Influence of degree of saturation on strength and consolidation properties of unsaturated soil and its centrifuge modelling

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ABSTRACT

Unsaturated soil mechanics has rapidly become an integral part of geotechnical engineering practice. The negative pore water pressure is the major interest in unsaturated soil situations. The present study was an attempt to examine the effect of saturation on strength and consolidation properties of two soils namely CH and CL type of soil at various percentage of maximum dry density (MDD). Result showed an apparent raise in the cohesion value of yellow soil increased with amplification in the saturation value as well as the density value. Black cotton soil followed a reverse trend of decrease in the cohesion as well as the angle of internal friction value with increase in degree of saturation, but comparatively increased for a given degree of saturation with increase in value of density. No definite trend was observed in the value of coefficient of consolidation. The work included few test on centrifuge to quantify the settlement of the selected soils at 80% saturation with 85% maximum dry density and 95% maximum dry density. The centrifuge showed an appreciable value of settlement for yellow soil with 85% maximum dry density at 80% saturation while the other tests showed some settlement but not to a measurable value.

Keywords: unsaturated Soil, centrifuge modelling, scaling laws, dry sand, saturated clays

1 INTRODUCTION

The general field of soil mechanics can be subdivided mainly into tow portion; the portion dealing with saturated soils that involves common soil types like saturated sands, silts and clays, and dry sands; these soils could either be saturated with water or have other fluids in the voids (e.g., air) and that portion dealing with unsaturated soil. There is largest category of materials encountered in engineering practice which do not stick the behaviour, principles and concepts of classical soil mechanics due to the presence of more than two phases which results in a material that is difficult to deal with in engineering practice. The development of classic soil mechanics has led to an emphasis on particular type of soils.

Most of the earth’s land surface comprises notoriously hazardous geo-materials called “unsaturated soils”. In general term an unsaturated soil is definite soil having three phases, namely, solids, water, and air. However, the existence of fourth phase, namely, that of the air-water interface or contractile skin (Fredlund and Morgenstern, 1977) differentiates it from the saturated soil. Because of presence of contractile skin, the interaction between the solid, water and air causes complex hydro-mechanical behaviour of the unsaturated soil element. The primary factor contributing to their unusual behaviour is their negative pore-water pressures. The presence of even small amount of air renders a soil unsaturated.

Modelling has a major role to play in geotechnical engineering with a primary objective of obtaining high quality and reliable data of a physical event. Some geotechnical works can be studied using reduced scale models under 1×g acceleration (modelling). In geotechnical engineering, centrifuge modelling is frequently used for model tests of prototypes and validation of numerical models.

In the recent past, Centrifuge modelling has become one of the powerful tools for physical modeling in geotechnical engineering. Centrifuge modeling is a technique for simulating the mechanical response of full-scale geotechnical structures in reduced-scale physical models. The aim of centrifuge modeling is to reproduce prototype stress conditions at homologous points in the model.

A centrifuge is essentially a sophisticated load frame on which soil samples can be tested. The art of centrifuge modeling is to minimize the effects of the constraints while maximizing the quality of the geotechnical data obtained. Centrifuge modeling is a powerful tool which has been extensively used for geotechnical studies to validate numerical models because the initial boundary conditions and soil
conditions in centrifuge model can be well monitored and controlled. It is also being applied to more general civil engineering studies including rock mechanics, hydraulics, and structures.

The overall purpose of the study was to examine the effect of degree of saturation on strength and consolidation properties on soil. This technical note presents some of the results obtained in analyzing centrifuge modelling from similarity and assessing model repeatability. While the study examined the behaviour of unsaturated soil prototypes, results of these tests are relevant to the modelling of other systems as well.

2 SCHEME OF INVESTIGATION

For the purpose of experiments, two different soil compositions had been selected. The first soil sample was procured from Valiya - Netrang Road, near Bharuch, Gujarat, India and the second soil sample was collected from village Sevasi near Vadodara, Gujarat, India. It was sieved through 425μ sieve and then tested for basic geotechnical properties as per IS classification system. Geotechnical properties of the soils were determined using standard methods as prescribed in I.S. 2720, and are summarized Table 1.

