Ground-Water Flow Analysis in the Slope Above Shum Wan Road, Hong Kong

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Key Terms: *Hydrogeology, Slope Stability, Hillslope, Landslide, Ground Water, Saturated Flow, MODFLOW, Transient Seepage*

ABSTRACT

On August 13, 1995, a slope above Shum Wan Road failed due to high rainfall and caused a 30-m section of Nam Long Shan Road to collapse. The slope consists of weathered tuffs with a clay layer on the surface of the failure. A hydrogeological study was carried out by saturated finite difference grid model, MODFLOW, for the slope at the Shum Wan Road area. From the ground-water model, it was found that the ground-water level reached three meters below the ground surface during failure. The model is sensitive to recharge and specific yield. The presence of the clay layer helped to maintain a high ground-water level. Stability analyses were performed using SLOPE/W. The result of stability analyses showed that the factor of safety, F, decreased due to the rising initial water table. On the 31st of July, the factor of safety was 1.41, and dropped down to 1.01 on the 3rd of August. The factor of safety again rose back to 1.31 on the 8th of August and it finally dropped down to 0.99 on the morning of the 13th of August. The present study showed that the antecedent rainfall had some influence on stability of the slope. The amount of water in the form of seepage, which drained out from the seepage surface from the lower part of the slope, is quantified and found to be 790 m^3. Preventive measures can be taken by inserting horizontal pipes in the slope to drain out the ground water in the form of seepage or by covering the slope with shortcrete or chunam.

INTRODUCTION

In Hong Kong, most of the landslides occur after high intensity rainfall events. Shum Wan landslide was one of them, which caused the collapse of a 30-m long section of Nam Long Shan Road on the 13th of August 1995 (Figure 1). The recorded 30-hr rainfall before the landslide was 381 mm (Geotechnical Engineering Office, 1996). This paper aims to characterize the changes in ground-water elevation due to high rainfall events and the effect on the stability of the slope above Shum Wan Road. A detailed investigation of the ground-water conditions is required for a thorough understanding of the failure. A hydrogeological study with appropriate boundary conditions was carried out by the saturated finite difference grid model, MODFLOW (McDonald and Harbough, 1988), for the slope above Shum Wan Road. In the proposed model, low permeable bedrock with little fractures is considered as part of the aquifer system. Different hydrogeological parameters used for model calculations have been calibrated to satisfy the observed field conditions. The factor of safety was calculated by SLOPE/W (Geoslope International Ltd., 1995). The amount of water, which drained out from the seepage surface from the lower part of the slope in the form of seepage, is quantified. The present findings suggest the preventive measures to be taken to prevent slope failure.

PREVIOUS WORK

Many workers studied the relationship between rainfall and landslide. Au (1993) has characterized the relationship between rainfall and the number of slope failures in Hong Kong. He concluded that the scale of slope failure event in Hong Kong is related to intensity of rainfall and degree of urbanization. He found that more slope failure occurs in more developed areas. Premchitt and others (1986) studied the rainfall-landslide correlation in Hong Kong. They have found that the majority of landslides in Hong Kong are induced by localized short duration rainfall of high intensity. A rainfall intensity of 70 mm/hr is the threshold value above which landslides may occur. They recommended that a theoretical model, emphasizing rapid infiltration and a large subsurface horizontal flow down a hillside during and after intense rainstorms, be set up to predict ground-water conditions in landslide-prone slopes leading to the buildup of pore water pressure. Iverson and Major (1987) studied the relation between rainfall, ground-water flow and seasonal movement at Minor Creek landslide in California. They found that transient ground-water responses early in the wet season are influenced by antecedent water storage in the unsaturated zone. In the later stage of the wet

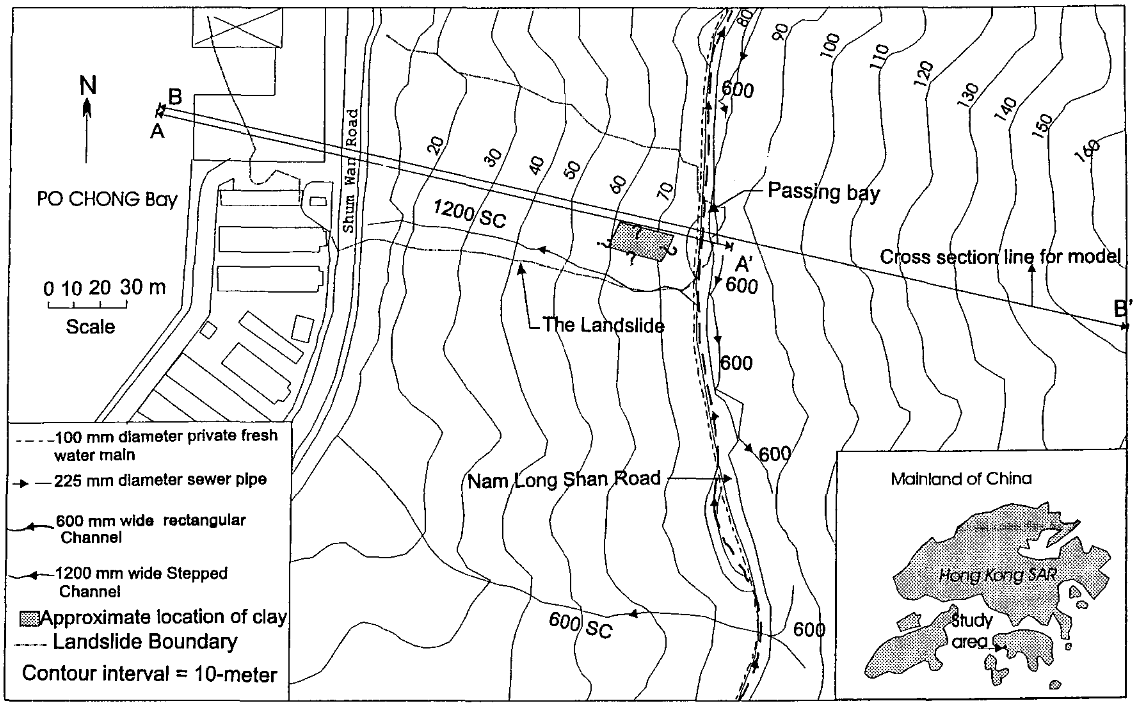

Figure 1. Location map of the area (modified from Geotechnical Engineering Office, 1996).

season, the ground-water responses are directly related to pore pressure transmission that accompanies saturated ground-water flow.

