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Experimental investigations of shear pin arrangement on soil slope resting on low interface friction plane

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Abstract: Slope failure along the bedding plane is a critical issue that existed in the past and will still continue to exist in the future. This problem causes socio-economic losses. This paper presents laboratory investigations of the effects of the shear pin arrangement on the stability of soil slope resting on a low interface friction plane. The effects of the slope width and thickness, the number of shear pins, the location of the shear pins and the mode of the shear pin arrangement were studied in the laboratory. Physical models were made of silica sand no. 6 that had a water content of 10% and rested on Teflon film simulating a low interface strength. Screw bolts with a diameter of 4 mm were used as the shear pins and were fastened perpendicularly to the interface plane. The results of this research show that shear pins can increase the failure slope angle in a slip test. The failure slope angle is mainly influenced by the number of shear pins and the thickness and width of the soil block, while the location of the shear pins is found to have little effect on the failure slope angle. The failure mechanisms are associated with the number of shear pins, their location, their mode of arrangement, and the thickness and width of the soil block.

Keywords: slope failure, slip test, shear pin, soil slope, low interface friction plane

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INTRODUCTION

Piles play an important role in the field of civil engineering. They are commonly used to increase the bearing capacity of foundations and to reduce the settlement of structures. In addition, piles are also employed to improve slope stability and were widely adopted by many researchers in the past [1-5].

Generally, piles used for slope stabilisation are subjected to lateral loads by the horizontal movement of the surrounding soil and are classified as passive piles [6]. The interaction between the piles and the soil is very complicated because it involves many factors such as pile location, pile deformation, soil strength and pile dimensions. Thus, studies on the use of piles to stabilise slopes have drawn much attention in recent decades. This paper presents experimental investigations on the effects of shear pin arrangement on the stability of soil slope resting on a low interface friction plane (as shown in Figure 1). The failure in this problem is due to the shear sliding of the soil slope on the low interface friction plane, together with the punching shear of the soil slope through installed shear pins, or to the detachment failure of the lower soil slope. The conditions in the experiments are similar to those at the actual site of an open-pit mine [7]. Two types of rock mass (shale and lignite) appear mostly in area 4.1 of Mae Moh mine [8] and rest on a bedding plane of clay seams with low interface strength. When the lignite at the toe of the slope is excavated at its full width, a large displacement of the rock mass occurs in the slope part. In order to reduce the displacement and ensure a higher level of safety, the Electricity Generating Authority of Thailand decided to install piles, known as shear pins, with a diameter of 150 mm. The pins were made of mortar and steel cable, 50 mm in diameter. Thus, the models studied here are intended to provide a better understanding of the influence of the shear pin arrangement on the stability and failure mechanisms at the actual sites.

Similar to several cases of soil profile conditions being considered, Lee et al. [9] used a modified boundary element method to analyse a row of pile response when subjected to lateral load from slope instability. Cai and Ugai [10] and Li et al. [11] employed two- and three-dimensional numerical methods to study the required position of piles installed for maximum safety. Ausilio et al. [12] presented an analytical expression based on a kinematic approach to the limit analysis to design a slope reinforced with piles. Kourkoulis et al. [13] and Kourkoulis et al. [14] presented a hybrid method for the analysis and design of a slope stabilised by a row of piles. The following were addressed: pile spacing, thickness of stable soil, depth of embedded piles, pile diameter, group pile configuration, structural non-linearity of piles and soil stiffness. The arching effect due to pile spacing was also investigated by Kourkoulis et al. [13] and Muraro et al. [15]. Liang et al. [16] concluded that there is no unique general rule for the optimal location of piles, pile spacing or pile diameter when designing soil slopes containing a row of piles. In order to obtain an optimum design, it is necessary to analyse the problem with a computer program.

Yang et al. [17] employed a three-dimensional finite difference analysis (FLAC 3D) to investigate the stability of a soil slope containing a row of piles. The effects of pile length, pile spacing, pile head conditions, pile bending stiffness and soil properties were also studied. Kanagasabai et al. [18] used FLAC 3D to study a single pile embedded in stable strata to stabilise the slipping mass of the soil. The effects of variation in strength of the slipping plane between stable and unstable strata, sloping ground surface and length of embedded pile were investigated. Three rupture mechanisms associated with the length of piles embedded in stable strata were proposed by Kourkoulis et al. [13] and Muraro et al. [15].

Pan et al. [19] conducted laboratory model tests, where the piles were installed in a row and in a line in soft clay subjected to lateral soil movement, to determine the pressure on the pile shaft. The relationship between the ultimate soil pressure and pile spacing was proposed in their study. Frank and Pouget [20] conducted a field observation of the full-scale lateral response of a single steel pile over 16 years at the experimental site of Sallèdes (located 30 km from Clermont-Ferrand), where the pile was 12 m in length, 0.915 m in diameter and 19 mm in thickness. The pile was installed to prevent the instability of a soil slope, whose thickness was 6.15 m. The results showed that the large displacement of the ground surface occurred in rainy seasons. Similar results were drawn by Song et al. [21]. Sivapriya and Gandhi [22] studied the behaviour of a single pile in a sloping clay layer subjected to lateral load by experimental and numerical approaches. Lirer [23] conducted a 3-year full-scale field observation and presented the results of a numerical analysis (FLAC 3D) of the lateral response of five steel piles in a row under soil lateral movement. The piles were 10 m in length, 0.4 m in diameter and 6 mm in thickness, and the spacing between them was 2.25 times the diameter. The thickness of the unstable layer was 5 m. The results showed that the piles were able to reduce the displacement of the soil above the piles, while no reduction in displacement was observed below the row of piles. The prediction of the lateral load of the piles was in good agreement with that by the numerical methods and field measurements of other studies.

