INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics
© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5

Dynamic debris flow impact force reduction in flexible barriers using novel brake elements

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ABSTRACT: Flexible barriers are commonly installed in mountainous slopes to intercept shallow landslides and debris flows. Dynamic impact of debris flows against flexible barriers can induce impulsive loading on supporting cables and increase the risk of failure. Energy absorbing brake elements may provide a cost-effective solution to attenuate peak cable tension during debris flow impact. The primary focus of this study is to investigate the role of energy dissipating brake elements in attenuating peak impact force on load bearing cables. Novel energy dissipating brake elements developed in-house at HKUST are used for a fully specifiable and repeatable loading response. In this study, channelized debris flow impact against a flexible barrier is modelled in a state-of-the-art 28 m-long and 2 m-wide flume facility in Hong Kong. Dynamic impact response of the flexible barrier impacted by a single surge of debris flow is studied. Preliminary results show that brake elements reduce peak cable loads in side anchored flexible barriers and increases energy dissipation by increasing barrier deformation.

Keywords: debris flows, flexible barrier, impact force, brake elements

1 INTRODUCTION

Steep creek flows comprised of poorly sorted mixtures of soil and water, surge downslope in mountainous areas under gravity at high velocities. Such flows often result in fatalities (Froude and Petley, 2018) and damage to infrastructure (Jakob et al., 2012). To arrest these flows, intercepting barriers are constructed at the downstream end of a catchment. Over the past decade, flexible barriers for rock fall have been impacted by debris flows and proved to be effective at arresting debris flows (Wendeler et al., 2006, Kwan et al., 2014). Flexible barriers (Fig. 1), initially introduced for intercepting rockfalls, have gained popularity in intercepting various types of geophysical flows such as debris flows (Wendeler et al., 2006), open hillslope failures (Kwan et al., 2014) and snow avalanches (Margreth and Roth, 2008). Flexible barriers are advantageous for steep terrain because they occupy smaller footprints, are easier to construct and blend in with the natural surroundings compared to reinforced concrete barriers. For effective use of flexible barriers, as structural countermeasures to arrest debris flows, there is clearly a need to understand flow barrier interaction in detail.

Several scientific approaches are used by researchers in physical modelling of debris flow impact on structural countermeasures. Full-scale field tests, scaled flume tests and centrifuge tests are commonly used methods. Currently, only limited studies of full-scale debris flow impact on flexible barriers are reported (Wendeler et al., 2006, Ferrero et al., 2015). Idiosyncrasies of site conditions in field monitoring hinder interpretation of results which are generally unreproducible (Iverson 2015). To alleviate some of the shortcomings, Ng et al., (2017) adopted centrifuge modelling with idealized impervious flexible barrier. The idealized model barrier purposefully simplifies the interaction mechanism by ignoring the influence of barrier perviousness and energy dissipating elements. This results in large impact loads. In this study, the influence of energy dissipating elements on attenuating peak impact force of debris flows on a flexible barrier is systematically investigated in a 2 m wide 28 m-long flume by using novel energy dissipating brake elements developed in-house at HKUST. The use of a 2 m wide flume also addresses the issue of disproportionate scaling of fluid viscous stresses compared to grain frictional stress (Iverson 2015) that are prevalent in small-scale flume modelling.

2 PHYSICAL FLUME MODELLING

A 28 m-long flume (Fig. 2) is used to conduct physical experiments to gain new insight on the impact mechanisms of two-phase debris flows against a single flexible barrier. The flume has a uniform rectangular cross-section with a width of 2 m and a depth of 1 m. A storage container that can hold up to 10 m^3 is inclined at

30° at the top of the flume. The main flume is 15 m in length and has an inclination of 20°. The inclined flume transitions to an 8 m long horizontal runout pad. A double door gate system retains debris material inside the storage container. The doors are secured and released using a mechanical arm, which is controlled by an electric motor.

Fig. 1. Flexible barrier (Nepal).

Fig. 2. Twenty-eight-metre-long debris flow flume (Hong Kong).

2.1 Model setup and instrumentation

The flexible barrier used in this study has a ring net panel that is 2000 mm wide and 800 mm high. The barrier is installed at an inclined distance of 13.5 m from the gate (Fig. 3). Each ring is 100 mm in diameter and made using steel wires that are 2 mm in diameter. The ring net panel is supported by two horizontal cables, which are anchored to the sidewalls of the flume. Tension load cells (TML TCLK50KNB) are used to measure the impact load of each cable. A mesh with 25 mm square openings made of 1 mm diameter stainless steel wire was overlaid onto the ring net to retain the debris material during and after impact. Novel dual bilinear spring brake elements developed in-house at HKUST are installed between ends of cable and anchors at flume side walls using eyebolts to replicate the loading response of an energy dissipating device used in prototype barriers.