Koo and Lumb (1981) found that the variations in ground-water levels were predominantly seasonal. According to them, the water table during the dry season is near the soil/rock contact, and during the wet season the ground-water response to rainfall is very high. Nash and Dale (1983) have shown rapid piezometric response to rainstorms in Hong Kong. Brand and others (1986) considered rapid transmission of ground water through natural pipes and other preferential drainage paths as another factor of landslides. While most of the landslides in Hong Kong occur during or immediately after rainstorms, some failures exhibit a delayed response (Jiao et al., 1999). They performed numerical analysis using MODFLOW for a delayed failure at Tuen Mun, Hong Kong. They found that the ground-water level at the place of failure increased to a maximum after six days of the rainstorm event.

Several workers have developed numerical models for better understanding of the hillslope hydrogeology of Hong Kong. Leach and Herbert (1982) first developed a finite difference model for understanding of hydrogeology in steep slopes of the Mid-Level area in Hong Kong. They proposed a model to observe piezometric response during the 1980 wet season (July to September). They also used a very low-permeable layer of 1-m thickness to get a rapid response of the water table rise. They state that there is no clearly defined thin low-permeable layer in the field, however, the colluvium in the lower slopes often becomes finer-grained toward its base. Hence, they considered a basal low-permeable layer for their model. They observed seepage from both the fresh granite and volcanic bedrock exposed high on the hillside of Mid-Level, Hong Kong. From the above observations they also acknowledge that the lower slope areas could be recharged from the up-slope aquifers.

Lerner (1986) studied piezometric levels in steep slopes and concluded that the response of the water table to rainfall was not the only ground-water factor affecting slope stability in urban areas. He found that the rainfall recharge was too low to sustain observed piezometric levels because in urban areas, most ground is covered by roads, concrete, buildings, or chunam, a protective covering. He mentioned in his model that the recharge to the aquifer was from two other sources rather than direct infiltration. One is from low permeable bedrock, and another is leakage from underground utility lines. He concluded that rainfall infiltrating into exposed bedrock on the highest slope and flowing to the aquifer down the slope might be a possible source of re-charge.

Ground-water distribution throughout a slope depends on the weathering profile of the slope. Several workers like Ruxton and Berry (1957), Lumb (1975, 1983) and Bennett (1984) studied weathering of the rocks in Hong

Kong. Berry and Ruxton (1960) described weathering profiles in the volcanics up to 60-m deep in Hong Kong. It is found that complete weathering of the parent rock has resulted generally in the formation of a 20-m thick residual soil in volcanics and a 50-m thick residual soil over the granites in some parts of Hong Kong (Premchitt et al., 1986).

Assessment of rainfall infiltration is important for geohydrological modeling. GEO (Geotechnical Engineering Office, 1992) reported that potential infiltration on slopes could be evaluated by simply subtracting runoff from the rainfall. Rushton and Ward (1979) have proposed different recharge models, and they have considered a model by taking 30 percent effective rainfall as direct annual recharge. They considered recharge on a yearly basis for water supply purposes, and according to them, Neat Recharge = Rainfall – Evapotranspiration – Runoff. The evaporation losses are generally reduced during rainfall (Rushton and Ward, 1979). The *Geotechnical Manual for Slopes* (Geotechnical Control Office, 1984) estimates that 50 percent of the rainfall is produced as runoff and 50 percent as infiltration. Mau and Winter (1997) estimated recharge varies from 15 to 43 percent of precipitation in the Mirror Lake area, NH. The ground-water studies related to slope stability, however, concern the short-term response of the ground-water system to rainstorms. The evaporation and transpiration losses are usually ignored (Jiao et al., 1999).

The Geotechnical Engineering Office of Hong Kong (Geotechnical Engineering Office, 1996) conducted an investigation at the Shum Wan landslide area. The investigation included interviews with witnesses, a topographic survey, observations and measurements at the landslide site, geological mapping, ground investigation, examination of the condition of drainage systems and water carrying services, theoretical stability and seepage analysis and diagnosis of the causes of the failure. The finite element model used for their seepage analysis assigned constant head boundaries on both the upper and lower parts of the slope. The GEO's model considers only a small section of aquifer and did not consider the entire upper part of the hillslope. They pointed out there might be some subsurface horizontal flow from the upper part of the hillslope but that flow would contribute mainly to the rise of the base ground-water level. For the modeling purpose, GEO considered a continuous clay layer, however, clay was not found as a continuous layer in the entire area (Figure 1). The main landslide was preceded by a minor failure at the passing bay and according to GEO, the saturation of the fill material (Figure 2) is the cause of this minor failure.

Osiensky and Williams (1997) pointed out that convergence for a small head change criterion is not a good indicator of accurate results for the ground-water flow model using MODFLOW unless the water balance error is also small.

