Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
Published by Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-122-P167-cd

THE MECHANISM FOR HYPERMOBILITY OF DEBRIS-ICE AVALANCHES

Xin He

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong, China.
E-mail: cexhe@ust.hk

Limin Zhang

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong, China.
E-mail: cezhangl@ust.hk

Shihao Xiao

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong, China.
E-mail: sxiaoai@connect.ust.hk

RuochenJiang

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Hong Kong, China.
E-mail:rjiangad@connect.ust.hk

In recent years, a rising occurrence of catastrophic rock/debris-ice avalanches in high-altitude regions has been witnessed, exhibiting hypermobility. In a changing climate, ice-related geohazards originating from high-altitude regions are expected to become more frequent, posing a great threat to downstream areas. However, the contribution of ice to the hypermobility of debris-ice avalanches (DIAs) remains unclear. This study aims to investigate the mechanisms behind the influence of ice content on the hypermobility of DIAs. A series of centrifuge modelling tests were conducted to simulate the flow process of DIAs, with a cooling system to replicate high-altitude cold environment. The flow dynamics of DIAs was quantified by PIV analysis. It was found the ice content displayed a positive relationship with DIAs mobility. Furthermore, an advanced Bingham model considering ice content was developed to describe the flow behavior of DIAs and further reveal the mechanism for its hypermobility. The findings have broad implications for numerical simulations and hazard mitigation associated with ice-related geohazards.

Keywords:Debris-ice avalanche; Centrifuge modelling test; Hypermobility.

1. Introduction

Debris-ice avalanches (DIAs) refer to the flow-like movements of mixture composed of ice and debris, whichare commonly observed in high-altitude regions (Moore, 2014; Schneider et al., 2011a). Distinguished by their hypermobility, DIAs consistentlyresult in severe consequences. Driven by climate change, glacier retreat and ice melting escalate susceptibility to such hazards(Huggel et al., 2012), posingsignificant threats to downstream areas. For instance, the Chamoli rock-ice avalanche of 2021 resulted in the devastation of a hydropower station located 25 km downstream, leading to a death toll exceeding 200 (Jiang et al., 2021). Consequently, heightened attention should be paid on such hazards, understanding the flow dynamics of DIAs for its hypermobility.

DIAs mainly originate in high-altitude regions, making field investigations logistically challenging. Consequently, physical modelling experiments have emerged as a reliable approach for underlying mechanisms of DIAs. However, due to the presence of the ice phase, physical modelling studies on DIA propagation remain limited. Most existing researchers have primarily focused on the apparent flow characteristics of DIAs and the low-friction properties associated with the ice phase (Ren et al., 2021; Schneider et al., 2011b; Yang et al., 2019). However, the influence of the ice phase on flow characteristics at the particle scale remains unclear. Furthermore, natural DIAs are often characterized by substantial volumes exceeding 10 m³ (Kääb et al., 2021). Small-scale flume tests may fail to adequately replicate the complex flow dynamics of such hazards due to scale effects, potentially impeding a comprehensive understanding of the governing mechanisms.

To address the above challenges, a centrifuge model system has been developed to simulate flow process of debris-ice avalanches under cryosphere environment, allowing for observation of detailed flow process. The centrifuge model system will be used to investigate the flow dynamics of DIAs and mechanism forhypermobility.The findings advance comprehension of the underlying mechanism of hypermobility in debris-ice avalanches, thus may have implications in practical hazard mitigation.

2. Centrifuge modelling

2.1 Centrifuge model setup

The centrifuge model system is developed based on the beam centrifuge at HKUST and comprises three main components: the flume system, the cooling system, and the circulating liquid cooling system. The flume system provides the necessary space for the propagation of DIAs, while the cooling system and circulating liquid cooling system provide a virtual cryosphere environment to maintain the ice phase. The assembledcentrifuge model is shown in Fig. 1. To minimize heat exchange between the model box and the surrounding environment, the inner walls were insulated with foam strips. Additionally, a foam cover was installed on top of the model box to further preserve the low-temperature conditions.Two high-speed cameras with a frame rate of 1500 frame per secondare installed at the side of the flume to record the whole flow process of DIAs. The images captured by the high-speed cameras will undergo subsequent analysis and processing using PIVlab (Thielicke et al., 2012).

