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Calibration and implementation of a sand plasticity plane-strain model for earthquake engineering applications

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ABSTRACT

The calibration and implementation of a sand plasticity plane-strain model for geotechnical earthquake engineering applications are presented. The constitutive model, as described by Boulanger and Ziotopoulou [1] in a companion paper, was formulated to improve its ability to approximate the stress–strain responses important to geotechnical earthquake engineering applications. A generalized calibration of the constitutive model is presented which attempts to produce drained and undrained, monotonic and cyclic responses under a broad range of stress conditions that are reasonably consistent with the behaviors expected based on engineering correlations to commonly available in-situ test data (i.e., SPT, CPT and V_s data). Simulated single element responses are compared to various design correlations to illustrate and evaluate the model's performance. The calibrated model has three primary parameters that require input by the user: a shear modulus coefficient that is determined from in-situ shear wave velocity data, an apparent relative density which is estimated from SPT or CPT penetration resistances, and a contraction rate parameter that the user adjusts to fit the cyclic resistance ratio determined from a design liquefaction triggering correlation. The remaining parameters are assigned default values based on the calibration process presented herein. The constitutive model is shown to be relatively easy to calibrate and provide reasonable responses for key liquefaction behaviors. The numerical implementation as a user defined material for use in a two-dimensional explicit finite difference program is described.

1. Introduction

Nonlinear deformation analyses for problems involving liquefaction are increasingly common in earthquake engineering practice. The fidelity of these analyses depends on the capabilities of the constitutive model used for the liquefiable sand and the capabilities of the numerical platform in which they are implemented. Constitutive models used for sand vary in complexity, but their calibration in practice can almost always only be based on empirical design correlations and the results of in-situ SPT, CPT and shear wave velocity (V_s) data. The numerical platforms for these types of analyses similarly vary in their capabilities, including differences in features such as alternative soil models, structural elements, numerical solution techniques, graphical user interfaces, and commercial availability.

In the companion paper, Boulanger and Ziotopoulou [1] present the formulation of a plasticity model for sand (referred to as PM4Sand) for geotechnical earthquake engineering applications. PM4Sand follows the basic framework of the stress-ratio controlled, critical state compatible, bounding surface plasticity model for sand initially presented by Manzari and Dafalias [2] and later extended by Dafalias and Manzari [3]. Modifications to the Dafalias–Manzari model were developed and implemented by Boulanger [4] and Boulanger and Ziotopoulou [1,5] to improve its ability to approximate a set of engineering design relationships that are used to estimate the stress–strain behaviors that are important to predicting liquefaction-induced ground deformations during earthquakes. In effect, the approach taken was to calibrate the constitutive model at the equation level, such that the functional forms for the various constitutive relationships were chosen for their ability to approximate the important trends embodied in the extensive laboratory-based and case history-based empirical correlations that are commonly used in practice. Motivations for the selected functional forms and examples of the capabilities provided by the various modifications and additions to the model were presented.

This paper presents the generalized calibration of the constitutive model against a set of engineering design correlations and its numerical implementation. The goal of the generalized calibration of the model was to produce drained and undrained, monotonic and cyclic responses under a broad range of stress conditions that are reasonably consistent with the behaviors expected based on engineering correlations to commonly available in-situ test data (i.e., SPT, CPT and V_s data). The responses obtained in single

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element simulations are compared to various design correlations to illustrate the model's performance. The calibrated model has three primary parameters that require specification by the user: a shear modulus coefficient that is determined from in-situ shear wave velocity data, an apparent relative density which is estimated from SPT or CPT penetration resistances, and a contraction rate parameter that the user adjusts to fit the cyclic resistance ratio (CRR) determined from a design liquefaction triggering correlation (e.g., Fig. 1). The remaining parameters are assigned default values based on the generalized calibration process presented herein. The results of these and other simulations [5] provide a reasonable evaluation of the conditions for which the model does and does not produce responses within the ranges observed experimentally for liquefiable soils. The numerical implementation as a dynamic link library (DLL) for use with the two-dimensional explicit finite difference program FLAC (Fast Lagrangian Analysis of Continua, Itasca [6]) is described. The results of element and boundary value simulations using different time step sizes indicate that the integration scheme is well-behaved and sufficiently accurate for engineering applications.