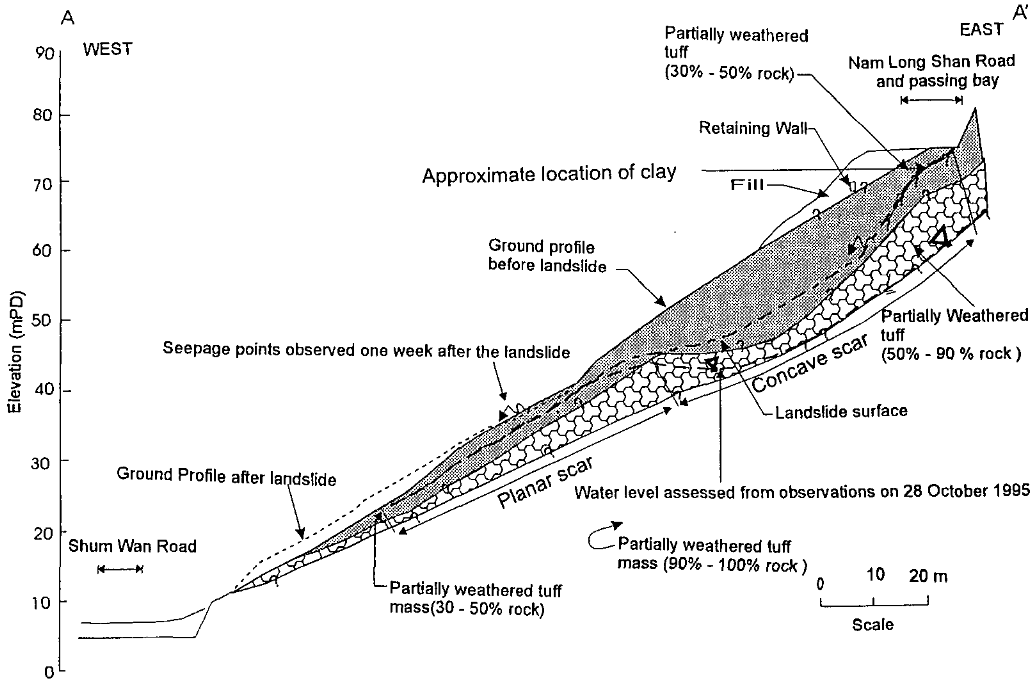

Figure 2. Geological cross section (along A–A' of Figure 1) of the site before the landslide (modified from Geotechnical Engineering Office, 1996).

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS AT THE SITE

The subsurface conditions of the Shum Wan Road landslide area were studied by Geotechnical Engineering Office (1996). GEO's investigations consist of a seismic refraction survey, geological mapping and borehole logging. A typical section along A–A' of Figure 1 is given in Figure 2. The landslide area, consisting of a thin mantle of colluvium overlying a partially weathered fine-ash to coarse-ash crystal tuffs, belongs to Repulse Bay Volcanic Group (Smith et al., 1989). The colluvium is composed of silty clay with gravel and cobble clasts and exposed on the adjoining hillside. Highly decomposed tuffs containing two sets of subvertical joints were found below colluvium. The subvertical joints exposed in the concave landslide scar are very closely spaced so that these would have permitted relatively easy downward passage of water through the partially weathered tuff. The joints are more closely spaced in the weathered tuff, and widely spaced in less weathered rock. A thin, 100-mm thick to locally 350-mm thick clay seam was observed within the floor of the concave scar; however, the distribution of the clay is not known. The clay layer, according to the Geotechnical Engineering Office (1996) report, is found below the failed area but not across the entire domain. Weathering depth and abundance of kaolinite-filled joints are both greater at the landslide site than the surrounding vicinity (Kirk et al., 1997). Less weathered bedrocks were underlain by highly decomposed rock. The hydraulic conductivity values were not measured by Geotechnical Engineering Office (1996). The hydraulic conductivity values for similar materials are listed in Table 1 from the previous work of the Geotechnical Control Office (1987).

The landslide scar is 140 m in plan length, and its width varies from 50 m at the level of Nam Long Shan Road to 90 m above Shum Wan Road. The landslide involved about 26,000 m^3 of soil and rock debris. The failure was progressive (Geotechnical Engineering Office, 1996). The slope angle before landslide was about 27°. The landslide resulted in a 70-m high scar.

Table 1. *Results of permeability tests on Hong Kong tuffs (Geotechnical Control Office, 1987).*

Material	Coefficient of Permeability (m/d)
Completely to highly decomposed tuff	1.1 to 6.1
Moderately to slightly decomposed tuff	1.03 to 5.5
Slightly decomposed tuff (with closely spaced joints)	1.1 to 1.5
Slightly decomposed tuff	0.0005 to 0.03

THE MODEL

A model can diagrammatically represent ground-water flow systems. Models simplify the field conditions and allow field data to be analyzed more readily. We attempted to characterize the hydrogeological conditions by modeling ground-water flow using MODFLOW, a software program for investigation of ground-water flow. MODFLOW is a 3-D cell-centered finite difference saturated flow model. Steady and transient state simulation with appropriate boundary conditions and input options can be performed with MODFLOW. Finite difference modeling requires the aquifer to be divided into grids. Therefore, our first step was to configure the model parameters. This involved designing the finite difference grid and defining the boundary conditions and the material properties.

In this study, the cross-sectional area along B–B' of Figure 1 was divided into grids (60 columns, 9 layers and 1 row) required for MODFLOW analyses. The width of each column is 6.25 m. Twenty-six columns at the failure area were refined to obtain a better accuracy for the hydraulic head values (Figure 3). Hence, the total number of columns in the present model becomes 86. The first layer is unconfined and the rest of the layers are fully convertible between confined and unconfined. Confined storage coefficient is used to calculate the rate of change in storage if the layer is fully saturated; otherwise, specific yield will be used. During a flow simulation, transmissivity of each cell varies with the saturated thickness of the aquifer. An observation well, P_1 was set along column 57 to observe the change of the ground-water level.

Boundary Conditions

The actual boundary conditions should be well known before starting any kind of numerical analysis. For the Shum Wan landslide, the mountain ridge of Nam Long Shan Road is considered as the ground-water divide and the sea, Po Chung Wan (Bay), as a constant head boundary. The bottom impervious boundary is taken 80 m below ground surface on the left-hand side of the model area and 127.5 m below ground surface on the right-hand side of the model area (Figure 3). Below this depth, we assume that there will be no ground-water flow, and it can be considered as a bottom impervious boundary. According to Geotechnical Engineering Office (1996) the weathered rock mass (50–90 percent rock) is less than 20 m thick at the upper slope and it becomes thinner in the lower slope. Below that, partially weathered rock mass (90–100 percent rock) is found. Hence, we believe that

