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IRSTI 67.11.29

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A Case Study of Slope Failure Induced by Rainfall During Super-Typhoon

Abstract. *Global warming and associated disasters have received wide social and political attention. This study focused on landslides resulting from the precipitation brought by hurricanes that may grow in intensity in the near future. A series of centrifuge simulations on a rainfall-induced landslide that occurred in Japan during 2005 Typhoon Nabi was performed. The procedures of the simulation on the slope (height=27 m, inclination=29 degrees) were illustrated. The precipitation was applied in increments to the slope surface until it exceeded that of the field measurement. The instability was examined using an infinite slope analysis and the mechanism of rainfall-induced failure was discussed. The study showed that incremental rainfall of less than 200 mm led to local failure, whereas that exceeding 200 mm resulted in global slope failure. A loss of apparent cohesion in the soil as well as an increase in pore pressure due to infiltration were responsible for the slope instability. Wide-spreading landslides, mudflows and debris flows are expected under an environment affected by global warming.*
Keywords: *slope, rainfall, failure, response, sand, clay.*

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Introduction. It is evident from statistical records that the earth's climate is facing a gradual increase in temperature. Several studies, such as those by the National Aeronautics and Space Administration (NASA), predicted an increase in ocean surface temperature of approximately 2 degrees Celsius by the end of century (Figure 1). The warming temperature is expected to melt icebergs and glaciers and thus raises the sea level. Many coastal cities and low-lying areas will be affected directly by such a sea level rise. Global warming may also affect the weather in several ways. One of the prime concerns is about the occurrence of hurricanes and typhoons [1,2,3,4]. The high wind speed may cause direct damages and surges at the coastal area, and hurricanes may also bring heavy rainfall which will lead to flooding.

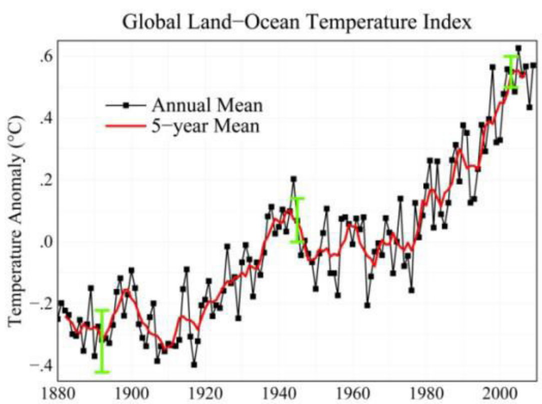

Figure 1. Variation of Ocean Surface Temperature (Credit: NASA)

Precipitation from rainfall or melting ice may lead to wide- spreading landslides. Many slopes have failed under heavy rainfall due to tropical depressions, tropical storms and hurricanes. Hundreds of lives and pieces of property are lost every year due to landslides [5,6]. Landslides may cut off highway infrastructure, utilities, food supply, and communication networks for an extended period of time. Residences may be destroyed and inhabitants located at the landslides areas may be killed. Most recent landslide disasters include the 2009 Typhoon Morakot which buried entire Hsao-Lin Village in Taiwan and caused approximately 500 deaths, and the heavy rain of August 2010 that killed more than 14000 people in Zhouqu County in the Gansu Province, China.

Table 1.

Saffir-Simpson Hurricane Scale.

Category	Wind Speed	
	km/h	mph
1	119-153	74-95
2	154-177	96-110
3	178-209	111-130
4	210-249	131-155
5	≥ 250	≥ 156
Additional classifications		
Tropical depression	0-62	0-38
Tropical storm	63-117	39-73

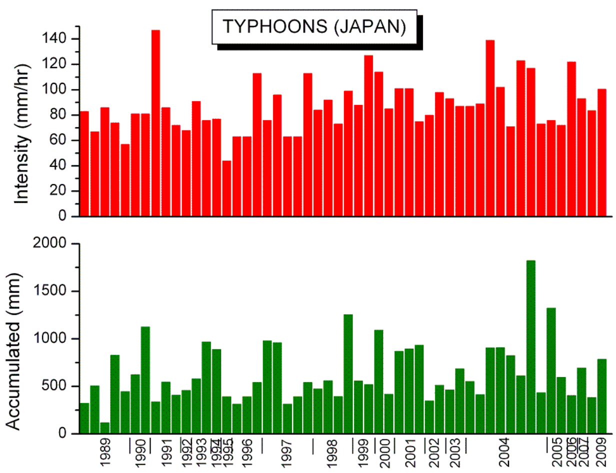

Figure 2. Rainfall characteristics of destructive typhoons in Japan since 1989 (compiled after data obtained from Japan Meteorological Agency).

