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Time-Dependent Resilient Response of Unbound Granular Materials

Dépendance Temporelle de la Réponse Élastique des Matériaux Granulaires Non Liés

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ABSTRACT: The deformation response of unbound granular materials (UGMs) is composed of two distinct parts: permanent and resilient. Both parts are commonly modelled assuming time-independent behavior. This work focused on the resilient response part; the objective was to experimentally confirm or invalidate the time-independence assumption. For this purpose, a cylindrical UGM specimen was exposed to a sequence of load-unload-rest in axial compression under two different confinement levels. Resulting strain responses were closely monitored during the rest phases, where no changes in deformation are expected. Nonetheless, it was observed that both axial and radial strains gradually recovered for several minutes subsequent to axial unloading, clearly indicating that the resilient response of the UGM is time-dependent.

RÉSUMÉ: La réponse à la déformation des matériaux granulaires non liés (MGNL) est constituée de deux composantes distinctes: permanente et élastique. Les deux composantes sont généralement modélisées en supposant un comportement indépendant du temps. Ce travail est axé sur la réponse élastique, l'objectif étant de confirmer ou d'infirmer expérimentalement l'hypothèse d'indépendance temporelle. À cette fin, un échantillon cylindrique de MGNL a été exposé à une séquence de chargement-déchargement-repos en compression axiale sous deux niveaux de confinement différents. Les réponses résultantes ont été étroitement surveillées lors des phases de repos durant lesquelles aucun changement de déformation n'est attendu. Néanmoins, il a été observé que les déformations tant axiales que radiales se sont progressivement rétablies pendant plusieurs minutes après que la charge axiale appliquée ait été retirée, indiquant clairement que la réponse élastique des MGNL dépend du temps.

Keywords: Unbound granular material; Resilient response; Time-dependent behavior; Triaxial testing

1 INTRODUCTION

Compacted layers of unbound granular materials (UGMs) serve an essential structural role in many geotechnical constructions, e.g., buried pipes, tunnels, foundations, retaining structures, embankments, and pavement systems. Within the framework of continuum mechanics, i.e., considering the bulk behavior of a representative volume element, the deformation response of an UGM is composed of two distinct parts, namely permanent and recoverable (Boyce 1976; Brown 1996; Adu-Osei 2000). The former represents changes in shape or volume (or both) that develop under load and that do not recover subsequent to unloading (Barksdale 1972). Such behavior is

typically modeled by means of plasticity or creep formulations (Hyde 1974; Rahman and Erlingsson 2015; Lekarp et al. 2000b). The latter deformation part represents resilient behavior, i.e., changes in shape or volume (or both) that also develop under load, yet recover in full subsequent to unloading. Such behavior is commonly assumed time-independent, and modeled as nonlinear elastic (Mitry 1964; Seed et al. 1967; Hicks and Monismith 1971; Lade and Nelson 1987; Lekarp et al. 2000a).

This work focuses on the resilient response of UMGs; the objective is to confirm or invalidate the time-independence assumption. A purely experimental approach is followed, involving axially loading and unloading a confined UGM specimen in a triaxial cell. If the resilient response is time-independent (as commonly assumed) then subsequent to axial unloading no change in strains should take place. Conversely, if the resilient response is time-dependent, then a gradual recovery of strains should be observed after unloading.

The current study is closely related to a previous contribution in which a confined UGM was also subjected to axial loading-unloading (Levenberg 2014). Both investigations share similar experimental details in terms of specimen fabrication procedure, instrumentation for force and deformation monitoring, and overall loading setup. However, the work in Levenberg (2014) included a single confining stress level, and was mainly focused on one-dimensional constitutive modeling of the axial response. In contrast, the work herein reports on material behavior under two different confinement levels, and reports on strain behavior in both the axial and radial directions.

The paper commences with describing experimental details related to specimen fabrication and instrumentation. Triaxial test results are presented and analyzed next, followed by a discussion of the findings.

