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Geometric anisotropy modeling and shear behavior evaluation of graded crushed rocks

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HIGHLIGHTS

- A numerical technique to simulate the geometric anisotropy of the graded crushed rocks (GCRs) was proposed.
- The discrete element models of the biaxial shear test and the California bearing ratio (CBR) test were established.
- The shear behavior of the GCRs in meso-structure was evaluated.

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ABSTRACT

To reveal the meso-mechanical mechanism of shear behaviors in the graded crushed rocks (GCRs), which are heterogeneous in geometry and widely used in the flexible pavement, a numerical technique was proposed to simulate the geometric anisotropy of the GCRs using randomly generated models. Then, studies on meso-mechanical responses during the loading were performed through the biaxial shear test and California bearing ratio (CBR) test. The results showed that the changes of both friction and anisotropy had a similar trend with the particle size enlarging in the dense assembly, which maintain stable when the size is less than 3.0 mm. In addition, the breaking sieve (BS) between coarse and fine aggregates was six times of the base diameter (0.8 mm). The predicted shear properties in macrostructure were in good agreement with those laboratory measurements. For the shear behaviors, the fractures and force chains were mainly distributed in the area of action that was limited by force size and side boundary.

1. Introduction

The graded crushed rocks (GCRs) are widely used in the flexible pavement construction because of its excellent performance on stress distribution [1]. The shear performance of the GCRs in base and sub-base layers significantly impacts on the fatigue cracking, rutting and other pavement distresses [2]. However, this shear behavior is still in experimental research stage and therefore not yet in-depth for failure mechanism on its mesostructure [3]. One of the primary issues for the shear mechanism is that more research efforts are needed to better understand the discretization and non-linearity of the GCRs' structure that is heterogeneous and composed of gravel aggregates and stone chips [4,5]. The characteristics and state histories of the meso-structure play significant roles in understanding and describing the mechanism of macroscopic performance change [6]. The rolling resistance has different effects on the stress-strain and strain localization behavior during the emergence and development of shear bands [7]. The shearing behavior of granular materials is dependent on the relative density, particle shape and stress path [8]. Considering the above factors, the mechanical and geometric anisotropies were employed to analyze the mesoscopic structures [9]. Mechanical anisotropy is defined as the orientation of the induced contact forces caused by external force and represents the uniformity of the assembly. Geometrical anisotropy mainly shows the global orientation of the contact planes between irregular granules. The anisotropy analysis provides an approach for understanding the change mechanism of the internal stress and strain during the initialized and shearing processes [10]. In particular, the geometric anisotropy results in an initial mechanical anisotropy of contact force [11]. Moreover, this geometric anisotropy contributes to key aspects of the shear strength via the size gradations and irregular geometries [12]. Thus, the geometric anisotropy of GCRs must be characterized effectively before the evaluation of shear behaviors.

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In the past decades, researchers have proposed some numerical methods aiming to analyze the geometric anisotropy and shear behaviors of GCRs since these are time-saving and can control the calculation conditions easily [13,14]. Since it is beneficial for studying discontinuous and discrete structures, the discrete element method (DEM) was employed widely for the evaluation of interfacial mechanical behaviors between the coarse and fine crushed rocks through the Newton's second law of motion and multiple contact models[13]. In the DEM, a simple linear contact model can be applied to predict the nonlinear stress-strain response of granule assembly instead of complex plastic constitutive equations. Both experimental and simulated results manifested that it is a way to explore fundamental evolving mechanism of the overall mechanical behavior in direct shear tests [15]. In addition, it is also a way to investigate the meso-structural features that include the orientated range of particles, distribution of contact forces and voids, et al [16]. At present, the structural anisotropy of granule materials was analyzed by performing mechanical tests on the idealized particles [17]. Few studies have been conducted to simulate the anisotropy of irregular shaped particles. This is because the influence factors are difficult to control. On the contact mechanics, compaction methods have influence on the induced anisotropy that results in a large difference in the final structural condition [18]. However, it is not considered to eliminate the effect of mechanical and geometric anisotropies of particles. Therefore, the effects of induced anisotropy on assembly must be minimized and the characteristics of geometric anisotropic can be achieved with irregular shapes of grains using the randomly generated method [19].

