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Revealing a Possible Shear Strength Weakening Mechanism Based on Microscopic Insights from Ring Shear Tests

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1. Introduction

Rock avalanches are normally featured by large volume, high running velocity, and long traveling distance, and then frequently result in greater damage (Heim, 1932; Legros, 2002). However, the hypermobility of rock avalanches remains a challenging research issue in geological disasters. Recently, nanoparticles (with particle diameters ranging from 1 to 100 nanometers) were found in rock avalanches and natural faults (Green et al., 2015; McSaveney and Hu, 2022). Much research supported that the nanoparticles could play as a lubricant and cause the ultra-low shear resistance of the materials along the shear surface (i.e. Han et al., 2010, 2011; Reches and Lockner, 2010; Tisato et al., 2012) However, the mechanism of shear strength weakening resulting from nanoparticles is unclear. To address this issue, a serais of ring shear test were performed on nanoparticles to check their shear behavior at first.

2. Materials and Methods

To investigate whether the nanoparticles can work as lubricants, resulting in a significant reduction in the shear strength of geomaterials, we utilized Silicon dioxide (SiO2) nanoparticles (SN). SN consists of nano-scale particles with a spherical microstructure, each having a diameter of approximately 50 nanometers (Fig. 1). Under natural dry conditions, some ring shear tests were performed by the ring shear apparatus of DPRI-5 and DPRI-6. We used the shear-stress controlled method, in which shear stress is increased at a rate of 1 kPa/s until the sample fails to reach the residual state under different normal stresses (σ_n = 107 kPa, 161 kPa, 215 kPa, 619 kPa, and 1030 kPa, respectively). Besides, we also used the shear-velocity controlled method, in which the samples were initially sheared slowly to reach the residual state and then sheared by increasing the velocity to a target value (0.1 ~ 220 cm/s). To better compare these shear behaviors, the stress ratio (μ = monitored shar resistance against normal stress) as a common index is used in this study.

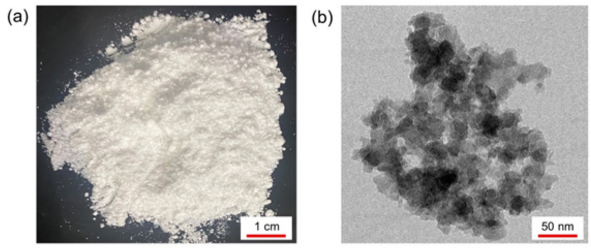

Fig. 1. (a) Pure SN; (b) TEM image of SN.

3. Results

The results of these tests are depicted in Fig. 2a in the form of the shear stress ratio against the shear displacement. At normal stresses of 107, 161, and 215 kPa, the stress ratios at the residual state are greater than 0.53. These values are close to the shear strength of typical natural soils (Keaton, 2017), suggesting that SN itself possesses high shear strength. However, it decreased to 0.34 and 0.25 approximately under the normal stresses of 619 and 1030 kPa, respectively. Fig. 2b presents the time series data of stress ratio and shear velocity for one test under normal stress of 161 kPa. It can be noticed that after the occurrence of shear failure, the stress ratio remains relatively consistent (around 0.52~ 0.63) and presents no significant variation even under the shear velocity of 2.1 m/s. Fig. 2c shows that in the tested range of shear velocities, the stress ratio of SN at residual state presents strong dependence on the normal stress, but at each normal stress level (161 kPa, 619 kPa, and 1030 kPa), it does not show significant variation with the shear velocity. As shown in Fig. 3, we also took sample blocks from the shear zone and conducted SEM observation on the sliding surface after tests. SN particles aggregate to form distinctive powder rolls on the shear surface with the long-axis direction of these rolls being approximately perpendicular to the shear direction. It is observed that the powder rolls have characteristics in common with the debris rolls that have been reported in the shear tests on different materials for the studies of fault dynamics (Chen et al., 2017a, 2017b). It is inferred that the rolling of powder rolls facilitates fault slip along the smooth patches of the principal shear zone, contributing to overall weakening and reduced friction.

