Time-Dependent Mechanical Behavior of a Granular Medium Used in Laboratory Investigations

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Abstract: The time-dependent mechanical response of an artificial granular medium consisting of glass beads is experimentally examined by performing one-dimensional creep tests on both saturated and dry specimens. The time-dependent compression of the oedometric sample, which is related to the internal rearrangement of the granular assembly, is modeled using an elastic-viscoplastic strain hardening constitutive model. The procedures used to identify the parameters defining the model are discussed; the incremental strain of the material is decomposed into reversible elastic and irreversible creep components. Finally, the capabilities of the proposed model in predicting the time-dependent response of the material are investigated through a comparison between experimental results and analogous results derived from computational modeling.

DOI: 10.1061/(ASCE)1532-3641(2009)9:1(1)

CE Database subject headings: Constitutive models; Creep; Granular media; Compression tests; Viscoplasticity; Laboratory tests.

Introduction

The mechanical behavior of granular materials is generally assumed to be time independent, although in many cases continued settlement of structures constructed on granular regions has been reported in the literature (Nonveiller 1963; Komornik et al. 1972; Sweeney and Lambson 1991; Hannink 1994). Time-dependent behavior in granular media can be attributed to several processes including progressive particle breakage due to intergranular contact stresses and the rearrangement of the grains with time due to micromechanical slip. The former processes that occur either under high overburden stresses or high confining stresses result in more angular particles, and on occasion lead to the development of more rounded grains mixed with fine grained materials (Yamamuro and Lade 1993; Leung et al. 1996; Lade and Liu 1998, Cheng et al. 2001). The latter processes that occur at shorter time scales of the order of days are important, particularly when granular materials at low relative densities are used in laboratory investigations (Murayama et al. 1984; Lade 1994; Di Prisco and Imposimato 1996; Kuwano and Jardine 2002). Oda (1972) conducted a series of drained triaxial tests on sand that mainly consisted of quartz grains. Photo-microphotographs from thin sections of sheared specimens revealed that the shearing process causes a continuous reconstitution of the initial fabric, by the sliding of grains along unstable contacts and the rolling of grains relative to a preferred reorientation. Murayama (1983) proposed a mechanical model to simulate the time-dependent stress–strain behavior of soil media, including coarse grained soil and caused by deviatoric stress. This model was then used to predict the creep behavior of sand specimens by appeal to the results obtained from experiments (Murayama et al. 1984). Conducting triaxial compression tests on the samples prepared from Toyoura sand, it was shown that the volumetric changes in the specimens ceased almost within 20 min.

In practical situations, creep phenomena lead to a gradual increase in the shear strength of the field deposits or the increase of the resistance with time (Mitchell and Solymar 1984; Schmertmann 1991). This hypothesis was investigated by Lade (1994), who conducted an experimental research program on Sacramento River sand. Allowing the triaxial samples to creep under drained conditions for various time periods, it was shown that the granular material achieved a stiffer state the longer the creep phenomenon was allowed to take place.

Another experimental study, involving a series of drained standard triaxial compression tests was conducted by Di Prisco and Imposimato (1996) on loose Hostun sand $(D_r \approx 20\%)$. The results clearly showed that the material strain response to an instantaneous stress increment exhibits a delay with time; this time-dependent behavior was not due to stress transfer from the pore water to the soil skeleton, but to a change in the microstructural configuration of the sand resulting from the rotation and sliding of grains along the unstable contacts. Lade and Liu (1998) also presented the results of a series of isotropic compression and triaxial compression tests, concluding that the viscous characteristics of the granular media results from slippage between grains as well (2000), who also provide additional references.

Kuwano and Jardine (2002) observed significant creep deformations in a series of triaxial tests under isotropic and anisotropic stress conditions conducted on sand and ballotini glass beads with $D_{50}=0.27$ mm. Their results showed that creep in a granular material is related to the gradual stabilization of the medium through

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Note. Discussion open until July 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on December 21, 2006; approved on March 17, 2008. This paper is part of the ***International Journal of Geomechanics***, Vol. 9, No. 1, February 1, 2009. ©ASCE, ISSN 1532-3641/2009/1-1–8/$25.00.

failure of the most critically loaded regions and, as a result, load transfer between the constituent grains.

