content, initial dry density, degree of saturation and void ratio; and Critical pressure.

Varying the degrees of these factors produces a range of different soil structure which is tested to reveal their effect on the soil's collapsibility. The triaxial test is used with the aim of obtaining a quick measurement of the soils shear strength; double oedometer test is done to check the collapse potential of the prepped soil sample; and finally a modified uniaxial setup is used for a proper mix of state parameters forming metastable structure soil to replicate what happens in the field.

1) Soil Type

Soil fabric plays a fundamental role in soil structural demeanor, which is influenced mainly by the particle size distribution (PSD) and plasticity of the soil's fabric. Samples are prepared at their best performance i.e. compacted at their optimum moisture content. The stress-strain parameters and consolidation properties are obtained using triaxial test and double oedometer test respectively. Finally the effect of wetting is tested and scrutinized to examine the effect on the soil's collapsibility.

2) Compactive Variable

Water content plays a huge role in acquiring the maximum dry density during compaction. For this reason, the moisture content (MC) is varied at a percentage of the soil's optimum moisture contents (OMC) as shown in Table II. These forms the initial moisture content of the soil and the initial dry

density is obtained from the compaction of the mixed samples. These give a series of structurally different soils which are investigated to note their effect on collapsibility. The degree of saturation and the void ratio at these percentages of MC are also noted as they are of importance to collapsibility.

TABLE II
MOISTURE CONTENT VARIATION

Moisture rate	Percentage range from optimum moisture content (OMC) of the fabric mix
Dry OMC	60% - 75% of OMC
At OMC	85% - 110% of OMC
Above OMC	130% - 150% of OMC

3) Critical Load

The prepared sample is loaded at different stress levels to identify the critical pressure. Using a double oedometer test method, the critical loading is surveyed at pressures, 50kPa, 100kPa, 200kPa and 300kPa. Results obtained from these tests would be presented in a series of graph curves of collapse verses compactive variables for the loading pressure of each soil type, from this critical points for which a soil is termed collapsible is drawn.

4) Testing Method

Triaxial and oedometer tests are the main testing methods used. For saturation of the samples, they are placed in the oedometer cell surrounded with water after preparation. They are kept this way for 24 hrs.

C. Quantifying Collapsibility Based on Past Studies

The factors that affect the stability of the soil have been drawn out at this point of the investigation. The results are compared against results obtained from past studies on collapsibility of soil (see Subchapter II.D above II.D). Conclusions drawn are then used for the synthesized soil structure to check how the dominant factors affecting metastability of the soil interact. The results are further compared with [18] which give the field results of collapsible soil.

D. Full Observation of Collapsibility

The parameters that make a soil structure collapsible are compacted into layers of metastable soil structures where the metastable soils (gathered from general findings) are tested to see the potential, pattern and extent of collapse. Hence a relationship is drawn between the soil fabric, soil structure, critical loading and wetting of a metastable soil.

1) The Mould Specifications

Fig. 3 shows the schematic diagram of the full mould design and features for a uniaxial loading and wetting sequence test. The mould has the following specifications:

- Full dimensions: 200mm × 400mm × 600mm height
- Detachable: one for sampling and the other for the loading and wetting test.
- Calibrated and made of a 12mm thick transparent acrylic or perspex material.
- Has two sharp thin sheets of 10 and 5mm thickness used to cut through the compacted layers to separate the

sampling soils and the loading/wetting soils, after which the sampling section of the mould is removed and the loading/wetting side of the mould is made air tight with the 10mm sheet as wall and glued on to prevent leakage during soil inundation.

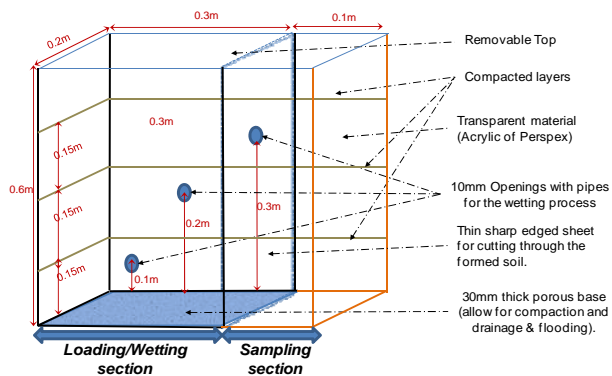


Fig. 3 Modified uniaxial setup

2) Equipment

Fabricated calibrated mould, compaction rammer, water source, weights

3) Compaction Specification

The soil is compacted into the mould by mean of a compressive machine, where the rate of compression is specified and the prepared soil is compressed at a constant rate.

