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Research Paper

A general approach to model interfaces using existing soil constitutive models application to hypoplasticity

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ABSTRACT

The modelling of interfaces is important for the holistic simulation of geotechnical structures (e.g. piles, tunnels and geogrids). For this reason, advanced constitutive interface models and numerical techniques are needed. There are few user-friendly models, and these are rarely implemented. In this paper, a new approach for advanced interface models is proposed. This is based on the assumption that the fully rough interface can be modelled considering simple-shear behaviour at the interface. A 3D soil model is used as a constitutive driver for a frictional subroutine. This minimises the effort required, and advanced interface models are available with less effort. Two different hypoplastic models are used with the new approach. The approach was verified for several aspects (e.g. mesh size dependence), and the volumetric behaviour was studied. The user-friendliness and absence of additional parameters led to more realistic simulation results. The proposed method can be extended to other modelling techniques and will improve the modelling of contacts in soil-structure interaction analysis.

1. Introduction

The modelling of interfaces is a challenging topic in geotechnical engineering. Advanced and specialised constitutive interface models should be used to realistically simulate soil-structure contact behaviour [1,2]. There are few numerical and constitutive models that adequately consider interface behaviour.

From the late seventies to nowadays, numerical techniques for interface modelling various [3–15] have been developed. To properly represent the interface, it is essential to use a suitable constitutive model. The simplified constitutive Mohr-Coulomb frictional model is often used. Various soil-structure interface models from non-linear elasticity [16,17], elasto-plastic models [18–22], state-dependent plasticity models [23–26], models using damage mechanics [27], and disturbed state concept models [28–30] have been proposed. There is only a limited number of 3D interface constitutive interface models [31,20,32,27,33–36].

The method proposed in this paper will overcome the problem of availability and implementation using a simple and robust approach. Recently published hypoplastic interface models [35,37] have been implemented using the new approach. Weißenfels and Wriggers [9] developed a projection method to integrate plasticity models into a mixed mortar formulation. In contrast, the goal of our method is to define an approach that can be adapted to constitutive interface modelling with the mortar method using existing 3D constitutive soil models.

In order to make such advanced models available, the whole constitutive model (here UMAT subroutine in ABAQUS [38]) is used, and the 3D model is modified so that surface roughness is accounted for. The necessary tensor entries are provided by the frictional subroutine (FRIC keyword in ABAQUS) to call the user-defined material subroutine (UMAT). This approach minimises the effort required to implement an adequate constitutive interface model.

The theoretical rationale is the hypothesis that the soil in the interface has the same deformation behaviour as the soil continuum surrounding the interface [39,40]. This hypothesis was also used when developing the enhanced hypoplastic interface models proposed by Stutz et al. [35,37,41].

After briefly introducing the hypoplastic interface models, the stress and strain rate tensor assumptions are explained, and the implementation approach is introduced. This is followed by a verification of the finite element analysis with Gauss point calculation [35,37]. The new model is used to simulate a large interface shear device [42] and compared to the results of the experimental data.

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2. Hypoplastic interface models

The hypoplastic interface models has already been applied to fine-grained soils [37], and the enhanced hypoplastic model has been applied to granular soil structure interfaces [35]. The underlying assumptions are introduced below. The interface model formulations are based on the clay hypoplastic model [43] and the granular hypoplastic model [44], which can be found in Appendices B and C.

2.1. Reduced stress and strain rate tensors

The original hypoplastic models can be used without modifying the tensorial equations [35,37]. The mathematical operators will be modified so that the model can be used with a reduced stress tensor in the Voigt notation as:

$$\boldsymbol{\sigma}^h = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \Rightarrow \begin{bmatrix} \sigma_n & \tau_x & \tau_y \\ \tau_x & \sigma_p & 0 \\ \tau_y & 0 & \sigma_p \end{bmatrix} \tag{1}$$

where $\boldsymbol{\sigma}^h$ denotes the whole stress tensor, and the degenerated vectorial form $\boldsymbol{\sigma}$ is:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_n \\ \sigma_p \\ \tau_x \\ \tau_y \end{bmatrix} \tag{2}$$

A brief comment for the in-plane stress σ_p: at the start of each simulation, the stress initialization is done by $\sigma_p = \sigma_n$. After the initialization, the normal and in-plane stresses are developed independently of each other.

The strain rate tensor $\dot{\boldsymbol{\varepsilon}}$ is defined as:

$$\dot{\boldsymbol{\varepsilon}}^h = \begin{bmatrix} \dot{\varepsilon}_{11} & \dot{\varepsilon}_{12} & \dot{\varepsilon}_{13} \\ \dot{\varepsilon}_{21} & \dot{\varepsilon}_{22} & \dot{\varepsilon}_{23} \\ \dot{\varepsilon}_{31} & \dot{\varepsilon}_{32} & \dot{\varepsilon}_{33} \end{bmatrix} \Rightarrow \begin{bmatrix} \dot{\varepsilon}_n & \frac{\dot{\gamma}_x}{2} & \frac{\dot{\gamma}_y}{2} \\ \frac{\dot{\gamma}_x}{2} & 0 & 0 \\ \frac{\dot{\gamma}_y}{2} & 0 & 0 \end{bmatrix} \tag{3}$$

where, $\dot{\boldsymbol{\varepsilon}}^h$ denotes the hole strain rate tensor, $\dot{\epsilon}_n$ the normal strain rate and $\frac{\dot{\gamma}_x}{2}, \frac{\dot{\gamma}_y}{2}$ the shear strain rate in the x and y direction, respectively. The vectorial form $\dot{\boldsymbol{\varepsilon}}$ is defined as:

$$\dot{\boldsymbol{\varepsilon}} = \begin{bmatrix} \dot{\varepsilon}_t \\ 0 \\ \frac{\dot{\gamma}_x}{2} \\ \frac{\dot{\gamma}_y}{2} \end{bmatrix} \tag{4}$$

