SIMULATION OF JOINTED ROCK SLOPE UNDER DYNAMIC LOADINGS AND SUBMERGED CONDITION USING PHYSICAL MODELS

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ABSTRACT : Plane failures of scaled-down rock slope models have been simulated under real gravitational force and pseudo-static acceleration. The simulations involve two-dimensional plane sliding of rock slopes formed by cubical (4×4×4 cm) and rectangular (4×4×8 cm and 4×4×12 cm) blocks of sandstone, under various slope face angles with the maximum slope height up to 1 m. The sandstone blocks prepared by saw-cutting are arranged to simulate rock slopes with two mutually perpendicular joint sets. Horizontal pseudo-static acceleration of up to 0.225 g with amplitudes between 24 to 64 mm is applied. The observed sliding angles under dynamic loading are considerably lower than those calculated by the deterministic method. The discrepancy becomes larger for slope models formed by shorter sandstone blocks and under a higher acceleration. The results from the physical model simulations under dry and submerged conditions agree well with those obtained from finite difference analyses using FLAC code. The findings imply that for the smooth, open and low-cohesion joints as simulated here, assessment of rock slope stability under static and dynamic loading by using the deterministic method alone may not be conservative, particularly for the slope mass comprising joints with small spacing.

KEYWORDS : Plane failure, friction, sandstone, dynamic load, acceleration.

1. INTRODUCTION

Physical models or scaled-down models have long been used to simulate the failure behavior of rock slopes in the laboratory. They have been used as teaching and research tools to reveal the two-dimensional failure process of rock slopes under various geological characteristics. They are sometimes employed to gain an understanding of a unique failure process under site-specific conditions. Perhaps the most popular and widely used model is Goodman's friction table [1, 2] discuss the base friction principle that is used widely to reproduce the effects of gravity in two dimensional physical models of excavations in rock. They develop mathematical principles upon which the analogy between gravity and base friction can be examined. The friction table has later evolved into several versions (e.g. [3-6]). The slope modeling with friction table however poses some disadvantages. The driving force inducing sliding or failure is not a true gravitational force. Instead it largely depends on the friction and velocity of the moving belt, and hence additional calibration or correction is required to reveal the actual slope behavior. A stick-slip behavior between the belt and testing materials is a common problem particularly under low speeds, making the driving force by belt moving unrealistic. Since the friction table is horizontal, or gently inclined, assessment of the true effect of water can not be made.

The objective of this research is to study rock slope failure under static and dynamic loads by means of laboratory simulation of scaled-down models. The observed results are compared with those calculated by deterministic methods and by numerical analyses. A vertical test platform has been used to host the slope models formed by cubical and prismatic blocks of Phu Phan sandstone to simulate two-dimensional plane sliding failure. The failure is induced by true gravitational force and horizontal pseudo-static acceleration of up to 0.225 g. The effect of water-submerging is investigated. Comparisons are made of the results from physical model simulations and from numerical analysis.

2. TEST PLATFORM

The test platform used in this research comprises two main components: a 2.2×2.2 m vertical test frame supported by a movable stand [7]. The frame is hinged through steel rods in the middle to the stand allowing frame rotation from horizontal position during arranging and loading block samples to vertical position for testing under true gravitational force (Figure 1). When the frame is in horizontal position, the aluminum plate becomes a flat bed supporting the rock blocks during loading. The clear and removable acrylic sheet is installed before rotating the frame to the upright position to prevent the block samples from tipping over. It also allows visual inspection and monitoring of slope movement during the test. The test frame can accommodate 4 cm thick rock

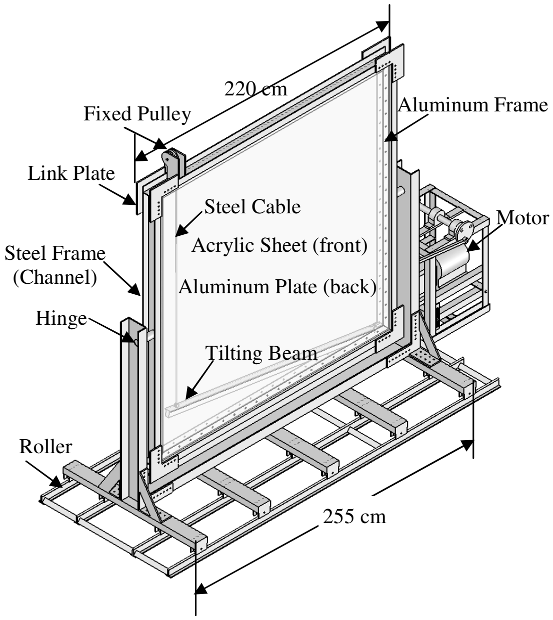


Figure 1 Schematic drawing of test platform used for physical model simulation.