2 EXPERIMENTAL DETAILS

2.1 Specimen fabrication

The tested UGM was a standard highway base course, composed of crushed limestone aggregates with a maximum size of 25 mm, densely graded according to ASTM D2940. Based on the modified Proctor procedure (ASTM D1557, Method C) the maximum dry specific density was found to be 2.368 at an optimal water content of 5.9%.

By means of a heavy vibrating piston, the loose UGM mix was compacted at optimum water content inside a cylindrical steel split-mold, 150 mm in diameter and 256 mm in height. After compaction the split-mold with densified material inside were frozen to minus 35°C. Subsequently, the frozen UGM was removed from the steel mold, and its internal part was extracted by coring and saw-cutting the ends. These operations resulted in a cylindrical test specimen, 100 mm in diameter and 200 mm tall, having a uniform compaction level that approached the modified Proctor density. More details on specimen fabrication can be found in Levenberg (2014).

2.2 Specimen instrumentation

While still in frozen state, the UGM cylinder was locally instrumented with force and deformation sensors. For this purpose, aluminum discs, each 25 mm thick and 100 mm in diameter, were attached to the cylinder bases (one on each end). The lower aluminum disk with specimen were fixed to the bottom cover of a triaxial cell; a load-cell was connected to the top disk.

Moreover, prior to covering with a latex sleeve, 12 gauge-points were fixed onto the cylinder mantel by a combination of drilling and gluing. Eight out of the 12 gauge-points served as mounts to four LVDTs each with 100 mm span for measuring axial strains (at right angles). The remaining four gauge-points served as targets to horizontally mounted LVDTs which were later fixed to the triaxial cell (also at right angles) for

measuring radial strains. Figure 1 shows this stage of preparation.

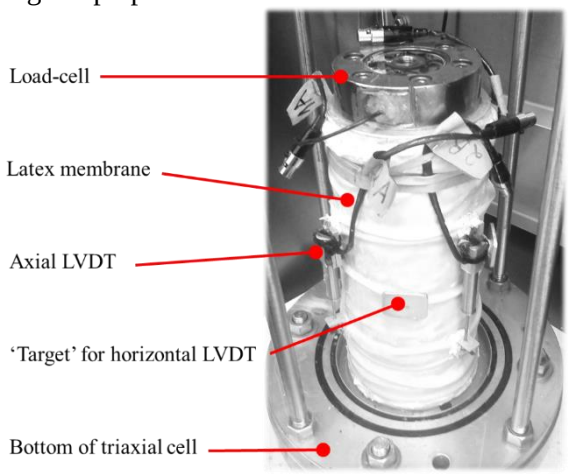

Figure 1. Cylindrical UGM specimen encapsulated by a latex sleeve, locally instrumented for force and deformation monitoring (photo taken after a test).

Subsequently, the instrumented specimen was enclosed by the triaxial cell and the entire arrangement was placed inside a temperature-controlled chamber set to 30°C. With silicone oil as cell fluid, a small confining pressure was imposed, and the UGM was allowed time to fully thaw.

3 TRIAXIAL TESTING

3.1 Loading conditions

A two-axis servo-hydraulic machine was utilized for the testing. One axis served as a silicone oil pump, having the task of controlling the confining pressure in the cell (p_0). The other axis included a piston for producing additional axial stress ($\Delta\sigma_A$) in compression mode. Two separate tests were performed, each under a different time-wise-constant confinement level: $p_0 = 100\,\text{kPa}$ and $p_0 = 300\,\text{kPa}$. The first confining level is within the high pressure range according to the AASHTO T307 resilient modulus protocol. The second confining level is very high, more than twice the highest level in the T307 protocol. These pressure levels were chosen based on the rational that UGMs under elevated confinement should essentially exhibit time-independent behavior.

In each of the tests $\Delta\sigma_A$ was gradually increased and then rapidly decreased to zero, generating a load-unload-rest sequence. This was done in displacement control mode by directly pushing against the load-cell (see Figure 1) and then quickly retracting the piston back to its original position. The above described loading history is schematically shown in Figure 2.

