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A New Fast Door-opening Method for Quick Release of a Rock Boulder or Debris in a Large-scale Physical Model

by

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Abstract

Study on mitigation of debris flows and rockfalls is a very challenging topic due to the complex moving and impacting mechanisms. Large-scale physical model is preferred by researchers in the study of debris flow and rockfall because large-scale tests can duplicate major phenomena of natural geo-hazard events. In the design of a large-scale physical model, how to initiate or release a certain volume of debris material or a giant rock boulder is the key technical issue. In current large-scale models for debris flow research, debris material is normally released from a reservoir with a trap door located at the upper end of the flowing path. It is found that the door-opening methods utilized in the models can interfere with the motions of the generated debris flows. In this note, a new fast door-opening method is introduced in detail. This method has been implemented in a large-scale physical model built in Hong Kong to study the impacts of rockfalls and debris flows on a flexible barrier. With the utilization of this novel door-opening method, the impact tests of rock boulders, dry granular flows, and debris flows were successfully performed. From the observations of the impact tests, the unbalanced resisting forces and the disturbance from the door were avoided. The successes of the large-scale tests using different testing materials demonstrated that the new fast door-opening method can be further utilized in physical modelling study of geohazards.

Keywords: Debris flow; Rockfall; Large-scale physical modelling; Door-opening method

Introduction

Many countries and regions (e.g. Japan, China, and Canada) are constantly threatened by natural hazards in the hilly terrain (Su *et al.* 2017; Takahashi 2014; Fan *et al.* 2017; Xu et al. 2019; Zhu and Randolph 2009). High degree of urbanization and a shortage of land resources in regions such as Hong Kong have necessitated the construction of infrastructures and residential buildings in the vicinity of natural hillsides with great risks of natural hazards (Kang and Chan 2017). European Organization for Technical Approvals (EOTA) introduced a comprehensive guideline for the design of rockfall net fences (Peila and Ronco 2009). Geotechnical Engineering Office (GEO) of Hong Kong Government published the first guide reference for the design of debris flow-resisting flexible barrier (Kwan and Cheung 2012). Volkwein et al. (2015) discussed the design standard of flexible barriers in preventing debris flows. However, the impact mechanisms of rockfalls, debris flows on a flexible barrier are still poorly understood. To fulfill this research gap, physical model tests have been advocated by researchers in the study of geotechnical engineering due to the good controllability in testing conditions and repeatability of tests (Volkwein *et al.* 2015; Iverson 2015; Xu et al. 2018).

In physical model tests to study the behavior of debris flows, scaling is a key factor because the influences of viscous shear resistance and excess pore-fluid pressure on the interaction of water with debris sediment have a close relationship with the scale of tests. Iverson (2015) concluded that miniaturized landslides exaggerate the effects of viscous shear resistance and weaken the effects of excess pore-fluid pressure. On the other hand, for the research of flexible barriers, which is a complicated structure with several major components, miniatured prototypes cannot realistically reflect the dynamic performance under the impacts of different geohazards, especially the influence of earth gravity or the stress level (Wendeler et al. 2018). Therefore, large-scale physical modelling is preferred by researchers to study the behavior of debris flows and their interaction with protection structures. The U.S. Geological Survey

(USGS) in cooperation with the U.S. Forest Service built a large-scale flume in 1991 to study landslide initiation and debris flow deposition behaviors (Iverson *et al.* 1992). Paik *et al.* (2012) built a real-scale field experiment facility in a natural gully in Korea with the main objectives of investigating the erosional and depositional patterns of debris flows. The Swiss Federal Institute for Forest Snow and Landscape Research (WSL) constructed a large-scale facility in Veltheim, Switzerland to study the impact of debris flows (Bugnion *et al.* 2012).