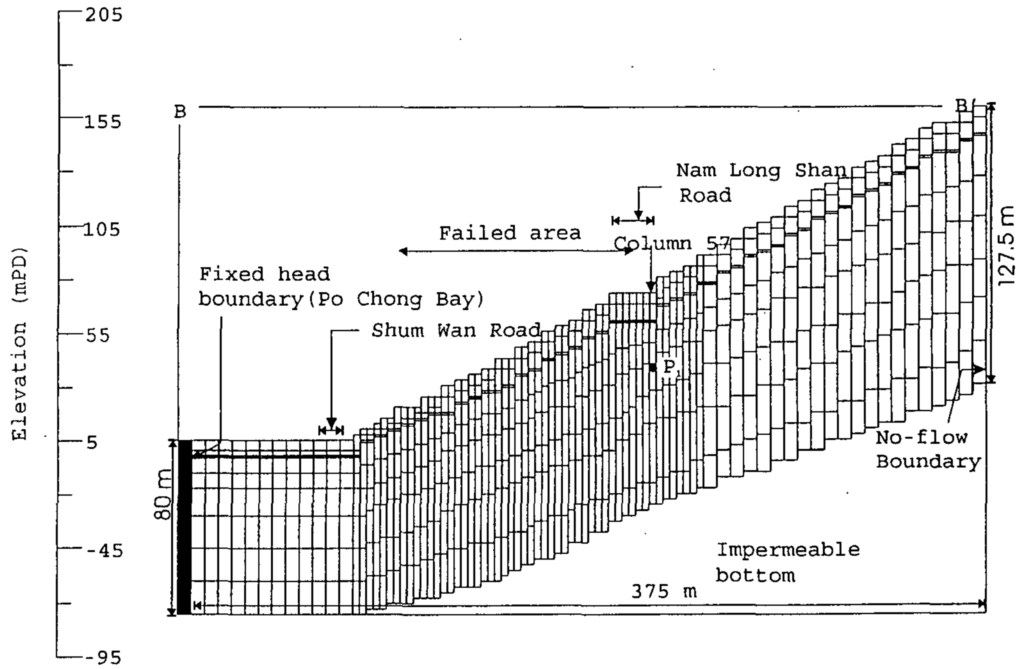

Figure 3. Mesh systems and boundary conditions used in the model.

the assumption of the bottom impervious boundary is reasonable.

Recharge

In Hong Kong, the annual rainfall is around 2,200 mm. A major part of the rainfall drains across the land as surface runoff with some going into the ground and some evaporating to the atmosphere. The rainfall data from the 13th of July to the 13th of August are shown in Figure 4 (Geotechnical Engineering Office, 1996). The amount of recharge is .006 (m/day), if recharge is considered as 15 percent of the total rainfall of 31 days before the failure. Fredlund and Rahardjo (1993) used almost the same amount of recharge (0.0057 m/day) for the steady state analysis in a steep slope in Hong Kong. In the model recharge is taken as 50 percent (Geotechnical Control Office, 1984) of the total rainfall during the transient state analysis between the 13th of July to the 13th of August. The recharge is taken as aerially uniform for simplification. Another factor, leakage from the underground utilities, is not applicable because no leakage was found before landslide according to Geotechnical Engineering Office (1996) report. The evapotranspiration losses are ignored in our model.

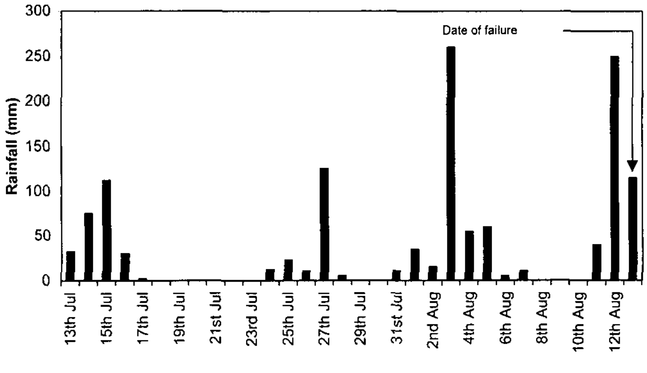

Figure 4. Rainfall data from the 13th of July to the 13th of August, 1995 (modified from Geotechnical Engineering Office, 1996).

Values of Different Parameters Used for the Model

The values of different parameters used in the model are given in Table 2. For the purpose of the modeling, permeability values for subsurface materials range from 1.6 m/day in the first layer to .009 m/day in the ninth layer. As the material becomes finer and less fractured in the lower part of the decomposed tuff, a sharp decrease in conductivity and other parameters has been taken into consideration in the model. The top two layers represent the thin colluvium and completely decomposed tuff, the next three layers are highly decomposed tuff, the next two layers are slightly decomposed tuff and the bottom two layers are slightly decomposed to fresh rock in the model. It is seen that fresh rock is exposed in the lower part of the slopes. Therefore, the parameters of layer 4 are used for the lower part of the slopes of layer 1, 2

Table 2. *Value of different parameters used in the model.*

Zone	Layer No.	Hydraulic conductivity (m/d)	Specific Storage	Specific yield (%)
Zone I, Completely decomposed rock	1 2	1.6 *1.2	0.00003 0.00003	0.05 0.01
Zone II, Highly decomposed rock	3 4–5	**1 0.5	0.00003 0.00001	0.005 0.005
Zone III, Slightly decomposed rock	6–7	0.1	0.00001	0.001
Zone IV, Slightly decomposed to fresh rock	8–9	0.009	0.00001	0.0001

* Parameters at the lower part of slope are taken as parameters of layer 4.

** Parameters at the lower part of the slope are taken as parameters of layer 4, and the permeability value is taken as 0.001 m/d below the failed surface to represent the clay layer.

and 3. The hydraulic conductivity data are chosen mainly from the Table 1 (Geotechnical Control Office 1987). The exact values used for the model are approximately median values of data ranges shown in Table 1. The clay layer was found only below the concave scar. Hence, a conductivity value of 0.001 m/day was taken for the cells of layer three below the concave scar. The specific yields are based on the model of Leach and Herbert (1982). Calibration of the specific yield by MODFLOW in a layered fractured aquifer is done by Gburek and others (1999). The calibrated values reported by them are 0.01, 0.005, 0.001 and 0.0001 for soil or overburden, highly fractured, moderately fractured and poorly fractured rocks respectively. Storage coefficients were automatically calculated in the model.

Steady-State Analysis

A steady-state analysis was conducted to determine the initial water table. The wetting capability of the BCF2 (McDonald and Harbough, 1988), a package of MODFLOW, was used which allowed the simulation of a rising water table into unsaturated dry model layers. The advantage of BCF2 is that a dry cell can become wet and it performs cell by cell flow calculation. From the steady-state analysis, the initial ground-water table and the initial hydraulic heads at different cells are determined. For the analysis, a recharge of .006 m/day was considered using the RECHARGE (McDonald and Harbough, 1988) package of MODFLOW. The ground-water table determined by the steady-state analysis is shown in Figure 5. From the volumetric budget of the entire model, it is seen that the percent discrepancy is 0.03, which is reasonable. The convergence value for hydraulic head is used as 0.0001 m. DRAIN (McDonald and Harbough, 1988), a package of MODFLOW, was used to calculate the ground-water discharge in the form of seepage from the lower part of the slope.

