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# Particle mechanics modeling of the effect of aggregate shape on creep of durable rockfills

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ABSTRACT

The role of aggregate shapes in creep of durable rockfills is investigated using particle mechanics method. Both one-dimensional compressional creep and direct shear creep tests are performed on numerical rockfills consisting of rounded or irregular aggregates. Under one-dimensional compression, the creep displacements of irregular samples were greater than rounded samples. Under direct shear, the creep displacements of rounded samples could be the same magnitudes of or even larger than irregular samples. A concept of key aggregates is proposed to explain the evolution of force chains in rockfills. The different creep behavior of wet rounded and irregular aggregates is briefly discussed.

## 1. Introduction

Rockfill materials, which are mainly composed of quarry rock debris or blasted rock fragments, have been widely used in civil engineering, such as dams, railways and airport foundations in mountain areas. A number of field observations showed that the mechanical behavior of rockfill materials is time-dependent, and especially the post-construction settlement may continue for many decades [27,32]. The operability and safety of railways and airports impose tight limits for post-construction settlements of the supporting embankments. Significant post-construction settlements may affect the infrastructure's serviceability, or even induce engineering disaster [36]. Although it is widely accepted that particle breakage is the main cause of rockfill creep behavior [22], the roles of many other factors, such as aggregate shape, size, and strength, water condition, and temperatures in rockfill creep still remain poorly understood.

Over the years, many efforts including both experimental and numerical investigations have been conducted to study the effect of aggregate shape on short-term behavior of rockfill materials or soils (Table 1). A couple of geometrical parameters, such as sphericity, angularity (or its opposite, i.e., roundness), and surface roughness, have been proposed to characterize aggregate shapes in different scales. Sphericity, $S$, refers to the global form of the aggregate and reflects the similarity between the aggregate's length, height, and width. Angularity, $A$, is a measure of the ratio of the curvature of the corners of an aggregate to an inscribed circle, as well as the corner's distance from the center of the inscribed circle. Surface roughness, $R$, is a measure of the surface texture. Because it is difficult to separate the relative contributions of sphericity and angularity to rockfill mechanical behavior, a single measure of deviation from "round spherical" shape, called regularity, $\rho = (S + A)/2$, was also proposed [7]. Most of the previous experimental and numerical studies have showed that aggregate shape can significantly affect the short-term behavior of rockfill materials or soils (Table 1), i.e., an increase in irregularity produces a decrease in stiffness, an increase in compressibility under laterally constrained compression, and an increase in the critical state friction angle [7]. Ng [21] studied the behaviors of assemblages of monodisperse smooth ellipsoids with different aspect ratios, and showed that particle shape is not essential for these well-rounded ellipsoids. However, the effect of particle shape on long-term deformation behavior of rockfill materials has not been reported to the authors' knowledge.

In engineering practice rockfills can be solely composed of durable or non-durable rock fragments, or a mixture of durable and non-durable rock fragments [4]. The creep behavior of rockfills under dry and saturated conditions has been experimentally and numerically studied in the past. It is generally accepted that creep settlement of rockfills under dry state is mainly due to delayed grain fracture process, and aggregate breakage mainly occurs in the forms of abrasion and total fragmentation [22]. It is known that water plays an important role in rockfill long-term deformation behavior [27,19,20]. For durable rocks (not slaking by water), wetting-induced reduction of contact friction coefficient (lubrication) is the primary cause of a sudden settlement immediately after wetting, and a wetting-induced reduction of bond strengths (weakening) plays a secondary role in rockfill creep, which may speed up the creep strain evolution [1,10,36]. For nondurable rocks, rapid slaking of rock fragments is the major cause of rockfill settlement due to

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**Table 1**
A brief review of effect of particle shape on short-term behavior of rockfill materials or soils.

| Literature | | Particle shapes | Tests | Main conclusions |
|---|---|---|---|---|
| Experimental study | Varadarajan et al. [30] | Rounded and angular particles | Consolidated drained triaxial tests | Rockfill samples consisting of rounded particles underwent continuous volume compression during drained triaxial testing, whereas the rockfill samples consisting of angular particles underwent various degrees of dilatancy |
| | Chuhan et al. [6] | Sands with different angularity | One-dimensional compression test | The yield stress is low when the grains are angular |
| Numerical study | Jensen et al. [12] | 2D clusters for rough particles | Interface ring shear tests | The interface shear strength increases with particle angularity |
| | Mirghasemi et al. [16] | 2D polygon-shaped | (1) Isotropic loading-unloading;<br>(2) Biaxial shear | (1) Assemblies of angular particles are more compressive than assemblies of rounded particles;<br>(2) The shear strength also increases as the angularity of particles increases |
| | Ng [21] | Monodisperse ellipsoids | Triaxial compression tests | Particle shape is not essential for well-rounded particles |
| | Ueda et al. [29] | 2D crushable particle | One-dimensional compression tests | The rates of occurrence of different crushing types depended on the particle shape:<br>(1) Cleavage destruction was mainly observed with circular and elliptical particle<br>s<br>(2) Bending fracture was observed only with elongated particle<br>s<br>(3) Edge abrasion was frequently observed with angular particles |