4) Wetting Fronts of the Soils

The mould is designed such that soil saturation from the bottom and other different 'near surface' wetting is possible.

5) Loading

The mould is designed to simulate structure/foundation loading. The loading is applied in two ways:

- Static loading as in a plate loading test simulating a large scale oedometer testing.
- Incremental loading using CBR machine for the loading process.

Loading stress values within the range of a single-storey commercial/industrial/domestic structure is used with a net bearing pressure of 66.3kPa [18].

V. CONCLUSION

This paper suggests a method to which geological behavioral pattern of a collapsible soil is identified. To accomplish this, a model in the form of a 'guide' with the key geological parameters affecting collapsibility of soil is generated. This guide would have contents such as soil type (size, percentage and atterberg limits), dry density, moisture content, degree of saturation, overburden pressure, and stress-strain and the limit that make them collapsible. Understanding the pedogenesis, geological make-up, and collapse mechanism, of collapsible soil is the first step to creating this model.

The geomorphological processes combined with geological behavior and properties of collapsible soils have been explained. Also the laboratory test processes that are necessary to harness the key factors have been documented. The laboratory tests propose the investigation into the effects of soil type, compactive variables, and critical load to soil collapsibility.

Experimental works on different soils following the laboratory methodology should be executed.

REFERENCES

- [1] Evans, R. D., Jefferson, I., Northmore, K. J., Synac, O., and Serridge, C. J. "Geophysical investigation and in-situ treatment of collapsible soils." *Geotechnical Special Publication*, n 126 II, *Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans*, 2004 pp. 1848-1857.
- [2] Northmore, K. N., Jefferson, I., Jackson, P. D., Entwisle, D. C., Milodowski, A. E., Raines, M. R., Gunn, D. A., Boardman, D. I., Zourmpakis, A., Nelder, L. M., Rogers, C. D. F., Dixon, N., Smalley, I. J., and Derbyshire, E. "On-Site Characterisation of Loessic Brickearth Deposits at Ospringe, Kent, UK." *Proceedings on the Institution of Civil Engineers, Geotechnical Engineering*, vol. 161, 2008, pp. 3-17.
- [3] Pererira, J. H. F., and Fredlund, D. G. "Volume change behavior of collapsible compacted gneiss soil." *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 126, No. 10, 2000, pp. 907-916.
- [4] Houston, S. L., Houston, W. N. and Lawrence, C. A. "Collapsible soil engineering in highway infrastructure development." *Journal of Transportation Engineering*, vol. 128, No. 3, 2002, pp. 295-300.
- [5] Rafie, B., Moayed, Z., and Esmaeli, M. "Evaluation of Soil Collapsibility Potential: A Case Study of Semnan Railway Station." *Imam Khomeini International University of Qazvin, Iran*, vol. 13, 2008.
- [6] Frye, J. C. "Collapsible soils in Colorado." <<http://geosurvey.state.co.us/hazards/Collapsible%20Soils/Pages/CollapsibleSoils.aspx>> 2009 (22 May 2011).
- [7] Jefferson, I., and Rogers, C. D. F. "ICE Manual of Geotechnical Engineering." *Geotechnical Engineering Principles, Problematic Soils and Site Investigation*, vol 1, 2012, pp. 391-411.
- [8] Habibagahi, G., and Taherian, M. "Prediction of collapse potential for compacted soil using Artificial Neural networks." *Scientia Iranica*, vol. 11, 2004 pp. 1 - 20.
- [9] Rogers C. D. F. "Types and distribution of collapsible soil. Genesis and properties of collapsible soils." eds. By Derbyshire, E., Dijkstra, T., Smalley J. Netherland: Kluwer Academic, 1995, pp.1-17.
- [10] Dudley, J. H. "Review of collapsing soils." *Journal of Soil Mechanics and Foundation Division*, ASCE, vol 96, No. 3, 1970, pp. 925-947.
- [11] Lin, Z. "Variability in collapsibility and strength of loess with age. Genesis and properties of collapsible soils," *NATO ASI Series C: Mathematical and Physical Sciences*, Kluwer Academic, Dordrecht, The Netherlands, vol. 468, 1995, pp. 247-265 cited in Houston, S. L., Houston, W. N., and Lawrence, C. A. "Collapsible soil engineering in highway infrastructure development." *Journal of Transportation Engineering*, vol. 3, 2002, pp. 295-300.
- [12] Barden, L., McGown, A., and Collins, K. "The collapse mechanism in partly saturated soil." *Engineering Geology*, vol. 7, 1973, pp. 49-60.
- [13] Mitchell J.K. "Fundamentals of soil behaviour. New York: Wiley 1976. cited in Pererira, J.H.F. & Fredlund, D.G. Volume change behaviour of collapsible compacted gneiss soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 126 vol.10, 2000, pp. 907-916.
- [14] Houston, S. L., Houston, W. N., Zapata, C. E., and Lawrence, C. "Geotechnical engineering practice for collapsible soils." *Geotechnical and Geological Engineering*, vol. 19, 2001, pp. 333-355.
- [15] Beckwith, G. H. "Foundation design practices for collapsing soils in the western United States in Unsaturated soils." In: *Proceedings of the 1st International Conference on Unsaturated Soils*, Paris, France, 1995, pp. 953 - 958.
- [16] Das, S. "Seismicity gaps and the shape of the seismic zone in the Banda Sea region from relocated hypocentres." *Journal of Geophysical Research-Solid Earth* vol. 10, 2004, pp. 1-18.
- [17] Jennings, and Burland, "Limitations to the use of effective stresses in partly saturated soils." *Geotechnique*, vol. 12, No. 2, 1962, pp. 125-144.