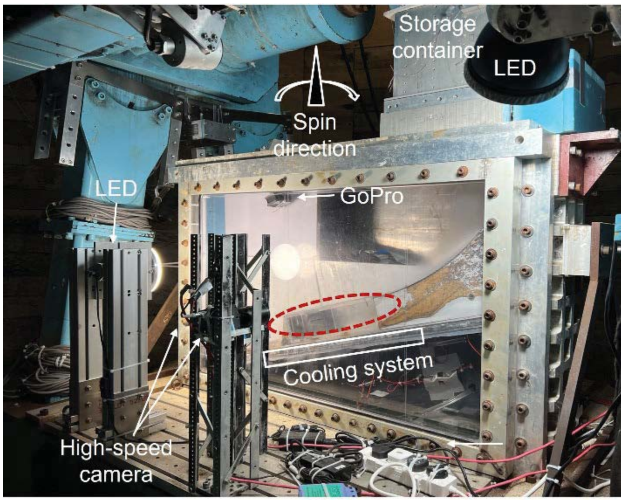

Fig. 1. Overview of the centrifuge model.

2.2 Test material and test plan

Quartz sand and ice particles are used as test materials to simulate DIAs. Their particle-size distributions are depicted in Fig. 2. The specific gravity value of quartz sand and ice particle are 2.66 and 0.93, respectively. After thoroughly mixing the quartz sand and ice particles evenly, the resulting mixture was then stored in a refrigerator.

Six centrifuge modelling tests are conducted using mixtures with varying mass ice contents. Pure quartz sand and pure ice tests are used as control groups. Subsequently, four DIAs tests are conducted with 10%, 30%, 50%, and 70% of mass ice contents to investigate the role of ice content on flow dynamics of DIAs. All tests are conducted under 35 g, and for each test, the total mass of release debris-ice mixture is 5 kg (model scale).

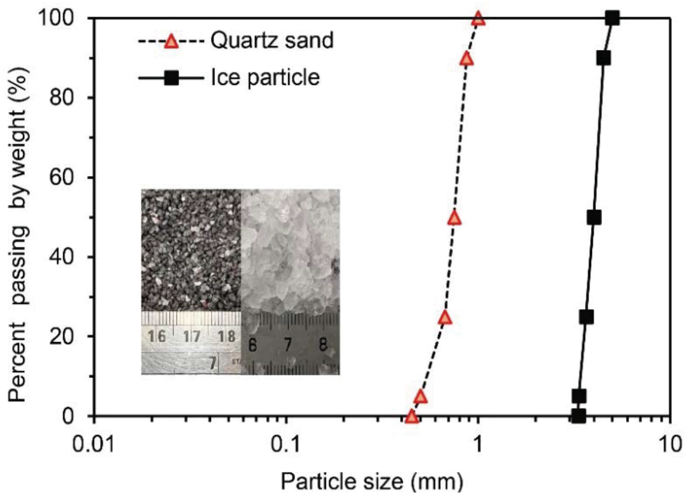

Fig. 2. Particle size distributions.

3. Flow dynamics

PIV analysis is utilized to extract velocity profiles of DIAs in all tests. Considering that tests under different ice content conditions exhibit similar velocity profile characteristics, the case of 30% ice content is taken as an illustration.Fig. 3adepicts the evolution of the velocity profile at a distance of 8 cm (model scale) from the beginning of the slope. As indicated from Fig. 3a, a concave-shaped velocity profile is observed, and it moves towards right with time. During this process, the flow depth exhibits a gradual reduction from 1.75 m to 0.77 m, and both the surface velocity and slip velocity show a gradual decrease over time. Here the depth-averaged shear rate $\overline{\gamma}$ can be calculated as:

$$\overline{\gamma} = \frac{u_t - u_s}{h} \tag{1}$$

whereu_t is the top surface velocity, u_s is the slip velocity and $h$is the flow depth. Over the course of the flow, the shear rate near the bed exhibits a gradual increase, and the depth-averaged shear rate similarly displays an incremental rise as Fig. 3b shown. These patterns are consistently observed across tests conducted under varying ice content levels, with the identified trends becoming increasingly pronounced with higher levels of ice content.Fig. 3c displays the velocity profiles obtained from tests conducted under an identical position and same normalized time 0.56 but different ice content levels. This velocity profiles consistently exhibit a concave shape and display leftward movement with an increase in ice content. As the ice content increases, both the surface velocity and bottom slip velocity exhibit incremental rises. As displayed in Fig. 3d, the shear rate near the bed also increases proportionately with the ice content, and the depth-averaged shear rate correlates positively with the ice content. These results reflect a positive correlation between ice content and DIAs mobility.