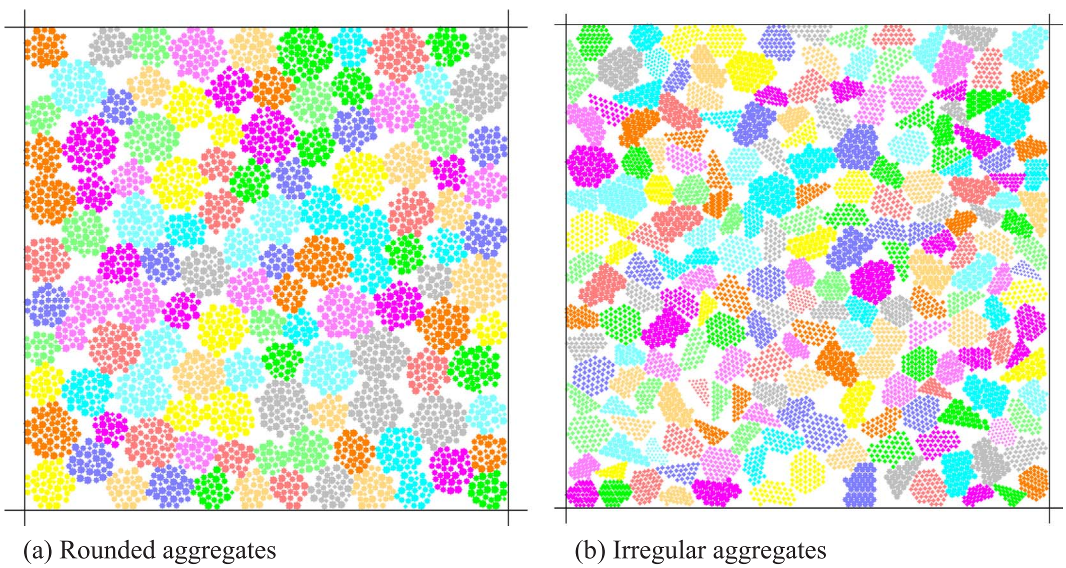


**Fig. 1.** Numerical rockfill samples consisting of rounded and irregular aggregates in a squared box of side length of 200 mm.

**Table 2**
Micro-parameters for the rockfill agglomerates.

| Micro-parameter | Unit | Value |
|---|---|---|
| Number of aggregates | – | 120 (rounded)<br>213 (angular) |
| Density | kg/m$^3$ | 2230 |
| Contact modulus | GPa | 4.0 |
| Ratio of ball shear to normal stiffness | – | 0.4 |
| Contact friction coefficient | – | 0.3 |
| Parallel bond radius multiplier | – | 1.0 |
| Parallel bond modulus | GPa | 4.0 |
| Ratio of parallel bond shear to normal stiffness | – | 0.4 |
| Parallel bond normal strength, mean | MPa | 10.0 |
| Parallel bond normal strength, standard deviation | MPa | 3.0 |
| Parallel bond shear strength, mean | MPa | 10.0 |
| Parallel bond shear strength, standard deviation | MPa | 3.0 |
| Empirical parameters $\beta_1$, $\beta_2$ and $\beta_3$ | – | 0.4, 40 and $5 \times 10^{-11}$ |

wetting [23,5,3,35,25]. Pappas and Vallejo [23] examined the creep behavior of various proportions of durable and nondurable rockfills at different constant stress levels, and found that the degree of creep decreased as the amount of durable rocks increased.

In this study, we used particle-based discrete element method (DEM) to examine the role of particle shape in rockfill creep. Many numerical studies have demonstrated that particle-based DEM is an accurate and robust tool to model the short- and long-term behavior of rockfill materials, by treating rockfill or soil aggregates as clusters of bonded circular particles [12,17,8,15,26,28,13,14,36,2,34]. This first-step study focuses on the effects of regularity ($\rho$) on rockfill creep under dry condition, i.e., numerical rockfill samples consisting of rounded or irregular aggregates are compared. The different creep behavior of rounded and irregular aggregates subjected to the action of water is briefly discussed. Note that the creep behavior of nondurable rockfills under saturated conditions is more complex, and we focus on durable rockfills in the present study.