Physical modelling investigation of a 3-stage landslide prevention system: case study

M A Md Said*, M H Ramli, M Azmi and A S Mohd Azam

1School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Penang, Malaysia.

*Corresponding author: ceazlin@usm.my

Abstract: A study was conducted to propose and assess the suitability of a structural design for landslide prevention system consisting of flexible barriers, concrete baffles and rigid barrier. A 1:20 scale model of the landslide system was conducted to observe the impact of a flexible barrier, the concrete baffle configurations and the appropriate rigid barrier height. Soils samples from site were also analysed to identify and characterize the soil properties. The experiments were conducted by varying the soil moisture content of the soils for the flexible barrier and concrete baffles. Results obtained showed that the flexible barrier is permanently deformed when the soil moisture is 26%. The configuration of several types of concrete baffles were studied where for unobstructed flow, the use of two rows of baffles had increased the degree of transverse blockage from 23% to 35% and provided up to 75% run-out distance reduction. A cantilever retaining wall is designed as a rigid barrier to ensure adequate retention and to prevent overflowing if the flexible barrier and concrete baffles failed. The combination of three different barriers was assessed and the result showed that the run-out distance was significantly decreased by 47 percent compared to unobstructed flow.

1. Introduction

Penang Island is a small island situated in northern part of Malaysia, approximately 300 km² comprised predominantly of steep topography of more than 50 percent above 60 meter. With a largely urban population, Penang is one of Malaysia's many rapidly industrialized states. In recent decades, efforts have been intensified to industrialize and develop other economic sectors, resulting in greater urbanisation and pressures on flat land [1]. Most of the lowlands have been developed in Penang Island, hills are therefore abundantly available on the island as the low land resources are poor [2]. Construction activities rapidly increase each day in Penang Island, particularly for residential and commercial purposes. Such rapid development jeopardizes the environment through natural disasters such as climatic changes, flood and landslide, has become threats to peace of life and property of locals.

Landslide events are common in Penang Island, particularly during wet seasons between April to May and October to November and in some cases due to slope failures or design failures. The district of Balik Pulau, Jelutong, Air Itam, Tanjung Bungah and Paya Terubong are among the most prominent landslide areas in Penang Island. Whenever heavy rain and flash floods occur, landslides on natural or man - made slopes would almost likely to happen because high amounts of precipitation are the major cause for landslide [3].

Recently, several landslides occurred in Penang which had no casualties such as at Taman Lau Geok Swee in Paya Terubong on 14th July 2017 [4], and at Sungai Kelian in Tanjung Bungah Bungah Hill on 28th May 2018 [5]. Several landslides with casualties had happened at Jalan Bukit Kukus, Paya Terubong, on October 2018 [6,7], and the Granito condominium site in Tanjung Bungah on 22 October 2017 [8].
2. Study Area

The study area shown in Figure 1, is located at a slope owned by Kek Lok Si Temple, Ayer Itam, Pulau Pinang. The Kek Lok Si Temple also generally known as the Temple of Supreme Bliss, is the largest Buddhist temple in Malaysia and the main attraction for Buddhists for other countries in Southeast Asia. The surrounding area are extensively developed, with the huge iconic Pagoda of Ten Thousand Buddha, main access road to Ayer Itam Dam, cable car facilities to carry pilgrims and visitors uphill and road and other facilities at the bottom of the hill.

![Figure 1. Location of the Study Area](image)

A landslide occurred at Air Itam Dam Road, Penang on 29th October 2016, after heavy rain for more than three hours which had loosened large boulders, trees, and vegetation on a 30-metre section of the hillside [9]. A 350 metre section of the road was closed right after the landslide occurred due to heavy rain causing difficulties for residents, vegetable farmers and tourists.

To prevent further landslides, a counterfort retaining wall was constructed at the location. Although the prevention measure has been taken, there is a still possibility of landslide as the slope above the retaining wall has not been improved or reinforced. Therefore, the retaining walls can be significantly affected if slope failure occurs again [10].

