Combined computational-experimental Laboratory Testing for Soil Behiavor

Combinaison d’essais numériques et expérimentaux pour la modélisation du comportement des sols

Hashash Y.M.A., Asmar R., Moon S.
Dept. of Civil and Environnemental Engineering, Univ. of Illinois at Urbana-Champaign, Urbana, USA

ABSTRACT: Solving complex boundary value problems in geotechnical engineering requires a soil constitutive model that reliably captures soil behavior under general loading conditions. Laboratory testing has greatly contributed to the development of constitutive models that reflect soil nonlinear and anisotropic behavior. Available laboratory tests are interpreted assuming uniform stress and strain states within a tested specimen and therefore provide information on material behavior within a narrow range of stress–strain paths and do not cover general loading conditions which occur in field problems. This paper presents the integration of self-learning simulations (SelfSim) inverse analysis framework with laboratory testing to extract soil-behavior. Application of this framework to Direct Simple Shear (DSS) tests shows that it is possible to characterize soil behavior over a wide range of stress paths from a single test. The paper also describes the development of a modified triaxial testing device intended to impose non-uniform loading conditions to increase the range of stresses and strains that can be extracted via SelfSim. The new device represents an important step towards a tighter integration between laboratory testing and constitutive model development.

RÉSUMÉ : Résoudre des problèmes complexes aux limites en géotechnique nécessite un modèle constitutif de sol qui capte de manière fiable le comportement du sol dans des conditions générales de chargement. Les essais en laboratoire ont grandement contribué à l'élaboration de modèles de comportement qui reflètent le comportement non-linéaire et l’anisotrope du sol. Les essais de laboratoire disponibles sont interprétés en supposant que les états de contraintes et de déformation sont uniformes au sein de l’éprouvette testée. Ceci permet de fournir des informations sur le comportement du matériau dans une gamme étroite de chemins contrainte-déformation, et ne couvrent pas les conditions générales de chargement qui se produisent dans les problèmes réels. Cet article présente l'intégration de l'auto-apprentissage des simulations (SelfSim) dans le cadre d’une analyse inverse à partir d’essais en laboratoire pour obtenir le comportement du sol. L'application de cette approche aux essais de cisaillement simple direct (DSS) montre qu'il est possible de caractériser le comportement du sol sur une large gamme de chemins de contrainte à partir d'un seul test. Le document décrit également le développement d'un dispositif d'essai triaxial modifié destiné à imposer des conditions de chargement non uniformes pour augmenter la gamme des contraintes et des déformations qui peuvent être obtenues par SelfSim. Le nouveau dispositif représente une étape importante vers une intégration plus étroite entre les essais de laboratoire et l’élaboration d'un modèle constitutif.

KEYWORDS: SelfSim, direct simple shear (DSS), triaxial shear, inverse analysis, constitutive modeling.

1 INTRODUCTION.

In geotechnical engineering problems, soil behavior interpretation is commonly based on laboratory tests, such as triaxial, plane strain, and direct simple shear tests (Ladd and Foott 1974, Jamiolkowski et al. 1985, Mesri and Choi 1985). These tests or devices allow soil behavior to be evaluated under a range of loading modes, and provide in-depth understanding of soil’s stress–strain–strength behavior (Bolton 1986, Jamiolkowski et al. 1985, Ladd et al. 1977). Uniform stress and strain states within the specimen are generally imposed in the device designed for laboratory testing and the soil response corresponding to a single loading path is provided. Measured soil response is interpreted assuming the specimen is a single element and is sheared uniformly even from devices such as the Direct Simple Shear (DSS) device, which generates non-uniform stresses and strains. This is due to the lack of means to extract the complex stress-strain behavior with a specimen. Due to this uniformity requirement or assumption, laboratory testing can only reveal a narrow range of soil behavior, which is significantly different from the general loading conditions experienced by the soil in the field.

Regardless of the extent of non-uniform conditions within the test itself, interpretation of stress–strain–strength response is based on the assumption of uniform conditions. The design of complex boundary value engineering problems whereby soils are sheared under general loading conditions requires material constitutive models that can represent soil behavior under these loading conditions. The process of development of material constitutive models is lengthy and requires numerous tests to cover a broad range of loading paths. However, all available models are developed based on limited behavior measured by existing laboratory tests. This limited information generally results in a model that may not be justifiable for representing loading conditions that differ substantially from the ones in laboratory tests.