The in-plane components of the strain rate tensor are $\varepsilon_p = 0$. For the use of the in-plane strain, $\dot{\varepsilon}_p = 0$, and for the in-plane stress, $\sigma_p \neq 0$. Using these modified stress and strain tensors will lead to simple shear stress and strain conditions at the interface [45,46]. These stress and strain tensors will lead to odeometric stress and strain assumption at the interface. More information about the initialization of σ_p are given in Stutz and Mašín [37]. These reduced versions are used in conjunction with the mathematical operators defined in Appendix A.

2.2. Fine-grained hypoplastic interface model

The fine-grained hypoplastic interface model is based on the hypoplastic soil model with explicit defined asymptotic states of Mašín [43]. The general form of the hypoplastic model [47] is:

$$\dot{\boldsymbol{\sigma}} = f_s(\boldsymbol{L} : \dot{\boldsymbol{\varepsilon}} + f_d \boldsymbol{N} \|\dot{\boldsymbol{\varepsilon}}\|), \tag{5}$$

where $\dot{\boldsymbol{\varepsilon}}$ and $\dot{\boldsymbol{\sigma}}$ are the strain and stress rate tensors, respectively. $\boldsymbol{L}$ and $\boldsymbol{N}$ are the fourth- and second-order constitutive tensors, f_s is a factor that controls the influence of the mean stress (barotropy) and f_d is a factor for the influence of the relative density (pyknotropy). Mašín [48] proposed an alternative expression for the hypoplastic clay model developed from the general form of the hypoplastic constitutive formula [47]:

$$\dot{\boldsymbol{\sigma}} = f_s \boldsymbol{L} : \dot{\boldsymbol{\varepsilon}} - \frac{f_d}{f_d^A} \boldsymbol{A} : \boldsymbol{d} \|\dot{\boldsymbol{\varepsilon}}\|, \tag{6}$$

where $\boldsymbol{d}$ is the asymptotic strain rate direction and f_d^A describes the value of f_d at the asymptotic state boundary surface. $\boldsymbol{A}$ is defined as:

$$\boldsymbol{A} = f_s \boldsymbol{L} + \frac{\boldsymbol{\sigma}}{\lambda^*} \otimes \boldsymbol{1}, \tag{7}$$

where λ^* is a model parameter. Eq. (6) enables the use and incorporation of an appropriate arbitrary shape for the asymptotic state boundary surface. This is done by specification of f_d^A in dependence of the void and stress ratio [48]. The formulation of the full model is given in Appendix C.

2.3. Granular hypoplastic interface model

Von Wolffersdorff [44] extended the basic formula of the hypoplastic model [47] by incorporating a predefined limit state surface from Matsuoka and Nakai [49]. The constitutive stress-strain equation is defined as:

$$\dot{\boldsymbol{\sigma}} = f_s(\boldsymbol{L} : \dot{\boldsymbol{\varepsilon}} + f_d \boldsymbol{N} \|\dot{\boldsymbol{\varepsilon}}\|), \tag{8}$$

The model is briefly described in Appendix B.

3. General approach for interface modelling

The model was implemented using the software package ABAQUS FEA [38]. However, the method proposed is not limited to a specific software package. It can thus be used in different codes and numerical techniques with simple modifications [4,5].

Using ABAQUS, it is possible to define a user constitutive model for frictional behaviour (FRIC). This subroutine is implemented by the use of a mortar method that is a segment-to-segment approach defining a master and slave surfaces [50].

For clarification, the UMAT subroutine can be used for: “User subroutine to define the mechanical behaviour of a material”. The FRIC subroutine can be used for:” User subroutine to define frictional behaviour for contact surfaces ”. Additional information about both subroutines is provided in the ABAQUS documentation [50].

In the finite element method, interface models are generally implemented with the primary state variables stress and the strain rate normal to the interface $(\sigma_n, \dot{\varepsilon}_n)$ and shear components $(\tau_x, \tau_y, \dot{\gamma}_x, \dot{\gamma}_y)$. To incorporate the in-plane σ_p stress into the formulation as an additional state variable together with the void ratio e must be considered. This is done by an algorithm that will be introduced below. With respect to the use of a stretching tensor $\boldsymbol{D}$, the spin tensor $\boldsymbol{W}$ can be neglected because rigid body rotations are assumed.

3.1. Implementation scheme

The reduced tensor notation (Section 2) will be used in the FRIC subroutine. The tensor entries are transformed and transferred to the 3D UMAT implementation available from the soilmodel.info project [51]. The general approach is presented in Fig. 1. In the actual time increment, the FRIC subroutine is invoked. The input of all necessary parameters, stresses and displacements are supple-