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A 3D model for earthquake-induced liquefaction triggering and post-liquefaction response

Arash Khosravifar[a,*], Ahmed Elgamal[b], Jinchi Lu[b], John Li[b]

[a] *Department of Civil and Environmental Engineering, Portland State University, Portland, OR 97201, USA*
[b] *Department of Structural Engineering, University of California, San Diego, La Jolla, CA 92093, USA*

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ABSTRACT

A constitutive soil model that was originally developed to model liquefaction and cyclic mobility has been updated to comply with the established guidelines on the dependence of liquefaction triggering to the number of loading cycles, effective overburden stress (Kσ), and static shear stress (Kα). The model has been improved with new flow rules to better capture contraction and dilation in sands and has been implemented as PDMY03 in different computational platforms such as OpenSees finite-element, and FLAC and FLAC^{3D} finite-difference frameworks. This paper presents the new modified framework of analysis and describes a guideline to calibrate the input parameters of the updated model to capture liquefaction triggering and post-liquefaction cyclic mobility and the accumulation of plastic shear strain. Different sets of model input parameters are provided for sands with different relative densities. Model responses are examined under different loading conditions for a single element.

1. Introduction

Soil liquefaction has been shown to be a major cause of damage to structures in past earthquakes. Several constitutive models have been developed to capture various aspects of flow liquefaction and cyclic mobility such as Manzari and Dafalias [21], Cubrinovski and Ishihara [8], Li and Dafalias [20], Byrne and McIntyre [6], and Papadimitriou et al. [25] to name a few. Simulating soil liquefaction using numerical models offers several challenges including: (a) reasonably capturing triggering of liquefaction or the rate of pore-water-pressure (PWP) generation for sands with different relative densities under various levels of shear stress, effective overburden stress and static shear stress, and (b) post-liquefaction cycle-by-cycle accumulation of shear and volumetric strains.

A constitutive model was developed within classical multi-surface plasticity formulation by using a mixed stress- and strain- space yield domain to reasonably capture soil liquefaction and specifically replicate the large shear strains that occur at minimal change in stress state in laboratory results [26,33]. This model was implemented into a solid-fluid fully-coupled OpenSees finite element (FE) framework ([26,7] and [23]). The first version of the multi-yield surface pressure dependent model (PDMY) was developed primarily to capture post-liquefaction cyclic softening mechanism and the accumulation of plastic shear deformations. The previous calibration was performed against a dataset of laboratory and centrifuge tests and the model parameters were provided for sands with different relative densities in Yang et al. [32] and Elgamal et al. [10]. The original experimental dataset was rather limited in terms of pore-water-pressure build up; therefore, liquefaction triggering was not the primary focus in the development of the original constitutive model and the calibration was performed including engineering judgment. Since new data and established procedures that have been under development in the past 30–40 years have become available, it became possible to make updates to the constitutive model to capture factors that affect triggering of liquefaction, as will be explained in the following paragraphs.

Various studies employing different analytical or experimental methods have been performed in recent years that provide insights on factors that affect triggering of liquefaction. Laboratory tests have shown the effect of number of loading cycles on the cyclic shear strength of sands (e.g. [34]). Laboratory tests, case histories and theoretical studies using critical-state soil mechanics suggest that the cyclic shear strength of sands against the triggering of liquefaction is affected by the effective overburden stress characterized by the Kσ factor (e.g. [4]). Furthermore, laboratory tests have shown that the cyclic resistance of sands against the triggering of liquefaction is affected by initial static shear stress which is often characterized by the Kα factor [12,5]. To be able to capture these effects in the model response, the contraction and dilation equations in the constitutive model were

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[*] Corresponding author.
E-mail address: karash@pdx.edu (A. Khosravifar).

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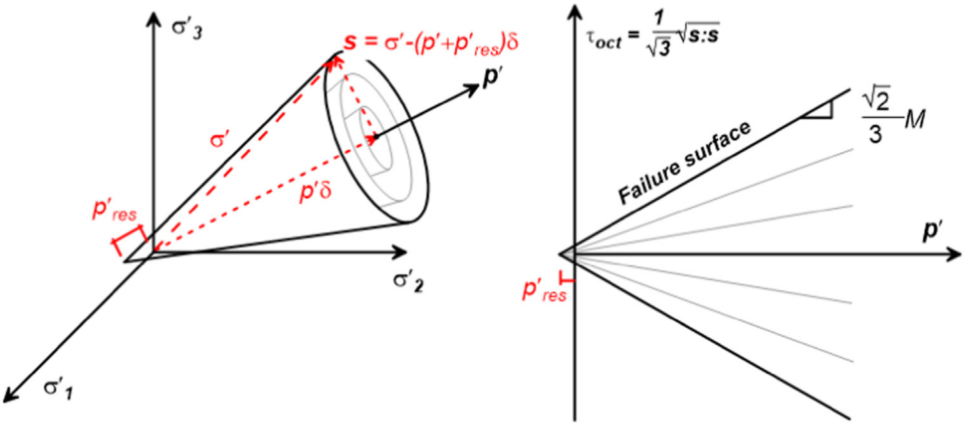

Fig. 1. Conical multi-surface yield criteria in principal stress space.

updated with a new set of equations. Specific attention was given to capture the dependency of liquefaction triggering on the number of loading cycles, effective overburden stress, and initial static shear stress. We took a model that had certain strengths in capturing post-liquefaction cyclic softening and strain accumulation, and updated it into a practical tool that can reliably capture the rate of pore-water-pressure generation, triggering of liquefaction at different number of loading cycles, overburden stress ($K\sigma$) and static shear stress ($K\alpha$) in both 2D and 3D applications.