3. Site Survey and Laboratory Tests

A site survey was conducted to determine the elevation, slope angles and information required for the study. The contour of study area is shown in Figure 2 where the elevation varies from 23.16m (maximum) to 8.18m (lowest).

Soil samples were obtained at different locations at the slope and stored in plastic bags for further analysis. Several soil tests were conducted, i.e. the Atterberg limit test, the particle size distribution test, the permeability of the coarse-grained test and the specific gravity test. All the tests followed different standards as shown in Table 1. Standard used for physical properties testing.

| Physical properties          | Testing method and abbreviated reference                  |
|------------------------------|----------------------------------------------------------|
| Particle size distribution   | BS 1377: Part 2: 1990: 9.5                               |
|                             | BS 1377: Part 2: 1990: 9.3                               |
| Specific gravity, G_s        | BS 1377: Part 2: 1990: 8.3                               |
| Liquid limit, LL             | BS 1377: Part 2: 1990: 4.3                               |
| Plastic limit, PL            | BS 1337: Part 2: 1990: 5.3                               |
| Permeability                 | BS 1377: Part 5: 1990:5                                  |
|                             | ASTM D 2434                                             |
3.1 Physical Model

The physical model is used to understand the behaviour of the landslide prevention system characteristics shown in Figure 3. The landslide prevention conceptual system can be visualized by the physical model. A 1:20 physical landslide modelling was performed using the most critical cross section obtained from the site survey in order to investigate the effect of changes in debris properties on the barrier’s structural response subject to debris impact. A 3.5m long with a width of 2m and 1m in height model is used to investigate the influence of baffle arrangement and the suitable height of rigid barrier. The slope inclination is according to site measurements, i.e. 70°. The topsoil is released at the top part of the model to imitate the landslide at the study area.
3.2 Baffle configurations

A series of 6 different baffles configurations were investigated to measure the run out distances. Two control tests without baffles were conducted as control tests for comparison. Baffles array are separated into 3 degree of transverse blockages and the number of rows is varied from 1 to 2 staggered rows. The degree of transverse blockages is varied as 23%, 26% and 35%. The spacing between each row is varied as 50mm, 75mm and 90mm which show real spacing at site 1m, 1.5m and 1.8m respectively.

Table 2 shows the control test while Table 3 and Table 4 show the baffle test configurations.

Table 2. Control Test

| Test ID | Soil Weight (kg) |
|---------|------------------|
| CT-1    | 13               |
| CT-2    | 20               |

Table 3. Single Row with constant baffle height of 75mm

| Test ID  | Soil Weight (kg) | Transverse blockage (%) |
|----------|------------------|-------------------------|
| R1-13-23 | 13               | 23                      |
| R1-20-23 | 20               |                         |
| R1-13-26 | 13               | 26                      |
| R1-20-26 | 20               |                         |
| R1-13-35 | 13               | 35                      |
| R1-20-35 | 20               |                         |
| R2-20-35 | 20               |                         |

Table 4. Double Rows with constant baffle height of 75mm

| Test ID  | Soil Weight (kg) | Transverse blockage (%) |
|----------|------------------|-------------------------|
| R2-13-23 | 13               | 23                      |
| R2-20-23 | 20               |                         |
| R2-13-26 | 13               | 26                      |
| R2-20-26 | 20               |                         |
| R2-13-35 | 13               | 35                      |
| R2-20-35 | 20               |                         |

4. Results and Discussion

4.1 Baffle Configuration Results

Three transverse blockages are examined, namely 23%, 36% and 35%. Furthermore, the number of rows investigated ranges from 1 to 2 with spacing between successive rows of 50 mm and constant baffle height of 75mm. Run-out distance results of the testing programme consisting of 14 tests are given in the Table 5 and Table 6 including control test.
Table 5. Control Test Results

| Test ID | Soil Weight (kg) | Run Out Distance (cm) |
|---------|------------------|-----------------------|
| CT-1    | 13               | 87                    |
| CT-2    | 20               | 107                   |