Transient State Analysis

For the analysis of the transient state, the head values of the steady-state analysis were taken as initial hydraulic head for the model. The wetting capability (BCF2) package was also used for transient state simulation. A 32-day simulation was done in the model by taking recharge as 50 percent of the rainfall. The recharge from rainfall is the only source of ground water in the study area. Due to heavy rainfall from the 13th of July to the 13th of August, there was high recharge. Recharge is applied to the highest active cell in the RECHARGE package. The DRAIN package was used to remove the water, which is discharged in the form of seepage from lower slope. SIP (McDonald and Harbough, 1988), an iteractive solver package of MODFLOW, based on a strongly implicit procedure, was used for the simulation. In the proposed model, we have set the convergence criterion as 0.0001 m and it is seen in Table 3 that the water balance (percent discrepancy) is –0.06 percent. Total inflows are 420 m^3 storage and 1,468 m^3 recharge. Total outflows are 732 m^3 storage, 367 m^3 constant head and 790 m^3 drains.

It is seen from the model that the water table rises immediately if the rainfall is high. During the simulation we have very high rainfall on the 27th of July, the 3rd of August and the 12th to 13th of August morning. The position of the water table on the 27th of July and the 13th of August is shown in Figures 6 and 7. The change of the ground-water level with daily rainfall in an observation well, P_1, along column 57 (below the failed area) of the model is shown in Figure 8. It is seen that the ground-water level rises with rainfall and lowers with no or decrease in rainfall. It is also seen from Figure 8 that on the 3rd of August, the water-table level rises to 65.34 m due to heavy rainfall, then falls with a decrease in rainfall and finally maintains a high water-table level

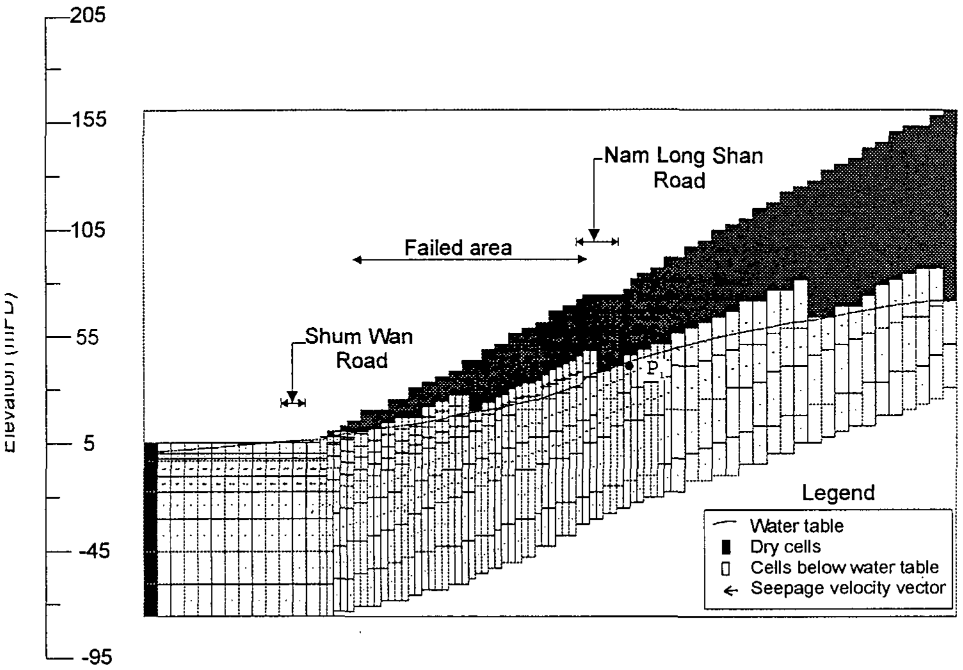

Figure 5. Position of the water table after steady-state analysis.

for a few more days though rainfall was negligible. The water-table level again rises on the 12th of August due to high rainfall and reaches a height of 69 m (three meters below ground surface, ground surface is at a height of 72-m) on the morning of 13th August, just before the failure. It is observed from Figure 8 that from the 8th to 10th of August there was no rainfall, but still the water-table level was high which was due to the presence of clay. Clay prevented the water from percolating downward and maintained a high water-table level. If we do not consider the presence of local clay, the ground-water level does not rise so high. The position of the water table without considering the presence of clay is shown in Figure 9. The water-table level at P_1 rises to a level of 64.87 m on the 13th of August instead of 69 m by considering the presence of clay. The model is sensitive to specific yield and recharge. If the specific yields are taken four times higher than the specific yield of the original model for each layer, then the water-table drops (Figure 10). The water-table level at P_1 rises to a level of 56.16 m after the 13th of August, whereas in the original model it rises to a level of 69 m. The model is sensitive to recharge. By taking recharge as 30 percent of the rainfall instead of 50 percent, the water table drops (Figure 11). The water table level at P_1 reaches to a level of 56.02 m on the 13th of August, whereas in the original model, it reaches to a level of 69 m.

Table 3. *Total water balance at the end of 31.17 days simulation.*

Inflows		Outflows	
Storage (m^3)	420.07	Storage (m^3)	732
Constant head (m^3)	0.000	Constant head (m^3)	366.96
Drains (m^3)	0.000	Drains (m^3)	790.80
Recharge (m^3)	1468.5	Recharge (m^3)	0.000
Total (m^3)	1888.57	Total (m^3)	1889.7

Percent discrepancy (error) = –0.06

We have quantified the amount of drained water in the form of seepage using the DRAIN package of MODFLOW. The relationship between rainfall and drained water is shown in Figure 12. It is also observed from the direction of vector arrow in the model (Figure 7) that there is a subsurface horizontal flow of water from the top of the hill to the base of the slope which has much influence to raise the water level at the concave scar. This factor was considered in the Geotechnical Engineering Office (1996) report, however, the report concluded that such recharge would have contributed largely to the base ground-water level. Our model suggests that the base water level is higher during rainstorms due to high infiltration. The subsurface flow of water from the up-slope and the presence of clay beneath the landslide scar have some influence on storing significant amounts of water during rainstorm events.