Current classification of hurricanes under the Saffir-Simpson scale (Table 1) is solely based on the wind speed, whereas rainfall characteristics, such as intensity and accumulation, are not considered. Through the information on the typhoons that brought considerable damages to Japan since 1989 (see Figure 2), there was a large variation in intensities and durations; the intensities varied between 40 and 150 mm/h (mean= 88 mm/h), whereas the total accumulations were between 120 and 1800 mm (mean= 645 mm). Recent numerical predictions by National Oceanic and Atmospheric Administration (NOAA) and Japan Meteorological Agency (JMA) have indicated a possible increase in the frequency of occurrences and the intensities of typhoons, such as the super-typhoon that has a wind speed exceeding 240 km/h, because of the increase in the ocean surface temperature. The precipitation is expected to increase by approximately 20 percent within 100 km of the storm center [7,8].

This study presents a centrifugal simulation of rainfall- induced landslide due to typhoon. A centrifuge modeling technique was used. While previous studies [9,10] were on hypothetical slopes, this study attempted to simulate a real slope failure. The procedures of simulation and model construction are illustrated. Several different incremental rainfall accumulations were used in the testing. The instability was examined using infinite slope analysis and the mechanism of rainfall-induced failure was given.

Typhoon Nabi and Landslide. There are very limited case histories of rainfall-induced landslides where the soil properties and rainfall characteristics are well known, allowing for validation of physical or numerical modeling technique. Typhoon Nabi (Typhoon #14), a super-typhoon, passed through the western part of Japan during 6-7 September, 2005. The maximum wind speed was 175 km/h with the central pressure depression of 925 hPa. Typhoon Nabi caused 21 deaths and 143 injuries in Japan. In addition, over 10,000 homes and 88 roads were damaged. There was a total of 168 landslides in the affected area [11].

This study was related to a landslide along the Sangyo Expressway in the Yamaguchi Prefecture, located between the Kuga and Iwakuni interchanges. A slope, 27 m high and of inclination 29 degrees, failed 7 hours after the peak rainfall. The rainfall records at the nearby Kuga and Iwakuni stations had a total accumulation of 437 mm 341 mm, respectively, and the peak rainfall intensities varied between 40-50 mm/h . Note that the site was not the area that received the highest rainfall intensity nor the total accumulation during typhoon Nabi. The landslide buried several houses at the foot of the mountain and killed 3 residents. The traffic was interrupted for more than 3 months.

The slope of interest had a layer of cover soil underlaid by weathered rocks. [12] presented a series of results on the soil investigation conducted after the landslide. There was a significant variation in the grain size distribution among the samples retrieved from the site. The fines content was between 10 to 40 percent by weight.

Centrifuge Modeling Procedures. Considering the capacity of the centrifuge facilities, the model was prepared for testing at 100-g; thus the height of the slope model was 27 cm. The model was housed in a rigid aluminum box with inner dimensions of 94 cm × 39.5 cm × 38 cm (length×width×height). Figure 3 shows the configurations of the model. In constructing the model, the slope geometry was first traced onto the walls of the box. The bottom weathered rock was simulated using concrete cement. A sand-clay mixture (Nevada sand and kaolinite) was prepared with a fines content of 30 percent to simulate the cover soil. A series of compaction tests were conducted on the sand-clay mixtures that yielded a maximum dry density of 1.94 g/cm at a water content of 8.9 percents (total density was 2.2 g/cm).