In the work of Khosravi [7], Khosravi et al. [24, 25] and Techawongsakorn et al. [26], experiments on a soil slope with and without side supports, and on an undercut slope resting on a low interface plane, were performed intensively. However, the effects of shear pins on the stability of soil slope were not investigated. The results showed that the slope failure was due to the shear sliding on the low interface friction plane in the slip tests. This failure mechanism occurred together with shear sliding on the side supports in the slip test with side supports. On the other hand, two types of failure were observed for the physical models of the undercut slopes, namely (1) an arch-shaped failure for mild undercut slopes and (2) a total failure with upheaval buckling of pillars for steep undercut slopes.

Researches on soil slopes stabilised by piles and soil slopes with a low interface friction plane are available in the literature. However, very few studies have been done on experimental investigations of soil slopes reinforced with small piles such as shear pins, and resting on a low interface friction plane. Thus, the aim of this research is to investigate the effect of the shear pin arrangement on the stability of a slope resting on a low interface friction plane, as summarised in Figure 1. The problem notation of each term is as follows: W, L, T = width, length and thickness of a soil block respectively; L_b = distance from the bottom edge of soil block to the centre of shear pin; α_f = failure slope angle; D = diameter of shear pin; S = spacing between shear pins; γ, c, ϕ = unit weight, apparent cohesion and internal friction angle of soil block respectively; c_i, ϕ_i = interface adhesion and interface friction between humid sand and Teflon film respectively. The failure mode is to be postulated in this research.

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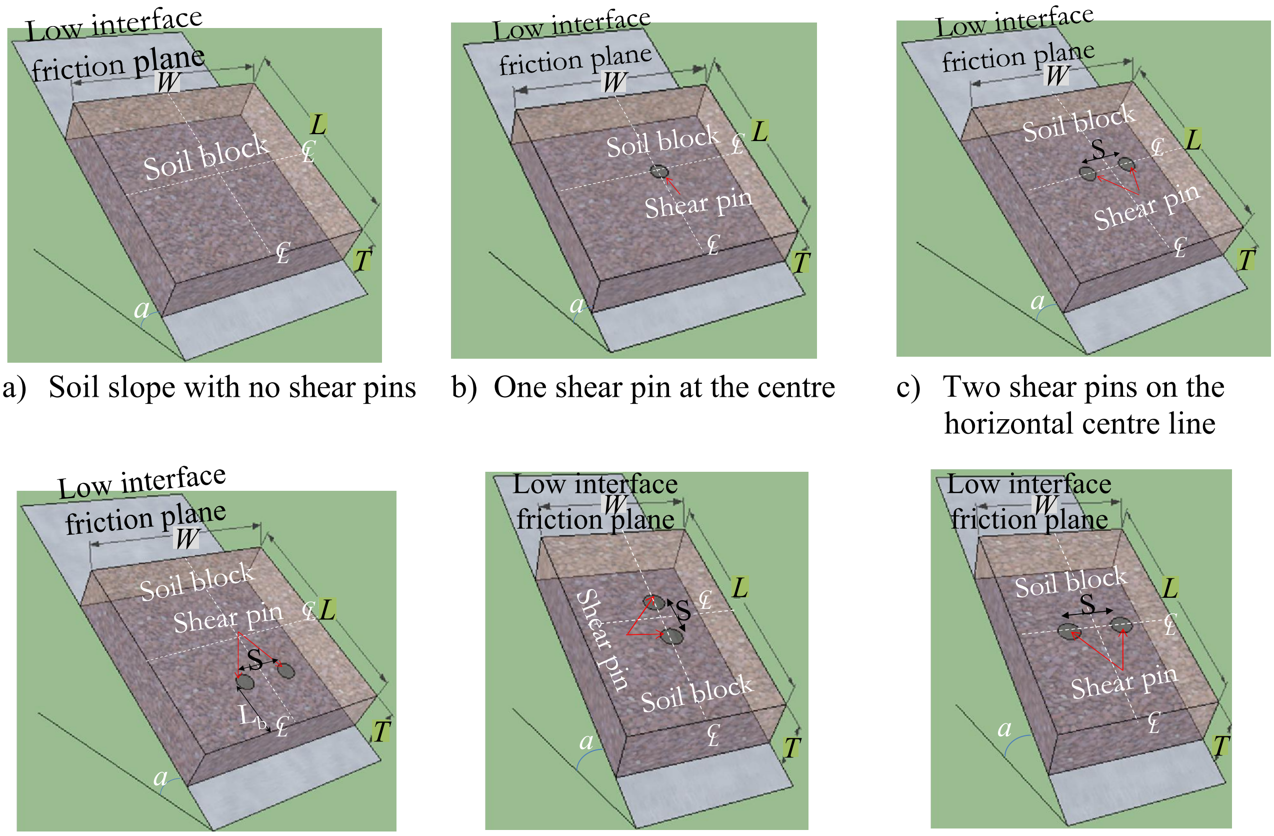

a) Soil slope with no shear pins

b) One shear pin at the centre

c) Two shear pins on the horizontal centre line

d) Two shear pins in a row at different locations

e) Two shear pins on the vertical centre line with different widths of soil block

f) Two shear pins in a row with different widths of soil block

Figure 1. Definitions of problems of soil block resting on low interface friction plane with and without shear pins

MATERIALS AND METHODS

Figures 1b-f schematically summarise the models of the soil slope resting on a low interface friction plane stabilised by shear pins, which correspond to the physical models of slip test. Figure 1a is the case without any shear pins. The physical models of the slip test were made of compacted humid silica sand no. 6, as shown in Figure 2, while the low interface friction was simulated by Teflon film. The parameters in each slip test are summarised in Table 1. The stability of the studied models depends on the strength of silica sand no. 6, the interface plane and the influence of the shear pin arrangement. The humid silica sand no. 6, whose basic properties are summarised in Table 2, was carefully prepared and compacted with controlled water content and humid density. The internal friction angle (ϕ) and the apparent cohesion (c) of the compacted sand tested by a direct shear apparatus (Figure 3a) were 41.5^{o} and 0.358 kN/m^2 respectively [7]. Humid silica sand no. 6 (w = 10%, and γ = 13.68 kN/m^3) was chosen since this material was extensively used in a previous study of undercut slope by Khosravi et al. [24, 25] and Khosravi [7].