Table 1. Basic properties of soils.

| Description                     | CL Soil | CH Soil |
|---------------------------------|---------|---------|
| Specific gravity (Gs)           | 2.66    | 2.64    |
| Free swell in %                 | 15      | 17      |
| MDD (gm/cm³)                    | 1.720   | 1.65    |
| OMC in %                        | 17.3    | 19.2    |
| Liquid limit (LL) in %           | 25      | 54      |
| Plastic limit (PL) in %          | 25.71   | 25      |
| Unconfined compressive strength (UCS) kg/cm² | 2.436 | 3.509 |

3 CENTRIFUGE SCALING LAWS WITH UNSATURATED SOILS

Soil properties are highly stressed dependent. In centrifuge modelling the restraining stresses in the model and prototype are equal. All centrifuge scaling rules are based on this important one to one association. According to scaling rule, the representative particle size should be N times smaller in the model than in the prototype.

4 EXPERIMENTAL STUDY

4.1 Triaxial and consolidation test

For triaxial and consolidation test, the samples were remoulded at required density and moisture content for 80%, 85%, 90% and 95% of proctor density and at various degree of saturation as 20%, 40%, 60%, 80% & 100%. Before testing soils were air-dried, sieved through I.S. sieve size 425μ sieve and then oven dried at 105°C for 24 h.

4.2 Centrifuge test

In this study, the centrifuge tests were run by mini centrifuge apparatus at Gujarat Engineering Research Institute (GERI), Vadodara, Gujarat, India. It is a beam type mini centrifuge with a maximum rotational speed of 900 rpm and 120g with effective radius of 0.4 m. The length of model box is 150mm, width is 120mm and height 120mm. The samples for 85% and 95% of proctor density with 80% of saturation for centrifuge modelling were run for a time period of 10 minutes each.

5 RESULT AND DISCUSSION

In this study as, triaxial and consolidation tests were performed on two types of soils (CH, CL) compacted at 80%, 85%, 90% and 95% of proctor density and at various degree of saturation as 20%, 40%, 60%, 80% & 100%. From the readings of triaxial test, cu and øu were obtained from the plot of Mohr’s circle. Also graphs for peak stress and failure strain were drawn.

5.1 Shear strength parameters test

Table 2 and 3 shows the maximum and minimum values of cohesion and angle of friction obtained at specific degree of saturation for specific maximum dry density for CH soil and CL soil respectively.

Table 2. Cohesion Values for CH and CL Soils.

| Soil type | MDD (%) | Cohesion (kg/cm²) |
|-----------|---------|------------------|
| Degree of saturation (%) | maximum | minimum |
| CH | 20 | 95 | 0.444 | - |
| CH | 100 | 80 | 0.114 | - |
| CL | 100 | 95 | 0.442 | - |
| CL | 20 | 80 | 0.122 | - |

Table 3. Values of angle of friction for CH and CL Soils.

| Soil type | MDD (%) | Angle of friction (°) |
|-----------|---------|----------------------|
| Degree of saturation (%) | maximum | minimum |
| CH | 20 | 80 | 23.8 | - |
| CH | 100 | 95 | 13 | - |
| CL | 20 | 80 | 28.6 | - |
| CL | 100 | 95 | 6.9 | - |

Figure 1 and Figure 2 shows the plot of cohesion with varying volumetric water content at different % MDD for CL and CH soils. It is seen that as the degree of MDD increases the value of cohesion increases for CL soil and decreases for CH soil. A curve used shows best fit for 80% MDD giving R² value as 0.985 for CL soil and 95% MDD giving R² value as 0.947 for CH soil. Equations for all fits with their respective R² for CL and CH soils are as shown in Table 4 and Table 5.
Figure 1 shows the plot of volumetric moisture content versus cohesion characteristics for CL soil compacted at different density. The relationship is given by the equation $y = 0.185\ln(x) - 0.262$, with $R^2 = 0.953$. The table below summarizes the relationship between volumetric water content and cohesion for CL soil at different MDD:

| MDD | CL Soil R^2 | CL Soil Relationship |
|-----|-------------|----------------------|
| 80  | 0.985       | $y = 0.127\ln(x) - 0.220$ |
| 85  | 0.976       | $y = 0.126\ln(x) - 0.150$ |
| 90  | 0.956       | $y = 0.150\ln(x) - 0.186$ |
| 95  | 0.953       | $y = 0.185\ln(x) - 0.262$ |