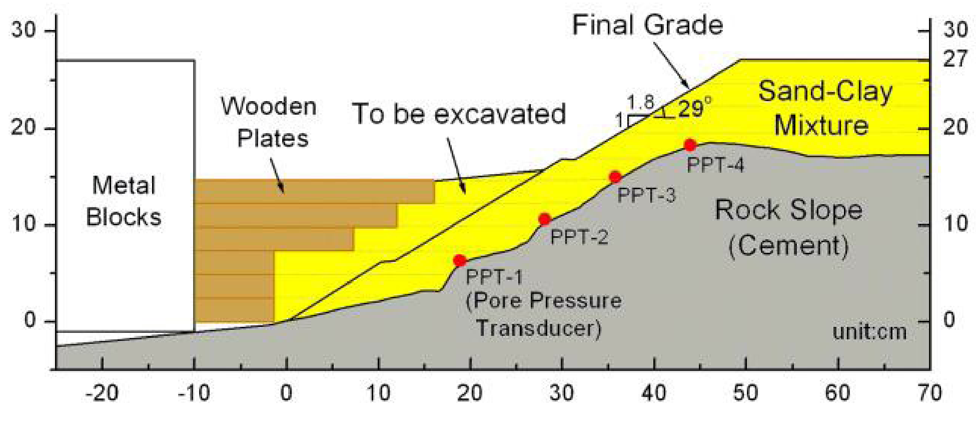

Figure 3. Configuration and preparation of slope model used in the centrifuge testing.

The cover soil was compacted in 11 horizontal layers at maximum density. The required volume of soil with the optimum water content was used to compact each soil layer based on the desired density. Wooden plates were placed in the front end of the slope in order to minimize the volume of soil used in construction. Four pore pressure transducers were embedded at different locations in the slope in order to observe the change in pore pressure during rainfall infiltration. After attaining the full height, the wooden plates were removed and the slope was cut to its final grade of 1(V):1.8(H) or 29 degrees. The finished slope was covered with plastic sheets and left overnight before rainfall testing was conducted.

A simplistic approach was adopted where the precipitation was introduced to the slope by spraying water prior to centrifugal acceleration. Note that in Ling et al. (2009, 2010), the rainfall was introduced during centrifuge flight using spraying nozzles. For each test, different values of precipitation ranging from 50 mm to 200 mm were applied in two or more increments (Table 2). In this model, based on the total area of the slope surface, 240 cm3 of water was equivalent to 100 mm of rainfall in the field. The centrifuge took about 5 minutes to attain the targeted 100g, after which it was kept for another 5 minutes before the centrifuge was brought to a stop in 5 minutes. Then, the next increment of precipitation was applied to the slope and the process was repeated until the total accumulation exceeded that of the field measurement.

In order to prevent the drying up of the slope surface by wind currents during centrifuge spinning, the box containing the slope was kept air tight with a cover on. Visual observation of the slope deformation and failure was done through a closed circuit camera. The response of the pore pressure transducers was also monitored through a wireless data acquisition system.

Test Results. As seen in Table 2, for the tests where precipitation was less than 150 mm in each increment (Tests 1, 2 and 3), only local failure of the slope was observed. That is, no global failure was observed even when the total accumulation exceeded that of the field measurements of 500 mm. The local failure typically occurred at the toe of the slope. Cracks are formed at the crest. When the increment was increased to 200 mm (Tests 4 and 5), local failure occurred in the first increment followed by a global failure in the second increment. Typical views of the slopes at failure, indicating both local and global failures, are shown in Figure 4.

Table 2.

Rainfall Testing Program and Results.

Test #	Rainfall Increme nt (mm)	Total Increments	Accumulated Rainfall (mm)	Failure Increment#	
				Local	Global
1	50 [120 cm^3]	11	550	4	No
2	100 [240 cm^3]	7	700	2	No
3	150 [360 cm^3]	4	600	2	No
4	200 [480 cm^3]	2	400	1	2
5	200 [480 cm^3]	3*	500	1	2

cm^3]