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Table 1. Parameters in slip tests of soil block

a) Slip tests without shear pin

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)
1	76	25	20	0.5
2	61	25	20	0.75
3	39	25	20	1
4	35	25	20	1.5
5	32.5	25	20	2
6	31	25	20	2.5
7	30	25	20	3
8	29	25	20	4
9	27	25	20	5
10	26	25	20	7.5
11	25	25	20	10
12	25	25	20	12.5
13	25	25	20	15
14	26	25	20	17.5

b) Slip tests with 1 shear pin at centre

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)
15	56	25	20	1
16	44	25	20	2
17	41	25	20	3
18	39	25	20	4
19	37.5	25	20	5

c) Slip tests with row of 2 shear pins at centre

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)
20	59	25	20	1
21	46	25	20	2
22	46	25	20	3
23	44	25	20	4
24	42	25	20	5

d) Slip tests with row of 2 shear pins with variation in soil block width for T=3 cm

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)	L_b(cm)
25	49	15	20	3	10
26	45	20	20	3	10
27	40	25	20	3	10
28	37.5	30	20	3	10
29	37	35	20	3	10

e) Slip tests with row of 2 shear pins with variation in soil block width for T=5 cm

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)	L_b(cm)
30	48	15	20	5	10
31	42	20	20	5	10
32	42	25	20	5	10
33	36	30	20	5	10
34	35	35	20	5	10

f) Slip tests with row of 2 shear pins with variation in shear pin location for T= 1 cm

Test no.	α_f(deg.)	W(m)	L(cm)	T(cm)	L_b(cm)
35	58	20	25	1	1.5
36	61	20	25	1	3
37	58	20	25	1	4
38	67	20	25	1	5
39	68	20	25	1	7.5
40	69	20	25	1	10
41	67	20	25	1	12.5

g) Slip tests with row of 2 shear pins with variation in shear pin location for T= 3 cm

Test no.	α_f(deg.)	W(m)	L(cm)	T(cm)	L_b(cm)
42	54	20	25	3	1.5
43	53.5	20	25	3	3
44	54	20	25	3	4
45	56	20	25	3	5
46	57	20	25	3	7.5
47	56	20	25	3	10
48	57	20	25	3	12.5

h) Slip tests with row of 2 shear pins with variation in shear pin location for T= 5 cm

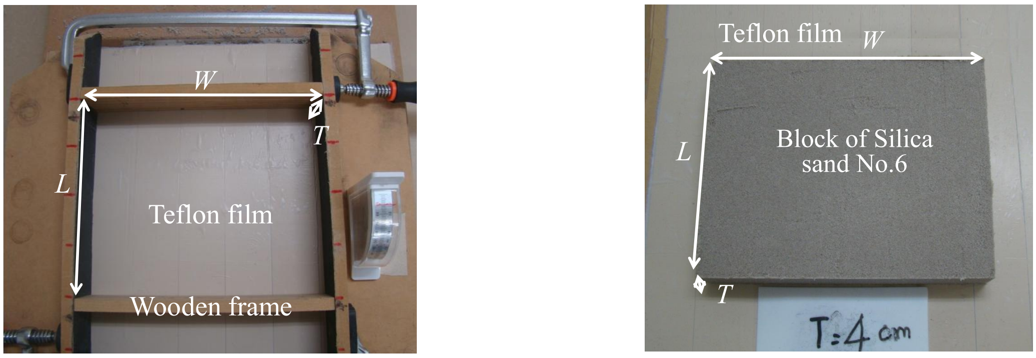
Test no.	α_f(deg.)	W(m)	L(cm)	T(cm)	L_b(cm)
49	46	20	25	5	1.5
50	48	20	25	5	3
51	52	20	25	5	4
52	47	20	25	5	5
53	50	20	25	5	7.5
54	50.5	20	25	5	10
55	48	20	25	5	12.5

i) Slip tests with line of 2 shear pins with variation in soil block width for T=3 cm

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)
56	47.5	15	20	3
57	41	20	20	3
58	38	25	20	3
59	34	30	20	3
60	33	35	20	3

j) Slip tests with line of 2 shear pins with variation in soil block width for T=5 cm

Test no.	α_f(deg.)	W(cm)	L(cm)	T(cm)
61	45	15	20	5
62	40	20	20	5
63	37	25	20	5
64	34	30	20	5
65	33	35	20	5



a) Wooden frame fixed on Teflon film b) Prepared soil block on Teflon film

Figure 2. Preparation of slope of soil block

Table 2. Basic properties of silica sand no. 6 [7]

Water content (w)	10 %
Bulk unit weight (γ)	13.68 kN/m^3
Unconfined compressive strength (σ_c)	1.59 kN/m^2
Internal friction angle (ϕ)	41.5^o
Apparent cohesion (c)	0.358 kN/m^2

Teflon film with a thickness of 0.5 mm was used to simulate the low friction interface plane and to cover the slope plane. The direct shear apparatus (Figure 3a) was used to measure the interface friction and the apparent adhesion between the humid silica sand and the Teflon film, following the procedure of Khosravi [7]. The upper and lower parts of a shear box with a hollow cylinder 60 mm in diameter and 20 mm in thickness were used, as shown in Figure 3b. A piece of Teflon film was cut and stuck on the lower part of the shear box. The upper part of the shear box was placed on the Teflon film, and the humid sand was compacted on the Teflon film inside the upper part. Five different levels of normal pressure were applied on the compacted sand to consolidate it within 10 min., after which it started to shear. Each shearing stage took around 30 min. to reach a shear displacement of 6 mm (10% of the inside diameter of the compacted sand). The shearing speed was around 0.02 mm/min. The interface shear strength parameters were determined by a plot of shear stress versus normal stress, as presented in Figure 4, which shows that the interface friction angle ϕ_i = 22^o and the apparent adhesion c_i = 0.06 kN/m^2. In Khosravi's study the interface friction angle and the apparent adhesion between the silica sand and the Teflon sheet were 18.5^o and 0.1 kN/m^2 respectively [7]. Thus, it should be noted that the interface strength properties of the Teflon film in this study were quite different from those of the Teflon sheet used in Khosravi's study because Teflon film is thinner than Teflon sheet.