blocks arranged to a maximum height of up to 1.5 m to simulate two-dimensional jointed rock slopes. Steel grooved rollers mounted underneath the stand are used for testing under dynamic loading. The rollers will be placed on a set of steel rails equipped with a high torque motor, gear system and crank arm to induce a cyclic motion to the entire test platform. The frequency and amplitude of the horizontal pseudo-static acceleration can be controlled by adjusting the rotational diameter of the flywheel and speed of the motor.

3. ROCK SAMPLE

Phu Phan sandstone has been selected for use as rock sample here primarily because it has highly uniform texture, density and strength. It is classified as fine-grained quartz sandstone with 72% Quartz (0.2-0.8 mm), 20% feldspar (0.1-0.8 mm), 3% mica (0.1-0.3 mm), 3% rock fragments (0.5-2mm), and 2% others (0.5-1 mm). The average density is 2.27 g/cc. To form slope models with two mutually perpendicular joint sets, cubical (4x4x4 cm) and rectangular (4×4×8 cm and 4×4×12 cm) shaped sandstone blocks have been prepared by using a saw-cutting machine. The cubical blocks are used to simulate joint sets with equal spacing, while the rectangular blocks simulate joint sets with different spacing. The friction angle and cohesion of the saw-cutting surfaces of the Phu Phan sandstone determined by tilt testing are 26 degrees and 0.053 kPa [7]. The simulated joints have their strike parallel to the slope face, and hence represent a worst case scenario for the stability condition.

4. SLOPE MODELS TESTED UNDER STATIC CONDITION

Over one hundred plane sliding failures have been simulated under dry and submerged conditions with the slope heights varying from 16 to 93 cm and slope face angles from 40 to 75 degrees. For submerged condition, the height of the water in the test models ranges from 7 to 60 cm. Each set of slope geometies is formed by sandstone blocks with the same dimension, and is simulated at least 3 times to ensure the repeatability of the results. Video records are taken during the test. Table 1 summarizes the test parameters and results for modeling under dry and submerged conditions. Pangpetch and Fuenkajorn [7] give solutions to calculate the slope height and sliding plane angle at failure. The video recorder allows examining the failure process of the slope models after the test. The failure usually initiates from the slope toe and progresses upward to the crest. A combination of plane sliding near the slope toe and toppling failure near the slope crest is often found for slope models formed by 4x4 cm blocks.

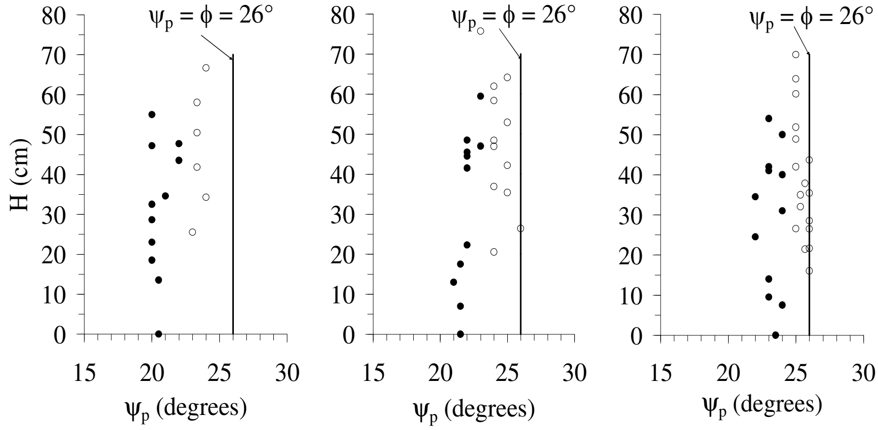
Figure 2 compares the simulation results by plotting the slope height at failure as a function of sliding plane angle. Since the measured cohesion is very low and negligible, the deterministic method simply yields the sliding plane angle equal to the friction angle of the block surfaces. The observed sliding plane angles tend to be lower than the rock friction angle. The discrepancy becomes larger for the slope models formed by shorter sandstone blocks. The sliding plane angles (ψ_p) also seem to be independent of the slope height. As expected, the observed sliding plane angles under submerged condition are lower than those under dry condition. However under the same slope conditions (e.g., slope height, face angle) the difference is less than 2-3 degrees.