*Third increment=100 mm

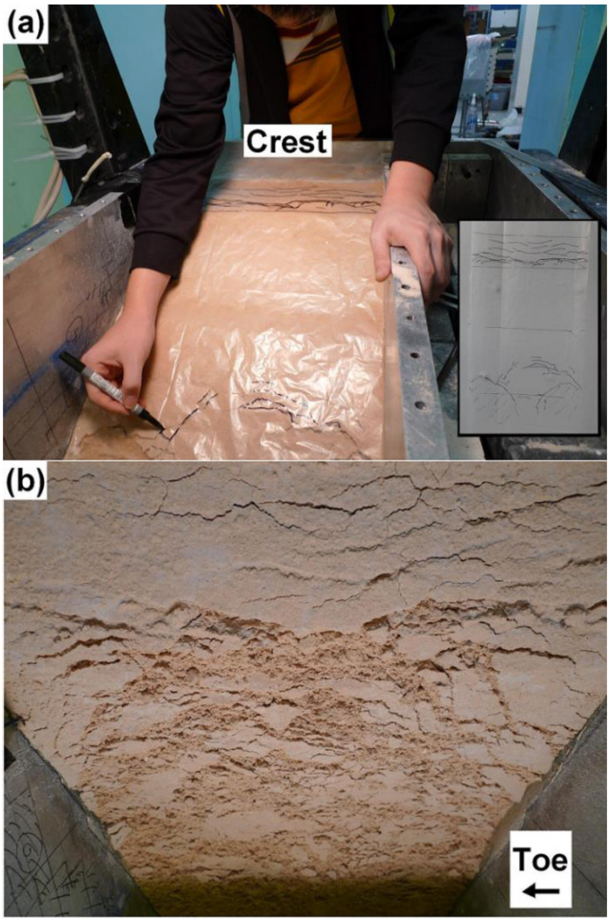

Figure 4. View of the slope at failure (Test 5): (a) local failure at the toe and cracks at the crest after first increment, (b) Global failure as viewed from the crest.

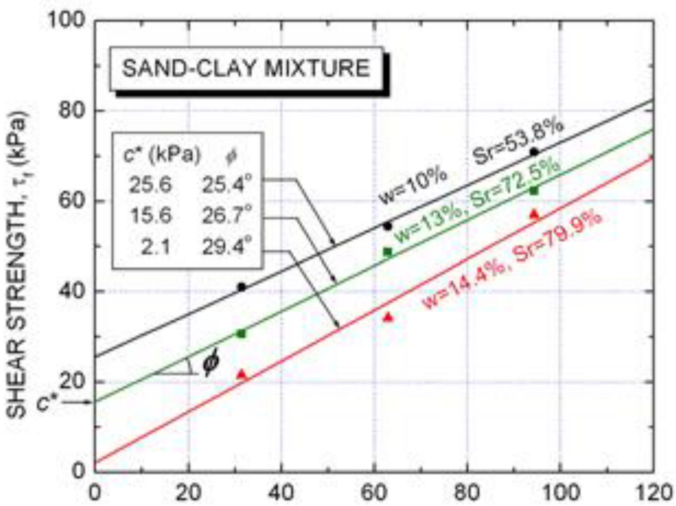

Figure 5. Pore pressure response in the slope during rainfall testing (Test 5).

Figure 5 shows a typical response of the pore pressure transducers for Test 5 recorded from the time of centrifuge spinning up. The pore pressure started to increase as the centrifuge was spun up. After attaining the targeted acceleration of 100g, the pore pressure started to dissipate. The local or global failure occurred right after the slope attained peak acceleration. The two transducers located at the upper portion of slope did not record significant change in pore pressure. It was due to the fact that the moisture did not infiltrate to a depth where the transducers were located. Rather, the flow occurred in the lower portions of the slope as indicated by the response of the transducers. At the instant of failure, there was a sharp drop in pore pressure, after which the reading increased again.

Mechanism of Instability. In previous studies [9] it was shown that the modified Coulomb failure criteria is applicable to partially saturated soil:

$$\tau_f = c^* + \sigma_n' \tan\phi$$

where τ_f, σ_n', c^*, and ϕ are the shear strength, effective normal stress, "apparent" cohesion, and angle of internal friction, respectively. The partially saturated soil possesses a small value of apparent cohesion due to the capillary action between the soil particles. Upon saturation, the apparent cohesion diminishes. Coupled with an increase in pore pressure, u, the effective stress, which is the difference between the total normal stress and pore pressure, is reduced $(\sigma_n' = \sigma_n - u)$. Thus, the shear strength of the soil as a whole becomes smaller than that of its unsaturated state. This mechanism of failure was associated with initially unstable steep slopes of 60 degrees or greater, whereas this study dealt with rather gentle slopes of 29 degrees.

