Development and calibration of constitutive model for sand

The behavioral diversity of sand for different loading conditions (drained/undrained, monotonic/cyclic, direction), and different initial state and fabric, render its modeling a difficult and challenging task. The suitability of the used constitutive model is evaluated by its capability to capture at least the trends across all these conditions without recalibration of its parameters for each specific case. Simplicity is needless to say a desirable attribute. Too many parameters might increase the versatility of the model at the risk, however, of losing its physical appeal.A novel constitutive model for sand is developed as an alternative plasticity formulation that exhibits critical state consistency for both monotonic and cyclic loading and uniqueness of its parameters for a given type of sand, irrespective of loading conditions. The model, designated as Ta-Ger sand model (Tasiopoulou and Gerolymos, 2012, 2014), is based on a reformulation of perfect elastoplasticity by introducing a hardening law inspired from Bouc-Wen hysteresis. The developed constitutive formulation can be regarded as a bounding single-surface model with vanished elastic region and the distinguished characteristic of a non-explicitly defined plastic modulus.The goal is to provide a simpler but equally efficient scheme of high versatility. The explicitly formulated plastic matrix, H, plays a triple role: (i) it offers a gradual and smooth ("hardening-type") transition from the elastic to perfectly plastic response in order to capture pre-failure nonlinearity and the coupling between elastic and plastic counterparts composing the total strain increment, (ii) it provides an appropriate loading/unloading/reloading mapping rule by tracking the distance from the ultimate perfectly plastic state as defined by the failure surface, which herein, serves as a bounding surface, and (iii) its terms attain values that are strictly bounded within the range of [0,1].Salient features of the proposed plasticity approach are: (i) a new plastic flow rule based on a revision of Rowe dilatancy theory (1962), accounting for anisotropic distribution of dilatancy to the normal plastic strain increments, as well as densification due to cyclic loading, (ii) a mapping rule and load reversal criterion based on the first order work, inspired from Bouc-Wen hysteresis, and (iii) a new formulation for the evolution of the bounding and phase transformation surfaces as a function of the cumulative deviatoric strain increment, ensuring critical state consistency not only for monotonic but also for cyclic loading.An extensive calibration methodology is then developed aiming at: (i) increasing model predictability and (ii) minimizing the number of internal model parameters. Initially, constitutive formulation was adjusted to Bolton's (1986) empirical correlations for dilatancy, given as a function of relative dilatancy index, Ir; the latter works as a state parameter in the constitutive framework. This step reduces the number of unknown model parameters to three, besides the ones related directly to measurable physical properties, such as critical state friction angle and elastic modulus. At this stage, the remaining three unknown parameters are expressed as functions of the initial state (relative density and pressure), while inherent fabric effects (such as particle shape, size and packing) on the calibration process are considered. At last, stress-induced anisotropy is dealt with introducing a scalar-valued variable in the model, a function of principal stress rotation angle, α, and the intermediate stress parameter, b, without affecting the number of unknown model parameters. Validation against experimental data was performed in every step for various drained and undrained loading paths in a wide range of α, b values, as well as initial states, for three different types of sand (Toyoura, Fontainebleau, Sacramento–River). Comparison with experiments reveals the capability of the model to describe complex patterns of sand behavior, as well as its versatility to reproduce liquefaction due to cyclic loading at very large strains (e.g. $\gamma > 8\%$) without exhibiting shear locking.