CASE HISTORIES OF LANDSLIDE INDUCED GRAVITATIVE DEBRIS FLOW

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RÉSUMÉ
Cette étude consiste à deux histoires de cas de glissements de terrain dans des pentes naturelles : le glissement de Lei Pue Street à Honk Kong et le glissement de Barabensi au Népal. Le premier glissement s'est transformé en coulée de débris contrairement au deuxième. Plusieurs modèles numériques (Slope/W, FLAC, DAN et FLO-2D) ont été utilisés pour l'analyse de ces glissements de terrain. Dans cet article sont identifiés le modèle numérique approprié ainsi que les paramètre influençants l'initiation des coulées de débris à partir de glissements de terrain dans un terrain naturel. Le modèle proposé par Hungr (DAN) a engendré des résultats raisonnables sur l'initiation ou non de coulée de débris ainsi que sur la distance de parcours si elle venait à se produire.

ABSTRACT
This study consists of two case studies of landslides in natural slope: Lei Pue Street landslide, Hong Kong and Barabensi Landslide, Nepal. The first landslide transformed into a debris flow while the second one did not. Several numerical models (Slope/W, FLAC, DAN and FLO-2D) have been applied for the analysis of these case studies. The appropriate numerical model and the influential parameters for initiation of gravitative debris flow from initial landslide in natural terrain are identified. The model proposed by Hungr (DAN) has been found to give reasonable results on whether or not a debris flow will occur and on the runout distance if one does occur.

1. INTRODUCTION

A debris flow induced from an initial landslide in wet seasons or during earthquakes causes heavy damage in hilly region where combination of steep slope and lose moving landslide mass often exists. Being a flow of fluid and solid-soil and transfer of momentum between each other (Iverson 1997), a debris flow travels large distance and is one of the most hazardous forms of landslides. Hence, an ability to predict the initiation of a debris flow from a landslide and the estimation of its runout distance in a natural terrain is crucial for saving lives and infrastructures in potentially landslide hazardous regions of the world.

This paper presents the application of a various mathematical models at different stages of a landslide through initiation to transforming into a debris flow and its runout distance. Two case recordshave been considered: one changed into a debris flow and the other did not. The first case record is from Hong Kong and the second from Nepal. Information available for the case records is reviewed. Different pieces of software (Slope/W, FLAC, DAN and FLO-2D) are used for backanalysis and recommendation is made for an appropriate mathematical model for analyzing the runout distance of debris flows in similar soil and topographical conditions.

2. TRIGGERING OF DEBRIS FLOW AND RUNOUT

The formation of a debris flow from an initial landslide have been studied by many researchers (eg.Johnson and Rodine 1976, 1984). They suggested that poor sorting of particles within the mobilized sliding mass was a cause of debris formation. Pierson et al. (1990) observed that a debris flow might be initiated from pyroclastic flows. Cannon and Ellen (1985) observed that intense rainfall triggered the initiation of a debris flow. Further, Iverson et al. (1997) suggested three processes for the formation of a debris flow: widespread failure, partial or complete liquefaction and conversion of landslide translational energy into internal vibrational energy within the sliding mass. Li et a1. (2005) observed that, a burst of high-intensity rainfall following a prolong rainfall caused capillary fringes to form above the watertable. These fringes lead to more fluidity in the landslide mass. However, different combinations of soil strength parameters and slope geometry are also important subject in studying the initiation of landslide induced gravitative debris flow and its distructive travel distance.

Voellmy (1955) and Salm (1966) proposed that the prediction of the travel distance of a debris flow might be computed from energy and momentum conservation principles similar to that of a snow avalanche. Takahashi and Yoshida (1979), and Takahashi et al. (2000) proposed a momentum conservation equation for the analysis of debris flow runout. Hungr (1995) proposed a one dimensional hydrodynamic equation (DAN) for debris flow runout prediction. McDougall and Hungr (2005) proposed a computer model to simulate a 3D terrain for debris flow runout without defining the debris flow path. Kwan and Sun (2006) proposed a debris mobility model (DMM) with some modification of the DAN model from a rectangular cross section to a trapezoidal section of the debris flow path. O'Brien (FLO-2D manual 2001) proposed a solution of continuity and energy equation for debris flow prediction.