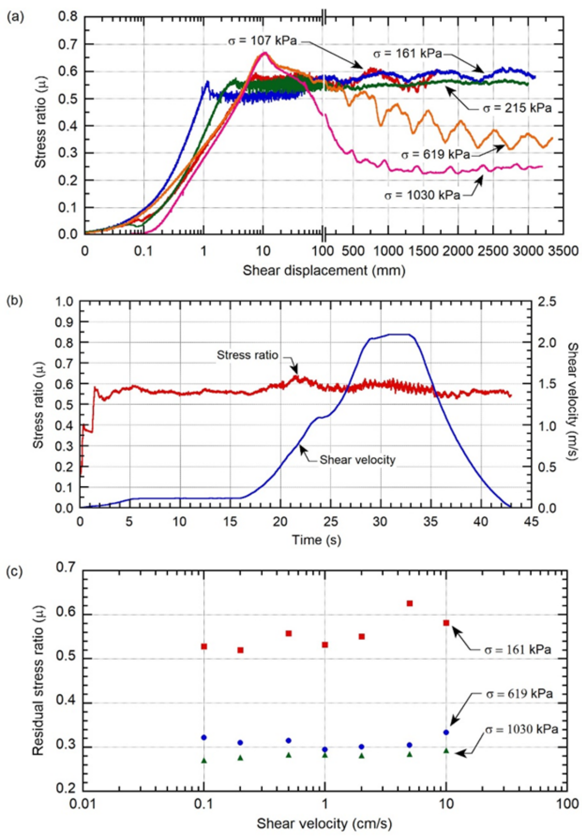

Fig. 2. Results of ring shear tests on SN: (a) Results of the shear stress-controlled method; (b) Result of high shear-velocity ring shear test on SN under normal stress of 161 kPa; (c) The residual stress ratio of SN at different shear velocities and different normal stresses.

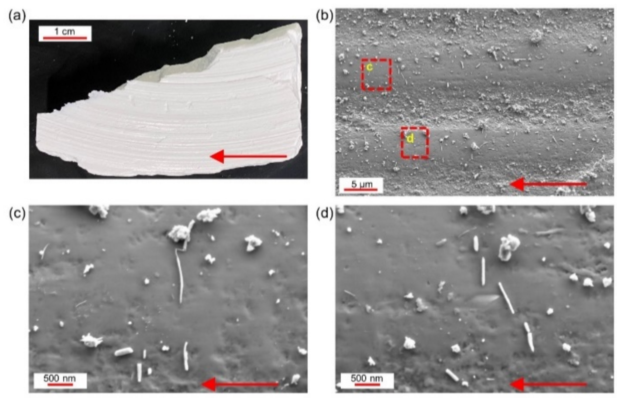

Fig. 3. Post-test photo and SEM images from a test conducted on SN under the normal stress of 1030 kPa. (a) Shear surface after the test. (b), (c), (d) SEM images obtained by scanning the shear surface. The arrow indicates the shear direction.

4. Summary

To clarify the role of nanoparticles in shear behavior and investigate their potential as lubricants to weaken shear strength during high-velocity shearing, we conducted a series of ring shear tests on SN under varying normal stresses and shear velocities. There are some summaries for this study:

a) The shear resistance of pure nanomaterial SN exhibits high and stable at lower normal stress levels but decreases significantly with the increase of applied normal stress.

b) The shear strength of SN does not present a significant change with the shear velocity, even though the shear velocity reaches approximately 2.1 m/s.

c) It is inferred that the significantly lowered shear strength of SN under higher normal stress results from the formation of these powder rolls, which enable the particle movement mode from sliding to rolling.

Nevertheless, some other possible effects resulting from the formation of nanoparticles, such as dehydration, and flash heating, may play key roles in the shear behavior. Concerning this, further study by using different types of nanoparticles will be necessary and are undergoing.