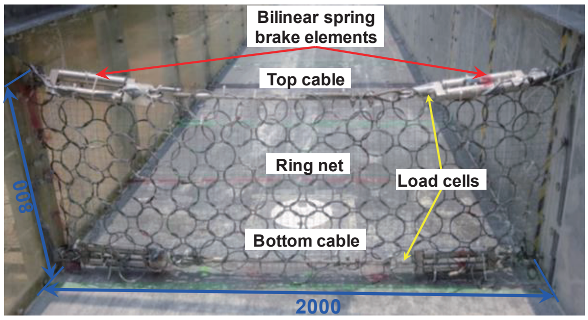

Fig. 3. Upstream front elevation of model flexible barrier with two brake elements per cable.

2.2 Novel dual bilinear spring brake element loading response

The novel dual bilinear spring brake element exhibits a bilinear elastic load-displacement response. Each of the dual spring element comprises two compression springs—one stiff (k_1) and the other soft (k_2)—in series inside a cylinder. The springs are separated inside the cylinder by a coaxial separator. The flexible spring is preloaded to a user specifiable load (P_{pre}) by adding a spacer between the spring and separator inside the cylinder. Before the applied load reaches the inflection point (P_{pre}), only the stiff spring resists the load at a slope $K_1 = k_1$. After reaching the inflection point, the load is shared by both springs in series and the equivalent stiffness reduces to model the elongation of energy dissipating elements $K_2 = k_1 k_2/(k_1 + k_2)$. The peak deformation of dual spring elements is preserved by a pneumatic locking system.

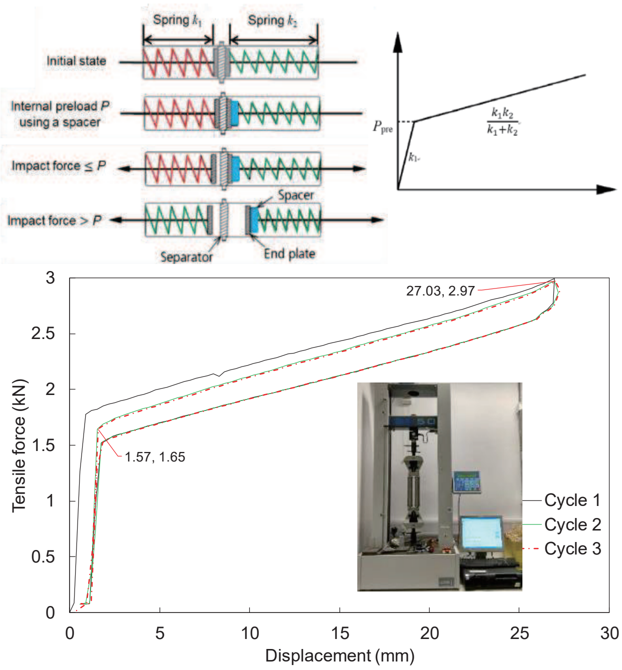

Fig. 4. Novel dual bilinear spring brake element working principle (top) and repeatable uniaxial tension response.

2.3 Test programme and procedure

To investigate the influence of brake elements on the loading response of flexible barrier impacted by debris flows, the brake element configuration is varied for different tests (Table 1). Prior to impact tests, a series of control tests are carried out to characterize the debris flow along the flume. In all the tests, the gates are closed and debris flow mixture is prepared in the storage container. Once the debris mixture is ready, the gates are opened and the debris is allowed to flow downstream simulating a dam break. The instrumentation is started simultaneously as the gate is opened and data is recorded at 2 kHz to capture debris flow interaction with the barrier.

Table 1. Test programme.

Test ID#	Number of brake elements per cable
DBr0	Nil
DBr1	1
DBr2	2

\# Debris volume = 2.5 m^3 in each test

3 INTERPRETATION OF TEST RESULTS

In the interpretation of experimental results, time t = 0 s represents the start of impact when debris flow front reaches the barrier.

