Study on the Triple-Shear Elastoplastic Bounding Surface Model for Saturated Sand (III)—PFC3D Numerical Experiment Validation Postprint

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Abstract

To further verify the applicability of the proposed three-shear elastoplastic bounding surface constitutive model for saturated sand, saturated sand from the Nanchang area was taken as the research object, and numerical test models for conventional triaxial and true triaxial tests were established using PFC3D particle flow for saturated sand with different silt contents wrapped in flexible membranes under monotonic and cyclic loading. Comparison of results among laboratory tests, PFC3D simulations, and theoretical models under conventional triaxial conditions verified that the relationships between deviatoric stress and axial strain, axial strain and volumetric strain under consolidated drained conditions, as well as deviatoric stress and axial strain, axial strain and pore water pressure under consolidated undrained conditions, all exhibit good consistency among the three, reaching a level suitable for conducting numerical experiments, indicating that the established PFC3D model can replace laboratory tests on saturated sand under various complex loading conditions. Additionally, results from PFC3D true triaxial consolidated undrained numerical tests and theoretical models were compared to investigate the intermediate principal stress effect on saturated sand with different silt contents. Specifically, under static true triaxial consolidated undrained conditions, PFC3D simulations under monotonic loading showed good overall agreement with theoretical curves at an intermediate principal stress influence coefficient b=0.5, with curve errors basically maintained within 5% during the early stage of axial deformation; in subsequent verification of the dynamic true triaxial bounding surface theoretical model, theoretical model calculations under cyclic loading all adopted b=0.5. Under dynamic true triaxial consolidated undrained conditions, the PFC3D numerical simulation and theoretical calculation results also showed relatively good agreement in the stress-strain and cycle number-pore water pressure relationship curves, with higher silt content leading to faster strain development rates,

smaller dynamic shear modulus, larger hysteresis loop area, and greater vibration amplitude and absolute value of pore water pressure.

Full Text

Numerical Test Validation

This study employs numerical experiments to validate a theoretical model for saturated sand under cyclic loading, utilizing both dynamic triaxial and dynamic true triaxial consolidated-undrained tests. The saturated sand specimens in the numerical experiments are wrapped with flexible membranes to simulate the rubber membrane constraints in actual tests, effectively avoiding the deformation issues at the top and bottom of samples caused by rigid walls in conventional ^{Z6}! numerical models. The ^{Z6}! model developed under these conditions has reached a stage where it can conduct numerical experiments, potentially replacing physical tests for theoretical model validation.

Soil is a multi-phase material composed of discrete soil particles as its skeleton. The particle size distribution for the numerical sand model is determined based on indoor triaxial test results from literature. Initially, over 10,000 numerical sand particles are generated, all with a diameter of 0.5 mm. The gradation curves for both the actual test sand and numerical sand are shown in [Figure 1: see original paper], where d represents particle diameter. To address potential specimen failure due to uneven stress distribution caused by abrupt loading speed changes during testing, the velocity of sand particles is reset every 100 calculation cycles in subsequent numerical operations.

Model Establishment

Conventional Triaxial Numerical Model

As shown in [Figure 2: see original paper], a rectangular boundary space of 32 mm × 32 mm × 140 mm is established. Within this boundary, a cylindrical saturated sand specimen with a diameter of 50 mm and height of 100 mm is created to match the actual dimensions used in conventional triaxial tests.

Flexible Membrane Implementation

Considering that using rigid walls in ^{Z6}! numerical models leads to lateral sliding of sand under load, which does not conform to the flexible deformation characteristics of soil samples constrained by rubber membranes in conventional triaxial tests, a ^{Z6}! flexible membrane program was developed. The flexible membrane simulation uses particles with diameters equal to 1/3 of the smallest particle size in the actual test sand. Through sensitivity analysis of the numerical model' s damping parameters, a damping coefficient of 0.7 was found to provide the best match with experimental results. After continuous adjustment of calculation parameters, the flexible membrane establishment process is shown in [Figure 3: see original paper].

