

**Experimental Study on the Shear Behavior of Granular Materials:  
Implications for Rock Avalanche Hypermobility with Focus on  
Nanoparticles, Hydrous Minerals, and Grain Shapes**  
粒状体のせん断挙動に関する実験的研究: ナノ粒子、含水鉱物、粒子形状  
に着目した岩屑なだれの超流動性に関する新たな知見

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論文要約

**CHAPTER 1 Introduction**

Rock avalanches are among the most hazardous natural events in mountainous regions. These events involve the rapid mass movement of bedrock broken from an unstable slope, forming a relatively thin sheet of fragmented rock. The transported materials are relatively dry rock or ice (at low temperatures), including sedimentary, metamorphic, igneous, and pyroclastic deposits. With their huge volume, extremely high velocity, and unexpectedly long runout, rock avalanches possess hypermobility that could cause devastating impacts on lives and property. Various assumptions have been proposed to explain the hypermobility of rock avalanches, such as air cushion theory, fluidization by trapped air, vapor, and dust dispersions, mechanical fluidization, acoustic fluidization, rock dissociation, and melting and lubrication by liquefied saturated soil. However, none of these assumptions have been widely accepted because they lack comprehensive experimental validation or actual case evidence.

To advance the understanding of the hypermobility of rock avalanches, this research investigates the shear behavior of granular materials, focusing on the nanoparticles, hydrous minerals, and grain shapes. This research aims to address the following key scientific questions:

- (1) Effects of nanoparticles: despite evidence of intensive rock fragmentation in actual rock avalanches and laboratory observations of nanoparticle generation during high-velocity shearing, the mechanisms by which nanoparticles contribute to strength weakening remain unclear.
- (2) Effects of dehydration on hydrous materials: it is uncertain whether the dehydration of materials occurs under landslide stress levels during shearing and whether this progress can regulate the movement behavior of displaced landslide materials.
- (3) The influence of grain shape: it is well understood that displaced materials of rock avalanches will change their shapes and size with the progress of movement. The effect of this change in the shape of rock blocks on the shear behavior of granular materials remains poorly understood.

To address these questions, a series of ring shear tests were conducted to examine the shear behavior of various granular materials. These experiments aim to reveal potential mechanisms behind strength weakening observed in the tests and provide insights into the mechanisms that contribute to the hypermobility of rock avalanches.

## CHAPTER 2 Experimental methods and materials

Chapter 2 introduces the methods and materials used in this research. To investigate the shear behavior, particularly the residual shear strength of various granular materials, shear tests were conducted using a series of ring shear apparatuses (termed as DPRI-5, DPRI-6, and DPRI-7) with different sizes in the shear box and shear velocities under dry conditions. In the tests, two testing methods were employed:

Shear stress-controlled method (SSCM): shear stress was increased at a rate of 0.5 or 1 kPa/s from zero until the shear strength reached the peak shear strength, at which the shear failure occurred on the sample. After that, shearing continued until the sample stabilized at its residual shear strength, after which the test was terminated.

Shear Velocity-Controlled Method (SVC): The samples were initially sheared by the SSCM until they reached the residual shear state. After that, the samples were subjected to shearing at varying shear velocities. After reaching residual shear strength at a specific velocity, the shear velocity was adjusted to the next level for continued testing.

The X-ray diffraction (XRD) patterns were obtained using a Mini Flex600 diffractometer (Rigaku Corporation, Japan) to analyze the mineralogical composition of samples both before and after the ring shear tests. Additionally, to observe the microstructure of the shear surface, a small part from the identifiable sliding surfaces was collected after tests and further observed by using scanning electron microscopy (SEM, ZEISS Ultra-55). The transmission electron microscope (TEM, JEM-2200FS) was used to observe the microstructure of samples.

Tests were conducted on different materials for different purposes as below:

(1) To examine whether nanoparticles can work as lubricants resulting in a significant reduction in the shear strength of geomaterials, Silicon dioxide ( $\text{SiO}_2$ ) nanoparticles (SN), silica sand no.8 (S8), and the mixtures of S8 with different contents of SN were used as the test materials. SN consists of nanoscale spherical particles with a diameter of about 50 nm. The specific gravity of SN is measured as 2.20. S8 is primarily composed of subangular to angular quartz grains with a specific gravity of 2.63. Mixtures of S8 with 10%, 20%, and 50% SN by weight were prepared and referred to mixtures as M10, M20, and M50, respectively. For consistency, S8 and SN were also called as M0 and M100, respectively.