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a) Direct shear apparatus   b) Teflon film stuck on shear box

Figure 3. Apparatus for measurement of interface strength between sand and Teflon film

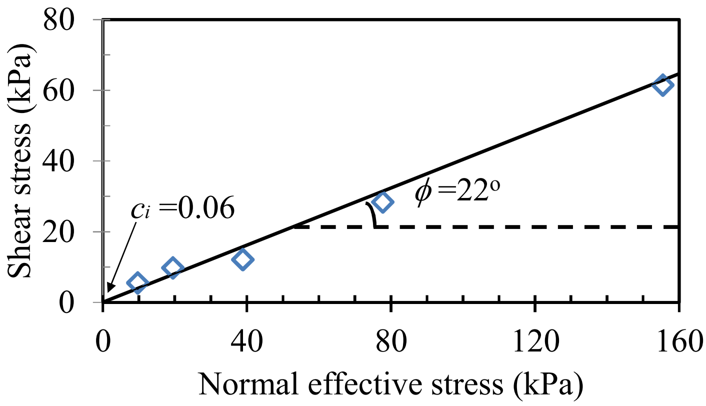


Figure 4. Plot of shear stress vs normal effective stress between sand and Teflon film

RESULTS AND DISCUSSION

Soil Slope without Shear Pins

Slip tests on a slope without any shear pins had been conducted by Khosravi [7] and Khosravi et al. [25]. Various experiments had been set up to study the effect of length, width and thickness of soil blocks without side support, with a Teflon sheet 2 mm thick being used to simulate the low interface friction plane. It had been shown that the failure slope angles of the soil block depended on the strength of the interface plane and the thickness of the soil block. The block could be stabilised if the resistance force was greater than the driving force. A stability number could be derived by considering the equilibrium of the forces parallel and normal to the slope [7, 25]:

$$\frac{\gamma T}{c_i} = \frac{1}{\sin(\alpha_f) - \cos(\alpha_f)\tan(\phi_i)} \tag{1}$$

where T is the thickness of the soil block, γ is the weight of the silica sand, c_i is the apparent adhesion of the interface between the humid silica sand and the Teflon sheet, ϕ_i is the interface friction angle between the silica sand and the Teflon sheet, and α_f is the slope angle at failure.

We conducted the slip tests again without any shear pins in order to verify the reproducibility of the experiments. In addition, different material was used in our study to simulate the low interface friction plane. A piece of Teflon film 0.5 mm in thickness was used in place of a

2-mm-thick Teflon sheet. The slip tests without any shear pins were conducted to investigate the effect of thickness of the soil block while the length and width were kept constant. A stiff wooden plate was covered by Teflon film to simulate the low interface friction plane. The humid silica sand was weighed, then filled and gently compacted inside the wooden frame that was fixed on the horizontal plane, as shown in Figure 2. The soil block layer was compacted every 2.5 cm while controlling its weight. After the compaction, the frame was removed and the stiff wooden plate was gradually tilted until the block started to slip down. The failure slope angle was recorded when the soil block started to slip. The results of the tests were used to plot the relationship between the failure slope angle (α_f) and the stability number ($\gamma T/c_i$), as shown in Figure 5. This Figure also plots the stability number predicted by the limit equilibrium method (LEM) and the results of previous research [7].

Good agreements are observed between the physical model and the LEM in Eq. (1). The failure slope angle has a non-linear inverse relationship to the thickness of the soil block; the curves converge to a certain value when the thickness of the soil slope is very thick. When the soil block has a small thickness, a large slope angle is required to bring about the sliding failure. The trend of the stability number curve in this study is similar to that observed in the previous study [7]; the plot of the former is above the latter because the strength parameters of the Teflon film are larger than those of the Teflon sheet. The observed failure mechanism in those tests shows that the soil block slipped along the interface plane without failure of the soil block. However, it was observed that both the failure of the soil block and its slippage along the interface plane happened when the ratio *T/L* was higher than 0.75. The results for the soil slope without any shear pins confirm the reliability of the tests such that they can be reproduced; the resulting data correspond very well to the equation developed for the LEM.

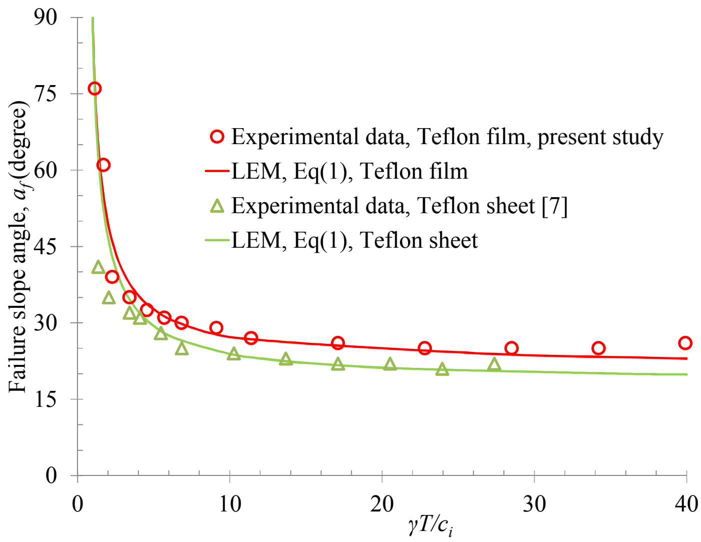


Figure 5. Variation in slope angle at failure as a function of stability number ($\gamma T/c_i$)