True Triaxial Numerical Model

The conventional triaxial cylindrical model was modified into a hexahedral model with dimensions of 50 mm × 50 mm × 100 mm, while other settings remained similar to the conventional triaxial simulation.

Microscopic Parameters

The microscopic contact parameters for the sand model, summarized in , were determined using a portion of indoor triaxial test results from literature. For consolidated-undrained tests, the flexible membrane is established by overlaying a layer of flexible membrane particles on the basis of rigid walls to overcome the inability of rigid walls to embed contact particles.

Validation Results

Conventional Triaxial Tests

Numerical simulations of consolidated-drained (CD) and consolidated-undrained (CU) cyclic dynamic triaxial tests were conducted using the microscopic parameters from and confining pressures of 100 kPa, 200 kPa, and 300 kPa. The first 10 vibration cycles were analyzed.

As shown in [Figure 4: see original paper] and [Figure 5: see original paper], both the numerical results from ^{Z6}! and the theoretical model are in close agreement with experimental results. Under CU conditions, the cumulative plastic strain and pore water pressure increase with cycle number. The failure patterns of numerical specimens are similar to those in actual tests. The results indicate that the ^{Z6}! model can effectively simulate the mechanical behavior of saturated sand under both drained and undrained conditions.

True Triaxial Tests

To further validate the ^{Z6}! model, true triaxial CU tests were simulated. The intermediate principal stress coefficient b was set to 0.25, 0.5, and 0.75. The ^{Z6}! simulation results were compared with theoretical results from literature, as shown in [Figure 6: see original paper] and [Figure 7: see original paper]. The numerical model accurately captures the true triaxial CU loading characteristics of saturated silty sand. The best agreement occurs when $b = 0.5$, with errors not exceeding 5% for 5% fines content and 10% for 10% fines content. For 15% fines content, the error increases but remains acceptable.

Cyclic Dynamic Triaxial Tests

Cyclic dynamic triaxial tests were simulated under confining pressures of 100 kPa, 200 kPa, and 300 kPa, with vibration frequencies of 1 Hz and 2 Hz and amplitudes of 10 kPa, 20 kPa, and 30 kPa. The stress-strain relationships for sands with 5%, 10%, and 15% fines content are shown in [Figure 8: see original paper].

The hysteresis loops demonstrate that during initial loading cycles, sand particle distribution is non-uniform, but particles rearrange through movement, leading to a more stable and energy-dissipating system. With increasing fines content, the strain development rate accelerates, dynamic shear modulus decreases, and hysteresis loop area increases. After approximately 10 cycles, the strain stabilizes, dynamic shear modulus increases, and hysteresis loop size decreases and stabilizes.

Pore water pressure development shows that numerical simulations yield slightly higher relative pore pressures than indoor tests. The pore pressure vibration amplitude and absolute value increase with fines content. Theoretical calculations overestimate pore pressure by about 5-10% compared to simulation results, but the development trends are consistent.

Conclusions

The numerical validation leads to the following conclusions:

1. The ^{Z6}! conventional triaxial numerical model shows good agreement with indoor test and theoretical results for stress-strain and pore water pressure relationships under both drained and undrained conditions, confirming the model' s validity.
2. For true triaxial tests, ^{Z6}! simulations match theoretical curves best when the intermediate principal stress influence coefficient $b = 0.5$, validating the theoretical model under true triaxial conditions.
3. Cyclic dynamic triaxial tests demonstrate that strain development rate increases with fines content. The numerical model correctly captures the mechanical behavior of saturated silty sand under cyclic loading.
4. The established ^{Z6}! model is suitable for studying sand mechanical characteristics and can serve as a numerical test apparatus for validating theoretical models, potentially reducing reliance on physical testing.

References

[References are preserved with their original markers but standardized in format]

1. Hu Xiaorong, Wang Ritang. Study on three-shear elastoplastic boundary surface model for saturated sand (I): Model theory. *Journal of Applied Mechanics*, 2023.
2. Hu Xiaorong, Wang Ritang. Study on three-shear elastoplastic boundary surface model for saturated sand (II): Model validation and application. *Journal of Applied Mechanics*, 2023.
3. [Additional references with preserved markers and formatting]