However, selection of a reliable runout predicting method, which provides reasonable runout distance with limited field information, is still a promising area.of research.

3. LANDSLIDE MODELING AT DIFFERENT STAGE

Slope/W and FLAC computer programs are used in the back analysis of landslides to study the conditions of pore pressure, cohesion, and friction during slope failure initiation. Two models, the dynamic analysis (DAN) and FLO-2D, are applied for runout distance analysis.

The dynamic analysis (DAN) model is a solution of the hydrodynamic equation based on Lagrangian finite difference solution proposed by Hungr (1995). In this model, different rheologies can be applied for the resistance term (Hungr 1995) such as plastic flow, friction flow, Newtonian laminar flow, turbulent flow, Bingham flow, Coulomb viscous flow and Voellmy fluid flow. The friction flow and the Voellmy rheology are used in this analysis.

The FLO-2D model (O'Brien et al. 1993) simulates the numerical integration of equations of motion and conservation of debris flow. FLO-2D is a volume conservation model, which distributes a mass of debris into a given area of grid elements. The result shows maximum flow depth and velocity in each grid system (FLO-2D Manual 2003). There are two options: diffusive wave, and full dynamic representation of the momentum equation. In this study, the debris flow is simulated with the full dynamic wave equations, which consider the convective and local accelerations (FLO-2D Manual 2003).

4. LEI PUE STREET LANDSLIDE

4.1 Description

The first case record in this research is the Lei Pue Street landslide in Hong Kong, which immediately changed into a debris flow. The required field information in this study is taken from Maunsell (2002). This case study is to simulate different stages of the landslide using different computer software and to compare the results to field observations.

The location of the landslide is on a natural hillside slope above Lei Pui Street, Hong Kong (Figure 1). The landslide occurred on September 01, 2001 at 10:50 p.m in between 9:30 PM. to 11:00 PM during heavy rainfall (Maunsell 2000). The slide mass initiated on a 41^o hill slope, spilled over a 25m high steep cliff and impacted on the moderately flat portion of the hill slope. The initial height of the slope was 17.0 m. The volume in the source area was approximately 250 m^3.

The first 25 m is the landslide source area located at 233 mean principal datum (mPD) and inclined at an angle of 41^o from the horizontal. The deepest exposed profile of the initiation area was composed of approximately 0.5 m of colluvium overlying 1.0m of moderately to slightly decomposed saprolite and granite outcrop. The detached material, approximately 15 m wide, is reduced to zero depth at the lower portion of the landslide.

Chainage 25 to 50 is a 25 m long rock cliff at an angle more than 52^o. The slope of the hillside decreases to 40^o beyond the base of the rock cliff. The debris trail is narrowed to 10 m from its initial average 15 m between Chainage 128 to 325. After Chainage 148, the debris flowed on cascade steps on rock slab with the slope angle ranging from 35^o to 45^o. At Chainage 190, small portion of debris was deposited, 3.0 m thick on the west bank and 1.3m thick on the east bank. Between chainage 185 to 270, 105 m^3 debris was deposited. Chainage 270 to 285 has steep cascade carved on bedrock. Most of the debris passed from this chainage and deposited immediately downstream of the trail due to the steep slope. At chainage 243, the deposited volume was approximately 80 m^3. About 50 m^3 outwash material reached to Lei Pui Street and flowed further for some distance.

4.2 Geotechnical Observation

The soil matrix of the initial slide mass was colluvium, composed predominantly of sand and gravel, about 64 to 95% (Maunsell 2002). Clay and silt contents were found to range from 0 to 22% and 5 to 15%, respectively. The landslide debris contained sand and gravel of 49 to 55%. The silt and clay contents range from about 25 to 30% and 15 to 19%, respectively.

The soil strength parameters, cohesion and friction, for the deposited debris were 0.0 kPa and 26^o, respectively. The mobilized friction angle of debris mass was 26^o with tests on the debris deposited within 24 hours of the incident. The joint infill sediment, which has low strength, was predominantly silt and sand mix, with sand ranging from 20 to 65%, and clay ranging from 8 to 32%. Natural joint surfaces tested in the shear box that has a friction angle of 42^o. The failure surface of the landslide is in the decomposed saprolite and colluvium with natural joints so that the operational range of angle of friction is not more than 42^o. Therefore, the operational angle of friction is taken as 41^o and zero cohesion for back analysis.