Soil Slope with Shear Pins

This section presents the effects of shear pins on the stability of a soil slope resting on a low interface friction plane. The first model corresponds to the case where one shear pin has been installed at the centre of the soil block, as schematically shown in Figure 1b. The second model corresponds to the case where two shear pins have been installed on the horizontal centre line of the soil block, as schematically shown in Figure 1c. The spacing between the shear pins was kept constant at 5 cm. Steel screw bolts 4 mm in diameter and 70 mm in length were selected as the shear pins for all tests since they can represent the case of rigid piles in the field. The bolt diameter, D = 4 mm, and soil thickness, T = 1-5 cm, gives rise to a dimensionless term, D/T = 0.08-0.4, which represents some limited cases in the field. The bolt length of 7 cm was chosen to match the tests with model thickness T = 1-5 cm. In addition, according to Kitakata [27], the screw bolts were fixed on the slope model and the sand was later filled and compacted. In order to sustain the screw bolt's shape and position during the process of sand compaction, the bolt's diameter of 4 mm was chosen by trials. A wooden plate 2.5 cm in thickness, 40 cm in width and 60 cm in length was used as the base support.

The model with one shear pin was firstly set up, where a vertical steel screw bolt penetrated around 2 cm into the wooden plate. Humid silica sand with controlled water content and humid density was then carefully compacted in a similar manner to the case without any shear pin. A small wooden plate 3 cm in width, 10 cm in length and 2 cm in thickness was used to effectively compact the sand close to the shear pin. The soil block 25 cm wide and 20 cm long was used in the two cases. The thickness of the block was varied from 1 cm to 5 cm in those tests. The prepared model was gradually tilted until the first failure was observed.

Figure 6 shows the stability number as a function of the failure slope angle for the cases of one and two shear pins. The results of the slip test without any shear pins are also plotted in this Figure. It can be observed that shear pins influence the failure angle of slope, as compared to that without shear pin. For the same stability number, the average of the first failure slope angle for the models with one shear pin and two shear pins increases about 28% and 35% respectively— the thinner the thickness of the soil block, the higher the failure slope angle for both models.

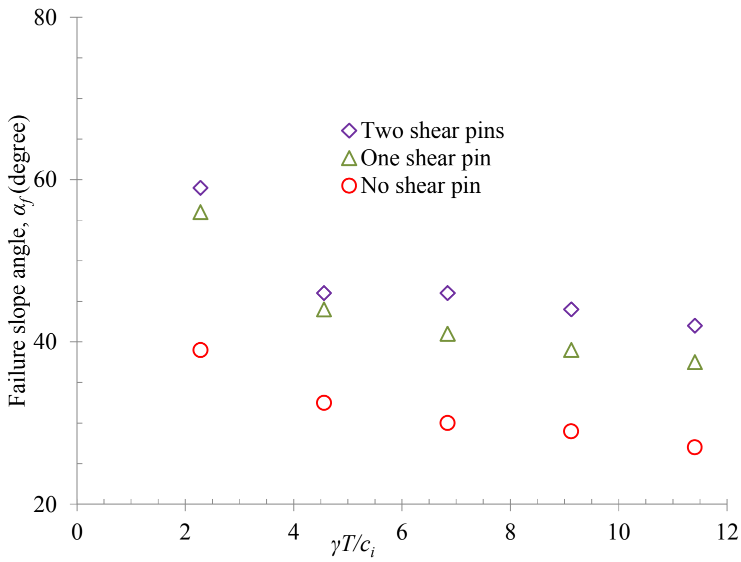
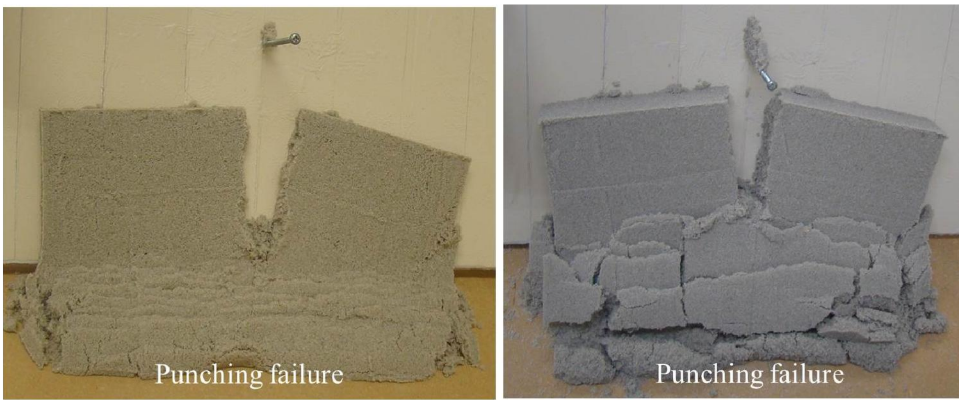


Figure 6. Variation in slope angle at failure as a function of stability number for slip tests with and without shear pins