Figure 3 shows the expected strain responses to the loading history of Figure 2. As can be seen, during the loading phase both axial and radial strains increase in magnitude (with opposing sign) from zero toward some peak level. Next, the rapid axial unloading generates a corresponding and practically instantaneous strain drop. Because the material experiences some permanent deformation under load, strains do not return to zero after the drop. Finally, the strain behavior during the rest phase is plotted with long lines that graphically appear to be flat.

Figure 2. Scheme of applied stress history, consisting of a timewise constant confinement level and a sequence of load-unload-rest in axial compression.

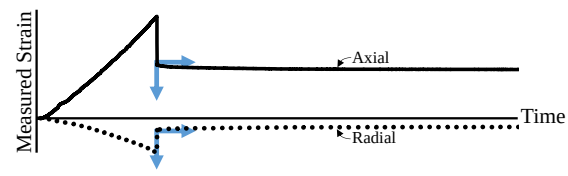

Figure 3. Axial and radial strain responses to the stress history shown in Figure 2.

The analysis hereafter focuses on the material's deformation behavior after the unloading event, with specific attention to any time-depend-

ent strain response during the rest phase. To facilitate this aim, new coordinate systems are introduced in Figure 3. They are positioned over the axial and radial strain curves, with the origin placed at the exact point in time when the rest period is commenced (i.e., when $\Delta\sigma_A$ has returned to zero). Subsequent test results will be displayed utilizing these coordinate systems.

3.2 Experimental results

Figures 4 and 5 present experimental results for $p_0 = 100\,\text{kPa}$ (high) and $p_0 = 300\,\text{kPa}$ (very high) respectively. In both figures the strain behavior during the rest phase is depicted for a duration of 140 seconds, i.e., a little over two minutes. As discussed above, the origin of both charts is the start of the rest phase, i.e., subsequent to axial unloading.

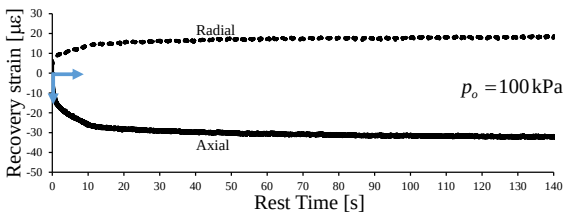

Figure 4. Measured deformations of the UGM specimen during rest phase (high confining cell pressure).

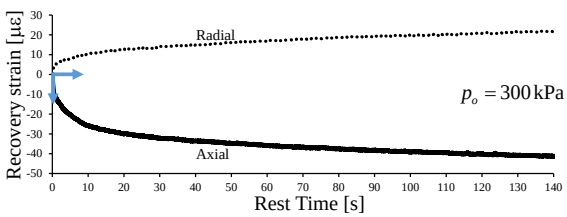

Figure 5. Measured deformations of the UGM specimen during rest phase (very high confining cell pressure).

It can be clearly noticed in Figures 4 and 5 that the measured strains exhibit gradual recovery after axial unloading. Both axial and radial strains increase in magnitude (again, with opposing sign) towards some asymptotic level. The axial strains are negative, indicating that the specimen elongates while the radial strains are positive, indicating a diminishing diameter. These results are especially interesting considering the elevated confinement conditions at which they were measured.

In general terms, recovery magnitudes should depend on the loading history prior to the rest phase, i.e., confinement level, shape and intensity of the axial loading phase, and the quickness of the unloading event. Therefore, given that the curves Figures 4 and 5 are the result of dissimilar set of loading conditions, they cannot be directly compared to assess the influence of confinement level on time-dependent behavior.

4 CONCLUSIONS

Direct experimental evidence was provided herein that the resilient response of the tested UGM is fundamentally time-dependent. This conclusion in based on the observation that for two different confining levels (high and very high) axial and radial strains exhibited gradual recovery during rest phases subsequent to axial unloading.

Although the investigation was limited to one aggregate blend with a given density and moisture content, the overall approach, methodology, and findings are expected to hold for other UGMs.

The direct implication of this work is that the resilient response of UGMs shares some common features with the mechanical behavior viscoelastic solids, namely: (i) creep of strains under constant level of stress, (ii) relaxation of stresses under constant level of deformation, and (iii) dependence of strains on the applied stress-rate (or vice versa).

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