(2) To investigate the potential effect of sample dehydration during shearing on the residual shear strength of the shear surface, ring shear tests were conducted using commercially available halloysite nanoparticles with a specific gravity of about 2.53 sourced from American Dragon (ADH) and New Zealand (NZH). The original ADH primarily comprises halloysite-10Å and halloysite-7Å phases, whereas NZH mainly consists of halloysite-7Å phases. Due to the interlayer water in the halloysite being weak and easily lost upon heating, Halloysite-10Å could irreversibly dehydrate at elevated temperatures, resulting in a reduction in interlayer spacing and its transformation into halloysite-7Å. Moreover, the morphology of ADH exhibits a tubular shape and NZH exhibits a mix of tubular, spherical, and platy structures. Four types of halloysite samples were used: original ADH ( $\text{ADH}_{\text{orig}}$ ), dried ADH at 500 °C

(ADH<sub>500</sub>), original NZH (NZH<sub>orig</sub>), and dried NZH at 500 °C (NZH<sub>500</sub>).

(3) To investigate the effect of grain shape on residual strength, glass beads with two different shapes were tested. The spherical glass beads (GBS) have a diameter of 0.85 ~ 1.18 mm and an aspect ratio (AR) of 1, and irregular glass beads (GBI) have a diameter of 0.85 ~ 1.18 mm and an AR of 0.72 ~ 0.78.

### **CHAPTER 3 Mechanical effects of nanomaterials on the residual shear strength of sandy mixtures**

Chapter 3 presents the detailed test results and discusses the potential mechanical effect of nanoparticles on the residual shear strength, based on the results of a series of ring shear tests on SN (M100), S8 (M0), M50, M20, and M10 under different normal stresses of 107 ~ 1030 kPa subjected to shear at different velocities of 0.1 ~ 210 cm/s.

Under lower normal stresses (107, 169, 215 kPa), the residual stress ratios ( $\mu_{ss}$ ) were about 0.56, 0.60, and 0.56, respectively. However, under higher normal stresses (619 and 1030 kPa), a significant strength-weakening phenomenon was observed during shearing by SSCM. After shearing to the residual state of samples, the  $\mu_{ss}$  decreased to 0.34 at 619 kPa and to 0.25 at 1030 kPa. SEM analysis of the shear surface at high normal stresses (619 and 1030 kPa) revealed that the original SN formed powder roll structures during shearing, whose population density increased with normal stress. Furthermore, it is inferred that these powder roll structures enable the particle motion on the shear surface to roll rather than simply slide, thus resulting in a weakening of the shear strength.

For the ring shear test on SN under lower normal stress at different shear velocities, the stress ratio ( $\mu$ ) remained high and stable (about 0.6), even at 210 cm/s. This stability indicates that shear velocity has no significant influence on the shear behavior of SN. For the ring shear tests on the mixtures of M10, M20, and M50, the addition of small amounts of SN (less than 20% in this study) slightly increased the shear strength of the mixtures. This increase can be attributed to the enhancement of the contact areas of grains and the elevating of the shear strength. However, with a higher SN content ( $\geq 20\%$  in this study), the shear behavior of mixtures showed that  $\mu_{ss}$  of the mixtures remained relatively stable across different shear velocities, while a lower value of  $\mu_{ss}$  was observed under high normal stresses. Due to the fact that the shear strength of mixtures with high SN content was predominantly controlled by SN, and similarly, some powder roll structures of SN were formed during shearing under high normal stress.

### **CHAPTER 4 Effect of hydrous material dehydration on the residual shear strength during shearing**

Chapter 4 represents the results of ring shear tests on original samples (ADH<sub>orig</sub> and NZH<sub>orig</sub>) and dried at 500°C samples (ADH<sub>500</sub> and NZH<sub>500</sub>), aimed at investigating

the effect of sample dehydration on the residual shear strength. These shear tests were conducted under a normal stress of 200 kPa but with different shear velocities ranging from 0.1 to 210 cm/s.