- [18] Houston, S. L., Houston, W. N., and Spadola, D. J. "Prediction of field collapse of soils due to wetting." *Journal of Geotechnical Engineering*, vol. 114, No. 1, 1988, pp. 40-58.
- [19] El-Sohby, M. A., and Rabba, E. A. "Some factors affecting swelling of clayey soils." *Geotechnical Engineering*, vol. 12, 1981 pp. 19-39.
- [20] Basma, A.A., and Tuncer, E.R.. "Evaluation and control of collapsible soils." *Journal of Geotechnical Engineering*, vol. 118, No. 10, 1992, pp. 1491-1504.
- [21] Derbyshire, E., and Meng, X. M. "Loess." In: (Fookes, P.G., Lee, E.M. & Milligan, G. eds), *Geomorphology for engineers*, Whittles publishing, Dunbeath, Scotland, 2005 pp. 688-728.
- [22] Jefferson, I., Tye, C., and Northmore, K.G. "The engineering characteristics of UK brickearth." In: Problematic soils, (Jefferson, I., Murray, E.J., Faragher, E. and Fleming, P.R. eds.) Thomas Telford Publishing, London, 2001, pp. 37-52.
- [23] Smalley, I. J., Mavlyanova, N. G, Rakhmatullaev, Kh. L., Shermatov, M. Sh., Machalet, B., O'Hara Dhand, K., Jefferson, I. F. "The formation of loess deposits in the Tashkent region and parts of central Asia; and problems with irrigation, hydrocollapse and soil erosion." *Quaternary International*, 2006, pp. 59-69.
- [24] Jennings, J. E., and Knight, K. "A guide to construction on or with materials exhibiting additional settlement due to collapse of grain structure." In: *Proceedings of the 6th African Conference on Soil Mechanics and Foundation Engineering*, Durban, 1975, pp. 99-105.
- [25] Batygin V.I. () "on the methods for estimate of soil subsidence." *Hydrotechnical construction* vol 7 Moscow. cited in Minkov M. (1984) "Quantitative prediction of collapsibility of loess soils." ed. by International Geological Congress, Bogdanov A.N. *Engineering geology: proceedings of the 27th International Geological congress*. The Netherland: VNU Science Press BV, vol 17, 1937, pp. 145 - 169.
- [26] Denisov, N. Y. "The engineering properties of loess and loess-like soils (in Russian)." Moscow: Gosstroizdat 1951, pp.133. cited in Darwell, J., and Denness, B. "Prediction of metastable soil collapse." *Publication of the 121st international association of Hydrological sciences*, 1976.
- [27] Priklonskij, V. A. "Vtoriaia Chast (Soil Science II)." *Gosgeolizdat, Moscow: Gruntovedenie*. 1952, pp.371. cited in Darwell, J., and Denness, B., "Prediction of metastable soil collapse." *Publication of the 121st international association of Hydrological sciences*, 1976.
- [28] Feda, J. "Structural stability of subsidence loess from Praha-Dejvice." *Engineering Geology*, vol. 1, 1966, pp. 201-219.
- [29] Gibbs, H. J., and Bara, J. P. "Predicting surface subsidence from basic soil tests." Special Technical Publication, vol. 332, ASTM, 1962, pp. 231-247.
- [30] Handy, R. L. "Collapsible loess in Iowa." *Soil. Sci. Soc. Am. Proc.*, vol. 37, 1973, pp. 281-284. cited in Bell F.G. "Engineering geology and construction." London: Spon Press, 2004, pp 310.
- [31] Abelev, Y.M.. "Fundamentals of Design and Construction on Macroporous Soils." Moscow: Stroivoenmorizdat, 1948. cited in Mansour, Z. M., Chik, Z. and Taha, M. R. "On the Procedures of Soil Collapse Potential Evaluation." *Journal of Applied Sciences Evaluation*, vol. 8, 2008, pp. 4434-4439.