A weak link clearly exists between laboratory testing and material modeling. Hashash, Ghaboussi and co-workers, over the last decade, successfully developed an integrated test-analysis framework to build a stronger link between material testing and material modeling. This is accomplished through the use of a biologically inspired inverse analysis framework, self-learning simulations (SelfSim), which uses a neural network (NN)-based material model to extract non-uniform stress–strain states from global measurements of load and displacement of boundary value problems such as deep excavations and seismic response of downhole arrays (Ghaboussi et al. 1998, Hashash et al. 2004, Tsai and Hashash 2008). Laboratory tests imposing non-uniform stress–strain within the soil are used within the SelfSim framework. Fu et al. (2007) applied the SelfSim framework to simulated laboratory triaxial specimens sheared with no-slip frictional ends, and Hashash et al. (2009) applied the SelfSim framework to drained triaxial compression tests to extract soil stress-strain. The SelfSim inverse analysis algorithm provides a unique opportunity to extract multiple paths of complex soil behavior from a test with nonuniform boundary conditions. The algorithm is unconstrained by prior assumptions on soil behavior such as anisotropy and nonlinearity.

This paper presents the integration of self-learning simulations (SelfSim) inverse analysis computational engine with the widely used DSS test and a newly developed next generation triaxial laboratory testing device that imposes non-uniform loading on a soil specimen beyond frictional ends. The stress paths after SelfSim learning are extracted within the specimens in terms of the relationship between principal stress direction (δ) and intermediate principal stress ratio (b) to interpret soil behavior that is not described sufficiently in conventional laboratory test due to limited information.

2 SELFSIM FRAMEWORK

SelfSim is a biologically inspired evolutionary inverse analysis framework that implements and extends the Autoprogressive algorithm to solve a wide range of engineering problems. The Autoprogressive algorithm was originally proposed by Ghaboussi et al. (1998) and applied to structure and material tests (Ghaboussi and Sidarta 1998). Shin and Pande (2000) implemented this algorithm on simulated structures and introduced it in the context of self learning finite element code. SelfSim treats the soil specimen as a BVP (Boundary Value Problem) instead of a single element test and extracts the nonuniform stresses and strains from within a specimen using external load and displacement measurements.

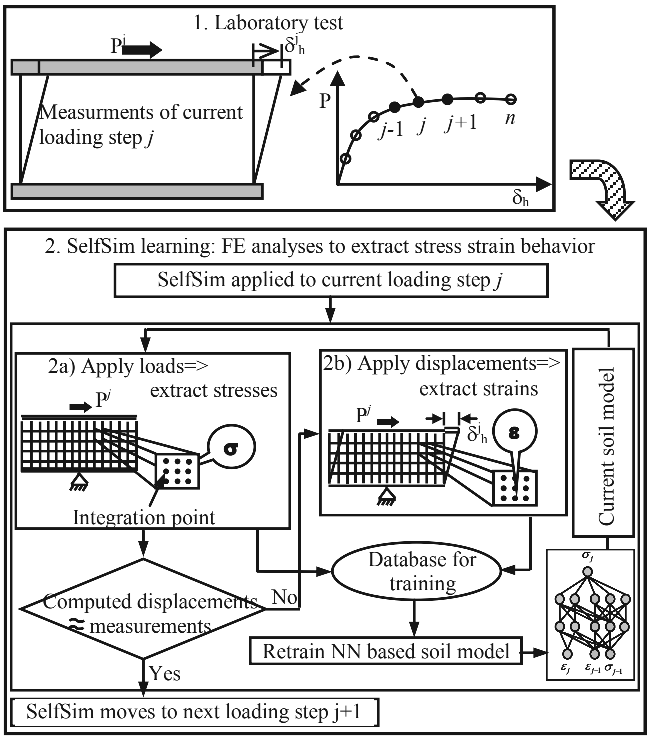

Figure 1. SeflSim framework applied to DSS laboratory test.

