Soils and Foundations 2014;54(6):1188–1201

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SOILS AND FOUNDATIONS

A bounding surface plasticity model for highly crushable granular materials

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Received 15 November 2013; received in revised form 25 August 2014; accepted 7 September 2014

Abstract

A bounding surface plasticity model is presented for crushable rockfills in the framework of the critical state soil mechanics which includes translation of the critical state line due to particle crushing. A translating limiting isotropic compression line is also introduced and incorporated in the model to describe the position and evolution of the bounding surface. A particle breakage index is introduced as a function of stress invariants which controls the translation of the critical state and limiting isotropic compression lines. The performance of the model is demonstrated using the results of experimental tests on different types of rockfill materials conducted under both monotonic and cyclic loading conditions. The study shows the capability of the model in capturing the characteristic features of the behavior of rockfill and other crushable materials such as ballast and coarse gravel under both conventional and complex loading paths.

Keywords: Rockfill; Bounding surface plasticity; Particle breakage; Cyclic loading

1. Introduction

Rockfills are widely used in earth and rockfill dams and other earthworks such as roads and railways. Rockfill embankments are usually subjected to high pressure and repeated loading from vehicles and earthquake. To study the behavior of rockfills, large-scale testing equipments were developed in some research centers (e.g. Sowers et al., 1965; Fumagalli, 1969; Marachi et al., 1969; Marsal, 1973), capable of performing most of the classical soil mechanics tests on rockfill specimens. The main conclusion drawn from all these experiments is that the mechanical properties of rockfills are closely related to breakage properties of rock particles (e.g. Oldecop and Alonso, 2001; Salim and Indraratna, 2004). In other words, particle breakage has been identified as the main reason for the differences observed between the behavior of sand (at low and moderate stress levels) and rockfill material. Particle breakage in rockfill depends on the strength of individual particles, grain size distribution, stress level and the relative humidity prevailing in the rockfill voids (Chávez and Alonso, 2003).

The hyperbolic elastic model of Duncan and Chang (1970) has been the main tool for modeling different types of rockfill materials for about three decades. This model is based on the generalized Hooke's law and was proposed to simulate the nonlinear stress–strain behavior of soils. Although it has been widely used mainly due to its simplicity and convenience, it

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2014.11.012
0038-0806/

can neither simulate the volumetric dilatancy of rockfills nor can it represent the particle breakage phenomenon which plays a distinct role in the behavior of rockfills.

To model the cyclic and dynamic behavior of rockfills, viscoelastic models are traditionally used: these are typically equivalent linear models of Masing nonlinear models. Although these models are simple and can capture some features of dynamic response of rockfills, they cannot represent many aspects of nonlinear behavior of rockfills such as strain softening, stress history and anisotropy. Generally, empirical relations need to be included in these models to take into account the accumulation of permanent strains and generation of pore pressure (e.g. Martin et al., 1975).

Since the 1970s, there have been extensive studies on the development of elastoplastic models for monotonic and cyclic behavior of soils. A great amount of effort has been devoted to modeling the cyclic behavior of granular materials using advanced constitutive frameworks, such as bounding surface plasticity (e.g. Dafalias, 1986; Bardet, 1986; Khalili et al., 2005) hypoplasticity (e.g. Gudehus, 1996; Bauer, 1996; Fu et al., 2011), generalized plasticity (e.g. Pastor et al., 1990; Ling and Yang, 2006), subloading surface plasticity (e.g. Hashiguchi, 1989; Kohgo et al., 2007) and the disturbed state concept (e.g. Varadarajan et al., 2003).

Recently, a rigorous bounding surface model based on the concept of the critical state soil mechanics was developed at the University of New South Wales (UNSW) by Russell and Khalili (2004) to model the stress–strain behavior of sands. Later Khalili et al. (2005, 2008) extended the UNSW model to simulate the behavior of sands subjected to cyclic loading under saturated and unsaturated states including hydraulic hysteresis effects. Kan et al. (2014) introduced a single stress point mapping rule for this model which has a simpler procedure and is more compliant to application to complex loading paths.