- [32] Jenning, J. E. B., and Knight, K. "The additional settlement of foundations due to collapse of structure of sandy subsoil on wetting." *Proc. 4th international conference on soil mechanism and foundation engineering*, vol. 1, 1957, pp. 316 -319. cited in Pererira, J. H. F., and Fredlund, D. G. "Volume change behavior of collapsible compacted gneiss soil." *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 126, No. 10, 2000, pp. 907-916.
- [33] Mansour, Z. M., Chik, Z. and Taha, M. R. "On the Procedures of Soil Collapse Potential Evaluation." *Journal of Applied Sciences Evaluation*, vol. 8, 2008, pp. 4434-4439.
- [34] Hormdee D., Ochiai H. and Yasufuku N. *Influence of stress history and socking pressure on collapsibility of Shirasu soil* (online) available from <<http://www7.civil.kyushu-u.ac.jp/geotech/cd/pdf/381.pdf>> 2004, (20 July 2010)
- [35] Lehr H. "Foundation engineering problems in loess soils." *Proc. 3rd Asian Reg. Conf.SMFE* vol. 1, No. 6, 1967, pp. 20-24. cited in Darwell, J., and Denness, B. "Prediction of metastable soil collapse." *Publication of the 121st international association of hydrological sciences*, 1976.
- [36] Clevenger, M. A.. "Experience with loess as a foundation material." *Transactions American Society of Civil Engineers*, vol. 123, 1958, pp. 151-180. cited in Bell, F. G. "Engineering geology and construction." London: Spon Press, 2004.
- [37] Larionov, A. K., Priklonskii, V. A., and Anan'ev V. P. "Lessovyie porody SSSR i ikh stroitel'nye svoistva," part 1. Leningrad, 1959. cited in Minkov, M. ed. "International Geological Congress, Bogdanov A.N. Engineering geology: proceedings of the 27th International Geological congress." The Netherland: VNU Science Press BV, 1984.
- [38] Lutenegger, A. J., and Saber, R. T. "Determination of collapse potential of soils." *Geotech. Test. J.*, vol. 11, 1988, pp. 173-178. cited in Mansour, Z. M., Chik, Z. and Taha, M. R. "On the Procedures of Soil Collapse Potential Evaluation." *Journal of Applied Sciences Evaluation*, vol. 8, 2008, pp. 4434-4439.
- [39] Nouaouria, M. S., Guenfoud, M., Laffi, B. "Engineering properties of loess in Algeria." *Engineering Geology*. vol. 99, 2008, pp. 85-90.
- [40] Lawton, E. C., Fragaszy, R. J., and Hetherington, M. D. "Review of wetting-induced collapse in compacted soil." *Journal of Geotechnical Engineering*, vol. 118, 1992, pp. 1376-1394.
- [41] Uchaipichat, A. "Hydraulic hysteresis effect on compressibility of unsaturated soils." *ARPJ Journal of Engineering and Applied Sciences* vol. 5, 2010, pp. 92 - 97.
- [42] Medero, G. M., Sehnaid, F., and Gehling W. Y. Y. "Oedometer behaviour of an artificial cemented highly collapsible soil." *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 135, 2009, Pp.840 - 843.
- [43] Derbyshire, E., Dijkstra, T. A., and Smalley, I. J. eds. 'Genesis and physical properties of collapsible soils.' Series C: Mathematical and Physical Sciences - Kluwer Academic Publishers, Dordrecht, vol. 468. 1995.