Di Benedetto et al. (2002) studied the viscous properties of two types of clean sand (Hostun sand with $D_{50}=0.31$ mm and Toyoura sand with $D_{50}=0.18$ mm), conducting drained plane strain compression tests on rectangular-prismatic specimens. Their experimental studies showed significant viscous effects in either creep and stress relaxation stages, or during a change in the strain rate. Nawir et al. (2003) used an automated triaxial apparatus to examine the viscous response of cuboidal prismatic specimens of Toyoura sand under triaxial compression conditions. The identical viscous responses obtained from saturated and dried specimens reconfirmed that the time-dependent response of the specimens was primarily due to the fabric rearrangement of the grains, with negligible effects from the delayed dissipation of excess pore pressure. Recently, AnhDan et al. (2006) experimentally evaluated the viscous behavior of the gravelly soils following the methods used by Di Benedetto et al. (2002)

maintained at the upper surface of the specimen for 24 h. The specimens were subjected to a priming stress of magnitude 81 kPa, resulting from the test arrangement used to apply the axial load (i.e., the weight of the plunger, the lever arm, and the weight rack). Conducting a study on the influence of stress level on physical properties of nonwoven polyester geotextiles, Palmeira and Gardoni (2002) indicated that geotextile layers can be compressed to approximately 0.35 of the initial thickness under the normal pressure of 1,000 kPa. Further, a significant part of the compression of the geotextile (80–90% of this compression) takes place at normal stresses up to 100 kPa. Thus it is assumed that a significant portion of the compression of the geotextile layers, with initial thickness of 1.2 mm, took place during the application of the priming stress, whereas the geotextile compression that occurs during the application of the five main loading increments was considered to be negligible. This fact was also verified by comparing the compression response of the saturated sample with that of dry specimen, in which no geotextile was placed at the top and bottom of the sample. Upon application of the initial stress, the void ratio of the specimen decreased from an initial value of 0.62 to approximately 0.61. During the experiment, the axial stress was increased, successively, to 149, 219, 273, 383, and 493 kPa and was maintained constant at each level for a period of approximately 1 day.

The instrumentation used in the experimental setup included a load cell located on the top of the plunger and two LVDTs arranged to measure the vertical compression of the sample. The load cell used in this experiment has a capacity of 10 kips (44.48 kN) with an accuracy equal to ±0.04% FS. Further, the accuracy of the signal conditioning block is ±0.08% span. Considering the sensitivity of the load cell (4.11 mV/V), the resolution of the system is estimated at 0.027 kN, which is higher than the accuracy of the load cell. This resolution corresponds to approximately 1.5 kPa, which is regarded as an acceptable accuracy for this series of experiments. Two LVDTs, with a displacement range of 2.5 cm, were attached to diametrically opposite sides of the plunger to record the average vertical compression of the specimen. The 10 V excitation voltage required for the transducers was supplied from the rack of the signal conditioner module (ISO-RACK8), which can be connected to eight signal conditioning blocks. In these tests, three signal conditioner blocks with a gain of 50 converted the transmitted signals to high-level analog voltage outputs after a filtering and amplification process. These output voltages were then transferred to a desktop computer through a USB-based DAQ module (PMD-1606FS). Due to the higher rate of axial displacement during the initial stages of the load increments, readings were taken every second during the first hour of each load step. The data acquisition rate was then reduced to one reading per minute during the remainder of the load step, where a lower rate of axial compression was observed.

The time-dependent variation of the void ratio at different stress levels is indicative of the viscous-type processes within the oedometer sample. Fig. 2 clearly indicates that the reduction in void ratio of the saturated ballotini sample subjected to an instantaneous stress increment has a delayed response. It is important to note that full drainage was ensured by connecting the lower and upper surfaces of the specimen to the water inlet and draining vent, respectively. Considering the high hydraulic conductivity of the granular ballotini ($\approx 1.6 \times 10^{-3}$ cm/s), this particular time-dependent behavior is completely unrelated to any processes resulting from transient pore water pressure dissipation effects. Consequently, this phenomenon can only be attributed to the mechanical response of the skeleton that results from the rearrangement of the fabric at the contact locations. This fact was verified by conducting similar tests on dry samples of ballotini, where an identical behavior in the axial strain response was observed.