4.3 Analysis

4.3.1 Landslide Initiation

The initial landslide mass was modeled as it was before the failure. The topographic information was taken from Maunsell (2002). The parameters used in the analysis are friction angle 41^o, cohesion 0.0 kPa, pore pressure (r_u) 0.0, and unit weight 19.5 kN/m^3.

Due to the prolong rain on the slope, the degree of saturation of the landslide mass was 90% down to 1 m depth at the time of failure (Li et al. 2005). The depth of failure surface of the landslide varied from zero to 1.45m from the ground surface with the average depth being less then 1 m. Therefore, the slide mass was under almost saturation condition before failure. At the landslide scarp portion, the soil within the top 1.0 m, might be subjected to positive pore pressure due to rainwater infiltration.

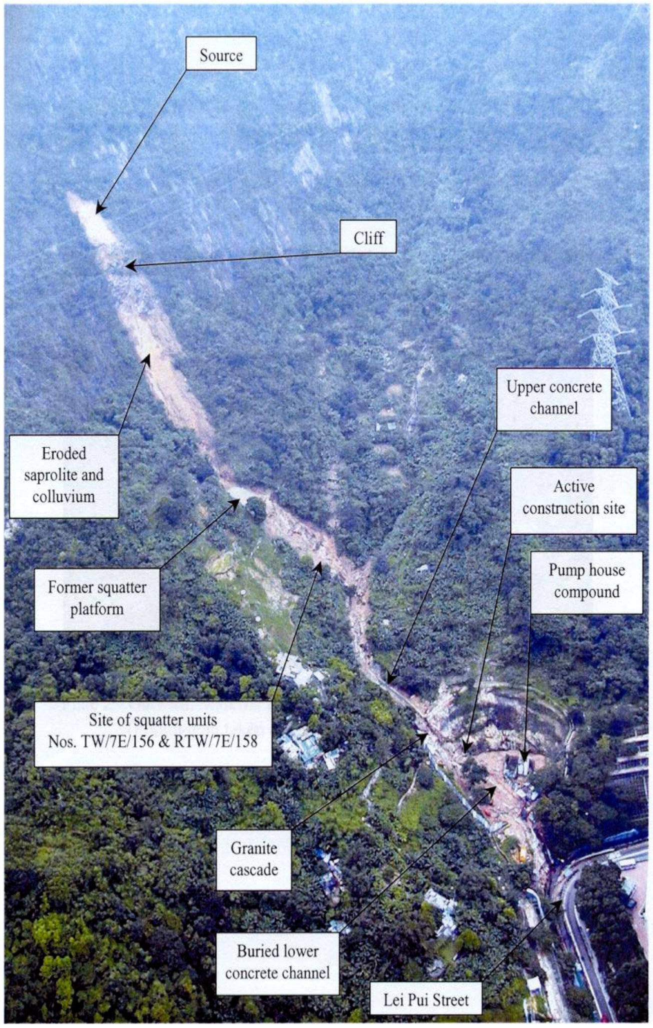

Figure 1 Lie Pui Street landslide (Manusell 2002)

The computed factor of safety (F) from back analysis was found to be 1.08. This F of the slope at zero pore pressure indicates that the slope was near limit equilibrium. When the pore pressure ratio (r_u) was raised from 0.0 to 0.04, the F dropped from 1.08 to 1.0.

Stability analysis showed that the slope was in limit equilibrium (marginally stable) with friction angle of 41°. If the soil had only frictional strength, it could have started the sliding during prolong rainfall. The fact that the failure did not occur during the prolong rainfall indicated some cohesion did exist in the soil. Due to the heavy rainfall after the prolong rainfall, the cohesion would be reduced because of infiltration and saturation. Therefore, the heavy rainfall contributed to the sliding.

The cohesion of soil played a vital role in the stability of such a steep slope. The F increased from 1.08 to 1.44 when the cohesion was increased from 0.0 to 1.0 kPa. At the cohesion of 1.0 kPa, the pore pressure ratio r_u required to reduce F from 1.44 to 1.0 was 0.24. Similarly, when the cohesion was increased to 2.0 kPa, the F of the slope increased to 1.8, and the r_u needed to reduce the F to 1.0 was 0.43.

