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Modeling the triaxial behavior of riverbed and blasted quarried rockfill materials using hardening soil model

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A B S T R A C T

Riverbed modeled rockfill material from Noa Dehing dam project, Arunachal Pradesh, India and blasted quarried modeled rockfill material from Kol dam project, Himachal Pradesh, India were considered for this research. Riverbed rockfill material is rounded to sub-rounded and quarried rockfill material is angular to sub-angular in shape. Prototype rockfill materials were modeled into maximum particle size (d_{max}) of 4.75 mm, 10 mm, 19 mm, 25 mm, 50 mm and 80 mm for testing in the laboratory. Consolidated drained triaxial tests were conducted on modeled rockfill materials with a specimen size of 381 mm in diameter and 813 mm in height to study the stress–strain–volume change behavior for both rockfill materials. Index properties, i.e. uncompacted void content (UVC) and uniaxial compressive strength (UCS), were determined for both rockfill materials in association with material parameters. An elasto-plastic hardening soil (HS) constitutive model was used to predict the behavior of modeled rockfill materials. Comparing the predicted and observed stress–strain–volume change behavior, it is found that both observed and predicted behaviors match closely. The procedures were developed to predict the shear strength and elastic parameters of rockfill materials using the index properties, i.e. UCS, UVC and relative density (RD), and predictions were made satisfactorily. Comparing the predicted and experimentally determined shear strengths and elastic parameters, it is observed that both values match closely. Then these procedures were used to predict the elastic and shear strength parameters of large-size prototype rockfill materials. Correlations were also developed between index properties and material strength parameters (dilatancy angle, ψ, and initial void ratio, e_{init}, required for HS model) of modeled rockfill materials and the same correlations were used to predict the strength parameters for the prototype rockfill materials. Using the predicted material parameters, the stress–strain–volume change behavior of prototype rockfill material was predicted using elastoplastic HS constitutive model. The advantage of the proposed methods is that only index properties, i.e. UCS, UVC, RD, modulus of elasticity of intact rock, E_{ir}, and Poisson's ratio of intact rock, ν_{ir}, are required to determine the angle of shearing resistance, ϕ, modulus of elasticity, E_{50}^{ref}, and Poisson's ratio, ν, of rockfill materials, and there is no need of triaxial testing. It is believed that the proposed methods are more realistic, economical, and can be used where large-size triaxial testing facilities are not available.

1. Introduction

Rockfill materials are being used all over the world in construction of rockfill dams because of their inherent flexibility, capacity to absorb large seismic energy and adaptability to various foundation conditions. Locally available materials and use of modern earth and rock moving equipment make such dams economical as well. Rockfill material consists of gravel, cobbles and boulders obtained either from the natural riverbed or by blasting the rock quarry. Riverbed rockfill materials primarily consist of rounded/sub-rounded particles obtained from the natural riverbed. Blasted quarried rockfill material primarily consists of angular/sub-angular particles. The factors such as mineral composition, particle size, shape, gradation, relative density (RD), individual particle strength, void content, and surface texture of the particles affect the behavior of rockfill materials. Therefore, understanding and characterization of the behaviors of these materials are of considerable importance for analysis and safe design of the rockfill dams.

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Prototype rockfill materials consist of maximum particle size (d_{max}) up to 1200 mm. Rockfill material with such a large particle size is not feasible to test in laboratory. Some modeling techniques are often used to reduce the size of particles so that the specimens prepared with smaller size particles can be tested. Among all available modeling techniques, the parallel gradation technique (Lowe, 1964) is most commonly used.

Hyperbolic and elastic models are often adopted to characterize the linear and nonlinear behaviors of rockfill materials. In recent years, attempts are being made to use advanced constitutive models based on elastoplastic theory to depict the behavior of rockfill materials. The material parameters required for the constitutive model are determined using the laboratory test results for different values of d_{max} of modeled rockfill materials. These material parameters are correlated with the index properties of rockfill materials, i.e. uncompacted void content (UVC) and uniaxial compressive strength (UCS). Material parameters for larger-size prototype rockfill materials are then determined using a best fit linear extrapolation (Honkanadavar, 2010; Honkanadavar et al., 2014; Honkanadavar and Sharma, 2014).

This paper presents laboratory test results, models the behavior of two types of modeled rockfill materials using hardening soil (HS) model, and compares predictions with the observed behaviors. Also the procedures are proposed to predict the material parameters for prototype rockfill materials using the basic index properties and prediction of prototype material behaviors using HS model.

1.1. Review

Prototype rockfill materials are scaled down to smaller size particles using some kinds of modeling techniques so that the specimen prepared with smaller size particles can be tested in laboratory. Four modeling techniques are being used to reduce the size of the rockfill materials, i.e. the scalping technique (Zeller and Wullimann, 1957), parallel gradation technique (Lowe, 1964), generation of quadratic grain size distribution curve (Fumagalli, 1969) and replacement technique (Frost, 1973). Among all the above-mentioned modeling techniques, the parallel gradation technique is most commonly used. Ramamurthy and Gupta (1986) considered the parallel gradation method more appropriate.