The objectives of this study are to develop a numerical technique to simulate the geometric anisotropy of the GCRs by randomly generated models and to investigate the shear mechanism in the mesoscopic structure by building virtual laboratory tests using this numerical methodology. The paper is organized as follows. The forthcoming section introduces the preparation of initial sample in isotropic and dense state. It is found that the mechanical anisotropy is significant on the initialization of geometric anisotropy and the particle size of the sample affects computational efficiency and material properties. After that, the procedures of a geometric anisotropy modeling technique are described in detail. In the 2D-DEM, the coarse aggregates with irregular geometry are established on the initial sample. In the following, the rationality of this modeling technique is verified through numerical simulations and laboratory experiments. For the shear behaviors, the structural transformation and meso-mechanical responses are analyzed. The final section summarizes the major findings of this study.

2. Initial sample and anisotropy analysis

On the mesoscopic mechanics theory, Cowin reported that the macroscopic shearing processes of granular materials can be characterized by the induced mechanical anisotropic [20]. Moreover, the induced mechanical anisotropy is one of the main elements for the assembly process. By calculating the mechanical anisotropy of the internal contacts, it is clear to analyze the evolution of the deviatoric stress resulting from the reorientation of the contact forces when the initial sample is assembled. Therefore, the evolution of mechanical anisotropy in the initial sample was displayed firstly and the effect of particle size on the homogeneous model was discussed in the following issues.

2.1. Initial sample preparation in isotropic and dense

The mechanical properties of granular materials are strongly dependent on the loose or dense state of the granular media [21]. Since the closely arrangement and interlocking of the GCRs have a decisive impact on the mechanical behavior, the preparation of an isotropic and dense numerical sample is important.

Several sophisticated methods are proposed to create the dense assembly with gravitational deposition but most of the results are not homogeneous [22]. To eliminate this anisotropy, Chareyre and Villard applied the radius expansion-friction decrease method to achieve the final porosity, which took into account the homothetic changes in the particle sizes [23]. In the random particle system, the given rectangular area is bounded by four frictionless walls and the size of particles is so small that the initial porosity is set to be 0.24 with an isotropous compressive stress as 1 kPa. Different from the servo operation of wall displacement, the desired porosity (such as 0.2) of this method is obtained by a continuous radius expansion and friction factor decrease without gravity or volume changes. During this expansion process, the stress in the system is kept as 1 kPa, which is calculated from the force applied by the boundary wall and the relative positions of the particles change less than the initial state.

The radius expansion-friction decrease method is reliable and stable during model assembly and provides a statistically isotropic and homogeneous state. The advantage of the radius expansion method is that the final state is consistent with the initial state in particle size distribution. With a slow decrease of contact friction, the porosity becomes smaller and the model becomes more homogeneous. Therefore, this method was applied to the sample preparation and anisotropy evaluation in the particle system.

2.2. Anisotropy evaluation of initial sample

The assembly of the initial sample is grouped as series of discrete particles with the specific form and contacting mechanical properties. To correlate the macro material properties, some statistical mean values are usually applied in a micro-perspective way to characterize granular materials, of which the average coordination number N_c is the basic one expressed as the ratio of the total number of contact M and the number of particles N, showed in Eq. (1).

$$N_c = \frac{M}{N} \tag{1}$$

As mentioned above, it is critical to evaluate the macro performance of a granular assembly, which quantifies the anisotropy in the micro-fabric. Thornton and Barnes observed that the discrete distributions of the normal vectors in the contacts or induced forces may be approximately expressed as a probability density function $E(\theta)$ by the angle θ, as shown in Eq. (2). If it is assumed as a continuous distribution, a second order Fourier series representation can be adopted as Eq. (3) [24].

$$\int_0^{2\pi} E(\theta) d\theta = 1 \tag{2}$$

$$E(\theta) = \frac{1}{2\pi}[1 + a\cos 2(\theta - \theta_a)] \tag{3}$$

where a stands for the Fourier series coefficient, which is considered as an anisotropic invariant; and θ_a stands for the principal anisotropy direction of the normal vectors.

It is the producing mechanism of the contact anisotropy that the interfacial contact surface is adjusted continuously to a direction consistent with the maximum principal stress during the loading process. In the granular assembly in 2D, the distribution of contact normal can be evaluated by counting the number of contact planes. The contact normal vector falls within the range of the angle $\Delta\theta$ (the interval is 10°), as shown in Fig. 1. The samples with the particle sizes of 6.0 mm and 3.0 mm were employed to