Response of Shallow Foundation Under Coupled Cyclic Loading For Unsaturated Sand at Large Number of Cycles

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ABSTRACT

The deformation of the unsaturated granular material under the action of large number of cycles can be interpreted by several ways. The various changes on the soil properties by the application of the cyclic loading creates an unique response to the applied external forces. A change in any one of the several properties of the soil will create a response which will be different from the responses created by altering other properties. One of the parameter influencing the soil response under the application of cyclic load is soil suction. For development of the realistic coupled model which takes the account of different nonlinear behavior coupled intrinsically in the model, needs a general experimental overview beforehand the model development process is undertaken. In this regard, this study is performed for the response of the rigid footing coupled by the multidimensional nonlinearity in the domain of the unsaturated soil and the angular loading. The coupled phenomenon is furthermore studied in detail by performing the experiment in one domain by keeping the parameters in the other domain constant. The evolution of the displacement in each cycle which leads to the unique accumulated cyclic strain in the system is studied for the unsaturated domain at a constant angle. The comparative study of the accumulation behavior of plastic strain within the imposed cycle for the saturated, dry and two unsaturated condition of Hostun sand is performed and presented.

Keywords: inclined cyclic loading, coupled loading, unsaturated soil, shallow foundation

1 INTRODUCTION

Majority of geotechnical structures are loaded with cyclic loads of various form. The structures free of cyclic loads are rarely present. Structural response from these cyclic loads can lead to a cyclic stress generation both on the structure and soil. This cyclic stress which can be a small in magnitude will lead to a large accumulated settlement with the increasing number of cycles. This may lead to the plastic failure even though the applied force is within the elastic limit.

The deformation of the granular material under the action of long term cyclic loading can be interpreted by several ways. The various changes on the soil properties by the application of the cyclic loading creates a unique response to the applied external forces. A change in any one of the several properties of the soil will create a response which will be different from the responses created by altering other properties. One of the parameter influencing the soil response under the application of cyclic load is soil suction. The influence of the microscopic to macroscopic phenomenon of soil by the soil suction has been studied by (Kafle and Wuttke 2015). As the soil in the unsaturated state is predominant over dry and saturated state, the study on the response of the geotechnical structures on the unsaturated soil is an utmost need. Under the cyclic excitation the displacement in each cycle decreases drastically as the number of cycle increases. This leads to the effective change in the response of the geotechnical structure with small change in the domain of the properties of either soil or structure.

The response of the footing is dependent on the direction of the application of the load. The common civil engineering structure is generally loaded with the resultant of the applied force in the direction other than the vertical direction (angular direction). The analysis of such structure taking into account of the unsaturated behavior of the soil brings the added complexity in the analysis of the structural response. The classical approach of the analysis of the structure acted with the angular resultant force is to analyze the structure by applying the two component of the forces in vertical and horizontal direction and the response in the direction of the application of the force is obtained by the principle of superposition. This method of analysis provides acceptable result when the system is linear. For the nonlinear mechanism, the study should be performed in the domain that is closer to the reality to obtain the acceptable result. The response of the footing
on the unsaturated soil is observed to be nonlinear (Vanapalli and Mohamed 2007 and Wuttke et al. 2013). This nonlinearity coupled with the angular loading needs a more realistic approach for the analysis.

1.1 Coupled cyclic loading of unsaturated soil

The study of the cyclic response of soil is done by notable researchers (Hueckel and Nova 1979 and Nova and Hueckel, 1981) from the microscopic level for single-phase soil. The study of the single-phase soil under the action of long-term cyclic response is undertaken by (Wichtmann, Niemunis, and Triantafyllidis 2009). The coupled long-term cyclic response of the footing over unsaturated soil has been a least studied phenomenon. A cyclic Macroelement (coupled model consisting of soil and foundation), for the unsaturated soil capable of the response under the large number of cycles is proposed by (Kafle and Wuttke 2013). But the response of unsaturated soil under the large number of cyclic excitation in the angular direction has been a missing link between the general understanding of the phenomenon and the model development.