Table 1 Test parameters and results of slope model simulations under dry and submerged conditions.

Block Size	No. of Testing	H (cm)	ψ_f (degrees)	ψ_p (degrees)	H_w (cm)
Dry					
4×4 cm	43	20-68	40-52	21-25	-
8×4 cm	53	16-77	49-75	23-27	-
12×4 cm	49	16-93	44-72	25-26	-
Submerged					
4×4 cm	10	36-75	40-66	20-22	13-55
8×4 cm	10	20-91	45-71	21-23	7-60
12×4 cm	11	22-70	49-69	22-24	8-54

5. FINITE DIFFERENCE ANALYSIS

Finite difference analyses using FLAC_Slope code [8] have been performed to calculate the factor of safety of some slope models. Twelve finite difference models have been constructed to represent the physical model geometry. For the dry condition, the simulations use the sliding plane angle of 25 degrees with slope heights varying from 21 to 70 cm, and slope face angles from 51



(a) (b) (c)

Figure 2 Slope height (H) as a function of sliding plane angle (ψ_p) for block sizes of 4×4 cm (a), 8×4 cm (b) and 12×4 cm (c). Solid points represent submerged condition.

to 72 degrees. Under submerged condition the sliding angles are taken as 20 to 23 degrees, with slope heights varying from 52 to 58 cm, slope face angles from 48 to 68 degrees, and water level heights (H_w) from 30 to 69 cm.

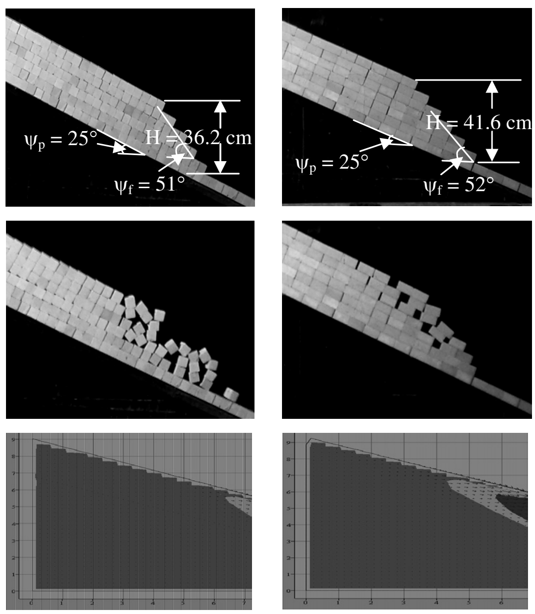
For all simulations the friction angle is maintained constant at 26 degrees with cohesion equal to 0.053 kPa. The results are compared with those observed from the physical model tests. Figures 3 compares the shape of the failure zone of the numerical simulation results and the slope model observations under dry and submerged conditions. The FLAC_Slope can well predict the shape and extent of the failure zone with the factor of safety close to those observed from the tested models.

Figure 4 compares the factors of safety calculated by FLAC code and by deterministic method with those of the physical model tests for the same slope geometry under dry condition. The factor of safety of 1.0 is taken to represent the condition at which failure occurs in the slope models. Assuming that the plane sliding mechanism follows the Coulomb criterion, the deterministic method uses an equation modified from Hoek and Bray [9] to calculate the factor of safety.

$$FS = 2 \cdot c / \left\{ \gamma \cdot H \cdot \sin^2 \cdot \psi_p \cdot \left[a + \left(\frac{a^2}{b} \right) \right] \right\} + \frac{\tan\phi}{\tan\psi_p} \quad (1)$$

where: $a = \cot\psi_p - \cot\psi_f$
$b = \cot(\alpha - \psi_p) + \cot\psi_p$
c = cohesion of rock surface
ϕ = friction angle
γ = unit weight of rock
α = angle of the back of slope model

The results from the three methods agree reasonably well. Very small discrepancies remain. Under dry condition, the deterministic method yields the highest factor of safety, which is about 10% greater than those observed from the test models. The factors of safety from FLAC simulations are less than 5% greater than the observations. This may be because the deterministic method assumes that the sliding block is a single and rigid mass lying on an incipient failure plane while the



(a) (b)

Figure 3 Comparisons of FLAC simulations with physiccal model tests for 4×4 cm blocks (a) and 8×4 cm blocks (b).

actual test models are a discontinuous mass formed by rock blocks. The discrepancies become even smaller for a greater slope face angle.