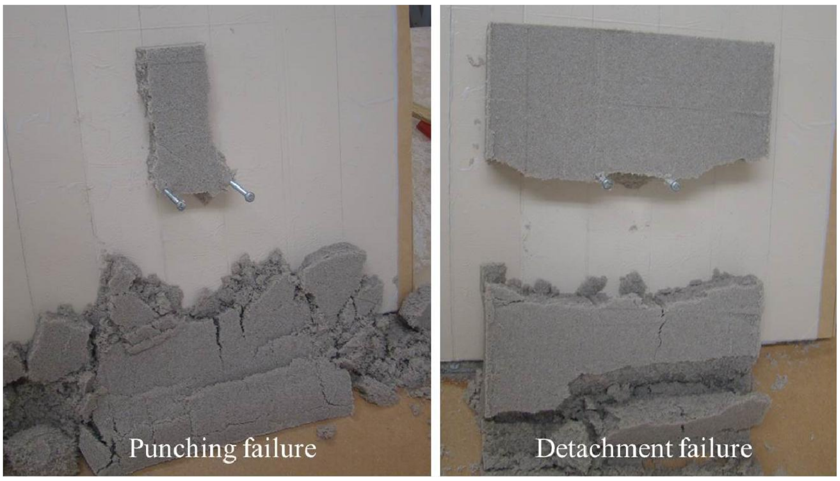
Figures 7 and 8 show the failure mechanisms of the models with one and two shear pins respectively for different thicknesses of the soil block. There are two modes of failure that can be observed from those tests. The first failure mechanism corresponds to punching shear failure (Figures 7a and 7b), while the second failure mechanism corresponds to detachment failure (Figure

8b). Regarding punching shear failure, an open crack starts to develop directly above the shear pin and extends to the top of the soil block, where the block starts to slip. This failure happens for the model with one shear pin for all values of slope thickness. Punching shear failure can also occur in the model with two shear pins and a smaller slope thickness (Figure 8a). In addition, when total failure happens for the model with two shear pins, there are some parts of the soil block which are stable above the shear pins, as shown in Figure 8a. This evidence indicates that arch action may develop between the shear pins in the case of punching shear failure.



a) Test no. 15 b) Test no. 17

Figure 7. Mode of failure in slip tests with one shear pin with different thicknesses of soil block



a) Test no. 21 b) Test no. 23

Figure 8. Mode of failure in slip tests with two shear pins on horizontal centre line with different thicknesses of soil block

Detachment failure occurs for the model with two shear pins, where slope thickness is large. There are two stages of failure observed in detachment failure. The first stage occurs when an open crack starts to develop along the row of shear pins and extends horizontally to the edge of the soil block. Therefore, some parts of the block below the row of shear pins slip down along the slope, but the top part above the shear pins is still stable, as shown in Figure 8b. The second stage of failure occurs if the block is continuously tilted in the test, resulting in the sliding of the top part. This result indicates that the arch action should develop between the shear pins when the failure of the bottom part happens. When the arch action develops between the shear pins, the top part of the soil block located above the shear pins is stable due to arching against shear sliding. This result indicates that the arch action can develop until the spacing between the shear pins is around 12.5 times the diameter of the shear pin. In fact, the observed results are in contrast to those by Kourkoulis et al. [14] and Muraro et al. [15], who reported that the arch action can be disregarded when the spacing is not greater than, respectively, 5 and 7.5 times the diameter of the stabilised pile.

The next physical model corresponds to the case of two shear pins in a row at different locations, with vertical location (L_b) being varied from 1.5 cm to 12.5 cm, measured from the lower part of the slope, as schematically shown in Figure 1d. The same spacing of 5 cm between the two pins was used in this test, the dimensions for the test model were 20 cm in width (W) and 25 cm in length (L), and the three values for soil thickness (T) were 1 cm, 3 cm and 5 cm. The preparation of the model including the shear pin installation and the soil block followed the two previous cases. Figure 9 shows the first failure slope angle as a function of the normalised parameter, L_b/L. All the results indicate that there is little difference in failure slope angles when the location of the two shear pins is varied. In other words, the location of the shear pins in a row has little influence on the stability of a soil slope resting on a low interface friction plane. As for the effect of thickness of the soil block, in general, a thinner soil block gives a greater failure slope angle.

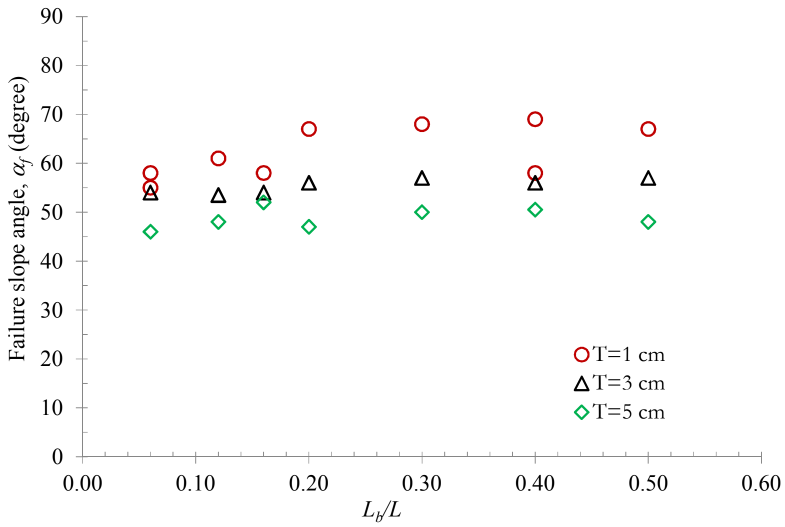


Figure 9. Plot of failure slope angle versus variation in location of shear pins (L_b/L)

Figure 10 compares the failure mechanisms of the model. In this Figure all the models have the same slope thickness of 3 cm. The punching shear failure mode occurs in tests in which the location of the shear pins, L_b/L, is less than 0.4, while the detachment failure mode occurs where L_b/L is more than or equal to 0.4. Even though there is only a small difference in failure slope angles (53.5°-57°) between the models with different shear pin locations, the locations of the shear pins do have some influence on the failure mode. Figure 11 compares the failure mechanisms of the soil slope with different thicknesses while keeping the same location for the shear pins. Punching shear failure could be observed mostly in the models with thin soil block (Figure 11a) or in models where the shear pins were installed at the lower part of the soil block (Figures 10a-c). Detachment failure, on the other hand, could be observed in models where the shear pins were installed close to the horizontal centre line of the soil block (Figures 11b-c).