As shown in Figure 1, SelfSim framework consists of two steps: 1) In Step 1, a laboratory test with constrained boundary loading conditions is performed and measurements of force and displacement are obtained at each loading step; 2) In Step 2, a numerical model is developed to represent the test with the corresponding measurements. Two parallel finite element (FE) analyses, Step 2a and Step 2b, are performed at each loading step. In these analyses a NN material model is employed that continuously evolves and learns new behavior through the SelfSim process instead of a conventional material model. Initially the soil response is unknown and the NN soil model is pre-trained using stress-strain data that reflect linear elastic response over a limited strain range. The FE analyses are performed to simulate the applied forces in Step 2a and the measured boundary displacements in Step 2b. The computed stresses from boundary forces in Step 2a and the computed strains from boundary displacements in Step 2b are respectively acceptable approximations of the actual stresses and strains experienced throughout the specimen. The stresses from Step 2a and the strains from Step 2b are extracted to form stress-strain pairs. These stress-strain pairs are used to “re-train” the NN soil model in the next step. The parallel analyses and the subsequent NN material model training, SelfSim learning cycle, are performed sequentially for all loading steps and they are repeated till the solution converges when both analyses provide similar results. This results in a single SelfSim learning pass. Several SelfSim learning passes are needed to extract soil behavior used in training a NN soil model that will adequately capture global measurements of force and displacement. The framework extracts material behavior via a continuously evolving constitutive model and thus is not constrained by conventional constitutive model assumptions.

3 APPLICATION OF SELFSIM TO DSS TESTS

The SelfSim framework is applied to K_0 normally consolidated-undrained direct simple shear (CK_0UDSS) tests, performed on normally consolidated re-sedimented Boston Blue Clay (BBC) (Ahmed 1989). SelfSim learning is performed on Test DSS14 up to 1.97% shear strain divided into 11 loading steps. The 3D FE model is developed as a cylindrical specimen with a height of 1.96 cm and a diameter of 6.68 cm. The specimen is assumed to have frictional loading cap and base that can produce non-uniform stress-strain distribution during shear. The consolidation process is not simulated but considered as an initial anisotropic state of stress (σ'_{v0}=1176kPa, σ'_{h0}=623kPa), from which shearing commences.

SelfSim learning is initiated with a trained NN constitutive model representing linear elastic behavior in the shear strain range of 0.07%. This linear elastic behavior is removed once the learning process starts. The global measurements, such as vertical loads, horizontal loads, and lateral displacements in x (longitudinal, in the direction of shearing) and y (transverse) directions, from CK_0UDSS test are employed in SelfSim learning. After initialization, SelfSim learning is conducted in 4 stages over all 11 loading steps using the updated NN material model from each stage.

Figure 2 shows comparisons of the global target responses and model responses after SelfSim learning, including normalized shear stress, normalized vertical stress, and lateral displacement. Through the process of SelfSim learning, the computed global responses match the global target responses of force and displacement measurements for DSS14 at the learning final stage. Thus, SelfSim learning makes it possible to extract sufficient information about the soil behavior to learn the global response. The stress behavior at integration points is extracted in a half slice of the specimen using a cylindrical coordinate system.

Figure 3 shows the extracted stresses in the plot between intermediate principal stress ratio (b) and the principal stress direction (δ). Through SelfSim learning, the extracted stresses from the CK_0UDSS specimen can cover a significant unexplored portion of the stress space (δ ranges from 0°~58° and b ranges from 0~1.0).

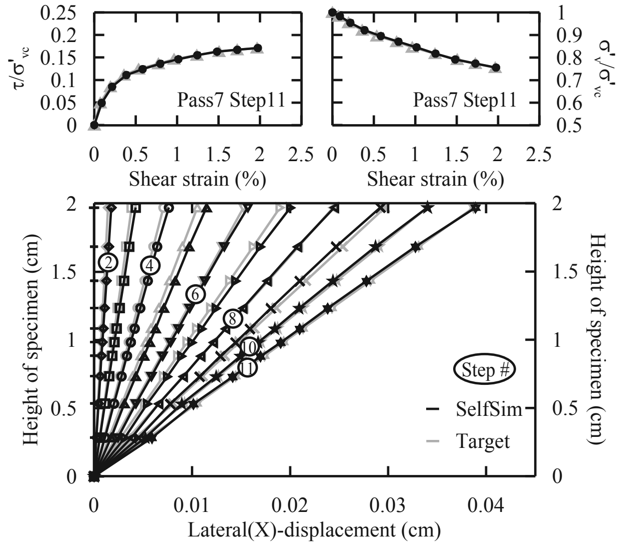

Figure 2. Global DSS14 responses after SelfSim learning (Final stage)