In the UNSW model, the position and evolution of the bounding surface is linked to the limiting isotropic compression line (LICL). To take the effect of the particle breakage on the mechanical behavior of geomaterials into account, both the LICL and the critical state line (CSL) are taken as two (Kan et al., 2014) or three (Russell and Khalili, 2004) segmented lines. Both the CSL and LICL are assumed to be fixed in a semi logarithmic compression plane. This assumption, which has been made based on the results of laboratory tests on sands, is revisited in this paper to be able to simulate the crushing phenomenon in rockfill materials. A novel approach in which the CSL and LICL are considered as translating curves is incorporated in the UNSW model. This approach significantly improves the capability of the model in simulating the irrecoverable permanent strains due to particle breakage which occurs in cyclic loading of crushable materials. This is an important characteristic of crushable materials which could not be simulated easily in constitutive models with a fixed critical state line.

In this paper the governing equations for the proposed model are described and the method by which the translation of the CSL and LICL is related to particle crushing is introduced. A procedure is introduced to obtain the material parameters required for the proposed model. The proposed model is then used to simulate the behavior of rockfills with rounded and angular particles as well as ballast and coarse gravel to highlight the capabilities of the model. In addition to the conventional triaxial tests under monotonic loading, simulations are also performed under more complex stress paths as well as under cyclic loading to demonstrate the robustness of the model in simulating actual stress paths that may occur in real boundary value problems.

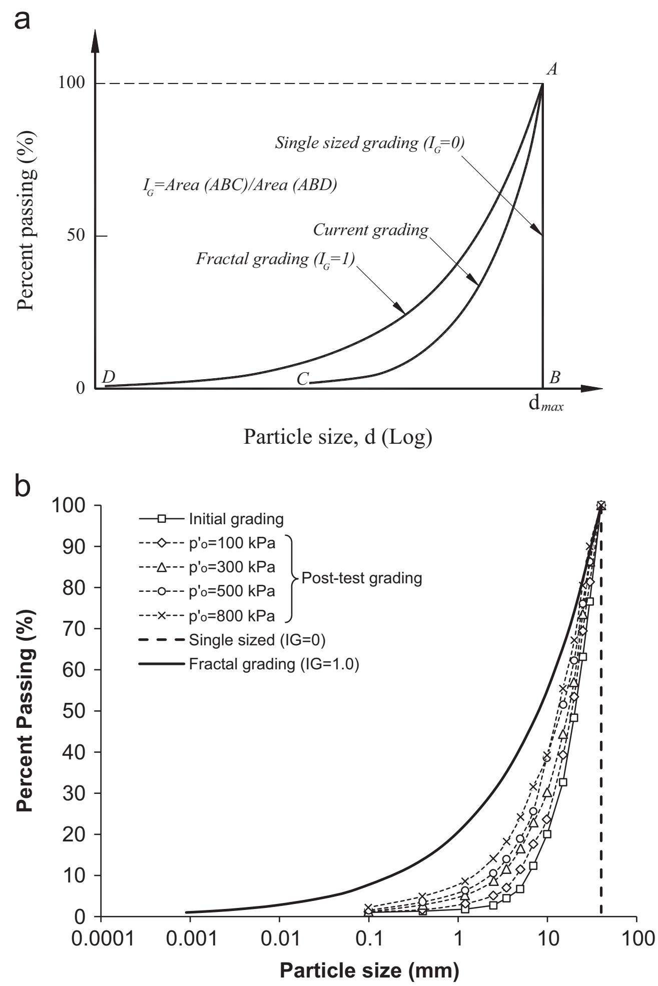

Fig. 1. (a) Definition of grading index, I_G and evolution of grading and (b) an example of grading degradation and fractal grading for a rockfill (data after Chávez and Alonso (2003)).

2. Preliminaries

In the model presented here, the material behavior is assumed isotropic and rate independent. Compression is considered positive. For the sake of simplicity, all derivations are presented in the $p'-q$ plane where p' and q are the mean effective stress and the deviatoric stress, respectively.

2.1. Critical state

The critical state (CS) is an ultimate condition towards which all states approach with increasing deviatoric shear strain. Traditionally, the critical state line has been chosen as