STABILITY ANALYSIS

Stability analyses have become a common analytical tool to measure the factor of safety of slopes. The soft-

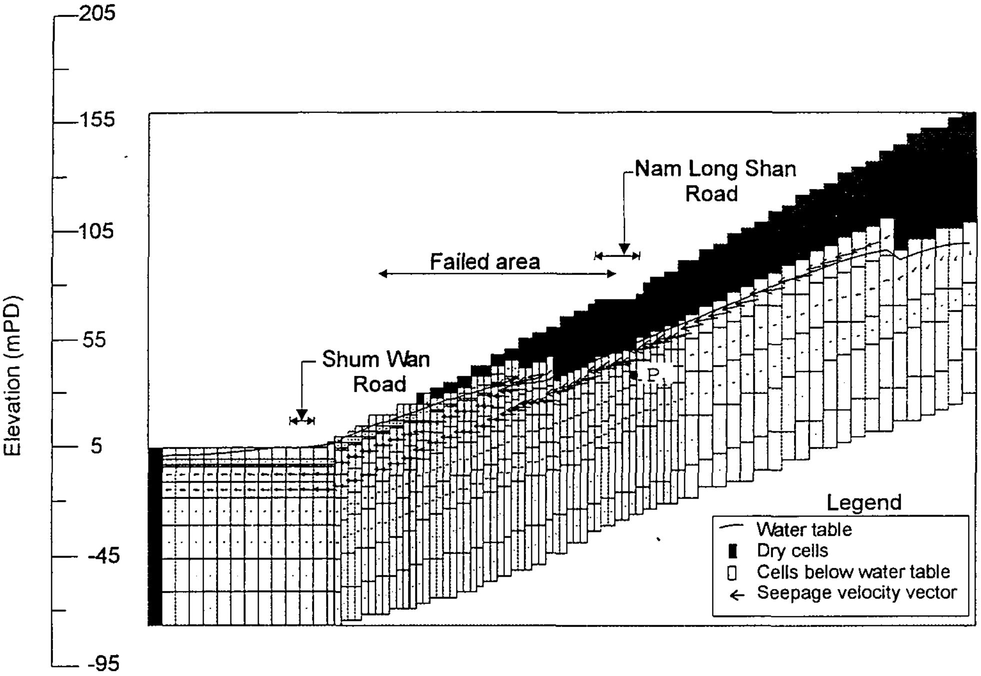

Figure 6. Position of the water table after 15 days.

ware SLOPE/W was used to measure the factor of safety. SLOPE/W uses the limit equilibrium theory to compute the factor of safety of slopes. Using this software, it is possible to calculate the factor of safety by various methods. Slope stability analyses were performed to measure the factor of safety for the upper concave failure. The material properties to measure the factor of safety are given in Table 4 from Geotechnical Engineering Office (1996) report. The triaxial compression tests were performed to measure the shear strength parameters of weathered tuffs and clay. The Geotechnical Engineering Office (1996) report described the presence of clay with

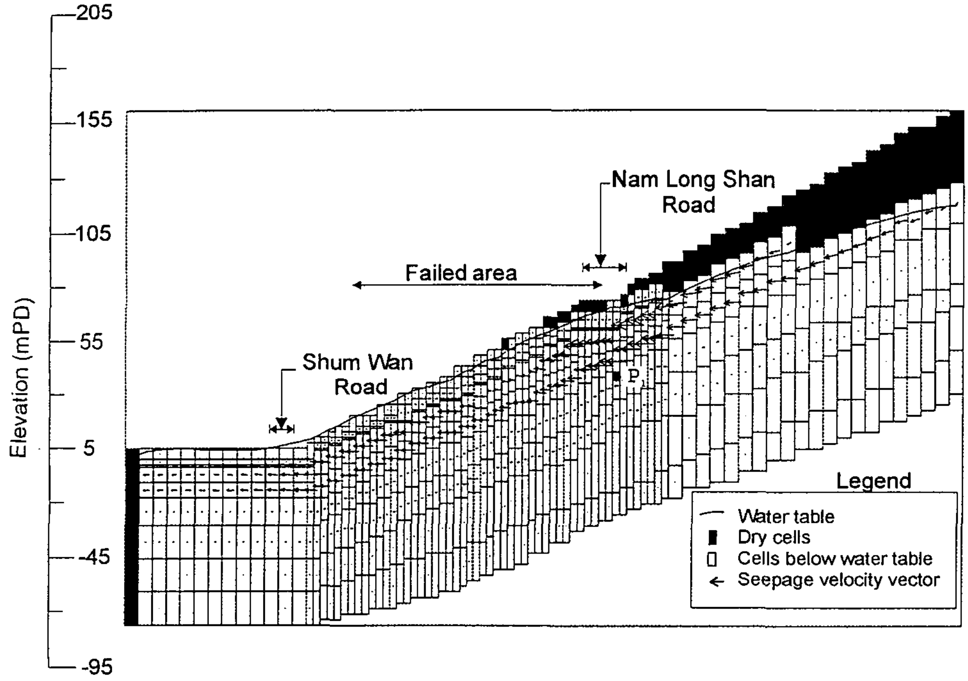

Figure 7. Position of the water table on the morning of the 13th of August.

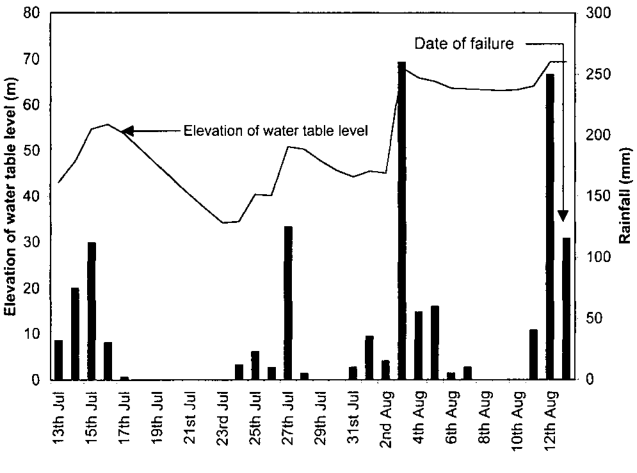

Figure 8. Response of the water-table level with rainfall along column 57 at P_1 of the model.

slickensides, and shear strength of $\phi = 21$ and C' = zero in a small area in the clay seam. According to the report, extensive sheared clay with weak strength would only require a relatively low perched water level to trigger the landslide. However, sheared clay was only found at a small area in the clay seam and we ignore the weakest strength in the present study. Slope stability analyses, using the Morgenstern and Price (1965) method, were performed for different days with changes of the position of ground-water level. Figure 13 shows the change of the factor of safety with time. Our results indicate that the factor of safety is high (F = 1.41) before the rainstorm and it became very low (F = 1.01) on the 3rd of August due to high rainfall, but slope did not fail. The calculated factor of safety became higher again after the 3rd of August due to the lowering of the ground-water level. It dropped again to 0.99 on the 13th of August during a rainstorm, which caused the failure. From the stability analysis, it is seen that the slope was stable before the rainstorm event on August 13, 1995.