a) Test no. 43 b) Test no. 44


c) Test no. 45 d) Test no. 48

Figure 10. Comparison of failure mechanisms in models with two shear pins in a row at different locations using the same thickness of soil block



a) Test no. 41 b) Test no. 48 c) Test no. 55

Figure 11. Comparison of failure mechanisms in models with two shear pins in a row with different thicknesses of soil block

The last two studied modes correspond to the case of two shear pins installed in the vertical centre line and two shear pins installed in a row on the horizontal centre line with different widths of soil block, as schematically shown in Figures 1e-f. In these tests, two soil thicknesses of 3 cm and 5 cm were used and the width of the slope was varied from 15 cm to 35 cm. Figure 12 shows the relationship between the failure slope angle and the normalised parameter, W/L. It can be seen that the width of the soil block and the mode of the shear pin arrangement have some influence on the failure slope angle: the wider the soil block is, the smaller the failure slope angle becomes, and for the same thickness and geometry of the soil block, two shear pins in a row give a higher failure slope angle than that obtained from two shear pins in a line. Figure 13 shows a comparison of the failure mechanism in models with two shear pins in a row and in a vertical line. The punching shear failure mode is observed in the case of two shear pins in a vertical line in all width ratios. It also occurs to the case of two shear pins in a row when W/T is greater than 4, but changes to the detachment failure mode when W/T is less than or equal to 4.

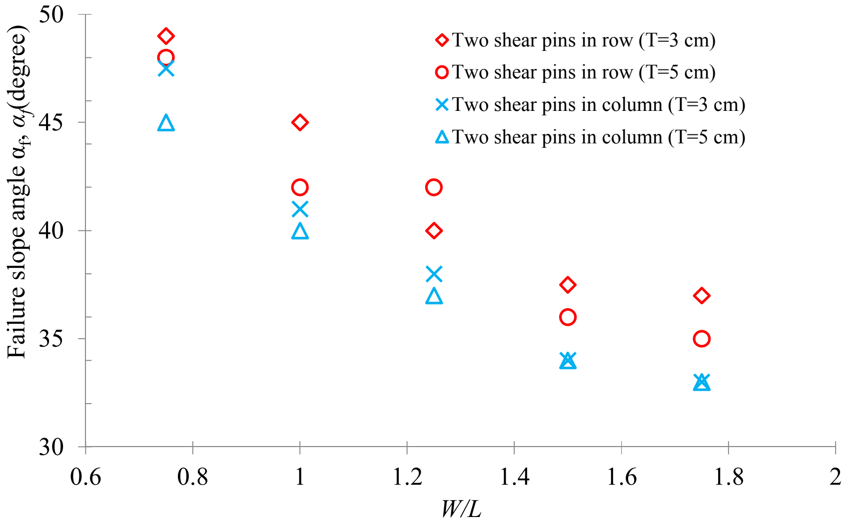


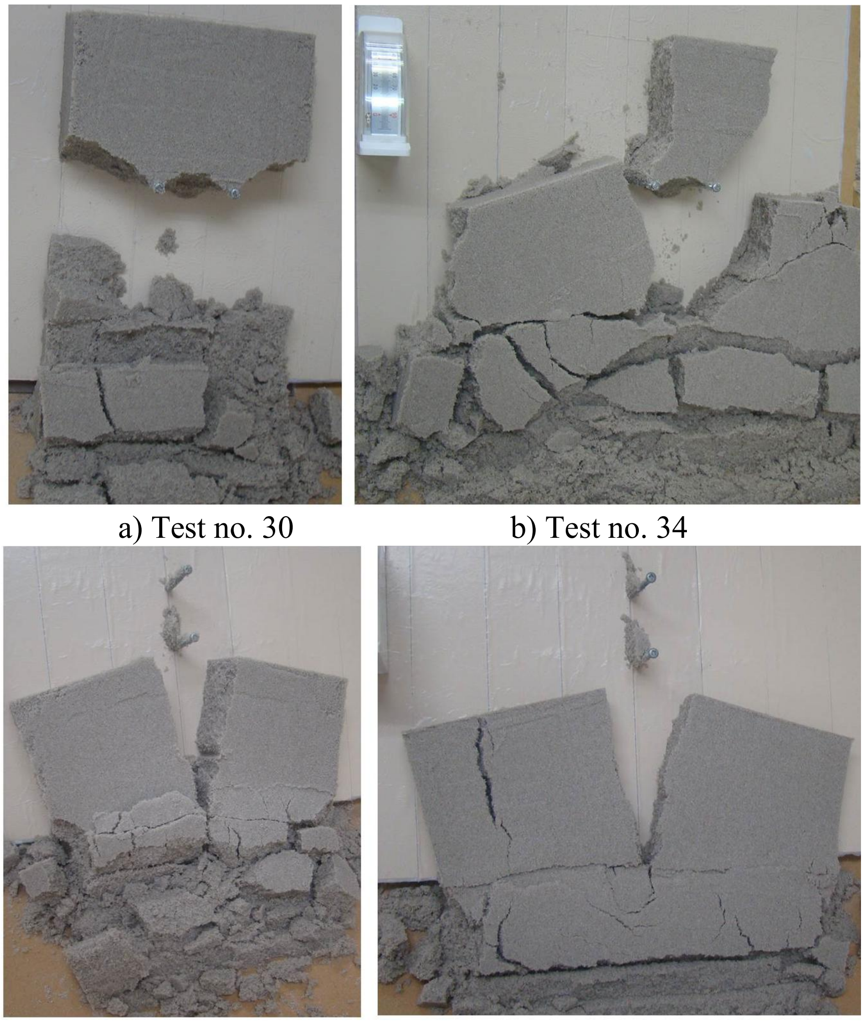
Figure 12. Plot of failure slope angle versus width ratio of soil block

Scaling Laws and Applications to Engineering Practice

This research does not attempt to model the specific site. Instead, it is the engineering problems at the mining site which motivate it [28]. Regarding the applicability of this study to the engineering practice, scaling laws can be set up by using a dimensional analysis following a concept proposed by Atkinson [29] and Powrie [30]. According to this concept, the behaviours of a 1g physical model are said to be similar to those of the prototype models when the dimensionless groups of principal variables of both models have the same values. Thus, the behaviours of the 1g physical model are scaled using the technique of dimensional analysis. A dimensionless group consisting of 10 dimensionless variables for the stability problem of slip tests with and without shear pins can be formed as follows:

$$\{c/c_i, \gamma T/c_i, W/T, L/T, L_b/L, D/T, S/T, \tan\alpha_f, \tan\phi \text{ and } \tan\phi_i\}.$$

It should be noted that the stiffness values of the soil and shear pin are not considered in the dimensionless group since stability and failure mechanism are the major concerns in 1g physical models. Stiffness parameters have more profound influence on observed deformation of a slope



a) Test no. 30 b) Test no. 34

c) Test no. 61 d) Test no. 65

Figure 13. Comparison of failure mechanisms in models with two shear pins in a row and in a vertical line with the same thickness of soil block

prior to failure, but not at the failure state. In the framework of limit analysis, the solution at the failure state is only affected by the strength properties of material, not by its stiffness owing to an assumption of a perfectly plastic material. Thus, the stability and failure mechanism of this problem significantly depends on the strength properties of the interface, soil, and unit weight of soil. However, since there is no failure of the shear pins in any physical models, the piles in an actual problem must be rigid in order to have comparable behaviours between the physical models and the actual problems.

It should be noted that the term $\gamma T/c_i$ and c/c_i are two dimensionless variables in the proposed dimensionless group for this problem. Alternatively, $\gamma T/c$ and c/c_i can be used; the final result of applying scaling laws with those two representations of a field problem is identical. For example, let us consider a problem with $\gamma T/c_i = a$, $c/c_i = b$. Thus, this problem has $\gamma T/c = a/b$, $c/c_i = b$. Very clearly, it follows that using $\gamma T/c_i$ or $\gamma T/c$ gives rise to the same thickness, $T = ac_i/\gamma$.

The values of dimensionless variables of an actual field problem must strictly follow those of each test in order to correctly scale the experimental results to match the actual problem in the field. More importantly, since a single value of interface friction angle and soil friction angle are used in 1g physical models, experimental results can be applied to the field problem that has only a limited condition, i.e. $\phi_i = 22^o$ and $\phi = 41.5^o$. Let us consider Test no. 35 in Table 1 as an example.

The results of this test can be related to a field problem with properties and geometry as follows. A set of field conditions must have conditions similar to this test as: $\alpha_f = 58^o$, $\phi_i = 22^o$ and $\phi = 41.5^o$, with a slope stabilised by a row of two rigid piles. The dimensionless variables in this test are: $c/c_i = 5.97$, $\gamma T/c_i = 2.28$, $W/T = 20$, $L/T = 25$, $L_b/L = 0.06$, $D/T = 0.4$ and $S/D = 12.5$. Let us assume that a rock mass in a mining slope has its material properties as: $\gamma = 20$ kN/m^3 and $c = 70$ kN/m^2. Consequently, the field conditions at the failure state shall have interface adhesion and other geometrical parameters of the slope as shown below.

[$c/c_i = 5.97$] $c_i = 11.72$ kN/m^2
[$\gamma T/c_i = 2.28$] $T = 1.34$ m
[$W/T = 20$] $W = 26.8$ m
[$L/T = 25$] $L = 33.5$ m
[$L_b/L = 0.06$] $L_b = 2.0$ m
[$D/T = 0.4$] $D = 0.54$ m
[$S/D = 12.5$] $S = 6.75$ m

CONCLUSIONS

The conclusions can be itemised as follows:

1) The curve of stability number versus failure slope angle in a slip test without any shear pin shows a similar trend to that from the previous research even though different materials were used to simulate a low interface friction plane.
2) The shear pins increase the stability of the soil slope resting on a low interface friction plane. The averages of failure slope angles in models with one and two shear pins are about 28% and 35% higher than that in a model without any shear pin. A thinner slope results in a higher failure slope angle.
3) There are only some small differences in failure slope angle for different locations of two shear pins in a row in the soil block. This indicates that the location of the shear pins has little effect on the stability of the soil block. Different failure mechanisms associated with different locations of the two shear pins in a row are observed.
4) For the same geometry of the soil slope, two shear pins in a horizontal row produce better reinforcement than do two shear pins in a vertical line. The average failure slope angle for the former cases is 7.6% greater than for the latter case.
5) There are two failure mechanisms in this study, namely punching shear failure and detachment failure. The punching shear failure can be observed in models with one shear pin and those with two shear pins and a small thickness of the soil block, as well as those with two shear pins in a vertical line for all width ratios of the soil block, *W/T*. The detachment failure mechanism is associated with the slope thickness and location of the shear pins. A stable soil slope above two shear pins in a row after the detachment failure indicates that an arching effect occurs between the two shear pins, where the spacing between the shear pins is as large as 12.5 times the diameter of the shear pin.
6) There are significant limitations in applying the results of 1g physical models to field conditions. It is too expensive to perform 1g physical models which cover all practical ranges of field problems. However, the aim of this paper is to present experimental results which provide a useful basis for a better understanding of the stability and failure mechanisms

involved in the problems, and thus they can be employed to validate a derived analytical solution using the framework of limit analysis or limit equilibrium method.

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