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Hypoplastic model for crushable sand

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Abstract

A constitutive model for granular materials which considers grain crushing effects is developed in the framework of hypoplasticity. As grain crushing occurs the behaviour of granular material can usually be significantly affected. Several empirical relations between peak strength, uniformity coefficient and stiffness of sand depending on stress level or amount of grain crushing have been derived in the past. In this paper, such relations are employed to improve a basic hypoplastic constitutive model based on the changes of stress level or grain size distribution. In the proposed modified hypoplastic model only two additional physical parameters, namely uniformity coefficient and mean grain size are incorporated. The validation of the modified model for three different sands under triaxial test response with cell pressures up to 30 MPa is presented and shows a significantly better correspondence with regard to the original basic hypoplastic model.

Keywords: Hypoplastic model; Grain crushing

1. Introduction

Many researches in soil mechanics have focused on soil behaviour at low stress levels which is suitable for most geotechnical engineering problems. However, there are several geotechnical applications which need thorough investigation of high stress conditions, as e.g. high earth dams, deep mine shafts, tunnels, deep well shafts or deep jacked pile foundations. During penetration of a cone or pile in sand, the stress level around the pile tip can vary significantly from very low at rest (i.e. a few kPa) to very high soil stresses which may be up to 70 MPa (Murphy, 1987). As the effective confining stress around the pile increases, the strength of the surrounding soil (such as friction or dilatancy) may reduce. For sands, Bolton (1986) attributed this to the grain crushing strength. Yamamuro and Lade (1996) and Lade et al. (1996) studied the effects of grain crushing in drained and undrained triaxial compression and extension tests at confining stresses between 0.5 MPa and 52 MPa. They concluded that increases in confining stress cause a measured increase in the amount of grain crushing.

Hence, for applications involving large stress variations it is inevitable to have a stress dependent soil model which can be used across a wide stress range and accounts for crushing of soil grains. Daouadji et al. (2001) and Daouadji and Hicher (2010) introduced the influence of crushable grain in an elastoplastic model by making the critical state line dependent on the evolution of the grain size distribution. Comparing with experimental data for three different types of materials: a quartzic, calcareous sands and a rockfill material, the model simulations can accurately reproduce the stress-strain behaviour which

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demonstrates its ability to reproduce the main features of sand behaviour subjected to grain crushing. However, the parameters controlling the amount of grain breakage along a given test have to be determined by curve fitting. Russell and Khalili (2004) presented a new bounding surface elastoplastic constitutive model for sands which is suited to a wide range of stress, including grain crushing. In this model, a unique shaped critical state line is defined to capture the three models of plastic deformation observed across a wide range of stresses, including particle rearrangement, particle crushing and pseudoelastic deformation. A good agreement between model simulations and experimental data from tests subject to five load paths was found. Furthermore, the basic concepts of critical state soil mechanics as well as a nonassociative flow rule commonly used in sand are confirmed to be valid when particle crushing occurs. Later, another bounding surface constitutive model based on Severn-Trent sand model was published, in which the critical state line was extended to include the effect of grain breakage through a grading state index (Fukumoto, 1992). The effect of crushing was found to shift the critical state line and compression line downwards in the compression plane. As a result, the state parameter tends to increase and the soil feels looser. In 2014, Engin et al. (2014) proposed a model which incorporates the effects of grain crushing at high stress levels, and which is a modification of Von Wolffersdorffs hypoplastic model. In this model, the void ratio is modified to be dependent on the uniformity coefficient, which is changing with vertical stress level. Their proposed model can model the suppressed dilatancy at high confinement stress level better than the original model, however, the simulation results are not so close with experimental ones. In addition, the performance of the model on the other hand has shown convergence issues during finite element simulations of boundary value problems.

In the first part of the paper, the relations between peak strength, uniformity coefficient and stiffness of sand depending on stress level and amount of grain crushing derived for different sands based on experimental results in literature are described. Then, a method to modify and improve a basic hypoplastic model in order to describe the behaviour of sand over a wide stress range, especially very high stress levels including grain crushing is developed. For the proposed modified hypoplastic model only two additional well-known physical parameters, namely the uniformity coefficient and the mean grain size are included. Those parameters are straightforward to determine, which is significantly simpler than currently existing models accounting for grain crushing (Hu et al., 2011; Engin et al., 2014).

The proposed modified hypoplastic model is validated using literature data of several triaxial test series for three different sands: Hostun sand in a stress range between 0.1 and 15 MPa (Colliat-Dangus et al., 1988), Toyoura sand in a stress range between 0.1 and 29.4 MPa (Miura and Yamanouchi, 1973) and Fontainebleau sand in a stress range between 0.1 and 30 MPa (Luong and Touati, 1983).

2. Behaviour of sand at high stress levels

2.1. Grain size and uniformity

2.1.1. Literature review

Grain size effects play a role in crushing strength, especially in brittle sand grain and rock aggregate. For a given shearing condition, the coarser the granular material is, the higher the grain breakage ratio (Marachi et al., 1969; Lee, 1992; Ovalle et al., 2014). Ovalle et al. (2014) also observed a slight decrease in the shear strength envelope for the coarser material. For instance, the maximum friction angle decreases about 2–3° for a particle size reduction factor of 4.

Fukumoto (1992) conducted one-dimensional compression tests on initially uniformly graded Ottawa sand to determine the grain size distribution at different applied vertical stresses between 7 MPa and 100 MPa. It was observed that with increasing effective vertical stress, the uniformity coefficient increases significantly. Nakata et al. (2001a,b) performed high-pressure one-dimensional compression tests on Silica sand samples, both initially uniformly graded and well-graded. They concluded that even for the same material the yielding characteristics depend on the initial grading curve with much more yielding occurring for uniformly graded sands in comparison to well-graded sands. As the material was changing from uniform to well-graded, the nature of grain crushing was changing from catastrophic onset to gradual breakage and rounding off surfaces.

It is observed that the change of the material characteristics can be captured by a change of the shape of the grain size distribution curve, characterized by the uniformity coefficient C_u (Biarez et al., 1994; Nakata et al., 2001b,a; Coop et al., 2004). Moreover the change of uniformity coefficient has a limit value and can be related to a change of applied effective stress. By using the test results of Nakata et al. (2001a), Rohe (2010) elaborated quantitatively the dependency of the uniformity coefficient on the applied (vertical) stress level characterized by the two stress invariants, namely mean effective stress p' (negative in compression) and deviatoric stress q and generalized as,

$$C_u = \alpha_p p'^2 - \alpha_q q^2 + \beta_p p' - \beta_q q + C_{u0} \quad (1)$$

in which α_p and α_q are the factors controlling the quadratic change of uniformity coefficient due to isotropic and deviatoric loading, respectively; β_p and β_q are the factors controlling the linear change of uniformity coefficient due to isotropic and deviatoric loading, respectively and C_{u0} is the reference uniformity coefficient at reference stress σ_{ref}. However, the determination of such factors was not elaborated and the suggested values are valid for a silica sand under one-dimensional compression only.