A part of the results of the tests conducted on a saturated sample was used to develop a generalized three-dimensional elastic-viscoplastic model capable of predicting the time-dependent mechanical response of the material. The proposed model was then used to predict the time-dependent effects in the remaining experiments.

Modeling of Time-Dependent Phenomena

Constitutive modeling of the time-dependent behavior observed

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son's ratio (ν) of the material was also estimated at 0.3. Thus, the magnitude of the viscoplastic strain is estimated using

$$d\varepsilon_{zz}^{c} = d\varepsilon_{zz} - \left[\frac{d\sigma_{zz}}{E} - \frac{2\nu\, d\sigma_{rr}}{E}\right] \tag{13}$$

During the straining process, the viscoplastic strain in the radial direction increases; therefore, the radial stress gradually increases to maintain the total radial strain equal to zero. This evolution of the radial stress decreases the magnitude of axial elastic strain (ε_{zz}^{e}) with time. Therefore, in each load step, the parameters are determined by assuming a value for the radial stress. These parameters were then used in the numerical model of the problem to obtain the new stresses applied to the specimen. The ultimate parameters were obtained after several iterations of the computational procedure.

Considering the rate of irreversible strain at each load, the equivalent viscoplastic strain used to derive the parameters was evaluated from the plastic strains taking place in the same08319.7367.66on o77.6o5o7520106wasTJ010ng-39348eT58ng theofulti-337.753bofuse sample. Each load was maintained for a period of 1 day and the stress condition at the end of this period was considered as the initial condition for the next load step.

The comparison between the experimental and computational modeling for the three load steps is shown in Fig. 6. In each graph, the variation in the axial strain at different load steps is compared with the numerical result. The comparison indicates that, although the model parameters were derived from the experimental results conducted on saturated ballotini, the model reasonably predicts the time-dependent response of both saturated and dry specimens.

Validation of the Elastic-Viscoplastic Model

The parameters of the proposed viscoplastic model were determined from the experimental results obtained from the first three load steps. The capability of this model to simulate the oedometric compression process can be evaluated by predicting the material behavior under different stress conditions. For this reason, the elastic-viscoplastic model was implemented in the computational modeling of the oedometric compression test. Using results from the first three load steps, the parameters of the viscoplastic model were defined as $m=-3.81$, $q^*=979$ kPa, $n=5$, and $A=7.72$ 10^{-16} s^{-1}. Conducting a sensitivity analysis on the range of parameters shown in Table 1, the selected values give rise to better numerical results for the first three load steps. The estimation of the elastic modulus of the material based on the presented method showed a nearly constant value in the first three load steps with an increase calculated in higher stress levels. Thus, the elastic modulus of the material is defined as a function of maximum principal stress $_1$; 36.2 MPa for $_1$ less than 273 kPa, and 45.7 and 56.0 MPa at $_1$ equal to 383 and 492.6 kPa, respectively. The next step in the validation of the model is the prediction of the time-dependent compression of the material in the last two load steps, which were not utilized for the estimation of the parameters. A comparison of the experimental results with the computational simulations is shown in Fig. 6; although there is a slight discrepancy between the results, it can be observed that the trends associated with the viscous compression of the granular sample can be well predicted. It is shown that the evolution of the void ratio during the compression process shows the same linear relationship between creep strain with log time at constant axial stress as that observed in other experimental studies (see, e.g., Leung et al. 1996; Lade and Liu 1998). Furthermore, the comparison ing out different simulations and comparing the numerical results with their experimental counterparts obtained from three load steps. In order to quantify the model parameters, the elastic part of the strain increment was determined in each loading step, from the instantaneous deformation of the sample. The strain hardening parameter m was established from the variation of the equivalent viscoplastic strain with time. The viscosity coefficient A and stress exponent n, which are linked by a simple relationship, can be obtained by assuming one parameter to be constant. In this study, the stress exponent was considered constant and a reference stress was assumed; this enabled the derivation of the parameters by introducing a single unit for the viscosity coefficient.

The compression behavior of the material was computationally modeled for the last two load steps using the viscoplastic parameters selected from the estimated range. Comparing these results with the experimental data, it was shown that the parameters derived from the proposed procedure can reasonably predict the

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Int. J. Geomech., 2009, 9(1): 1-8