Experimental results on ADH show that at low shear velocities (0.1–2 cm/s),  $\mu_{ss}$  remains stable at approximately 0.60 ~ 0.64. As the shear velocity increases to 5 ~ 20 cm/s,  $\mu_{ss}$  peaks at 0.71 at 10 cm/s before decreasing to 0.66. Overall,  $\mu_{ss}$  varies between 0.60 and 0.71 for shear velocities below 20 cm/s. In contrast, at a high shear velocity of 210 cm/s, significant strength weakening occurred, with the residual stress ratio dropping sharply to 0.22 (much lower than values observed at lower velocities). XRD analysis of post-shear samples and shear surface temperature estimations at high velocity suggests two primary causes for this weakening: (1) When shear velocity exceeds the critical weakening velocity ( $V_w$ ), flash heating occurs due to particle motion, raising the shear surface temperature. (2) Interlayer water in ADH may be released as vapor when shear surface temperatures exceed 100 °C, reducing effective normal stress and further weakening shear strength.

The results of the ring shear test on the ADH<sub>500</sub> represent a similar phenomenon. At the shear velocity of 0.1 ~ 0.5 cm/s,  $\mu_{ss}$  kept a stable value of about 0.6. However, during high-velocity (~ 210 cm/s) shearing,  $\mu_{ss}$  also dropped obviously to 0.44, which is twice that in the test on ADH<sub>orig</sub>. However, the experimental samples were dried at 500°C, resulting in the loss of interlayer water in ADH before testing. Consequently, there are no obvious changes in the XRD pattern after shearing. Additionally, the estimations of temperature increasing on the shear surface revealed that the values exceeded 100°C during shearing, but remained well below 500°C. Therefore, it is reasonable to infer that the dehydration, if any, occurring on ADH<sub>500</sub>, is negligible. Comparing these findings with the experimental results for ADH<sub>orig</sub>, it can be reasonably inferred that the release of interlayer water as vapor during high-velocity shearing may contribute to shear strength reduction.

High-velocity shear test results for NZH and NZH<sub>500</sub> reveal that the  $\mu_{ss}$  decreased and stabilized at 0.33 and 0.59, respectively, at the maximum shear velocity of about 206 cm/s. Since NZH<sub>500</sub> is a pre-dried sample, sample dehydration during shearing is negligible. In contrast, NZH undergoes dehydration during high-velocity shearing, resulting in a further reduction in  $\mu_{ss}$ .

## **CHAPTER 5 The effect of particle shape on the residual shear strength of glass beads**

Chapter 5 represents the results of ring shear tests on spherical glass beads (GBS) and irregular glass beads (GBI) under normal stress of 200 kPa, at different shear velocities of 0.005 ~ 10 cm/s.

Repeatability tests were conducted for GBS and GBI at various shear velocities, showing the crossover phenomenon in the  $\mu_{ss}$  with shear velocity. Specifically,  $\mu_{ss}$  gradually decreased between 0.005 and 1 cm/s but increased at speeds greater than 1 cm/s. As shear velocity increases (assuming the thickness of the shear zone remains

constant), the inertia number also rises, and the particle movement changes from a transitional regime to an inertia regime, thereby producing the observed crossover phenomenon for the shear strength. A comparison of  $\mu_{ss}$  values between the two shapes of glass beads showed that GBS consistently had lower values than GBI. As shear velocity increased, the sample height within the shear box decreased in a step-like manner, with GBI showing greater height reduction than GBS. Since the height change remained smaller than the particle size, and no particle breakage was observed post-shearing, the variation in shear strength can be linked to differences in particle arrangement. Furthermore, after rearrangement, the force chain in GBI was more complex, with more complete interparticle contact, resulting in a smaller critical angle compared to the simpler force chain formed by GBS. Consequently, GBI exhibited higher shear strength than GBS.

## CHAPTER 6 Integrated discussion

This chapter discusses the implication of the above-mentioned test results to the hypomobility phenomenon of rock avalanches. The results highlight several key factors contributing to shear strength weakening. While nanoparticles, such as SN and halloysite, exhibit high shear strength under low stress and velocity, their strength significantly weakens under extreme conditions. For SN, high normal stress ( $>619$  kPa) induces powder roll structures that facilitate rolling, reducing shear strength. In mixtures, a critical SN content ( $\geq 50\%$ ) further weakens strength under stress. Halloysite nanoparticles exhibit a significant shear strength drop under high-velocity shearing ( $\sim 2$  m/s) due to sample dehydration during shearing, releasing interlayer water of sample by vapor phase, after that reducing effective normal strength and shear strength. The experimental findings provide some valuable insights into the hypermobility of rock avalanches. These nanoparticles may form on the shear surface due to the intense rock fragmentation under high-stress conditions in actual rock avalanches. While nanoparticles themselves typically exhibit high shear strength, their behavior can change significantly during sliding. Under high stress, the nanoparticles undergo morphological transformations, such as forming powder roll structures, which results in a reduction in the shear strength. Moreover, an increase in the nanoparticle content on the shear surface can weaken or partially weaken the strength.