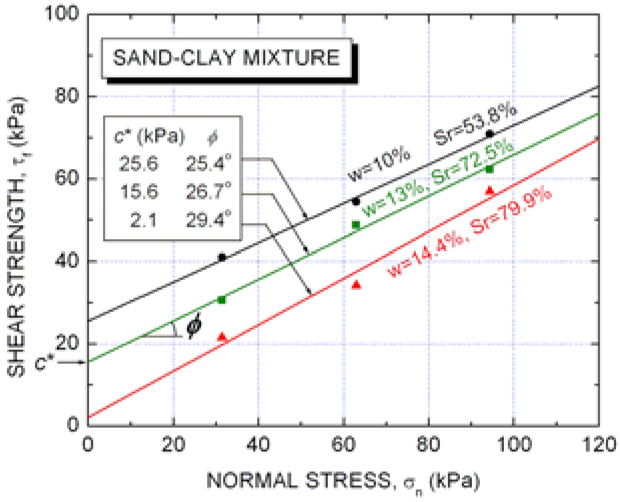

Figure 6. Effects of moisture content on the shear strength

In order to validate this concept further, a series of direct shear tests was conducted on the sand-clay mixture using different percentages of moisture contents: 10%, 13%, and 14.4 %. These values corresponded to a degree of saturation of 53.8% (slope as constructed), 72.5% (after 200 mm of precipitation), and 79.9% (after 400 mm of precipitation). The soil specimens were sheared rapidly at a displacement rate of 2 cm in 3 minutes. The results presented in Figure 6 show that the soil at 10% moisture possessed an apparent cohesion of 25.6 kPa. The apparent cohesion reduced with an increase in moisture content, and it almost vanished when the moisture content reached 14.4% or 80% degree of saturation. The variation in the angle of friction with moisture was rather small.

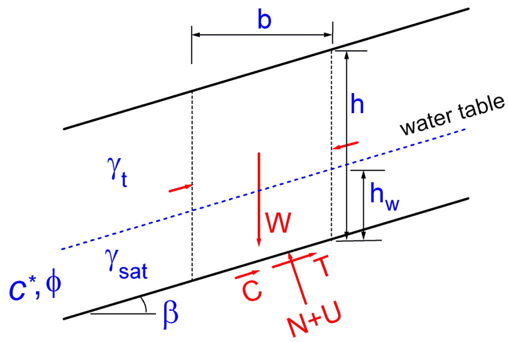

Figure 7. Infinite slope stability in the presence of water table (Ling and Ling, 2012).

An analysis was conducted to examine the stability of the slope using the test results obtained from the direct shear and centrifuge testings. The analysis considered an infinite slope (Figure 7), since the slope was much longer than its thickness. The general equation to evaluate the factor of safety for the slope in the presence of apparent cohesion and water table is derived and given below in convenient form, where the first part is attributed to the apparent cohesion c* and the second part due to the angle of friction ϕ [13]:

$$F_s = \frac{2c*}{\{\gamma_t(1-\alpha) + \gamma_{sat}\alpha\}h\sin 2\beta} + \frac{\gamma_t(1-\alpha) + (\gamma_{sat} - \gamma_w)\alpha}{\gamma_t(1-\alpha) + \gamma_{sat}\alpha}\frac{\tan\phi}{\tan\beta}$$

where γt, γsat, γw, β, h and hw are the total unit weight, saturated unit weights of soil, unit weight of water, slope angle, thickness of soil layer and depth of water, respectively (α= hw/h). Based on the measured pore pressure in the centrifuge test, an equivalent height of the water table hw was obtained. The average value of the angle of internal friction of 26.2o was used. The values of these parameters are summarized in Figure 8.

As can be seen in Figure 8, a reduction in apparent cohesion and an increase in water table led to a reduction in the factor of safety. The factor of safety of the slope without rainfall was 1.52, indicating a stable slope. It reduced to 1.28 at 200 mm of precipitation, but dropped to 0.79 after 400 mm of precipitation that indicated an unstable slope. Thus, a reduction in apparent cohesion coupled by an increase in pore pressure due to the rising water table contributed to the failure of this particular slope.