CONCLUSIONS

Most landslides in Hong Kong occurred after a rainstorm. The Shum Wan landslide involved about 26,000 m^3 of soil and rock debris and the failure was progressive. The present study can explain the failure in a slope of weathered tuff with a clay layer. The established model shows how the water table rises due to high recharge during rainfall. This is a total 32-day simulation. Total inflows are 23 percent storage and 77 percent recharge. Total outflows are 39 percent storage, 19 percent constant head and 42 percent drain. It is seen that the ground-water level did not rise up rapidly during low rainfall, but rose suddenly to 65 m below the concave scar on the 3rd of August due to high rainfall. The ground-water level again dropped down and it started rising again on the 12th of August. It reached to a level of 69 m on the 13th of August and the slope failed. The observed seepages found in the field after the landslide can be explained by the presence of high water level during a rainstorm. Our model can demonstrate this fact because in the simulated result, ground-water level was three meters below the ground surface at the time of failure in the failed area.

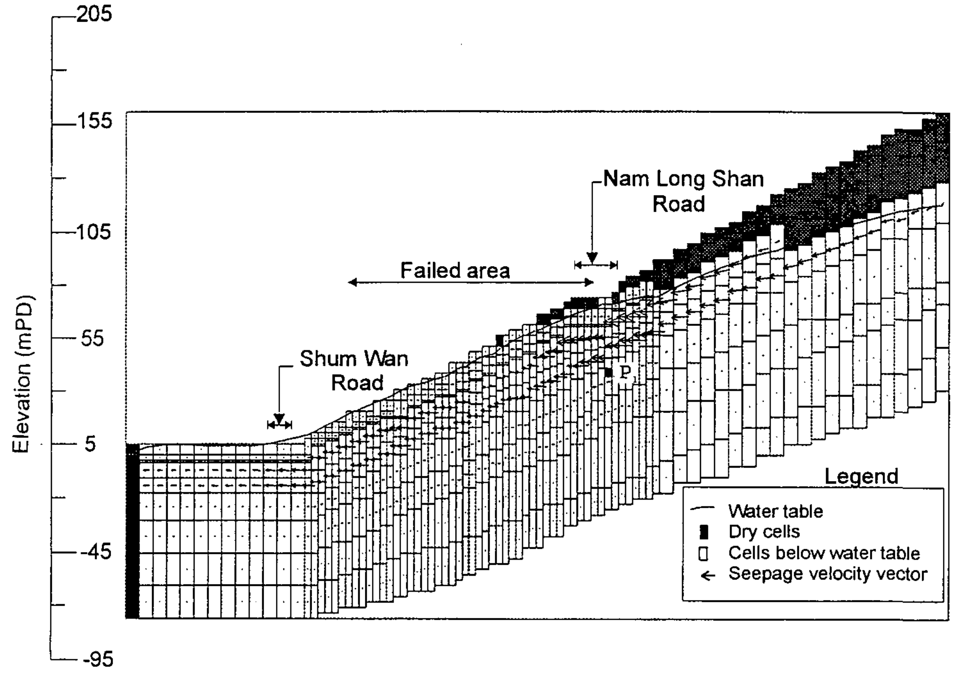

Figure 9. Position of the water table on the 13th of August without considering clay in the original model.

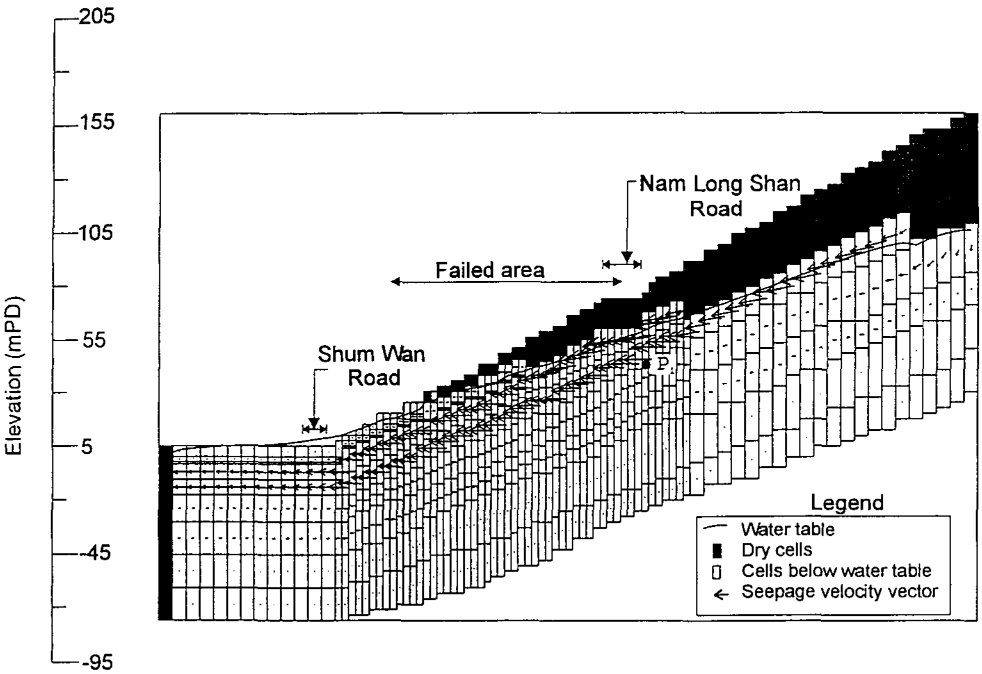

Figure 10. Position of the water table on the 13th of August by taking specific yields four times higher than the original model.

