Engineering Geology 198 (2015) 78–86

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Effects of fines on the strength characteristics of mixtures

Xiangang Jiang [a,b,*], Peng Cui [a,c], Yonggang Ge [a]

[a] Key Laboratory of Mountain Hazards and Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610044, China
[b] University of Chinese Academy of Science, Beijing 100049, China
[c] CAS Center for Excellence in Tibetan Plateau Earth Sciences, China

ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form 30 September 2015
Accepted 30 September 2015
Available online 3 October 2015

Keywords:
Fines
Mixtures
Strength

ABSTRACT

Mixtures composed of coarse and fine particles are complicated inhomogeneous materials and are widely encountered in nature. Mixtures with different fines contents have different strength characteristics, and the study of these characteristics is still nascent. To analyze the relationships between fines concentration and strength, 27 unconfined compressive tests and 27 radial-splitting tests with 9 different fines contents were conducted. Laboratory tests on samples with different fines concentrations indicated that the percentages of fines in the mixtures significantly impacted their strength, and 3 regions could be identified. The compressive strength of the mixture increased slowly with increasing fines content for fines concentrations of <55% by weight, rapidly for fines concentrations of 55% to 75% by weight, and slowly again for fines concentrations >75% by weight. The tensile strength increased slowly when the fines content was less than 45%, quickly for concentrations from 45% to 85% by weight, and then slowly for concentrations >85%. The maximum compressive and shear strengths (95% fines concentration) were approximately 25 times greater than the minimum strengths (5% fines concentration). Meanwhile, the maximum tensile strengths were 50 times greater than the minimum values, but the strain values only differed by a factor of 3 regardless of mode (compressive or tensile). The fines had stronger effects on the strengths of the mixtures than their strains. As a whole, the ratio of different compressive-tensile strength lines varied by fines concentration. Based on the relationships between compressive and tensile strengths, a new strength criterion was established. Three additional unconfined compressive, radial-splitting, and direct shear tests were conducted to verify the rationality of the new criterion. The results indicated that values calculated by the criterion were in good agreement with the tested data. Comparison and analysis revealed that the surfaces between coarse and fine particles were weak zones. The fines influenced the strength by modifying these zones. This finding reveals how fines affect the strength of mixtures for a fixed void ratio.

1. Introduction

The materials that form landslide dams, glacial tills, mudflows, debris flows, landslides, residual and colluvial soil deposits have distinct structures consisting of mixtures of coarse particles (gravel or sand) and fine particles (clay or silt) (Deere and Patton, 1971; Legget, 1976; Vallejo, 1979, 1989, 1997; Loganathan et al., 1992; Rahardjo et al., 2008). These individual components have different mechanical and physical proprieties and react differently under internal and external loads, and the relationships between fine and coarse particles are very difficult to discern. Thus, there are many differences between mixtures and homogeneous geomaterials, such as the failure propagation, transformation of stress, carrying capacity, and soil structure. The obvious differences in the inhomogeneous properties of mixtures and homogeneous geomaterials motivate this study.

To understand the complexity of mixtures, many researchers have conducted laboratory tests and field tests employing a variety of methods to analyze their behaviors (Lindquist and Goodman, 1994; Medley and Lindquist, 1995; Medley, 2004; Chen and Wan, 2004; Xu et al., 2007, Xu et al., 2011; Coli et al., 2012; Li et al., 2013). These researchers have studied the influence of the particle size composition on strength and deformation on the macro- and micro-scales. However, they have generally focused on the properties of coarse particles, e.g., the particle shape, size, or roundness, and ignored the effects of fines. Hence, our understanding of the effects of fines content on strength and deformation remains insufficient.

Fines have vital effects on the strength of soil (Kemper et al., 1987; Ley et al., 1989). The results of many experiments show that soil strength increases with increasing fines content. For a given soil type, fine particles are involved in binding or cementing the other soil particles, which improves the integrity and resistance of soil (Coughlan et al., 1978; Kemper et al., 1987; Ley et al., 1989). Moreover, mixtures of different fines contents have different strength characteristics (Skempton, 1985; Georgiannou et al., 1990; Kumar and Wood, 1999; Vallejo and Mawby, 2000; Vallejo, 2001; Cabalar, 2011). However, all

* Corresponding author at: Key Laboratory of Mountain Hazards and Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610044, China.
E-mail address: jxgjim@163.com (X. Jiang).

http://dx.doi.org/10.1016/j.enggeo.2015.09.011
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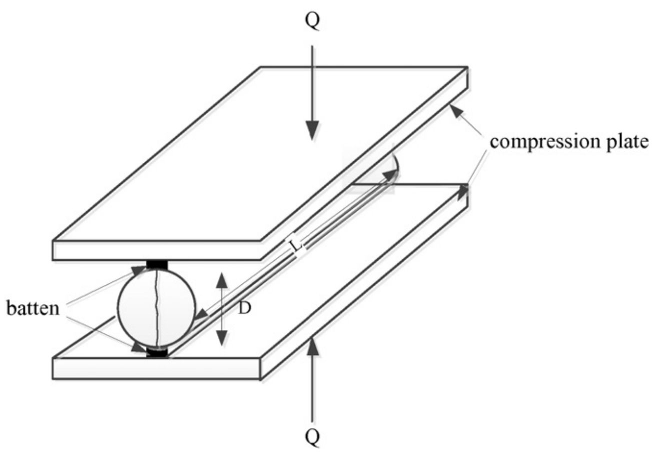

Fig. 1. Radial-splitting test method.