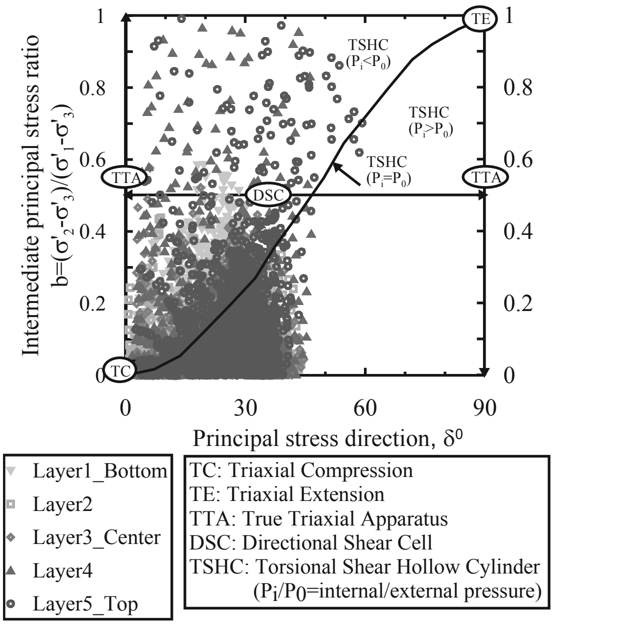

Figure 3. Extracted soil behavior of a half slice of the specimen corresponding to each 5 layer at all Gauss points

4 APPLICATION OF SELFSIM TO A NEWLY DEVELOPED TRIAXIAL DEVICE

This section presents important modifications to the conventional triaxial testing device to induce nonuniformity within the sample. Advanced imaging devices in addition to more traditional load and displacement sensors are used to capture specimen response. The loading of the specimen is treated as a boundary value problem and is integrated with the SelfSim inverse analysis framework to extract a multitude of loading paths.

The new device inherits essential features of the standard triaxial cell, including specimen preparation, device set-up, consolidation and shearing procedures as well as instrumentation. Additional boundary constraints are introduced to generate 3D shearing conditions within a tested specimen.

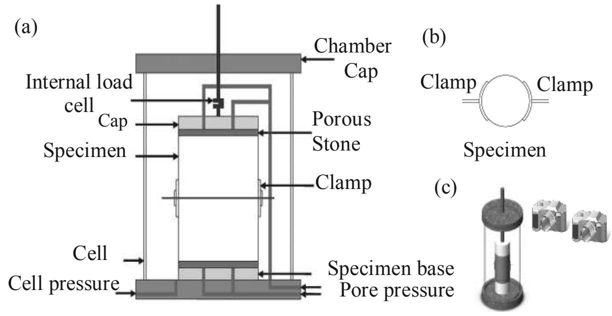

Figure 4. Schematic of proposed TX cell based device. (a) Close-up of device with center clamps, (b) cross- section with center clamps, (c) Digital photogrammetry system

Figure 4 shows the main elements of the device. A soil specimen stands in-between the top and bottom loading platens encased in a liquid pressured cell. A back-pressure system connects to the specimen via platens to provide drainage control.

The design of the new device includes the following boundary restraints to generate non-uniform stress states and general loading modes during shearing:

(1) Fully frictional loading platens: The platens use embedded porous stones glued with coarse sand particles larger than the particles of the soil specimen to provide full friction.

(2) Lateral displacement restraint clamps: A pair of opposite clamps is attached symmetrically to the mid-height of the specimen. Both clamps are prevented from moving laterally outwards during the shearing process. The clamps are linked with a rod that goes through the sample as shown in Figure 4.

(3) A close-range photogrammetry system to accurately measure the 3-D lateral deformations of the specimen (Medina-Cetina and Rechenmacher 2006). Using two high resolution digital cameras mounted in front of the cell as illustrated in Figure 4 (c), the system will capture the specimen's deformed shapes. Global deformations are monitored by using the technique of three-dimensional Digital Imaging Correlation (3D-DIC) as was similarly employed by Medina-Cetina and Rechenmacher (2006).