6. SLOPE MODELS TESTED UNDER DYNAMIC LOADING

The dynamic loading is studied by considering the effects of the horizontal pseudo-static acceleration induced by cyclic motions of the test platform in the direction parallel to the dip direction of the slope face. These cyclic motions are used to simulate the earthquake shaking. The vertical acceleration is assumed to be zero. Over one hundred plane sliding failures have been simulated with the horizontal pseudo-static accelerations between 0.013 g and 0.225 g. These accelerations are within the range tested and observed elsewhere [10, 11, 12]. The amplitude is maintained constant at 23.5 mm. The slope models have the sliding plane angles varied from 1 to 22 degrees, heights from 44 to 83 cm, and slope face angles from 28

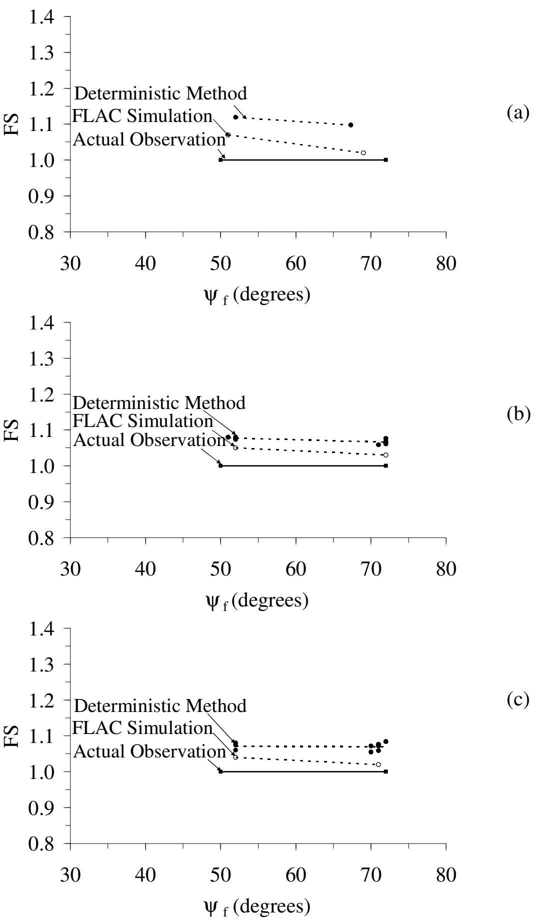


Figure 4 Factors of safety determinated for 4×4 cm blocks (a), 8×4 cm blocks (b), and 12×4 cm blocks (c) at ψ_p equal 25 degrees.

to 68 degrees. Table 2 summarizes the test parameters and the results. For all slope geometries the duration for cyclic motion is maintained at one minute. If failure does not occur within one minute of shaking, the sliding plane angle is progressively increased by one degree interval and the test is repeated. Figure 5 shows an example of the plane sliding failure for 8x4 cm blocks.

Table 2 Results of rock slope stability analysis under dynamic loading with amplitude = 23.5 mm.

Block Size	No. of Tests	Frequency (Hz)	a (g)	H (cm)	ψ_f (°)	ψ_p (°)
4×4 cm	7	0.403	0.013	69-83	40-44	15-18
	3	0.504	0.017	80-82	40-43	15-17
	3	0.629	0.027	76-78	41-44	14-16
	4	0.700	0.033	44-53	33-44	12-17
	7	0.833	0.046	50-77	31-41	4-15
	8	1.000	0.067	46-75	28-38	1-12
	4	1.233	0.102	49-54	28-32	3-6
	4	1.346	0.119	46-62	28-32	1-4
	1	1.833	0.225	46	46	1
8×4 cm	7	0.403	0.013	55-58	61-67	16-21
	7	0.504	0.017	55-56	64-68	18-20
	3	0.629	0.027	54-56	63-68	18-19
	3	0.700	0.033	55-57	60-64	15-18
	11	0.833	0.046	51-55	57-63	10-16
	8	1.000	0.067	48-52	52-59	10-12
	6	1.346	0.119	45-48	48-54	1-5
	1	1.700	0.193	45	51	1
	1	1.833	0.225	45	46	1
12×4 cm	2	0.403	0.013	58-59	66-67	21-22
	4	0.833	0.046	55-57	60-63	15-18
	2	1.117	0.083	52-53	58-59	12-13
	2	1.429	0.136	49-50	52-53	6-7
	1	1.700	0.193	45	46	1
	1	1.833	0.225	45	46	1