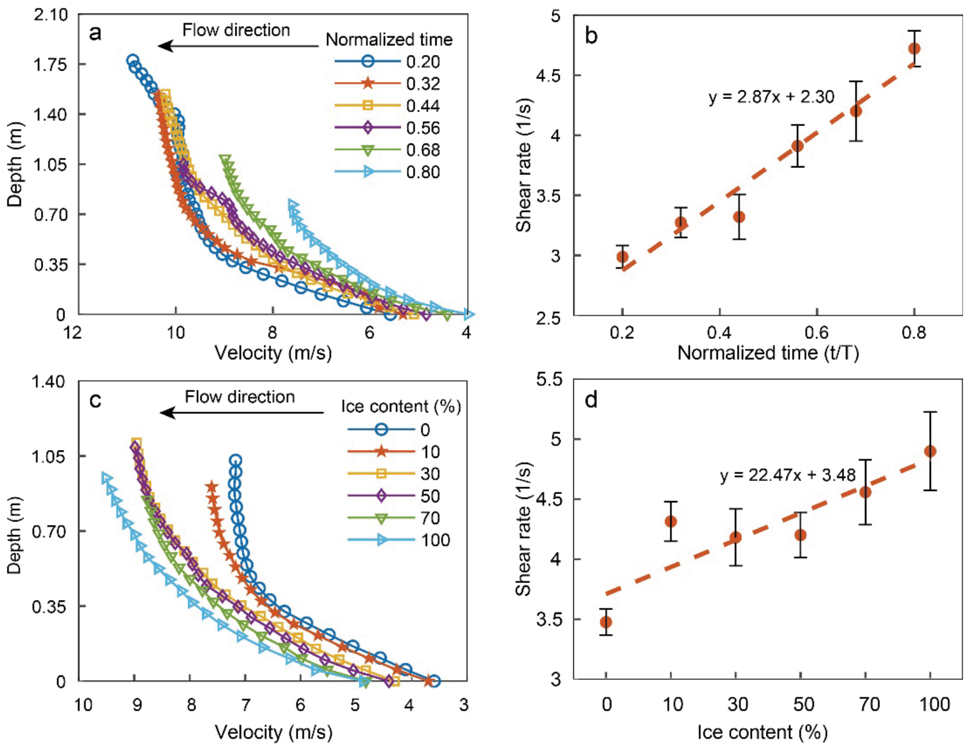

Fig. 3. Velocity profile of debris-ice avalanches (a) at different normalized time (b) with its corresponding depth-averaged shear rates in the case of 30% ice content, and (c) with different ice contents at the same normalized time of 0.56 (d) with its corresponding depth-averaged shear rates.

4. Rheological behavior

In this section an advanced Bingham model is developed to describe the rheology of DIA. In the series tests, velocity profiles are extracted through PIV at three distinct locations (0, 8, and 16cm) (model scale) from the beginning of the slope, at a consistent normalized time. The depth-averaged shear rate is subsequently calculated based on the obtained velocity profiles. Concurrently, the calculation of shear stress at these locations is based on the assumption that it is equivalent to the static shear stress:

$$\sigma_\tau = \rho g h \sin\theta \tag{2}$$

where Á is bulk density, g is gravitational accelerationand ¸ is slope angle. Consequently, the relationship between shear rate and shear stress is established to reflect flow behavior of DIAs with varying ice content conditions, as shown in Fig. 4a.Accordingly, relationships between viscosity (μ), yield stress ($Á_y$) and ice content are obtained as shownin Fig. 4b. This figure illustrates a negative correlation between μ and ice content, with the

μ decreasing from 735 *Pa·s*to 182 *Pa·s* with increasing ice content. Likewise, the correlation between $\ddot{A}_y$ and ice content exhibits a similar pattern whereby $\ddot{A}_y$ diminishes from 4.5 kPa to 3.0 kPa as the ice content increases. As a result, an advanced Bingham model considering ice phase can be developed:

$$\tau = (4.77 - 0.014i) + (694.46 - 4.75i)\overline{\gamma} \tag{3}$$

where *i*is the ice content. With an increase in ice content, the decrease in both rheological parameters of μ and $\ddot{A}_y$ causes a reduction in total basal flow resistance, thereby enhancing mobility of debris-ice avalanches. This advanced Bingham model can be used for numerical modeling to accurately simulate the flow behavior of DIAs for further DIAs risk management.