Brief Description of the Large-scale Physical Model in Hong Kong

Based on the previous works and conditions in Hong Kong, a large-scale physical modeling facility has been designed and built in the Road Research Lab of The Hong Kong Polytechnic University for studying the interaction of rockfalls or debris flows with a flexible barrier. This large-scale facility is built in a reinforced steel frame, as shown in Fig.1(a). This facility can be divided into 4 main components: (i) a reservoir with the capacity of 5 m^3 locating 5 m above the bottom cable of the flexible barrier; (ii) a flip-up door and corresponding fast door-opening system; (iii) a flexible barrier with supporting posts and cables; and (iv) a flume connecting the reservoir to the flexible barrier. This flume has a channel width of 1.5 m, a length of 7 m, and an inclination of 35 °. Side walls of the flume are made up of tempered glass to provide a clear observation of the generated rockfalls and debris flows.

Instrumentation

To monitor the dynamic response of a flexible barrier under the impact of natural hazards, this facility is instrumented by a high-frequency monitoring system (see Fig.1(a)). The monitoring system consists of tension link transducers, a dynamic datalogger, and two high-speed cameras. Two types of transducers are installed on the flexible protection system: mini-tension link transducers and high capacity tension link transducers. The mini-tension link transducers are utilized to link two adjacent rings in the central area of the flexible barrier to measure the impact force on the flexible barrier directly, as shown in Fig.1(a). Besides, four commercial high capacity tension link transducers (Type: CFBLBH) with a certified capacity of 50 kN are installed on the supporting cables of the posts. A dynamic data-logger with the capability of sampling 48 transducers at 1000 Hz simultaneously is used to collect the data of all transducers. Two high-speed cameras capable of capturing a resolution of 1024 ×768 pixels at a sampling rate of 1000 frames per second are used to capture the motions of the impacting mass and the dynamic response of the flexible barrier. One high-speed camera is installed at the right side of the barrier, and the other camera is set in front of the barrier.

A New Fast Door-opening Method for Quick Release of a Rock Boulder or Debris Flow

Limitations of door-opening methods in current large-scale physical models

In the design of a large-scale physical model for debris flow study, the release method of debris material is of concern, because a poorly designed release method could seriously interfere with the motion and the impact characteristics of the debris flow. Table 1 lists the basic parameters and the door-opening methods of representative large-scale physical models in the literature. To better understand the possible influences of the existing door-opening methods on the generated debris flows, the large-scale physical facility built by USGS in 1991 is reviewed in this note. From the description of testing procedures and the videos of the experiments (Iverson 2015), it is observed that a pair of steel head-gates were side opened by the self-weight of the debris deposit when the lock was released. The steel head-gates used in that testing facility could affect the generated debris flow in three aspects: firstly, the kinetic energy of the debris flow can be obviously dissipated when pushing the heavy steel head-gates open; secondly, the unbalanced frictions of the side-open doors may cause deviation of the flow direction or asymmetrical flow velocities and depths of the generated debris front; thirdly, the side-open doors are left in the flume as obstacles after being opened, which impedes the motion of the debris flow continuously.

To solve those problems, the following aspects should be considered for development of the door-opening method: (i) the lock of the door should be easy to operate and sturdy enough to sustain the earth pressure from the stored debris material; (ii) the door should be opened faster than the moving of the testing material to prevent disturbance of the generated rockfall or debris flow; (iii) the door should be out of the flowing path of the generated debris flow after being opened to avoid continuous obstruction to the debris flow.

Development of a new fast door-opening method and the release system

Based on the above review, a developed fast door-opening method is proposed in this study to fulfill the requirements:

(a) A flip-up door is utilized, which can be out of the moving path after being pulled up to avoid the continuous obstruction to the released boulder or debris flow.

(b) A spring set is connected to the flip-up door to lift the door up in a short period and keep the door open.

(c) Rotatable levers are utilized to lock the door and impose excessive compressive force on the door to provide water tightness by rotating toward the door.

Following the above door-opening method, a new release system has been designed and implemented in the large-scale facility. Beside a steel reinforced flip-up door, the new release system contains 3 main components: a set of springs, a pair of rotatable steel levers, and a pair of quick release hooks (see Fig. 1(b)). Detailed descriptions of the functions and characteristics of those components are presented as follows:

The springs: in our design, 4 springs are attached to the back surface of the flip-up door. The functions of the springs are lifting the door up in a short time period and keeping the door open during the test. The springs are pre-stretched by the wire twisters before each test to store the potential energy and bonce the door up. Energy dissipation blocks are installed on the frame to dissipate the potential energy of the springs to prevent the swing of the door after being bounced up in a short period and keep the door open in a designed opening angle. In our facility, the designed door-opening angle is 55 ° to keep the door parallel to the flume. Based on the video recordings, the flip-up door can be opened in less than 0.5 s with the assistance of the spring set.

The steel levers: the levers are curved steel bars with the fulcrums installed on an I-bean underneath the flip-up door and the flume basal plate (see Fig. 1(b)). The levers are used to lock the door before the test and release the door to start the test. The levers can transform from the lock status by rotating up to the unlock status by rotating beneath the flume in a short period (less than 0.5 s) to be out of the flowing path after releasing the door with the help of dead weight. Rectangular openings (300 mm * 100 mm) on the flume base plate provide rotation paths to the levers. To prevent leakage of debris material during the test, fiber-reinforced flexible rubber mats with the dimension of 5-mm-thick, 300-mm-width, and 500-mm-length are used to cover those openings. The flexible rubber mat can flip with the rotation of the lever and cover the opening when the lever rotates beneath the basal plate. The upper end of the rubber mat is fixed on the flume basal plate by compression of a steel bar (300 mm * 10 mm) with screws. Due to the small thickness of the rubber mat to reduce obstruction of the moving particles, the rubber mats should be replaced after every three tests to prevent being ripped. The levers should have a high strength to resist the earth pressure from debris material in the reservoir and a high stiffness to reduce the deformation under the earth pressure. The large deformation can form a gap between the flip-up door and the reservoir, which can lead to a leakage of the debris material. In our study, the dimensions and the parameters of the lever have been calibrated by numerical simulation using the software ABAQUS. The designed loading for the numerical simulation is the maximum earth pressure from the debris material with a Factor of Safety (FoS) of 2.0. By performing numerical simulations with the designed loading, the stiffness and the strength of the lever are determined following the principle that no plastic deformation occurs in any part of the lever, and the deformation is small (less than 5 mm) to prevent leakage of slurry. Referring to the simulation result, the hardening technique has been utilized on the steel levers to improve the mechanical performance.

The quick release hooks: two quick release hooks are used to lock the flip-up door, which are provided by the RELEASE company with the model name TGQ-5T-LS. The specially designed hook can be released by a small pulling force (around 50 N) under the maximum working load of 50 kN. To make sure that the hooks can be released at the same time, the triggers of both hooks are connected to one rope, and the test is started by arranging an authorized person to pull the rope and release the hooks simultaneously. With the application of the hooks, the door can be locked easily in the preparation stage and opened fast in the test. As shown in Fig. 1(b), the lock of the door is realized by utilizing the hooks to stretch the steel chains connecting the levers with the frame foundation and restrict the rotation of the levers. Once the hooks are released at the beginning of the test, the levers can rotate beneath the flume basal plate and open the door to start a test.

Operating procedures of the release system using the fast door-opening method

The operation procedures of the release mechanism are presented in Fig. 1(b). The procedures can be specified into 4 steps:

(a) Lock the door by using the quick release hooks to stretch the chains and restrict the rotation of the levers.

(b) Lift the testing boulder or debris material into the reservoir, and pre-stretch the springs by the wire twisters connected to the upper ends of the springs.

(c) The test is started by releasing the quick release hooks. Afterwards, the levers rotate beneath the flume with the assistance of dead weight connected to their tails. Meanwhile, the door is lifted in less than 0.5 second and kept open by the pre-stretched springs.

(d) After the test, the door can be closed again by releasing the springs.

With these simple procedures, a series of large-scale physical modelling tests with different testing materials have been successfully conducted using the large-scale testing facility with implementation of this new fast door-opening method.

Performance and Evaluation of the New Fast Door-opening System

A comparison of the door-opening systems in representative large-scale debris flow physical models in the literature (Bugnion *et al.* 2012; Iverson *et al.* 2010; Paik *et al.* 2012) and the new door-opening system in the present model in PolyU, Hong Kong is made in Table 1. Based on the comparison, the door-opening method in PolyU model has the best performance among all listed large-scale physical models. Moreover, the impact tests of rockfalls, dry granular flows, and debris flows have been successfully performed in this large-scale physical model to assess this new door-opening system and study the interaction between different impacting masses and a flexible barrier.

Fig. 2 plots the performance of the door-opening system in a rockfall impact test. In the test, the flip-up door was firstly locked by the levers, and the boulder was located behind the center of the door to make sure the boulder can hit the central area of the flexible barrier. At the beginning of the test, the flip-up door was pulled up in a short time and kept open by the pre-stretched spring set. After that, the boulder rolled down along the central axis of the flume and hit the central area of the flexible barrier. From the photographs plotted in Fig. 2, it can be observed that the motion of the boulder was not impeded by the release door due to the utilization of the fast door-opening system. The results and findings of the rockfall impact tests were analyzed and presented in Tan et al. (2018b).

The performance of the door-opening system in a granular flow impact test is shown in Fig. 3. In this test, around 4 m^3 aggregate was filled in the reservoir in the preparation stage, which imposed a large earth pressure on the flip-up door and the lever locks. At the beginning of the test, the door flipped up fast with the assistance of the spring set, the levers rotated beneath the flume base, and the rubber mats covered the openings at the flume basal plate to prevent leakage of the granular material. It can be observed from Fig. 3 that the door was opened much faster than the initiation of the granular flow. Neither the levers nor the flip-up door interfered with the granular flow during the test. The results and findings of the granular flow impact tests were analyzed and presented in Tan et al. (2018a).

The debris flow material consists of a mixture of aggregate and completely deposited granite (CDG) slurry with a high water content (higher than 45% in mass). Therefore, leakage of slurry should be taken into serious consideration. The leakage of slurry and water can obviously reduce the fluidity and weaken the homogeneity of the generated debris flow. To prevent the leakage problem, highly compressible rubber cushions and silicone glue were sandwiched in the gap between the door and the reservoir to provide water-tightness. Besides, basket screws were attached to the ends of the chains to provide excessive compressive stress on the door to enhance the sealing ability. It can be observed from Fig. 4(a) that no leakage of slurry occurred before the test, and the generated debris front was uniform and undisturbed. The peak loads measured by the mini-tension link transducers in the debris flow impact test is shown in Fig.4(b), which indicates that the debris flow imposes a horizontally symmetrical impact pressure on the flexible barrier.

Therefore, it can be concluded from the tests that this new fast door-opening system implemented in the large-scale physical model has a reliable performance and can avoid interference from the door.

Conclusions

A new fast door-opening method is proposed and introduced in detail in this note. This new method has been implemented in a large-scale physical modelling facility to study the impact mechanisms of different natural hazards. A series of tests including single boulder, dry granular flow and debris flow impact tests were performed using this facility. From the observations of those tests, it was found that the interference of the release door with the testing material has been avoided by utilizing this new system. The reliable performance of the new door-opening method proves that it can be utilized in the experimental study of natural hazards.

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References

Bugnion, L., McArdell, B. W., Bartelt, P., and Wendeler, C. (2012). Measurements of hillslope debris flow impact pressure on obstacles. *Landslides*, 9(2), 179-187.

Fan, W., Wei, Y.N., and Deng, L. (2017). Failure modes and mechanisms of shallow debris landslides using an artificial rainfall model experiment on Qin-ba Mountain. *International Journal of Geomechanics*, 18(3), p.04017157.

Iverson, R.M. (2015). Scaling and design of landslide and debris-flow experiments. *Geomorphology*, 244, pp.9-20.

Iverson, R.M., Logan, M., LaHusen, R.G. and Berti, M. (2010). The perfect debris flow? Aggregated results from 28 large-scale experiments. *Journal of Geophysical Research: Earth Surface*, 115(F3).

Iverson, Richard Matthew, John E. Costa, and R. G. LaHusen. (1992). *Debris-flow flume at HJ Andrews experimental forest, Oregon.* No. 92-483. US Geological Survey, Dept. of the Interior.

Kang, C., and Chan, D. (2017). Modeling of Entrainment in Debris Flow Analysis for Dry Granular Material. *International Journal of Geomechanics*, 17(10), p.04017087.

Kwan, J. S. H., and Cheung R. W. M. (2012). *Suggestion on design approaches for flexible debris resisting barriers.* Discussion note DN1/2012. Geotechnical Engineering Office, HKSAR Government.

Paik, J., Son, S., Kim, T., and Kim, S. (2012). A real-scale field experiment of debris flow for investigating its deposition and entrainment. In AGU Fall Meeting Abstracts.

Peila, D., and Ronco, C. (2009). Design of rockfall net fences and the new ETAG 027 European guideline. *Natural Hazards and Earth System Sciences*, 9(4), 1291-1298.

Su L.J., Xu X.Q., Genge X.Y., and Liang S.Q. (2017). An integrated geophysical approach for investigating hydro-geological characteristics of a debris landslide in the Wenchuan Earthquake Area. *Engineering Geology,* 219: 52-63, DOI: 10.1016/j.enggeo.2016.11.020

Takahashi, T. (2014). Debris flow: mechanics, prediction and countermeasures. CRC press.

Tan, D. Y., Yin, J. H., Feng, W. Q., Qin, J. Q., and Zhu, Z. H. (2018a). Large-scale physical modelling study of a flexible barrier under the impact of granular flows. *Natural Hazards and Earth System Sciences, 18, 2625-2640, https://doi.org/10.5194/nhess-18-2625-2018.*

Tan, D.Y., Yin, J.H., Qin, J.Q., Zhu, Z.H. and Feng, W.Q. (2018b) Large-scale physical modeling study on the interaction between rockfall and flexible barrier. *Landslides*, pp.1-11.

Volkwein, A., Baumann, R., Rickli, C., and Wendeler, C. (2015). Standardization for flexible debris retention barriers. *In Engineering Geology for Society and Territory*-Volume 2 (pp. 193-196). Springer, Cham.

Wendeler, C., Volkwein, A., McArdell, B. W., and Bartelt, P. (2018). Load model for designing flexible steel barriers for debris flow mitigation. *Canadian Geotechnical Journal*, 99 1-39.

Won, S., Lee, S.W., Paik, J., Yune, C.Y., and Kim, G. (2016). Analysis of Erosion in Debris Flow Experiment Using Terrestrial LiDAR. *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*, 34(3), 309-317.

Xu, D.S., Liu, H.B., Luo, W.L. (2018) Evaluation of interface shear behavior of GFRP soil nails with a strain-transfer model and distributed fiber-optic sensors. *Computers and Geotechnics*, 95: 180-190.

Xu, D.S., Tang Z., Zhang L. (2019) Interpretation of coarse effect in simple shear behavior of binary sand-gravel mixture by DEM with authentic particle shape. *Construction and Building Materials*, 195: 292-304.

Zhu, H., and Randolph, M.F. (2009). Large deformation finite-element analysis of submarine landslide interaction with embedded pipelines. *International Journal of Geomechanics*, 10(4), pp.145-152.