For the development of the realistic coupled model which takes the account of different nonlinear behavior coupled intrinsically in the model, needs a general experimental overview beforehand the model development process is undertaken. In this regard, this study is performed for the response of the rigid footing coupled by the multidimensional nonlinearity in the domain of the unsaturated soil and the angular loading. The coupled phenomenon is furthermore studied in detail by performing the experiment in one domain by keeping the parameters of in the other domain constant. The evolution of the displacement in each cycle which leads to the unique accumulated cyclic strain in the system is studied in the unsaturated domain at a constant angle. The study in the evolution of the cyclic accumulated strain for the different soil suction provides an understanding on the response of the footing under the coupled nonlinear system for the large number of cycles. Furthermore, the evolution of strain in each cycle with the change in soil suction provides the understanding of the interrelation between the accumulated strain and the variation in force exerted by the water meniscus on the soil. As the variation of soil moisture and the corresponding soil suction takes places constantly within the lifetime of the structure, the response of the unsaturated soil will be crucial to understand the performance of the structure at particular time of study.

2 EXPERIMENTAL STUDIES OF MULTIPHASE GRANULAR MATERIAL UNDER COUPLED LONG TERM CYCLIC LOADING

The laboratory study includes the study on the physical properties of the used Hostun sand and cyclic coupled loading of the rigid square footing resting over unsaturated Hostun sand under the large number of cycle excitation.

2.1 MATERIAL USED

The material used in the present study is the Hostun sand (Flavigny 1990). From the USCS classification, Hostun sand is poorly graded sand (SP). The important properties of the Hostun sand is presented in Table 1. The particle size distribution of the used Hostun sand is presented in Fig. 1 and the macroscopic image and the typical measured particle width is shown in Fig. 2.

![Particle size distribution of used Hostun sand](image1)

Table 1. Properties of Hostun sand.

| Property                  | Value  |
|---------------------------|--------|
| Specific gravity          | 2.65   |
| $C_u$                     | 1.50   |
| $C_c$                     | 1.11   |
| Classification (USCS)     | SP     |
| $D_{50}$                  | 0.35mm |
| $\phi$ (friction angle for rough footing) | 41.8° |

![Macroscopic image of used Hostun sand](image2)

The SWCC of the used Hostun sand is determined using modified pressure plate apparatus Fig. 2. The detail of the test procedure can be obtained in (Wuttke et al. 2013).
2.2 UNSATURATED SAMPLE PREPARATION FOR CYCLIC LOADING

Cyclic loading of a surface footing was performed in a specially designed box Fig. 4. The box has the wooden rigid frame which supports the inner transparent plexiglass container. The plexiglass container has the dimension of 1000 X 500 X 500 mm. The soil sample is placed in the plexiglass container. The outer frame is made rigid to avoid any lateral displacement due to the loading in the sample. The box has four number of openings, two in each smaller side, in the bottom to saturate and de-saturate the sample. Two transparent and semi rigid pipes are fixed in two diagonal side in the box for the internal measurement of the water level in the sample. One external burette is also placed to measure the water level in the sample externally by hanging water column technique. A tentative suction was obtained by measuring the location of water table from the surface of the specimen with the help of pipe attached to the wall of the transparent plexiglass box. A precise measurement of suction is done by the use of Tensiometer and TDR. The four numbers of Tensiometers are placed in four different depth below the soil surface. The eight numbers of TDR are placed in eight different depth from the surface at different locations in the soil sample to have a clear overview of the soil moisture distribution in the sample, in horizontal and vertical plane, located at the different depth of the specimen from the surface. The sand sample with the height of 35±2 cm was prepared for the test by filling the Hostun sand in different layers. A hand compaction is done with a standard compactor with the standardized procedure to obtain the void ratio within the tolerance limit of 10%. In all the prepared sample the void ratio of the sample was maintained at 0.7±0.03. After the completion of the sample preparation, the sample is saturated with the distilled and de-aired water by slowly filling the box from bottom. The sample is placed in the saturated condition for 24 hours to provide enough time to wet all the particles and to remove unwanted trapped air, if any. The saturated sample was drained after 24 hours. As the desaturation process forms the water meniscus which exerts the forces on the soil particles, which will then homogenize the sample, if there are any pockets of sample where the voids are larger than the average. For this reason, two more cycle of saturation and desaturation at an interval of 24 hours was performed. The arithmetic average of soil suction measured by different Tensiometer and TDR up to the depth of 1.5B was used as the representative soil suction (Vanapalli and Mohamed 2007). During the test soil suction is precisely controlled and kept constant in the soil sample by connecting the box with the water reservoir and continuously monitoring water level in the sample. The experiment is performed in a closed room to maintain a constant humidity during the entire period of the test. The detail of soil suction measurement is shown in Table 2.