the abovementioned studies were focused on the compressive and shear strengths of clay and silt. Although, different categories have been presented, the relationship between fines content and soil strength is still unclear. In addition, the relations of strengths among different categories are still unknown. Such as, Vallejo and Mawby (2000) and Vallejo (2001) divided the soil into three categories base on their contents of fine particles, which are 0 to 25%, 25% to 60%, and 60% to 100%, and each category had the same characteristics of strength. We wonder if the rates of change of strength in the three categories are equal. If not, what are the relationships among the rates of strength change? What's more, direct shear test was usually used in the former researches, but this test cannot quantitatively reflect the effect of fines content on the stress–strain relationship. Compressive strength, tensile strength, and shear strength are three important parameters of soils. Quantitative relationships among them in each category have not been studied yet. Some researchers have investigated mixtures and revealed the failure mechanisms (Xu et al., 2007; Medley, 2001). It indicated that shears in mixture typically tortuously negotiated around blocks at the block/matrix contacts. However, the mechanism of failure around coarse/fines contacts was not discussed. In this paper, we confirmed this phenomenon existed in mixture, and explained it using theory of strain energy.

The Mohr-Coulomb criterion is applied widely by researchers and engineers in stability calculations and failure analyses for landslides and debris flow (Bishop, 1955; Fredlund and Rahardjo, 1993; Stianson et al., 2011; Iverson, 2012). However, an increasing number of experiments have found that the strength criteria for soils are nonlinear (Charles, 1973; Maksimovic, 1989; Zhang and Chen, 1987; Yang and Yin, 2004). These nonlinear criteria were most established on clay. The strength criterion characteristics for mixtures are still unclear. Moreover, the current criteria have uncertain variables that are difficult to determine. Although, Zhang and Chen (1987) analyzed effect of variables on the criterion, the calculation method of the variables was not presented. Therefore, it is essential to analyze the influential factors and quantitatively describe the complicated strength envelopes.

This paper presents the results of the following research. First, 27 unconfined compressive tests were performed to investigate the contribution of fine particles to the compressive and shear strengths. Next, 27 radial-splitting tests were conducted to study the tensile behavior as a function of fines content. The relationships between tensile strength and compressive strength were then analyzed and used to establish a new strength criterion. Three unconfined compressive, radial-splitting, and direct shear tests were conducted to verify the rationality of the new criterion. Finally, the last section of this manuscript discusses the effects of fine particles on the failure mechanism and shortcomings of the new criterion.

2. Methods

The compressive strengths and stress–strain relationships of mixtures can be conveniently determined by unconfined compression tests. In these tests, there is no lateral confinement on the soil sample, and axial loading is applied.

The most common method for determining the tensile strength is the radial-splitting test, also known as the Brazilian test, which is considered an indirect tensile strength test method. In this test, a cylindrical specimen is placed horizontally between compression plates. Two battens, one above and one below the specimen, are used to distribute the applied load evenly along the entire length, as shown in Fig. 1.

The load is applied on the top of the batten to induce tensile radial failure in the specimen. Based on elasticity theory, the lateral stress along the diameter is the tensile stress of the specimen. The tensile strength σ_t is obtained using the following relationship:

$$\sigma_t = \frac{2Q}{\pi DL} \quad (1)$$

where Q is the applied load, N; D is specimen diameter, m; and L is the specimen length, m.

Davies and Bose (1968) analyzed the stress distribution of the specimen using finite element analysis based on linear elasticity theory. The results show that Eq. (1) is valid for calculating the tensile strength. Chen (1975) applied plasticity theory to study the failure mechanism of radially split specimens, demonstrating the validity of Eq. (1).

3. Sample preparation

To investigate the tension and compression behaviors, soil materials were obtained from the surface of a slope in YingXiu, Sichuan province, PRC (N31°05′30.24″E103°29′06.94″). The soil from this slope was composed of coarse particles (i.e., particles larger than 0.075 mm following ASTM (2002)) and fine particles (i.e., particles smaller than 0.075 mm). The fines content of the natural soil was 9.4%. The natural soil was sieved into 10 different particle size ranges: 5 mm–2 mm, 2 mm–1 mm, 1 mm–0.5 mm, 0.5 mm–0.25 mm, 0.25 mm–0.075 mm, 0.075 mm–0.05 mm, 0.05 mm–0.01 mm, 0.01 mm–0.005 mm, 0.005 mm–0.001 mm, and <0.001 mm. The grain size distribution for this mixed soil is given in Fig. 2.

The soil was non-uniform with the following parameters: coefficient of uniformity $C_u = 1.56$, average soil material diameter $d_{50} = 0.55$ mm, specific gravity of coarse particles $G_{sc} = 2.655$, specific gravity of fine particles $G_{sf} = 2.728$, water content $w = 8.3\%$, and density $\rho = 1.85$ g/cm^3. The natural soil was sieved into a coarse particle group (5 mm–0.075 mm) and fine particle group (<0.075 mm). To analyze the effects of fines on the mechanical properties, the other parameters (i.e., water

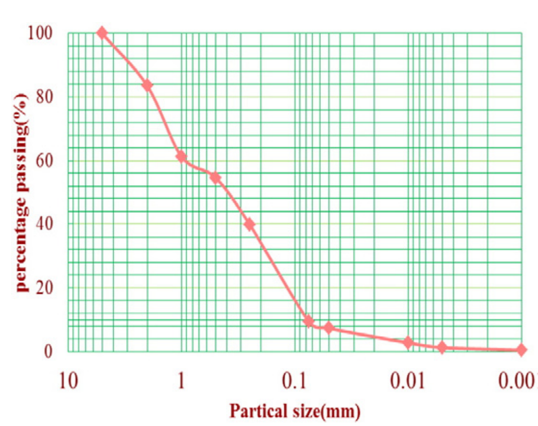

Fig. 2. Gradation curve of the material.