$x = \text{degree of saturation}$ and $y = \text{cohesion}$

Figure 2 shows the plot of volumetric moisture content versus cohesion characteristics for CH soil compacted at different density. The relationship is given by the equation $y = 0.030\ln(x) + 0.556$, with $R^2 = 0.947$. The table below summarizes the relationship between volumetric water content and cohesion for CH soil at different MDD:

| MDD | CH Soil R^2 | CH Soil Relationship |
|-----|-------------|----------------------|
| 80  | 0.950       | $y = 0.014\ln(x) + 0.313$ |
| 85  | 0.955       | $y = 0.026\ln(x) + 0.409$ |
| 90  | 0.917       | $y = 0.050\ln(x) + 0.527$ |
| 95  | 0.959       | $y = 0.085\ln(x) + 0.536$ |

$x = \text{degree of saturation}$ and $y = \text{cohesion}$

Consolidation results are shown in Table 8.

5.2 Consolidation result

Consolidation results are shown in Table 8.
Table 8. CV Values for CH and CL soils.

| Soil Type | Degree of Saturation (%) | MDD | Coefficient of Consolidation, c_v (cm²/min) (Maximum) | Coefficient of Consolidation, c_v (cm²/min) (Minimum) | Consolidation Pressure (kg/cm²) |
|-----------|--------------------------|-----|---------------------------------------------------|---------------------------------------------------|-------------------------------|
| CL        | 20                       | 80  | 0.149                                             | -                                                  | 3.2                           |
|           | 80                       | -   | 0.007                                             | 0.2                                               |                               |
|           | 100                      | 85  | 0.146                                             | -                                                  | 0.8                           |
|           | 60                       | 85  | -                                                 | 0.01                                              | 0.2                           |
|           | 20                       | 90  | 0.187                                             | -                                                  | 3.2                           |
|           | 60                       | 90  | -                                                 | 0.002                                             | 0.8                           |
|           | 60                       | 95  | 0.139                                             | -                                                  | 0.4                           |
|           | 100                      | 95  | -                                                 | 0.006                                             | 0.2                           |
| CH        | 20                       | 80  | 0.157                                             | -                                                  | 1.6                           |
|           | 20                       | 80  | -                                                 | 0.009                                             | 0.2                           |
|           | 100                      | 85  | 0.259                                             | -                                                  | 6.4                           |
|           | 100                      | 85  | -                                                 | 0.008                                             | 3.2                           |
|           | 100                      | 90  | 0.111                                             | -                                                  | 1.6                           |
|           | 100                      | 90  | -                                                 | 0.002                                             | 0.2                           |
|           | 20                       | 95  | 0.140                                             | -                                                  | 3.2                           |
|           | 20                       | 95  | -                                                 | 0.005                                             | 0.4                           |

5.3 Settlement

5.3.1 Result of CL soil

Figure 5 shows the settlement impression for the centrifuge run of a sample compacted at 85% MDD with 80% of saturation. The sample showed some settlement of the order of 0.413mm which is equal to 1.85mm settlement under an isolated footing model at the end of 6 days for prototype. The sample compacted at 95% MDD with 80% of saturation showed only an impression which could not be measured.

5.3.2 Result of CH soil

The centrifuge run for sample compacted at 85% MDD and 95% MDD with 80% of saturation showed only an impression which could not be measured.

6 CONCLUSION

This study was carried out to examine the influence of degree of saturation on strength and consolidation properties of unsaturated soil and its constitutive modelling. To this end, a series of triaxial tests and consolidation tests were first carried out on an unsaturated soil. Both types of tests were performed on soil samples compacted at 80%, 85%, 90% and 95% of proctor density at various degree of saturation as 20%, 40%, 60%, 80% & 100%.

The results of the research presented in this paper confirm that degree of saturation can play a major role in the shear strength parameters of the soil. Specifically, the following conclusions can be reached:

- Cohesion value of yellow soil (CL) increased and internal friction angle value decreased with increase in the saturation value as well as the density value.
- Cohesion as well as the angle of internal friction value of black cotton soil (CH) decreased with increase in degree of saturation, but comparatively increased for a given degree of saturation with increase in value of density.
- No definite value of coefficient of consolidation
- Studies about centrifuge modelling showed an appreciable value of settlement for yellow soil (CL) with 85%MDD and at 80% saturation while the other tests showed some settlement but not to a measurable value.

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