Table 2. Measurement of suction of the soil sample.

| Condition | Water Level From Surface (cm) | Soil Suction at the Surface (kPa) [Ψ] (a) | Soil Suction at 1.5B (kPa) [Ψ] (b) | Arithmetic Average: 0.5(a+b) (kPa) [Ψavg] |
|-----------|-------------------------------|------------------------------------------|-----------------------------------|-----------------------------------------|
| Saturated | +1                            | +0.1                                     | 0                                 | +0.05                                   |
| Unsat. (1) | -10                           | -15.48                                   | -5.72                             | -10.6                                   |
| Unsat. (2) | -35                           | -37                                      | -1.4                              | -19.2                                   |

Fig. 4. Detail of experimental setup for unsaturated cyclic loading

2.3 COUPLED CYCLIC LOADING

The rigid rough surface footing of size 100 X 100 mm was placed at the middle of the surface of the
unsaturated sample. The footing was fixed at the chosen angle with the loading piston. The displacement transducer was connected with the piston for the measurement of the displacement [R-Displacement {Fig. 5(a)}] during loading. Two external, vertical and horizontal displacement transducers were also placed precisely at the middle of the footing. These transducers were placed perfectly in vertical and horizontal plane at the center of the footing as shown in Fig. 5(a). The footing settlements were measured with a resolution equal to 0.001 mm and the accuracy of the applied load [R-Force] was equal to 0.05 %. A National Instrument (NI) data logging system was used to collect all the experimental data. The noisy signal received from load and displacement transducers of the device was filtered using third order Zero-Phase Low Pass Butterworth filter in MATLAB. To obtain a smooth signal after filtering, the unwanted transients were eliminated by using Median Filtering technique available in MATLAB.

The loading piston was connected with the footing at an angle of 15 degrees with vertical Fig. 5(a). This provides an angular loading to the footing of 15 degrees to impose a coupled cyclic excitation. A force controlled coupled harmonic excitation from Equation 1 is imposed to the footing at a constant amplitude of 0.25kN, with the frequency of 0.1Hz with respective static load as shown in Fig. 5(b).

\[
[R - \text{Force}]_{\text{cycle}} = F_{st} + A \cos(\omega t) \tag{1}
\]

Where,
- \(F_{st}\) = Static Load
- \(A\) = Amplitude = 0.25kN
- \(\omega\) = Angular Frequency = \(2\pi f\)
- \(f\) = frequency = 0.1Hz
- \(t\) = Total time of loading = 0 to 5 \(\times\) 10^5 sec for 50000 cycles.

The detail of cyclic experimental program is shown in Table 3.

| Condition | Water Level From Surface (cm) | Static Load \([F_{st}]\) (kN) | Amp. \([A]\) (kN) | Freq \([f]\) (Hz) | Number of Cycle \((n)\) |
|-----------|-------------------------------|-----------------------------|----------------|----------------|----------------|
| Dry       | --                            | 0.7                         | 0.25          | 0.1            | 39472         |
| Saturated | +1                            | 0.3                         | 0.20          | 0.1            | 28076         |
| Unsat. (1) | -10                           | 0.8                         | 0.25          | 0.1            | 41542         |
| Unsat. (2) | -35                           | 0.8                         | 0.25          | 0.1            | 38716         |

3 RESULTS AND DISCUSSION

The cyclic response of Hostun sand at different soil suction or water table depth, due to the imposed coupled loading at 15 degrees to vertical [R-Force, Fig. 5(a)] at the frequency of 0.1Hz is presented in Fig. 6. The accumulation of displacement with increasing number of cycle is presented in Fig. 7. It is observed that the saturated soil accumulates the large displacement compared with unsaturated and dry soil.
Fig. 6. The response of sand at different soil suction (or water table depth) under the cyclic excitation applied at 15 degrees to vertical [Fig. 5(a)]