It is generally observed that under similar slope geometry and block arrangement the failure zone induced under dynamic load is more extensive than those under static loading.

To compare the test results with those calculated by the deterministic method, a closed-form solution given by Kramer [10] is adopted here. The solution offers a simple approach to calculate the factor of safety of plane failure per unit thickness of slope mass under vertical and horizontal pseudo-static accelerations.

$$FS = \frac{c \cdot l + [(W - F_v)\cos\psi_p - F_h \sin\psi_p]\tan\phi}{(W - F_v)\sin\psi_p + F_h \cos\psi_p} \quad (2)$$

$$F_h = a\,W/g = k_h W \quad (3)$$

$$F_v = a_v\,W/g = k_v W \quad (4)$$

where F_h and F_v = horizontal and vertical inertial forces, a = horizontal pseudo-static acceleration, a_v = vertical pseudo-static acceleration (assumed here = 0), W = weight of the failure mass, ψ_p = angle of planar failure

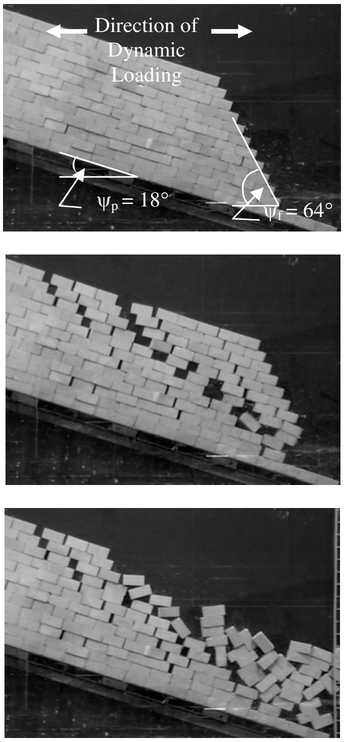


Figure 5 Simulation of sliding failure for 8×4 cm blocks at a = 0.046 g and amplitude=23.5 mm.

surface, g = gravitational acceleration, l = the length of the failure plane, and k_h and k_v = dimensionless horizontal and vertical pseudo-static accelerations.

In relation to the earthquake phenomena Kramer [10] postulate that the horizontal pseudo-static force decreases the factor of safety by reducing the resisting force and increasing the driving force. The vertical pseudo-static force typically has less influence on the factor of safety since it reduces (or increases, depending on its direction) both the driving force and the resisting force. As a result, the effects of vertical accelerations are frequently neglected in pseudo-static analyses resolving the forces on the potential failure mass in a direction parallel to the failure surface.

In this study the vertical pseudo-static acceleration (a_v) is assumed to be zero, subsequently the vertical inertial force (F_v) becomes zero. This assumption conforms to Kramer's conclusion above. The above equation is therefore reduced to:

$$FS = \frac{c \cdot l + [W \cos \psi_p - F_h \sin \psi_p] \tan \phi}{(W \sin \psi_p + F_h \cos \psi_p)} \qquad (5)$$

By setting FS=1, the relationship between the acceleration, a, and the angle of the failure plane, ψ_p, can be developed. Under this condition the acceleration required to induce plane failure for a rock slope decreases with increasing failure plane angle.