Subsurface horizontal flow from the upper hillslope may also contribute to the high ground-water level rise below the concave scar during the rainstorm. The clay layer was handled more carefully and based on field observations. The presence of clay has some influence on storing more water above the concave scar. If the clay is not considered in the model, the water level does not rise up as much as found in the field. The present study has also shown that failure is possible by using higher shear strength of the clay without slickensides of C = 8 Kpa and $\phi = 26$. The model explains the antecedent rainfall affect on the stability of the slope. The factor of safety on the 31st

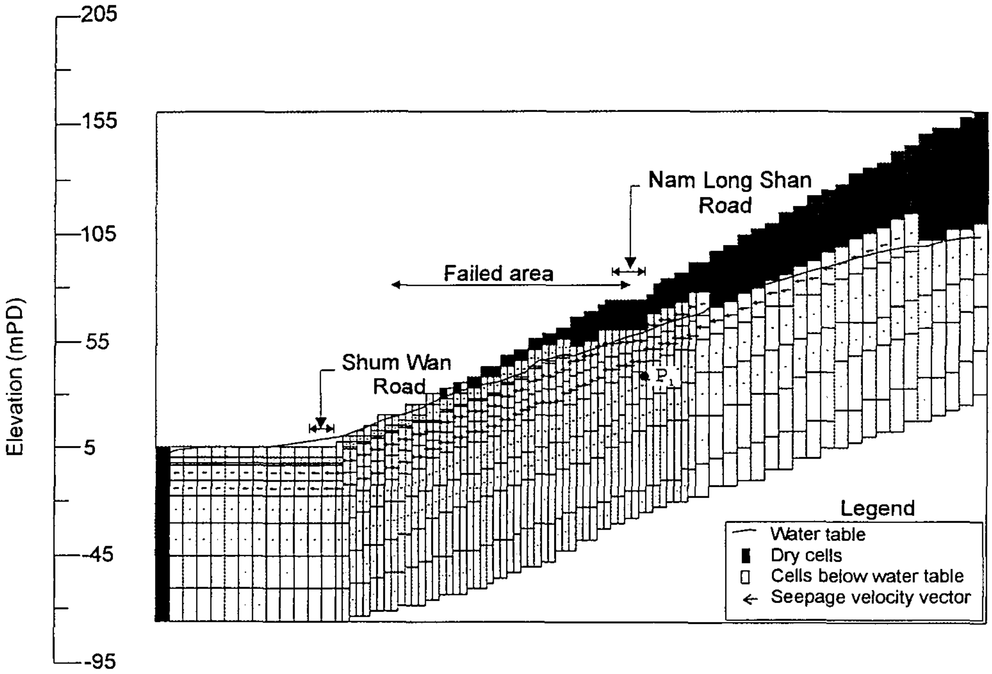

Figure 11. Position of the water table on the 13th of August by taking 30 percent recharge in the model.

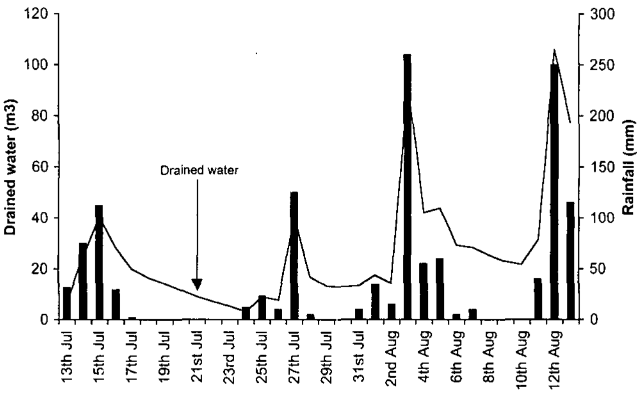

Figure 12. Relationship between rainfall and drained water in the form of seepage.

of July was 1.41 and dropped to 1.01 on the 3rd of August. It again became higher, F = 1.32 on the 8th of August, and never rose back to 1.41 because of antecedent rainfall. Hence, the storm of the 13th of August started with a lower factor of safety value. The antecedent rainfall has some influence on maintaining a high water level for a few days after the rainstorm event of the 3rd of August. In the model, the drained water in the form of seepage has been quantified. The amount of drained water in the form of seepage is 790 m^3.

The predictive measures can be taken by inserting horizontal pipes to drain out much water from the slope. Horizontal drains are used to reduce the ground-water pressure, which increases during high intensity rainfall. In the slopes, horizontal boreholes are drilled and along these horizontal holes, pipes are inserted to make horizontal drains. The size of the drain should be adequate to carry the maximum ground-water flow without development of excessive outflow pressures and without re-infiltration. The calculated inflow and outflow values of water in the ground-water system of the present study area will help to design the horizontal drainage system. Chunam, or shortcrete, can also be used to improve the stability of slopes. It will reduce the infiltration rate. From the hydrogeological study it was found that the model is sensitive to recharge. Hence, if the infiltration rate becomes lower, the rises of the water table will be lowered and the slope can be stable.

ACKNOWLEDGEMENT

We would like to thank to three anonymous reviewers for their valuable comments and suggestions, which have helped us to improve the manuscript. The study is supported by Committee on Research and Conference Grants (CRCG) at the University of Hong Kong.

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Table 4. *Material and their properties, used for stability analysis (Geotechnical Engineering Office, 1996).*

Material	Apparent Cohesion C' (kpa)	Angle of Shearing Resistance (ϕ)	Unit Weight (KN/m^3)
Partially weathered tuff	5	38°	19
Clay	8	26°	19

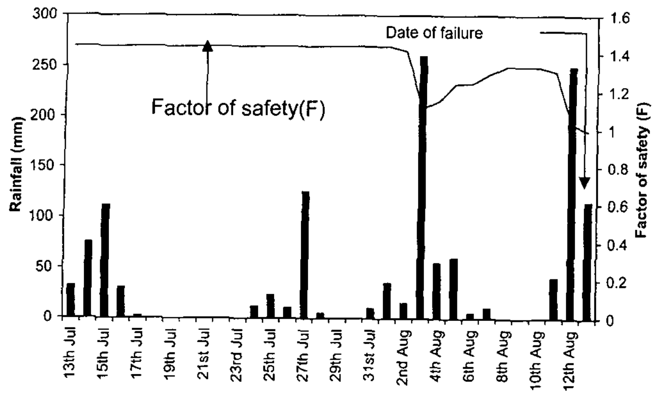

Figure 13. Change of factor of safety with time.

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