Table 6. Testing Program Results

| Soil Weight (kg) | Transverse blockage (%) | Run out Distance (cm) |
|------------------|--------------------------|-----------------------|
| R1-13-23         | 13                       | 23                    | 92                    |
| R1-20-23         | 20                       | 26                    | 46                    |
| R1-13-26         | 13                       | 35                    | 39                    |
| R1-20-26         | 20                       | 23                    | 48                    |
| R2-13-23         | 13                       | 23                    | 73                    |
| R2-20-23         | 20                       | 26                    | 37                    |
| R2-13-26         | 13                       | 35                    | 27                    |
| R2-20-26         | 20                       | 35                    | 29                    |

Baffles are arranged in a staggered configuration as previous study [11] which disrupts streamlines between successive rows with optimal energy dissipation. Transverse blockage percentages are adopted for ease of applicability to prototype conditions.

4.2 Flexible debris resisting barrier test program

A flexible net with a height of 17.5 cm after scaled down was used in physical modelling to investigate its purpose, by minimizing the run-out distances. From the results obtained in Table 7, the flexible barrier undergoes permanent deformation when the moisture content is 26%. This shows that flexible barriers must be provided with robust foundations and anchors to withstand the impact, as well as the effect of debris weight on the slope [12]. The structure of the flexible barrier may fail due to the high water content in the soil caused by continuous rainfall.

Table 7. Flexible Barrier Test Results Program

| Soil Weight (kg) | Water Content (%) | Moisture Content (%) | Run Out Distance (cm) |
|------------------|-------------------|----------------------|-----------------------|
| 30               | 0                 | 0                    | 47                    |
| 30               | 20                | 13%                  | 58                    |
| 30               | 40                | 26%                  | Failed                |

Figure 4. Flexible Net Testing Results

Figure 4 shows flexible net testing results. At some point during heavy rainfall, the weight and forces exceeded the design load of the flexible barrier. The mass of soil with 26% moisture content has
damaged the flexible net as presented in (c) before enabling the energy absorption system to fully operate.

4.3 Combination of Three Phases Results

For ease of interpretation and calibration of theoretical models, dry top soil is used in the test. A 45kg source weight, 35% transverse blockage, two rows of baffles, 17.5cm flexible net were adopted to investigate the effectiveness of the 3-phase combination. Comparing with unobstructed flow, the use of three types of resisting barriers can reduce up to 47% of the debris run out distance from 110cm to 58cm. There is an obvious influence of baffles geometry and flexible net on flow interaction which reduce run-out distance as shown in Table 8.

Table 8. Combination of Three Phases Results

| Net Height (cm) | Soil Weight (kg) | Distance Between Baffles (mm) | Transverse Blockage | Run Out Distance (cm) |
|-----------------|------------------|-------------------------------|---------------------|-----------------------|
| -               | 45               | -                             | -                   | 110                   |
| 17.5            | 45               | 50                            | 35%                 | 58                    |

(a) 30kg of soil with 0% moisture content

(b) 30kg of soil with 13% moisture content

(c) 30kg of soil with 26% of moisture content

Figure 4. Flexible Net Testing Results
4.4 Retaining Wall

Rigid barrier for this study are of reinforced concrete construction and is practically the same as the one proposed in Hong Kong. Rigid barrier are designed to withstand the impact force of debris and occasional boulders [12] A cantilever retaining is designed based on BS8100: 1997 where all the geotechnical properties given in Table 9 were obtained from the SI/GI Contractor.

| Table 9. Geotechnical Properties |
|----------------------------------|
| Unit Weight of Soil, $\rho$      |
| 19.64 kN/m³                     |
| Internal Angle of Friction, $\phi$|
| 34°                             |
| Bearing Pressure                 |
| 100 kN/m²                       |
| Coefficient of Friction          |
| 0.4                              |
| Unit Weight of Concrete, $\rho$  |
| 24 kN/m³                        |

5. Conclusion

In conclusion, the study was satisfied as the geotechnical and geological parameters for landslide prevention system were identified, three different passive earth retaining system were proposed, the influence of each different type of barriers on flow interaction were assessed and rigid barrier is designed and evaluated using common geotechnical and reinforcement concrete design code.