Many researchers have conducted triaxial tests on modeled rockfill materials using large-size triaxial testing equipment. They have used the specimen diameter varying from 38 mm to 1130 mm and the d_{max} varying from 2.54 mm to 260 mm (Hall and Gordon, 1963; Marsal, 1967; Fumagalli, 1969; Marachi et al., 1972; Gupta, 1980; Thiers and Donovan, 1981; Ansari and Chandra, 1986; Venkatachalam, 1993; Gupta, 2000; Abbas, 2003; Varadarajan et al., 1999, 2003, 2006; Okamoto, 2004; Honkanadavar and Sharma, 2008a,b, 2010, 2011, 2012; 2014; Honkanadavar, 2010; Aghaei Araei et al., 2010; Soroush and Jannatiaghdam, 2012; Honkanadavar et al., 2012, 2014). Evaluation of grading effect on the behavior of rockfill materials was studied by Mohammadzadeh (2010). The materials consisted of rock fragments, blasted quarried rockfill materials, and natural riverbed rockfill materials from different project sites.

The constitutive models based on linear and nonlinear elastic theories have been used to characterize rockfill materials. Hyperbolic models are often adopted to depict the behavior of rockfill materials, for example, Kulhawy and Duncan (1972), Venkatachalam (1993) and Saboya and Bryne (1993). Constitutive models based on elastoplastic theory are being used to characterize rockfill materials (Kondner and Zelasko, 1963; Duncan and Chang, 1970; Varadarajan et al., 1997, 1999, 2002, 2003; Schanz and Vermeer, 1998; Schanz et al., 1999; Usmani, 2007; Honkanadavar, 2010; Honkanadavar et al., 2014; Honkanadavar and Sharma, 2014; Xiao et al., 2014).

The behavior of granular materials have been studied and characterized by using constitutive models (Varadarajan and Desai, 1987, 1993; Liu and Zou, 2013; Liu et al., 2014).

1.2. Scope

The scope of the present work is to conduct large-size consolidated drained (CD) triaxial tests on riverbed and blasted quarried modeled rockfill materials, to determine the index properties of rockfill materials, to characterize the behavior for different values of d_{max} of riverbed and quarried rockfill materials using an elastoplastic HS constitutive model, and to propose a procedure to determine the material parameters and prediction of behaviors for modeled and prototype rockfill materials.

2. Laboratory tests

2.1. Rockfill materials

Riverbed modeled rockfill material from Noa Dehing dam project, Arunachal Pradesh, India and quarried modeled rockfill material from Kol dam, Himachal Pradesh, India have been considered in the present research. Riverbed rockfill material from Noa Dehing dam and quarried rockfill material from Kol dam have been modeled with six sizes of d_{max}, i.e. 4.75 mm, 10 mm, 19 mm, 25 mm, 50 mm and 80 mm. Parallel gradation technique (Lowe, 1964) has been used to model the d_{max}. The prototype and modeled grain size distribution curves of rockfill materials from Noa Dehing and Kol dam sites are shown in Figs. 1 and 2, respectively.

2.2. Index properties of rockfill materials

It is learnt that the shear strength of granular materials is dependent on the RD, confining pressure (σ_3), individual particle strength, d_{max}, shape, surface texture and mineralogy. The individual particle strength is one of the important factors affecting the behavior of the granular materials and it is represented by a parameter known as UCS of the rock from which rockfill material is derived. To determine UCS value, the rock cores of NX size (54 mm in diameter) were collected from both projects rock and tested under uniaxial compression testing machine at Central Soil and Materials Research Station (CSMRS), New Delhi, India, a premier Government of India Research Station which provides consultancy service on field and laboratory geotechnical investigations for various major and minor irrigation and hydropower projects in India and abroad. Three cylindrical specimens of NX size were tested as per the ISRM suggested method (Ulusay and Hudson, 2007) and the procedure of IS: 9143 (2001) for both projects rock and the average value is reported in Table 1 (Honkanadavar, 2010; Honkanadavar et al., 2014; Honkanadavar and Sharma, 2014).

Basic characteristics of rockfill materials, i.e. size, shape, gradation and surface texture of the particles, are expressed by a single parameter known as UVC (Alhrich, 1996; ASTM C1252-98, 1998). The details of test apparatus and procedure to determine UVC are given by Honkanadavar (2010), Honkanadavar et al. (2014), and Honkanadavar and Sharma (2014).

The UVC apparatus is designed to test the modeled rockfill materials of $d_{max} = 4.75$ mm, 10 mm and 19 mm. Modeled rockfill materials for $d_{max} = 4.75$ mm, 10 mm and 19 mm were obtained using parallel gradation technique and they were tested to determine the UVC. The UVC is determined by allowing the rockfill material filled in an upper cylindrical container to fall through a height in a lower cylindrical measure. The UVC is expressed in percentage as