High-speed movement, characteristic of actual rock avalanches, introduces another potential factor of frictional heating. This heating accelerates the dehydration of hydrous minerals on the shear surface, further contributing to the reduction in shear strength. In actual sliding cases, the weakening of shear surface strength is rarely attributed to a single factor; instead, it often results from a combination of complex influences. Nevertheless, the role of dehydration in nanoparticles and hydrous minerals, as highlighted in this study, is a significant factor that cannot be overlooked.

Additionally, rock avalanche movement is often accompanied by a transformation in particle shape, where particles change from irregular to spherical after long-distance transport. The experimental results of this study indicate that this change in particle

shape significantly reduces. This finding implies that particle shape transformations during avalanche movement also play a critical role in reducing shear resistance, further contributing to hypermobility.

Despite these experimental evidence and insights, this research has certain limitations. Such as microscopic analyses of shear surfaces under low normal stress were not successful, and direct measurements of shear surface temperature during high-velocity shearing were lacking. Future research should address these gaps by improving experimental methods, enabling better observation of shear surface and temperature changes.

## CHAPTER 7 Conclusions

The key findings of the study are summarized as follows:

- (1) Shear strength of nanoparticles: Nanoparticles such as SN, ADH, and NZH exhibit high shear strength under low normal stress or low shear velocity. However, their shear strength significantly decreases under extreme conditions, such as high normal stress or high shear velocity.
- (2) Shear strength reduction of SN under high normal stress: When subjected to high normal stress ( $>619$  kPa), the shear strength of SN reduces considerably. SEM analysis revealed the formation of powder rolls along the shear surface during shearing. These rolls are inferred to facilitate rolling on the shear surface, resulting in a reduction in shear strength.
- (3) Impact of nanoparticle content in mixtures: The inclusion of SN in mixtures with S8, especially at critical proportions ( $\geq 50\%$ ), further decreases the shear strength of the mixture, particularly under high normal stress. Due to the high content of nanoparticles mainly control the shear behavior of mixtures.
- (4) Shear strength weakening of halloysite at high shear velocity: Significant shear strength weakening was observed during high-velocity shearing ( $\sim 2$  m/s) of halloysite particles in ring shear tests. Temperature of shear surface estimations during shearing and X-ray diffraction (XRD) analysis on the post-test samples around the shear zone confirmed dehydration of the samples, particularly in the test on the ADH<sub>orig</sub>. Furthermore, the dehydration of the sample during high-speed shearing can result in the release of water vapor due to flash heating. This vapor may elevate the pressure along the sliding surface, consequently reducing the shear strength.
- (5) Impact of particle shape on residual shear strength: Experiments with glass beads (GBS and GBI) show that irregularly shaped particles present higher resistance than spherical particles, indicating that particle morphology significantly influences the shear behavior.
- (6) Implications for rock avalanches: The findings from this study offer significant insights into the dynamic mechanics of natural rock avalanches, where stress conditions and movement speeds far exceed those in laboratory experiments. Under such extreme conditions, intensive friction along the sliding surface

generates significant heat, leading to a rise in temperature. This frictional heating may weaken the sliding surface, potentially altering the mechanical properties of the displaced material in unpredictable ways, such as changing particle arrangement on the shear surface or causing sample dehydration. Additionally, the intense particle fragmentation that occurs during avalanche motion may produce nanoparticles, which could further contribute to shear strength reduction. While the role of these nanoparticles in natural settings remains largely unexplored, their potential influence on avalanche mobility should not be overlooked. Furthermore, particle shape evolution during movement is a well-documented phenomenon in rock avalanches, and it likely plays a crucial role in modifying shear behavior. Moreover, nanoparticle formation and sample dehydration are also common phenomena in rock avalanches, which contribute to shear strength weakening, enhancing the mobility of the rock avalanches.