Three small scale debris resisting barriers including a flexible net, set of baffles and rigid barrier are used to demonstrate and confirm the practicability of the proposed method. The result showed that the usage of a single flexible barrier had failed due to high water content in the soil as it could not withstand the impact and weight of the soil. The flexible barrier undergoes permanent deformation when the moisture content reached 26% only by adopting the flexible barrier. From the findings, an increasing number of rows is the most effective way in reducing the kinetic energy of debris flow compared with unobstructed flow. The use of double rows of baffles can provide more than 50% run-out distance reduction. Furthermore, the arrangement of baffles in staggered position promotes optimal energy dissipation and induced the soil pattern fell more evenly in placed and less dispersed. Moreover, a 45kg source weight, 35% transverse blockage, 2 rows of baffles, 17.5cm flexible net were adopted to investigate the effectiveness of the 3-phase combination.

A 5 meter cantilever retaining is designed based on BS8100: 1997. The height of rigid barrier is designed to ensure adequate retention and avoid overflowing debris. The stability of the whole structure under the service loads including overturning, sliding and bearing failure modes was assessed. The rigid barrier is designed against lateral sliding and overturning and both Factor of Safety (FOS) values exceed 1.5 which achieved the stability.

The combination of three different barriers experiments showed that the run-out distance has reduced up to 47% compared to unobstructed flow.

Acknowledgement

The authors wish to express sincere appreciation for the support and encouragement provided by the Engineering Department, MBPP and School of Civil Engineering, Universiti Sains Malaysia in making this project a success.
References

[1] See Sew G and Chin Y C 2003 The Engineering Aspects of Hill-Site Development Hillside Development – Issues and Challenges (Kuala Lumpur)

[2] Chan N W 1998 Environmental hazards associated with hill land development in Penang Island, Malaysia: some recommendations on effective management Disaster Prev. Manag. 7 305–18

[3] Pradhan B and Lee S 2010 Landslide susceptibility assessment and factor effect analysis: backpropagation artificial neural networks and their comparison with frequency ratio and bivariate logistic regression modelling Environ. Model. Softw. 25 747–59

[4] The Star Malaysia Past landslide cases reported in Penang Accessed 15/6/2020

[5] The Star Malaysia Huge landslide in Tg Bungah hill | The Star Accessed 15/6/2020

[6] Anon Two confirmed dead, one rescued and 10 missing in Bukit Kukus landslide Accessed 15/6/2020

[7] The Sun Daily Chronology of landslides in Penang since 2017 Accessed 15/6/2020

[8] The Straits Times Three dead, 11 missing in Penang landslide, SE Asia News & Top Stories - The Straits Times Accessed 15/6/2020

[9] Malay Mail Penang water authority closes Air Itam Dam road for safety | Malay Mail Accessed 15/6/2020

[10] Mandali A K 2011 Reliability Analysis of Counterfort Retaining Walls Electron. J. Struct. Eng. 11 15

[11] Ng C W W, Choi C E, Kwan J S H, Shiu H Y K, Ho K K S and Koo R C H 2012 Landslide_Mobility_Analysis_for_Design_of_Multiple.pdf Proceedings of the One Day Seminar On Natural Terrain Hazard Mitigation Measures One Day Seminar On Natural Terrain Hazard Mitigation Measures (Kowloon, Hong Kong: HKSAR) pp 16–21

[12] Kwan J S H, Chan S L, Cheuk J C Y and Koo R C H 2014 A case study on an open hillside landslide impacting on a flexible rockfall barrier at Jordan Valley, Hong Kong Landslides 11 1037–50