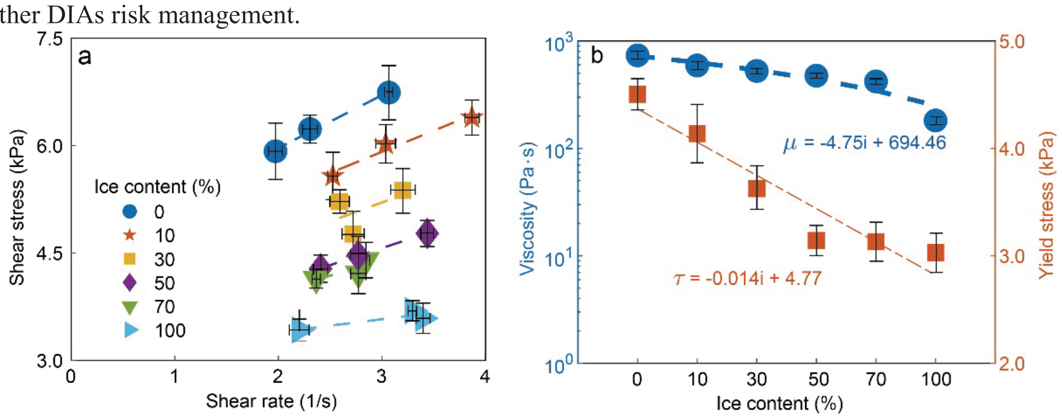

Fig. 4. Apparent rheological properties of debris-ice mixtures: (a) extracted flow curves of debris-ice mixtures at different ice contents and (b) variation of mixture viscosity and yield stress with ice content.

5. Conclusion

In this study, six centrifuge modelling tests have been conducted to simulate the flow process of DIAs for investigating the mechanism of hypermobility. The key findings are as follows:

- Enhanced mobility is observed with increasing ice content. With larger ice content, the surface and slip velocities increase and the corresponding depth-averaged shear rate also increases.
- An advanced Bingham model considering ice content is used to quantitatively describe the flow behavior of debris-ice avalanches. The decrease in viscosity and yield stress with increasing ice content indicates a reduction in flow resistance, thus an improved mobility.

Acknowledgement

This work was supported by the Research Grants Council of the Hong Kong SAR Government (16210122, 16206923 andT22-606/23-R).

References

Huggel, C., Clague, J. J. and Korup, O. (2012). Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes Landforms* 37, No. 1, 77-91.

Jiang, R., Zhang, L., Peng, D., He, X. and He, J. (2021). The landslide hazard chain in the Tapovan of the Himalayas on 7 February 2021. *Geophysical Research Letter*48, No. 17, e2021GL093723.

Kääb, A., Jacquemart, M., Gilbert, A., Leinss, S., Girod, L., Huggel, C., Falaschi, D., Ugalde, F., Petrakov, D., Chernomorets, S., Dokukin, M., Paul, F., Gascoin, S., Berthier, E. and Kargel, J. S. (2021). Sudden large-volume detachments of low-angle mountain glaciers – more frequent than thought. *The Cryosphere*15, No. 4, 1751-1785.

Moore, P. L. (2014). Deformation of debris-ice mixtures. *Reviews of Geophysics*52, No. 3, 435-467.

Ren, Y., Yang, Q., Cheng, Q., Cai, F. and Su, Z. (2021). Solid-liquid interaction caused by minor wetting in gravel-ice mixtures: A key factor for the mobility of rock-ice avalanches. *Engineering Geology*286, 106072.

Schneider, D., Huggel, C., Haeberli, W. andKaitna, R. (2011a). Unravelling driving factors for large rock-ice avalanche mobility. *Earth Surface Processes Landforms*36, No. 14, 1948–1966.

Schneider, D., Kaitna, R., Dietrich, W. E., Hsu, L., Huggel, C. and McArdell, B. W. (2011b). Frictional behavior of granular gravel-ice mixtures in vertically rotating drum experiments and implications for rock-ice avalanches. *Cold Regions Science and Technology*69, No. 1, 70–90.

Thielicke, W. and Sonntag, R. (2021). Particle Image Velocimetry for MATLAB: Accuracy and enhanced algorithms in PIVlab. *Journal of Open Research Software*9, 12.

Yang, Q., Su, Z., Cheng, Q., Ren, Y. and Cai, F. (2019). High mobility of rock-ice avalanches: Insights from small flume tests of gravel-ice mixtures. *Engineering Geology*260, 105260.