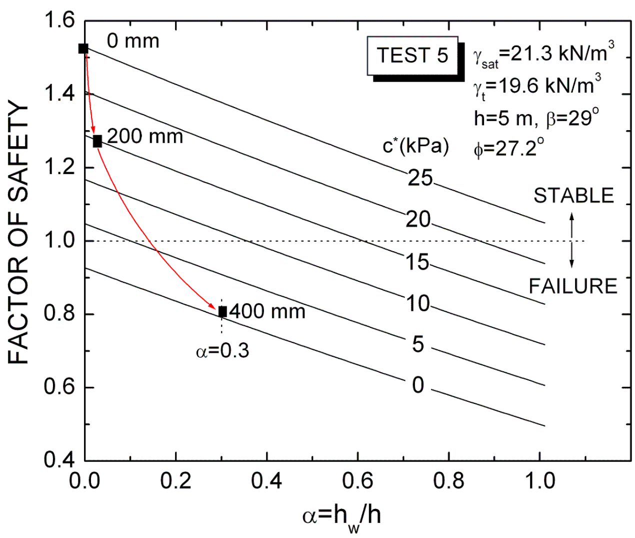

Figure 8. Effects of water table and apparent cohesion on slope stability

Conclusions. The results of simulation showed that centrifuge modeling technique can be used to simulate full-scale slope failure induced by rainfall. An increased saturation due to infiltration led to a reduction in apparent cohesion and effective stress, thus a loss of shear strength. Relatively gentile slopes may become unstable in the events of heavy rainfall. Thus, under increasing amounts of precipitation during hurricanes in an environment affected by global warming, more landslides are expected.

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Генри Линг, Хое И. Линг

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Супертайфун кезінде жауын-шашыннан туындаған беткейдің бұзылу мысалы

Аңдатпа. Жаһандық жылыну және онымен байланысты апаттар кең қоғамдық және саяси назарға ие болды. Бұл зерттеу жақын арада күшеюі мүмкін дауылдан туындаған жауын-шашыннан туындаған көшкіндерге бағытталған. 2005 жылы Наби тайфуны кезінде Жапонияда болған жауын-шашыннан туындаған жер көшкінінің центрифугалық модельдеу сериясы жүргізілді. Көлбеу модельдеу процедуралары көрсетілді (биіктігі=27 м, көлбеу=29 градус). Жауын-шашын дала өлшеулерінде алынған мәндерден аспағанша біртіндеп беткейдің бетіне қолданылды. Тұрақсыздық шексіз көлбеу талдау арқылы зерттелді және жауын-шашыннан туындаған бұзылу механизмі талқыланды. Зерттеу көрсеткендей, жауын-шашынның 200 мм-ден аз болуы жергілікті бұзылуға әкеледі, ал 200 мм-ден асып кетуі беткейлердің Ғаламдық бұзылуына әкеледі. Беткейдің тұрақсыздығының себебі топырақта көрінетін адгезияның жоғалуы, сондай-ақ, инфильтрацияға байланысты тері тесігі қысымының жоғарылауы болды. Жаһандық жылынудан зардап шеккен қоршаған орта жағдайында кең таралған көшкіндер, сел және қоқыс ағындары күтіледі.

Түйін сөздер: көлбеу, жауын-шашын, сәтсіздік, жауап, құм, саз.

Генри Линг, Хое И. Линг

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Пример разрушения склона, вызванного осадками во время супертайфуна

Аннотация. Глобальное потепление и связанные с ним бедствия получили широкое общественное и политическое внимание. Это исследование было сосредоточено на оползнях, вызванных осадками, принесенными ураганами, которые могут усилиться в ближайшем будущем. Была проведена серия центрифужных симуляций вызванного дождями оползня, произошедшего в Японии во время тайфуна «Наби» в 2005 году. Были проиллюстрированы процедуры моделирования на склоне (высота=27 м, наклон=29 градусов). Осадки наносились постепенно на поверхность склона до тех пор, пока они не превышали значения, полученные при полевых измерениях. Неустойчивость была исследована с помощью анализа бесконечного наклона и обсужден механизм разрушения, вызванного осадками. Исследование показало, что увеличение количества осадков менее 200 мм приводит к локальному разрушению, тогда как превышение 200 мм приводит к глобальному разрушению склонов. Причинами неустойчивости склона были потеря видимого сцепления в почве и увеличение порового давления из-за инфильтрации. Широко распространяющиеся оползни, селевые потоки и потоки мусора ожидаются в условиях окружающей среды, затронутой глобальным потеплением.

Ключевые слова: склон, осадки, провал, отклик, песок, глина.

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