More over the unsaturated soil tends to show the plastic shake down within small number of cycle compared to saturated and dry soil. It is also observed from Fig. 8 and Table 4, that the displacement within each cycle decreases significantly within the cycle number as low as 20, for all the soil saturation condition. The similar behavior was observed as well for the vertical cyclic loading of same soil by (Kafle and Wuttke 2015). But with the further analysis of only the unsaturated soil [Unsat(1) and Unsat(2)] the soil still shows extra accumulation of the displacement with the increasing number of cycles, Fig. 9 and Table 4. The current experimental set up was formulated to understand the shakedown behavior of unsaturated soil in 3D strain case. From the analyzed results which are presented in Fig. 7, Fig. 8, and Fig. 9, the soil sample under the cyclic excitation of low frequency and low amplitude is also showing the presence of plastic displacement within the cycle at large number of cycle.

Though the plastic displacement within the cycle decreases with the increasing number of cycle, the absolute shakedown may not be reached even with the large number of cycle as well. The Table 4 presents the plastic strain dissipation within the cycles. The saturated and dry soil reaches the plastic accumulated displacement at the 10th cycle within 2.7% of accumulated plastic strain compared to almost 10% for both unsaturated soils. Similarly at 1000th cycle, saturated and dry soil reaches 36% and 26% respectively, whereas the unsaturated soil accumulates as much as 50% of the final accumulated displacement.

It is observed that, though the unsaturated soil shows very less plastic displacement within each cycle
compared to the saturated and dry soil, the amount of plastic accumulated displacement with reference to the final accumulated displacement is large within the smaller number of cycle compared to saturated and dry soil. Thus the energy dissipation in a cycle which is proportional to the plastic displacement within a cycle, during cyclic excitation is rapid for unsaturated soil compared to the saturated and dry soil as the cyclic loading progresses.

4 CONCLUSION

A strong influence of soil saturation on the plastic displacement of the sand under coupled cyclic excitation is observed. The change in the plastic strain within each cycle of granular soil is predominantly affected by the amount of soil saturation. The final accumulated displacement is dependent on the soil saturation level. The rate of dissipation of plastic displacement within the cycle is strongly influenced by the soil saturation.

REFERENCES

1) Flavigny, E., Desrues, J. and Player, B. (1990). “note technique, le sable d’hostun RF.” Revue Française de Geotechnique, 53, 67-70.
2) Hueckel, T. and Nova, R.(1979): Some hysteresis effects of the behaviour of geologic media, International Journal of Solids and Structures, 15(8), 625-642.
3) Kafle, B., and Wuttke, F. (2013): Cyclic macroelement for shallow footing over unsaturated soil, 1st Pan-American Conference on Unsaturated Soils, Cartagena, Colombia, 521-526
4) Kafle, B., and Wuttke, F. (2015): Soil Behavior under Unsaturated and Long term Vertical Cyclic Loading. Sixth International Symposium on Deformation Characteristics of Geomaterials, V.A. Rinaldi et al. eds., Buenos Aires, Argentina, 15-18.
5) Nova, R. and Hueckel, T. (1981): An engineering theory of soil behaviour in unloading and reloading, Meccanica, 16(2), 136-148.
6) Vanapalli, S. K. and Mohamed, F. M. O. (2007): Bearing capacity of model footings in unsaturated soil. Experimental unsaturated soil mechanics, T. Schanz, ed., Springer Proceedings in Physics, 112, 483–493.
7) Wichtmann, T., Niemunis, A. and Triantafyllidis, Th., (2009) Validation and calibration of a high-cycle accumulation model based on cyclic triaxial tests on eight sands, Soils and Foundations, 49(5), 711-728.
8) Wuttke, F., Kafle, B., Lins,Y. and Schanz,T. (2013): A macro-element for statically loaded shallow strip foundation resting on unsaturated soil. Int. J. Geomech., 13(5), (https://doi.org/10.1061/(ASCE)GM.1943-5622.0000254)