This paper presents the basic formulation of the new model and provides calibrated parameters for sands with different relative densities. The focus of this paper is to show how the new model can capture the effects of various factors discussed above on liquefaction triggering. Despite the many input parameters required by the model, the calibration is developed with a goal to derive model input parameters using minimal data available to user (i.e. the relative density) and filling the gaps using design correlations. The calibration process has been primarily based on the correlations proposed by Idriss and Boulanger [14] for liquefaction triggering curves. A similar calibration process can be followed when lab data are available or if other triggering correlations are chosen. The model responses are illustrated for single-element simulations under undrained-cyclic loading conditions.

The updated model has been implemented in OpenSees finite-element, and FLAC and FLAC^{3D} finite-difference frameworks as PDMY03. The results shown in this paper are created using OpenSees framework; however, similar results can be obtained using FLAC or FLAC^{3D}. The source code for this model is available in public domain as part of the OpenSees computational framework (http://opensees.berkeley.edu). A user manual, a library of example files, element drivers and post-processors are available and maintained at http://soilquake.net/.

In FLAC, the solid domain is discretized by a finite difference mesh consisting of quadrilateral elements or zones [15]. Each element is subdivided internally by its diagonals into two overlaid sets of constant-strain triangular sub-elements or subzones (resulting in four sub-elements in total for each quadrilateral element). FLAC employs a “mixed discretization technique” [22] to overcome the mesh-locking problem: The isotropic stress and strain components are taken to be constant over the whole quadrilateral element, while the deviatoric components are maintained separately for each triangular sub-element [15]. Similarly, the above-mentioned mixed discretization approach is also applied in FLAC^{3D} [16] where each 8-node hexahedral element or zone is subdivided into 10 tetrahedral sub-elements.

In the soil model implementation, each sub-element (analogous to a Gauss integration point in Finite Element method) is treated independently. A complete set of soil modeling parameters including stress state and yield surface data is maintained separately for each sub-element. At each time step, the soil model is called to obtain a new stress state for each sub-element given the strain increments of the sub-elements.

For FLAC and FLAC3D, site response simulations (shear beam-type response) have shown that the stress state of subzones of any given element were virtually identical and similar to the overall averaged FLAC/FLAC3D response for the element. However, further work might be required to enforce additional constraints on the sub-zone responses for general scenarios of 2D/3D soil and soil-structure interaction responses as highlighted in the works of Andrianopoulos et al. [1], Ziotopoulou and Boulanger [35], and Beaty [3]. This effort is currently underway.

Originally, the soil modeling code was implemented in OpenSees (written in Visual C++). The implementation in FLAC and FLAC^{3D} mainly involved the addition of interfaces between FLAC (or FLAC^{3D}) and the existing OpenSees soil model code. It was verified that similar results are obtained using FLAC, FLAC^{3D} and OpenSees for the implemented model. As such, the soil constitutive model has been compiled as a dynamic link library (DLL) with corresponding versions for FLAC (Versions 7 and 8) and FLAC^{3D} (Versions 5 and 6).

2. Constitutive model formulation

Based on the original multi-surface plasticity framework of Prevost [27], the model incorporates a non-associative flow rule and a strain-space mechanism [10,32] in order to reasonably simulate cyclic mobility response features. This section will briefly define the components of the material plasticity including yield function, hardening rule and flow rule. Further details on model formulations are provided in Yang and Elgamal [33] and Yang et al. [32].

2.1. Yield surface

The yield function in this model is defined as conical shape multi-surfaces with a common apex located at the origin of the principal space (Fig. 1). The outermost surface defines the yield criterion and the inner surfaces define the hardening zone [17,24,27]. It is assumed that the material elasticity is linear and isotropic, and that nonlinearity and anisotropy results from plasticity [13].

The model is implemented in the octahedral space and it is important to differentiate the horizontal plane shear stress (and strain) in 2D modeling from octahedral shear stress (and strain) in 2D and 3D modeling. The deviatoric stress is defined in Fig. 1 as $\tilde{\mathbf{s}} = \tilde{\boldsymbol{\sigma}}' - p'\tilde{\mathbf{I}}$ and the second invariant of deviatoric stress tensor is defined as $J_2 = \frac{1}{2}[\tilde{\mathbf{s}} : \tilde{\mathbf{s}}]$. The octahedral shear stress (τ_{oct}) is defined as: