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МАЗМҰНЫ/ CONTENTS/ СОДЕРЖАНИЕ

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Centrifuge modelling on granular flow and boundary erosion

Abstract. *Boundary forces generated by debris flows can be powerful enough to erode bedrock and cause considerable damage to infrastructure during runout. Performing experiments large enough to generate realistic boundary forces is a challenge. An alternative is to run table-top simulations with unnaturally weak but fast-eroding pseudo-bedrock, another is to extrapolate from micro-erosion of natural substrates driven by unnaturally weak impacts. A different approach was taken by using centrifuge modelling to scale up the granular impact forces and produce boundary erosion. A 40cm-diameter rotating drum on the centrifuge at effective gravity levels up to 100 g was deployed to generate analog debris flows with an effective flow depth up to several meters. The granular flow and boundary erosion were studied (a) by using high-speed video and particle tracking to measure their velocity fields, and (b) by mapping patterns of wear in a synthetic bedrock wall plate using 3D micro-photogrammetric methods. By combining these experimental results with theoretical developments, basic ingredients for constructing an erosion law for sliding wear at the margins of a dense granular flow were obtained.*

Keywords: *debris flow, bedrock erosion, centrifuge modeling, granular flow, particle tracking velocimetry (PTV), microphotogrammetric mapping.*

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Introduction. When debris flows pass through bedrock canyons or reinforced concrete structures, they can seriously abrade and damage lateral and bottom boundaries. Such damage processes are difficult to study in-situ during events, since both their timing and location is difficult to anticipate and such flows can easily destroy instrumentation. Knowledge gained from the field is therefore mostly limited to observations acquired after events and is often qualitative in nature.

As an example shown in Figure 1, serious debris flow impacts caused by Typhoon Morakot that made landfall on Taiwan on 7-9 August 2009. This cyclone brought 24-hour rainfall accumulations exceeding 500 mm to mountainous terrain in the south-west of the island (Chien and Kuo 2011, Xie and Zhang 2012). Heavy mass-wasting ensued, such as along the Putunpunas River, a tributary of the Laonong River, which suffered massive landsliding and subsequent debris flow. Sediment from this and nearby tributary flows has raised the bed-level of the Laonong River by about 30 m. A typical section in the feeder canyon for the Putunpunas debris flow is shown in Figure 2: its shape is the result of boundary erosion by multiple, similarly powerful debris flows over millennia.

In this study, we try to demonstrate the feasibility of running centrifuge model tests on analog debris flows that simulate this kind of wear process in a controlled environment. The final goal is to use experimental data to develop a semi-empirical boundary erosion law for debris flows.

Background. Granular materials can behave like solid, a liquid or a gas. For the intermediate dense regime, it still lacks a unified view to describe and has motivated many studies over the past decades. In the review of empirical data on dense granular flow, GDR Midi (2004) summarized a wide range of test device used for laboratory experiments. Of particular interest here are heap and drum

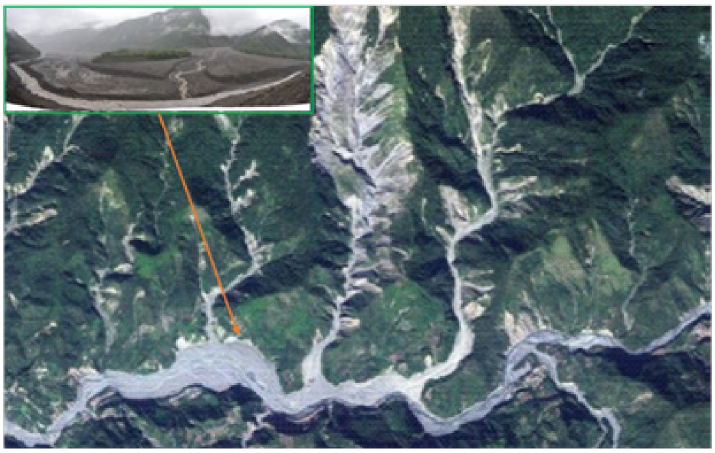

Figure 1 - Debris flows caused by Typhoon Morakot: Putunpunas River, SW Taiwan

Figure 2 - Typical debris-flow channel, Putunpunas River

flow apparatus. Heap flow rigs are popular in debris flow experiments (e.g., Savage, 1984; Iverson 1997; Azanza et al. 1999 and Parsons et al. 2001). Typically, single event, short duration flows are generated, making any study of their long-term erosive effects impractical. In contrast, drum-driven flows are less realistic, but they provide a form of recirculating flume that makes long-term erosion study feasible. The work of Hsu (2010) is a good example: she used a 4 m-diameter drum to drive thin, persistent flows using a range of media mixtures (sand, gravel, mud, water). Drum-driven granular flows have wide industrial application, and there is a substantial literature on their use (Ristow 1996; Boateng 1998 and Ding et al. 2001). By considering both the granular flow and the boundary erosion, we opted to use a small (0.4 m-diameter) drum to explore the effects of erosive granular flows. Unlike the Hsu (2010) experiments that focused on thin flows by loading the drum with a small amount of sediment, we used a half-filled drum to drive a central zone of channelized granular avalanching. Instead of studying wear caused by impacts at the frontal tongue of a simulated debris flow (Hsu et al. 2008), we looked at the wear induced by frictional sliding along the drum wall. Despite its relevance to debris-flow driven erosion, this sliding wear process has not been widely studied.

Experimental design and test procedure.

Scaling-up granular flows. A key goal was to study the erosion of materials with strength and erodibility properties similar to real rocks. To achieve this, we have to work with granular flows whose boundary forces match those of natural debris flows. Rather than building a very large drum and working with large grain impacts, we scaled up small-grain impact forces by running the drum experiments under enhanced gravity in a geotechnical centrifuge. Brucks et al. (2007) were the first to demonstrate the feasibility of performing drum-based granular flow experiments on a centrifuge. Partly inspired by their work, a similar drum apparatus was built for deployment on the 100 g-ton capacity centrifuge at Columbia University (Figure 3).

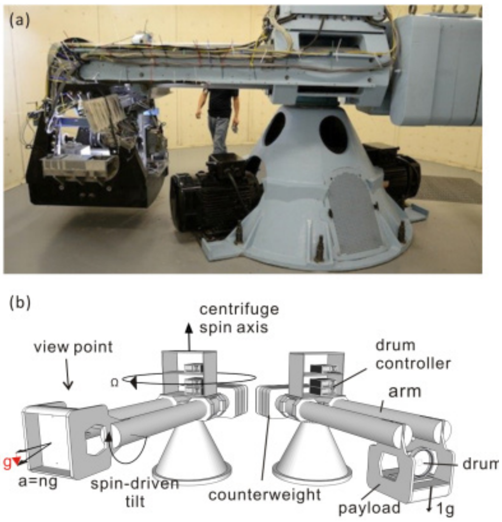

Figure 3 - Schematic view of the centrifuge

Drum design Our primary design goal is to drive steady granular avalanching on the drum such that we mimic debris flow erosion at drum wall. The flow regime on a drum is roughly predicted by Froude number Fr and effective g (Brucks et al. 2007), suitable design parameters of the drum can be determined. Main constraint is the maximum power supply on the centrifuge payload of Pmax=1 kW. Taking into account the physical space available on the payload, the maximum g level (100g), material densities, and a reasonable grain size range of D=2.3~4 mm, we settled on a drum of Diameter D=400 mm built of aluminum alloy (Figure 4).

Erosion plate To simulate debris-flow-driven boundary erosion, we embed a disk of synthetic rock into the wall of the drum (Figure 7). Grain flow past this erosion plate drives sliding wear at rates determined by the strength of the rock, grain size, speed and depth of flow, and effective g at the drum center. We opted to mount the synthetic rock on an aluminum plate with diameter 200 mm and depth 10 mm.

The synthetic rock was made with a mixture of gypsum cement, sand and water. The weight ration of gypsum to sand was 7:3, and 35% W/C ratio was adopted. The strengths of the synthetic rock at different aging were checked through element tests in both tension and compression. Test results together with the density of the specimens are shown in Figure 5. Although a stably converged strength was hardly determined, by comparing compressive strength with density, we deduced that the synthetic rock reaches a stable strength after about 20 days.

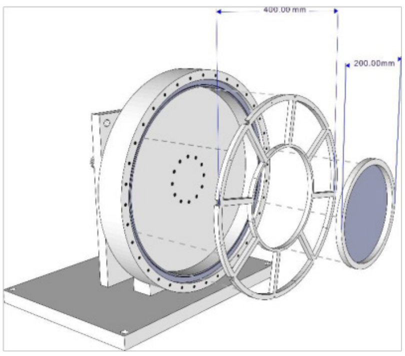

Figure 4 - Drum and the erosion plate

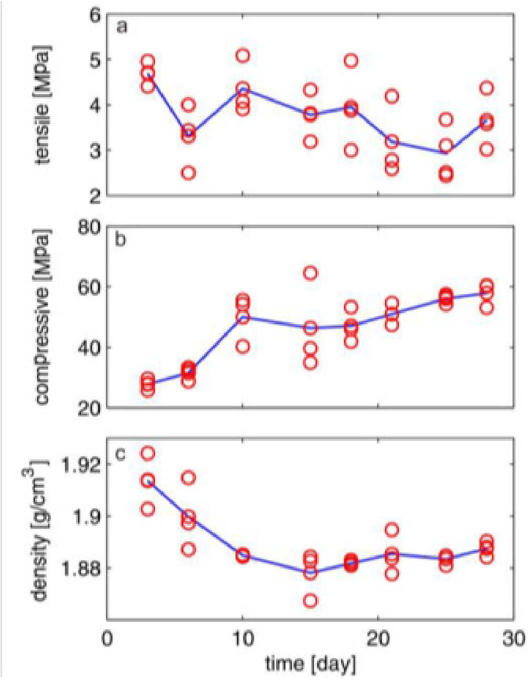

Figure 5 - Strength and density of synthetic bedrock

High-speed video camera To acquire high definition images for analyzing the velocity field this limitation, a high speed video camera, Phantom Miro 320s, which delivers a raw image size of 1400x1210 at 1800 fps was used. By placing the camera orthogonally in front of the drum at a distance of 400 mm, and by using a 16 mm wide-angle C-mount lens, we were able to view the entire drum with little distortion (Figure 6). Image acquisition was controlled remotely over Wi-Fi during centrifuge spinning, allowing us to record 2~3s bursts of video at a series of effective g-levels and drum rotation rates during a single run.

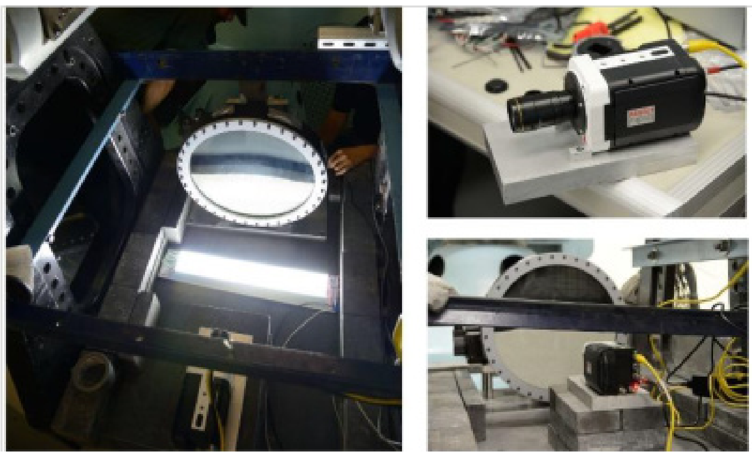

Figure 6 - High speed video camera and installation

Image analyses.

Grain flow velocity field Particle tracking velocimetry (PTV) has been applied in wide range of experimental contexts (Adrain 1991) and has been shown to be capable of high accuracy. The research group has adapted the PTV method and developed code tailored to tracking ensemble coarse grain motions (Capart 2002). The code was adapted further during the present study to address the particular challenges posed by drum-driven granular avalanching.

The PTV image processing sequence is illustrated in Figure 10. First, to establish a mapping between the images and the drum, a calibration plate with fixed target pattern was used to measure the drum-sensor distance. Then each image was projected into a Cartesian coordinate system whose origin is at the center of the drum. Next, filtering techniques were applied to identify characteristic points on grains (Figure 7, left inset, yellow points). By pairing grains in successive images based on their proximity, apparent grain displacements over time were tracked and a time series of grain velocity fields was obtained (Figure 7, top right). Since the drum generates steady non-uniform flow, multiple frames were picked up to bin and average the grain velocities (here 4980 frames lasting 2.77s were adopted) and calculate the gridded velocity field (Figure 7, right bottom). Finally, the stream function of the grain flow field was obtained by processing further the velocity field data and eliminating the empty cells.

Multitemporal Mapping of Erosion Patterns Drum rotation drives a lens-shaped zone of granular flow at whose wall boundaries frictional sliding takes place. The goal of the tests is to induce erosion on the synthetic rock plate embedded in the back wall and to measure the pattern and degree of erosion over a series of tests. To achieve the latter, a novel microtopographic mapping technique was adopted. This mapping method was based on close-range photography and modern photogrammetric techniques, specifically structure-from-motion and multiview stereo (Verhoeven 2011 and Fonstad et al. 2013) provided by the commercial software tool PhotoScan created by AgiSoft. To map microtopography at a resolution of ~1 mm to a vertical precision of ~100 μm over the entire 200 mm-diameter erosion plate, a 36 Mpixel professional DSLR with a good quality 35 mm prime lens was used. Sixteen (16) accurately measured ground control points arrayed around the erosion plate to guide calibration and scaling. The lighting was also carefully controlled. A 3D topographic model of the required resolution with a set of only 16 oblique photos taken at a distance of 350 mm was constructed as shown in Figure 8.

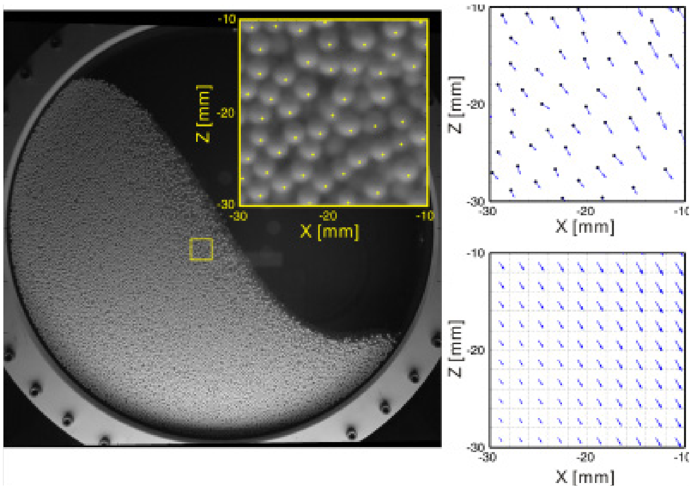

Figure 7 - Particle tracking velocimetry (PTV) processes

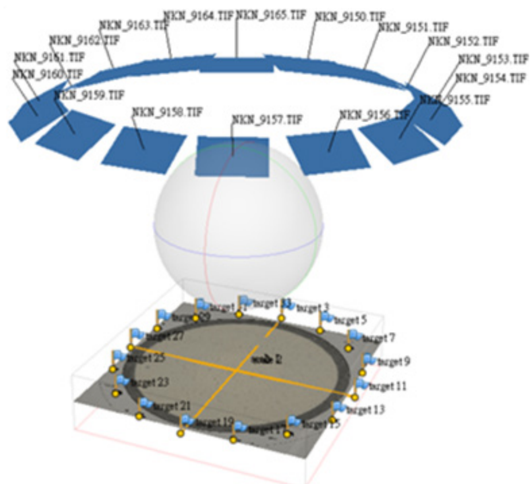

Figure 8 - Microphotogrammetric mapping of erosion plate

Test results. A series of drum tests at different effective g levels and rotation rates has been conducted to explore the granular flow behavior (Figure 9), and the boundary erosion process (Table 1).

As for the flow behavior, results drawn from this study are in broad agreement with Brucks et al., (2007). It is found that a series of flow regimes from intermittent avalanching, to continuous planar avalanching, to avalanching with a sigmoidal free (upper) surface, all approximately delimited by Froude number.

Figure 9 illustrates these results. The left-hand column shows long-exposure images generated from about 100 video frames spanning a little over 0.05 s. These images demonstrate the broad dependence of flow geometry on Froude number: first, as the rotation rate is increased from low (2 rpm, Fr~0.001) to high (20 rpm, Fr~0.1; bottom to middle images) and the free upper flow surface ranges from planar to sigmoidally curved; second, as effective gravity is increased from 1 g to 50 g (Fr~0.002) and the free surface is forced to return to a planar form (middle to top images). The middle column visualizes some raw results from PTV mapping of the velocity field: warm colors indicate high granular flow speeds, while cool colors indicate slower flow.

The cases with similar Froude numbers Fr, i.e., 1 g and 2 rpm (bottom) and 50 g and 20 rpm (top), show quite similar flow patterns, but order-of-magnitude difference in granular flow speed. The right column shows the streamlines (pink) and the base of the granular flow layer (green). The flow layer is thinner at 1 g and 2 rpm (bottom) and at 50 g and 20 rpm (top), i.e., lower Fr, and thicker at 1 g and 20 rpm (middle), i.e., at higher Fr. By combining the granular flow fields with the flow layer boundaries identified using the streamlines, we can make the measurements of grain-wall velocity and stress that will be the essential ingredients in an empirical erosion law.

Table 1 summarizes the series of erosion tests subsequently carried out with the synthetic rock erosion plate placed axially on the drum wall (Figure 4). The rock surface in its initial state (S1) was smooth and flat, and its microtopography was mapped before and after progressive erosion at various effective g levels, rotation rates, and grain types. By testing with these parameters the degree of erosion for each state were identified.

As the results, negligible erosion at low effective g (S2 to S3), centrally localized erosion at high g with spherical (2.3 mm and 4 mm, mean diameter) grains (S1 to S2, S3 to S4, S6 to S7, S7 to S8), and faster erosion over a broader area with angular 4 mm grains (S4 to S5, S5 to S6) were observed as shown in Figures 10 and 11. It is also found that, by fixing the flow depth while tuning the grain size and rotation rate (S6 to S7 and S7 to S8), faster flow speeds and larger grain sizes strongly enhance erosion. It is important to remember that these patterns of plate erosion are the result of angular integration (as the drum rotates) of a spatially variable wear rate field induced by frictional sliding at the wall of the granular flow zone. The central localization of erosion is therefore the result of either a velocity threshold or a threshold in wall-normal stress (therefore frictional shear stress) – or a combination of both – surpassed in the faster, deeper flow zone near the drum axis.

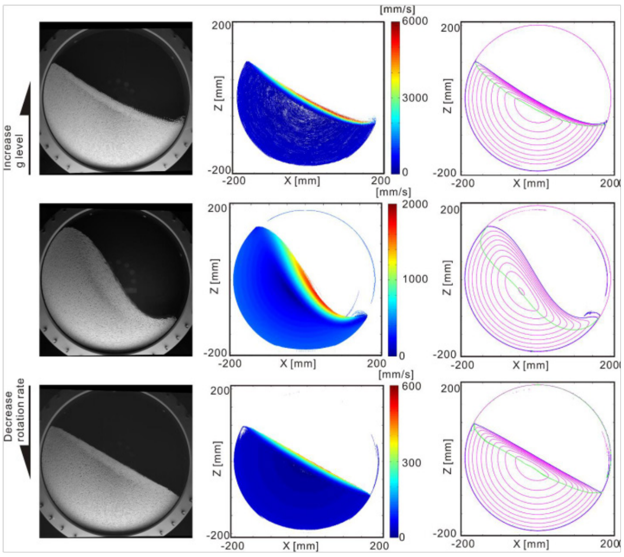

Figure 10 -- Granular flow behavior. Top row: 20 rpm at 50 g; middle row: 20 rpm at 1 g; bottom row: 2 rpm at 1 g. Left column: long exposure images; middle column: velocity fields; right column: stream lines

Table 1 - Summary of erosion plate tests

States Before/After	Grain size (mm)	Grain shape	Duration (min.)	Rotation rate (rpm)	g-level (g)	Weight lose (gram)
S1~S2	2.3	spherical	30	30	50	Not measured
S2~S3	2.3	spherical	30	30	1	0.076
S3~S4	2.3	spherical	30	30	50	14.835
S4~S5	4	angular	0.6	48	50	4.806
S5~S6	4	angular	5	30	50	21.483
S6~S7	4	spherical	10	45	50	26.238
S7~S8	2.3	spherical	30	30	50	10.088

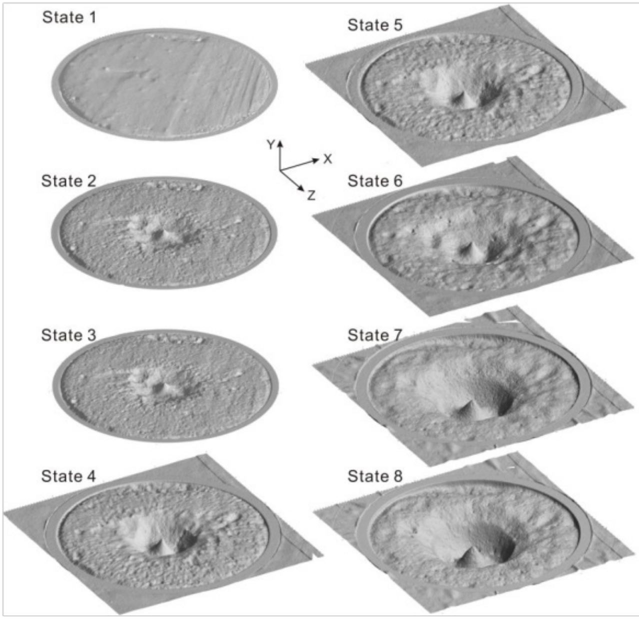

Figure 10 - Microtopography of the erosion plate for successive states

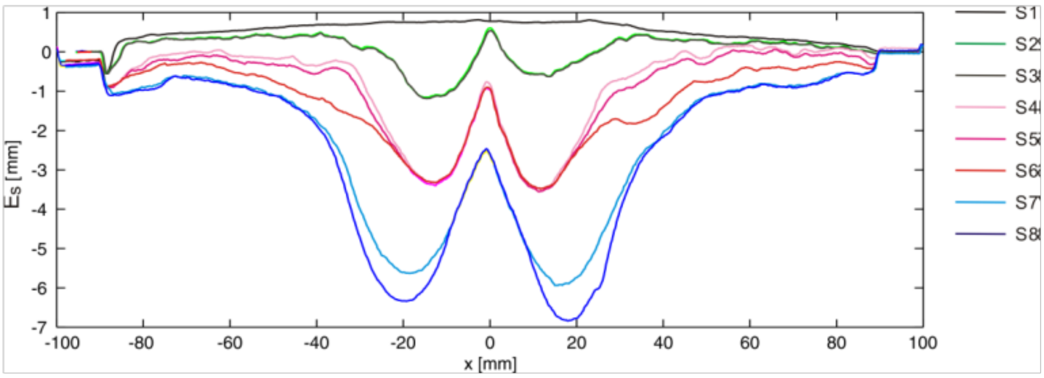

Figure 11 - Profiles of the erosion plate at different state (z = 0)

Concluding remarks. In this study, we have demonstrated the feasibility of using a centrifuge to scale up table-top-size experiments with granular flows to drive erosion of material similar to natural bedrock. In addition, methods for quantifying the patterns and rates of granular flow and their consequent boundary erosion were developed. These methods are accurate and reliable enough to provide the kinds of measurements needed to build an empirical law for sliding wear at the margins of a dry dense granular flow. Furthermore, based on pilot experiments not described here, we anticipate that wet granular flows that better mimic true (i.e., wet and muddy) debris flows will also be amenable to this kind of treatment.

As Brucks et al. (2007) have pointed out, granular flow experiments at effective g levels over 10 g are prone to non-negligible Coriolis forces. The effects of Coriolis forces on the granular flow were investigated in detail and reported separately (Hung et al. 2016).

On the long term, the observation of a velocity-stress threshold in the wear process may be of use in the mapping of debris flow induced erosion hazard.

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Түйіршікті ағын мен шекаралық эрозияны центрифугалық модельдеу

Аңдатпа. Сел ағындары құрған шекара күштері байырғы тау жыныстарын бұзып, соққы кезінде инфрақұрылымға айтарлықтай зиян келтіруі мүмкін. Нақты шекара күштерін құруға жеткілікті үлкен эксперименттер жүргізу ауыр міндет болып табылады. Балама-бұл табиғи емес әлсіз, бірақ тез ыдырайтын жалған тамырлы жыныстармен жұмыс үстелі модельдеулерін жүргізу, сондай-ақ, табиғи емес әлсіз соққылардан туындаған табиғи субстраттардың микроэрозиялық қасиеттерін экстраполяциялау. Центрифугадағы диаметрі 40 см айналмалы барабан 100 г дейін тиімді ауырлық деңгейінде Аналогты қоқыс ағындарын жасау үшін бірнеше метрге дейін тиімді ағынмен орналастырылды. Түйіршікті ағын және шекара эрозиясы (а) жылдамдық өрістерін өлшеу үшін жоғары жылдамдықты бейне және бөлшектерді бақылау арқылы және (Б) 3D микрофотограмметриялық әдістерді қолдана отырып, байырғы тау жыныстарының синтетикалық қабырға пластинасындағы тозу заңдылықтарын картаға түсіру арқылы зерттелді. Осы эксперименттік нәтижелерді теориялық әзірлемелермен біріктіре отырып, тығыз түйіршікті ағынның шекараларында жылжымалы тозу эрозиясының Заңын құру үшін негізгі компоненттер алынды.

Түйін сөздер: сел тасқыны, байырғы жыныстардың эрозиясы, центрифугалық модельдеу, түйіршіктелген ағын, бөлшектерді бақылаудың велосиметриясы((ПТВ), микрофотограмметриялық карталау.

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Центрифужное моделирование зернистого потока и пограничной эрозии

Аннотация. Пограничные силы, создаваемые селевыми потоками, могут быть достаточно мощными, чтобы разрушать коренные породы и наносить значительный ущерб инфраструктуре во время биения. Проведение экспериментов, достаточно больших для создания реалистичных граничных сил, является сложной задачей. Альтернативой является проведение настольных симуляций с неестественно слабыми, но быстро разрушающимися псевдокоренными породами, а также экстраполяция микроэрозионных свойств природных субстратов, вызванных неестественно слабыми ударами. Другой подход был применен при использовании центрифужного моделирования для увеличения сил зернистого удара и создания эрозии границ. Вращающийся барабан диаметром 40 см на центрифуге при эффективном уровне гравитации до 100 г был развернут для создания аналоговых потоков мусора с эффективной глубиной потока до нескольких метров. Зернистый поток и пограничная эрозия были изучены (а) с помощью высокоскоростного видео и слежения за частицами для измерения их полей скоростей и (Б) путем картирования закономерностей износа в синтетической стеновой пластине коренных пород с использованием 3D-микрофотограмметрических методов. Объединив эти экспериментальные результаты с теоретическими разработками, получили основные компоненты для построения закона эрозии скользящего износа на границах плотного зернистого потока.

Ключевые слова: селевой поток, эрозия коренных пород, центрифужное моделирование, гранулированный поток, велосиметрия слежения за частицами(ПТВ), микрофотограмметрическое картирование.

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