Brake element effects on peak impact force

Fig. 5 shows the deflection of the load bearing cables and the barrier mesh resulting from different normal impact forces. The measured peak deflection of the cables and the barrier mesh are normalized by the barrier span (L) while the peak normal impact force is normalized by the hydrodynamic impact force (Kwan & Cheung 2012). The hydrodynamic impact force is defined as:

$$F_{\mathrm{dyn}} = \alpha \rho v^2 h w \tag{1}$$

where α is the hydrodynamic pressure coefficient, $\rho = 2000\ \mathrm{kg/m^3}$ is the bulk density of debris flow, $v = 6\ \mathrm{m/s}$ is the velocity of debris flow front impacting the barrier, $h = 0.06\ \mathrm{m}$ is the average flow depth of the debris flow and $w = 2.0\ \mathrm{m}$ is the flume width. Kwan & Cheung, (2012) proposes a hydrodynamic impact pressure coefficient of 2 for the design of flexible barriers subjected to debris flow impact, which also takes into account the effects of sizeable boulder impact and is shown for comparison. However, results of current study show that the measured normalized peak impact force (used as a measure of the hydrodynamic pressure coefficient) is 1.1 for flexible barrier without any brake elements. For tests with brakes, this pressure coefficient is much lower around 0.6. This discrepancy of more than 80% in the normalized peak impact force indicates there is room for optimizing the design impact coefficient value for debris flow without sizeable boulders.

The square, circular and triangular markers represent data points for tests DBr2, DBr1 and DBr0 respectively. The size of the markers corresponds to the magnitude of the normalized deflection and impact force. The largest markers (black) represent the barrier mesh, the intermediate markers (red) represent the bottom cable and the smallest markers (green) represent the top cable. In all the tests, it is observed that the barrier mesh has the largest deflection followed by the bottom and top cable respectively. The peak deflection of the bottom cable in test DBr2 is 30% larger than that measured in test DBr1 and 80% larger than in test DBr0. The influence of larger barrier deflections is reflected in the decreasing trend of the normalized peak impact force in test DBr2 compared to test DBr1 and DBr0. The normalized peak impact force in the case of test DBr0, DBr1 and DBr2 are 1.10, 0.64 and 0.57 respectively. Use of two brake elements per cable reduces the peak normal impact force by 50% compared to the test with no brake elements in the cables. The deflection of the barrier increases the impact duration and allows increased internal shearing of the flow by promoting frictional dissipation (Ng et al., 2019, 2020). The relative velocity between the flow and the deflected barrier leads to a decrease in momentum transfer during impact. The outflow of fine materials through the mesh opening and the curvature of the deflecting barrier further reduces momentum transfer from the flow. These combined processes result in lower impact force on a flexible barrier that undergoes larger deformation.

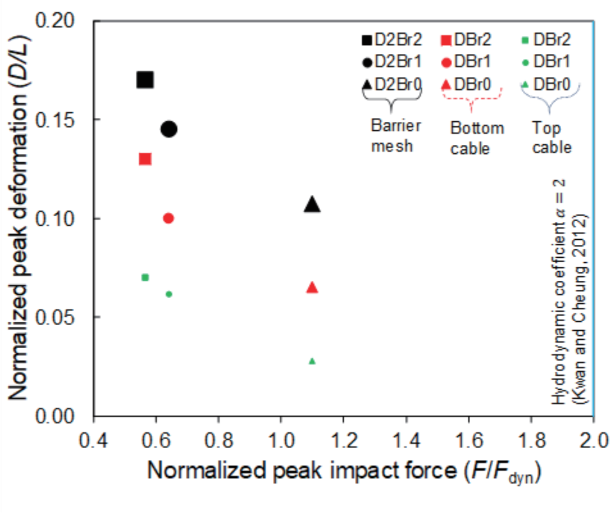

Fig. 5. Normalized peak impact force and normalized peak deformation for different brake element configurations.

4 CONCLUSIONS

A series of physical experiments modelling the impact of channelized debris flow on a side anchored flexible barrier was conducted in a state-of-the-art 28 m-long flume. Novel energy dissipating elements developed in-house at HKUST are used to vary the stiffness of the load bearing cables in order to attenuate peak impact force. A large deflection of the load bearing cables and mesh (D/L> 5%), due to the mobilization of brake elements, results in the reduction of the peak impact force induced on the barrier by up to 50 % compared to flexible barriers without brake elements.

ACKNOWLEDGEMENTS

The work described in this paper was supported by two grants from the Research Grant Council of the Government of Hong Kong Special Administrative Region, China (AoE/E-603/18). S. Poudyal gratefully acknowledges the support of Hong Kong PhD Fellowship Scheme (HKPFS) provided by the RGC of HKSAR, China.

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