The initial condition of the slide mass is back analyzed with FLAC. The Mohr Coulomb failure criterion is used in the analysis. Input parameters of soil are selected from the field report and literature as listed in Table 1.

Table 1 Strength Parameters

Parameters	Value
Friction Angle	41°
Cohesion	0.0 kPa
Unit Weight	19.5 kN/m^3
Bulk Modulus	66.7 MPa
Shear Modulus	40 MPa

The F calculated using FLAC is 0.9, which is lower than the F calculated from SLOPE/W (1.08). Similarly, the F for the cohesive strength of 1 kPa and 2 kPa is 1.0 and 1.12, respectively. It is seen that small value of cohesion influences significantly the stability of steep slopes. The analysis also shows that F is less than 1.0 with zero cohesion. This result supports the existence of apparent cohesion before the slope failure.

4.4 Dynamic Analysis

The sliding volume was 250 m^3 in the landslide source. Entrainment of debris mass is not considered. The landslide mass is divided in 10 mass blocks and separated by 11 boundariues for DAN analysis. The position and the height of the boundary are fixed according to the initial position of the landslide mass at the 41° slope.

The debris flow surface is not a defined channel but lying along the deepest profile of the natural terrain so that both friction and Voellmy rheology are used for the initial observation (Hungr 1998, Ayotte et al. 1999). Table 2 shows the various parameters used for the friction and the Voellmy models in DAN. The surface width of the debris trail is taken as an average of 15 m.

Table 2 Input Parameters for DAN

Model	DAN	
Parameters/Rheology	Friction Rheology	Voellmy Rheology
Initial friction angle	41°	41°
Cohesion	0	0
Mobilized friction angle	26°	26°
Turbulence Factor	-	200 to 500

Both the frictional rheology and the Voellmy rheology in DAN model are used for computation and compared with field observation. The runout distance in friction rheology is shown in Figure 2. The friction rheology yields a velocity that gradually increases from the begnning and reaches a maximum as shown in Figure 2. The runout distance obtained from the analysis is 235m. The maximum debris flow velocity is found to be 20m/s at 90.0m on the runout path.

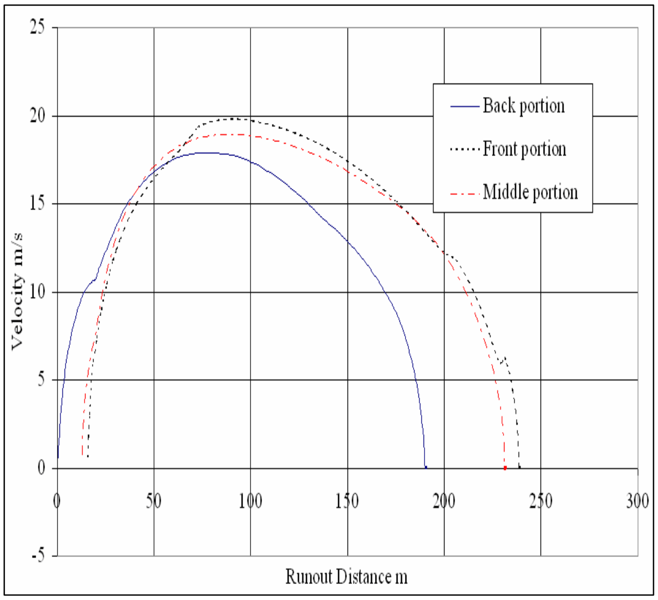

Figure 2 Runout Distance of Lei Pue Street landslide from DAN model with friction rheology

In the field, side drainages mixed with the debris flow at Chainage 190, a confluence point of a natural drainage. The landslide mass might be further mobilized with the addition of drainage water after the drainage confluence. Field observation shows that the majority of debris is deposited at 282m starting from 220m, which is after Chainage 190. Therefore, the runout distance calculated using DAN gives a reasonably similar value to the field observation (235m). The slightly higher value in the field observation is due to influence of drainage water on the movement of the sliding mass.