The refraction at the Plexiglas-oil boundary was suppressed by using an external Plexiglass box which is positioned in front of the cameras and filled with the same oil used around the sample. At the same time, oil that has a refraction index similar to the Plexiglas is used. Therefore, the image will effectively see only one medium, and the sample will have negligible magnifications. The digital-imaging technique is initialized with a calibration process in which camera parameters are established. These parameters control the transformation between the system-wide coordinates and the coordinates on each camera's image plane. Once the transformation matrix has been extracted, the technique then proceeds to the processing phase where digital images of the specimen are transformed into 3-D models which then can be used to determine the deformation of the specimen.

The measurements of loads, axial displacement, pore pressures/volume change and sample shape during the shearing process provide input to SelfSim inverse analysis to extract induced stresses and strains within the tested specimen.

A series of numerical analyses simulating the proposed device are conducted to study the range of stresses and strains induced in the soil specimen as a result of the lateral restraints imposed by the clamps.

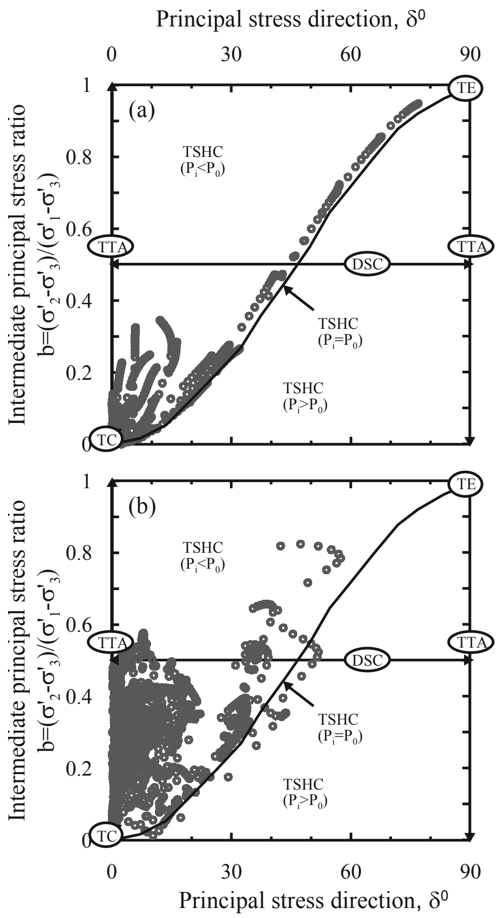

Figure 5. Extracted soil behavior in b-δ space at center Gauss points. (a) Without and (b) With clamps

These analyses show that the sheared specimen includes shear modes that cannot currently be mobilized with available testing devices and that they are the direct result of using the side clamps as shown in

Figure **5**. We are currently conducting tests on sand samples using this new device.

5 CONCLUSIONS

This paper describes the application of the relatively novel SelfSim inverse analysis framework to CK_0UDSS tests and a newly developed next generation testing device. For the DSS test, SelfSim learning is used to successfully match the measured global responses. The extracted stress paths reveal soil response and stress paths, such as non-uniform stress distribution and rotation of principal stress axis during shearing, that cannot be developed from conventional laboratory tests.

The paper also introduces a new laboratory testing device which is designed to test a specimen in a triaxial cell for generating soil behavior under general loading conditions. The design inherits features of the conventional triaxial test, and adds frictional ends and lateral displacement restraint clamps. SelfSim learning is coupled with the proposed devices to extract stress strain behavior generated with a tested specimen. A close-range digital photogrammetry system is used for measuring lateral displacements throughout loading to be used for SelfSim learning. The numerical analyses show that the stress states cover a wide portion of b-δ space and can greatly enrich soil behavior information.

The proposed developments have significant ramification with regards to the way laboratory testing is conducted and soil constitutive models are developed. It allows for tight integration of numerical modeling and laboratory testing. A soil constitutive model can now be directly developed from one or few laboratory tests in a short period of time and subsequently used in the solution of a boundary value problem. This constitutive model is soil specific yet can be efficiently developed in a short period of time.

6 ACKNOWLEDGMENT

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