Results of the test models under dynamic loading are plotted in terms of the acceleration as a function of the sliding plane angle in Figure 6. A failure envelope (line separating the stable and failure conditions) can be drawn from the test results for each block size, and is compared with the results from the deterministic method using FS=1. It is clearly shown that the deterministic method significantly over-estimates the actual observations. Under the same sliding plane angle the deterministic solution gives the acceleration at failure at more than twice of those observed from the test models. This is probably because the deterministic method assumes a rigid and continuous mass of rock above the incipient sliding plane while the slope models are formed by discrete rock blocks. The deterministic method also assumes that all relevant forces pass through the centroid of the sliding mass. The presence of interaction forces between the blocks in the slope model could enhance the shape effect of the individual blocks above the sliding plane. This behavior may be better demonstrated by a discrete element analysis that can incorporate the effect of dynamic loading. The discrepancy between deterministic method and test models becomes greater for a lower sliding plane angle, and particularly for the slope models formed by short blocks (4×4 cm). In addition the acceleration required to fail slope models with the shorter blocks tends to be lower than those with longer ones (8×4 cm and 12×4 cm).

7. DISCUSSIONS AND CONCLUSIONS

It is recognized that the joints simulated in the slope models here are very smooth and clean with low cohesion and friction angle, which may not truly represent most actual rock joints found in in-situ rock slopes. Nevertheless the comparisons of the test results with the deterministic solutions (by Hoek & Bray [9] and computer simulations (FLAC_Slope code) under the same test parameters (e.g., joint properties and slope characteristics) have revealed significant implications. Under static condition the deterministic method and computer simulation over-estimate the factor of safety for the plane sliding failure by about 5 to 10%, particularly for the slope models with shorter blocks. This is probably due to the impacts of the block spacing, block shape and interaction forces between the discrete blocks in the sliding mass. This implies that stability analysis by assuming that the sliding mass is continuous as used by the deterministic method may not be conservative, particularly for slope masses with short-spaced joints compared to the slope height.

The discrepancy between the deterministic method and the test results under dynamic loading is highly significant. The deterministic solution proposed by Kramer [10] over-estimates the acceleration at failure by more than twice those observed from the test models. The discrepancy however reduces for slope models

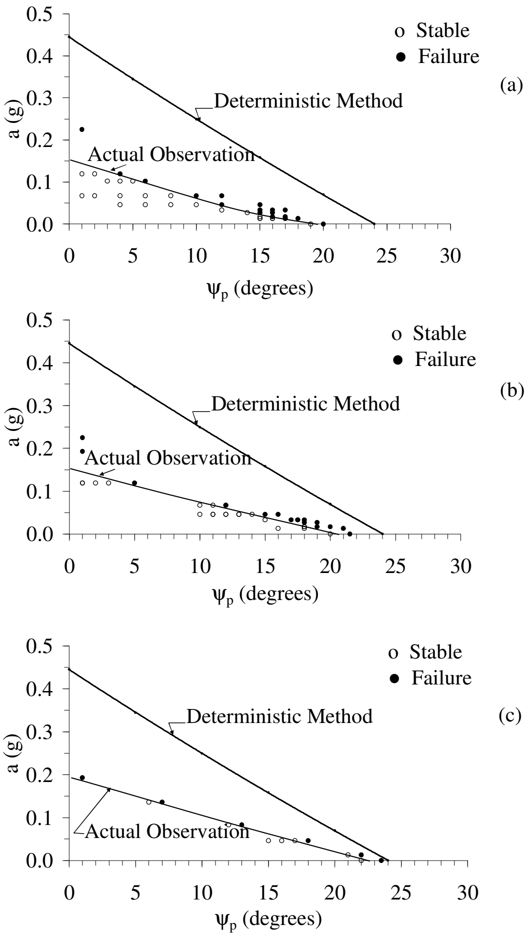


Figure 6 Pseudo-static acceleration (a) as a function of sliding plane angle (ψ_p) at failure for 4×4 cm (a), 8×4 cm (b), and 12×4 cm (c) blocks.

formed by larger sandstone blocks and under a greater sliding plane angle. This is again probably due to the assumption of the continuous mass imposed by the deterministic method. These findings indicate that under dynamic loading plane sliding analysis using the simple deterministic method for rock slopes with small joint spacing compared to the slope height will give a non-conservative result. In addition, the deterministic approach for stability analysis of low-angled sliding planes under dynamic loading may be inappropriate. In this case an additional physical model testing or discrete element analysis that is capable of dynamic simulation should be performed.

The physical models tested here have a narrow range of the size and shape of the rock blocks used to simulate the joint spacing in the test frame. Additional test results obtained from slope models with larger blocks, probably up to 20×20 cm, and with smaller blocks, 2×2 cm, would provide a clearer indication of the effect of joint spacing on slope stability

8. ACKNOWLEDGEMENT

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