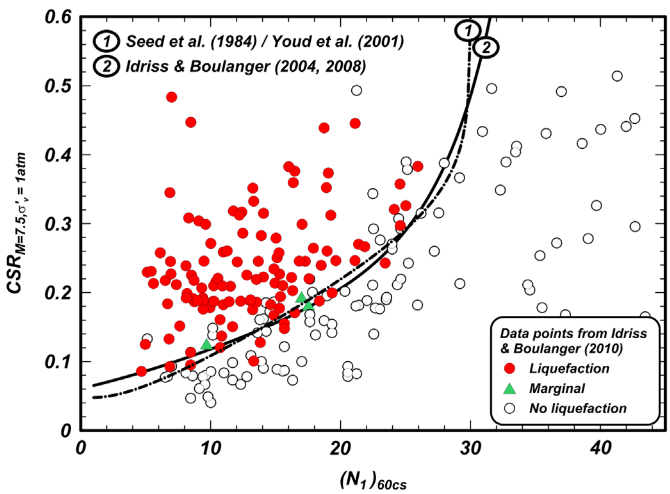

Fig. 1. Correlations for cyclic resistance ratio (CRR) from SPT data (Idriss and Boulanger [27], Seed et al. [28] and Youd et al. [29]).

2. Constitutive model calibration

2.1. Model input parameters

The constitutive model parameters are grouped into two categories; a primary set of three parameters that are most important for model calibration, and a secondary set of parameters that may be modified from their default values in special circumstances (Boulanger and Ziotopoulou [1,5]). All of the parameters are listed in Table 2.

2.1.1. Primary input parameters

The three primary input parameters are the sand's apparent relative density D_R, the shear modulus coefficient G_o, and the contraction rate parameter h_{po}. Values for D_R can be estimated in practice by correlation to penetration resistances. For example, a common form for SPT correlations is

$$D_R = \sqrt{\frac{(N_1)_{60}}{C_d}} \tag{1}$$

where D_R is expressed as a ratio rather than a percentage. Idriss and Boulanger [7] recommended a value of C_d=46 for clean sands in the

Table 2
Input parameters for example single-element responses.

Scenario field condition				Model input parameters[a]		
D_R	$(N_1)_{60}$	V_{S1} using Andrus and Stokoe [8]	$CRR_{M=7.5}$ using Idriss and Boulanger [7]	D_R	G_o	h_{po}
0.35	6	144	0.090	0.35	476	0.96
0.55	14	171	0.147	0.55	677	0.71
0.75	26	196	0.312	0.75	890	0.98

[a] Unless noted otherwise, all secondary input parameters were assigned the default values listed in Table 1.

Table 1
Model parameters.

Parameter	Comments
D_R	Apparent relative density: primary variable controlling dilatancy and stress–strain response characteristics.
G_o	Shear modulus coefficient: primary variable controlling the small strain shear modulus, G_{max}.
h_{po}	Contraction rate parameter: primary variable that adjusts contraction rates and hence adjusts the CRR.
h_o	Adjusts the ratio of plastic modulus to elastic modulus. Default value of $h_o=(0.25+D_R)/2$, with a minimum value of 0.30, was chosen to provide reasonable G/G$_{max}$ and damping relationships for the default value of G_o. This variable may require adjustment in combination with any adjustments to G_o.
e_{max} and e_{min}	Default values of 0.8 and 0.5, respectively, were adopted. Refinements in these parameters for a practical problem may not be necessary, as the calibration of other parameters will have a stronger effect on monotonic or cyclic strengths.
n^b	Default value is 0.50. Controls dilatancy and thus also the peak effective friction angles.
n^d	Default value is 0.10. Controls the stress-ratio at which contraction transitions to dilation, which is often referred to as phase transformation.
A_{do}	Default value is computed based on Bolton's dilatancy relationship [9] at the time of initialization.
z_{max}	Default value is 0.28 exp(6.1D_R), with an upper limit of 40. This returns values of 2.4, 8.0, and 27.2 at D_R of 35, 55, and 75%, respectively.
c_z	Default value is 250. Controls strain levels at which fabric effects become important.
c_ε	Default value is 5.0 for D_R less than 35%, and linearly decreases to its minimum value of 1.0 at D_R=75%. Can be used to adjust the rate of strain accumulation in undrained cyclic loading.
ϕ'_{cv}	Default value is 33°.
ν_o	Default value is 0.30, which results in a K_o value of 0.43 in 1D consolidation.
C_{DG}	Default value is 2.0. The small-strain elastic modulus degrades with increasing cumulative plastic deviator strains (z_{cum}). The maximum degradation approaches a factor of $1/C_{DG}$.
C_α	Default value is 0.0 for D_R less than 55%, and linearly increases to its maximum value of 8.0 at D_R=75%. This variable controls the effect that sustained static shear stresses have on plastic modulus.
Q	Default value is 10 for quartzitic sands per recommendations of Bolton [9].
R	Default value is 1.5. Default value for quartzitic sands would be 1.0 per recommendations of Bolton [9]; a slight increase in R is used to lower the critical state line for a slightly more conservative approximation of various sands in different loading tests.
m	Default value is 0.01.