The maximum velocity computed with the friction rheology is higher than that with the Voellmy rheology. The maximum velocities are 18 m/s at 100 m with the friction rheology and 9 m/s at 40 m with Voellmy rheology. The velocity of debris flow could not be compared due to the lack of field information.

The parameters for the Voellmy model are the same as for the friction model except the turbulence coefficient, ξ, which is taken as 200 m/s^2. The runout distance and velocity with the Voellmy rheology is given in the Figure 3. The runout distance and the maximum velocity obtained from this model are 120m and 9m/s, respectively.

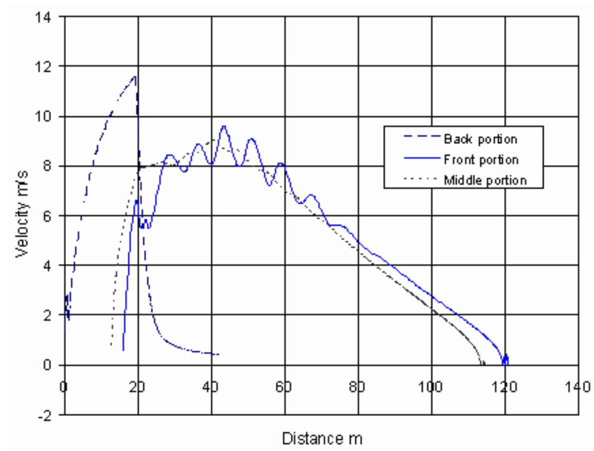

Figure 3 Runout distance from DAN using Voellmy rheology and turbulent factor 200 m/s^2

A study of the runout distance with different turbulent coefficients in the Voellmy rheology has been carried out. Figure 4 shows the runout distance with a larger turbulent coefficient of 500m/s^2. The maximum recommended turbulent coefficient for debris flow is 500m/s^2 (Hungr 1995). If the turbulent coefficient increases from 200 to 500 m/s^2, the resulting runout distance changes from 120 m to 130 m and the maximum velocity from 9 to 11 m/s. This shows that significant increase in turbulent factor only slightly increases the runout distance. This increased value is still smaller than the runout distance observed in the field.

4.5 Analysis with FLO-2D

Input parameters for the FLO-2D model are collected from field information and laboratory testing by Maunsell (2002) and from literature. The topography of the flow surface, its roughness and physical features were digitized along the flow surface manually. The relation of flow with sediment concentration is taken from the literature and laboratory analysis reports proposed by O'Brien (FLO-2D manual 2003). The rheological relations of viscosity and of yield stress are taken from the test results obtained by Kang and Zhang (1980) for similar soils.

Among the proposed different rheological relations between yield stress and viscosity with debris concentration given in the literature, the Kang and Zang's relation (1980) is more appropriate because the soil they studied was similar to the soil in this case study. Hence, the empirical coefficients α and β are taken taken to be 1.75, 7.82 and 0.0405, 8.29 for viscosity (η) and yield stress (Γ), respectively.

The volume of the moving mass of the landslide and the volume of runoff above the landslide source are considerd together. A total volume of 283 m^3 of moving mass is considered for the analysis, of which 250 m^3 is the landslide mass and 33 m^3 is the surface runoff.

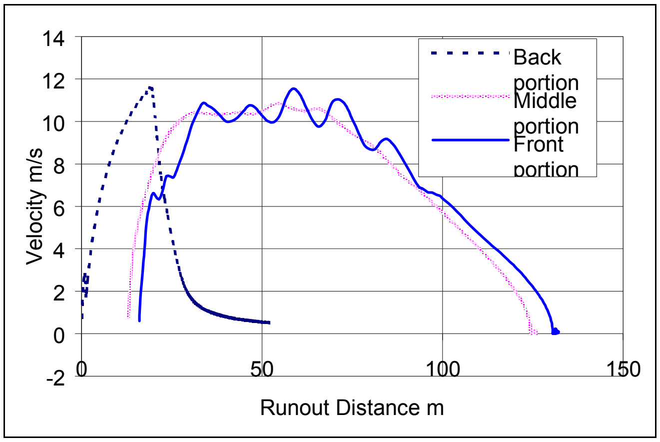

Figure 4 Runout distance from DAN using Voellmy rheology and turbulent factor 500 m/s^2

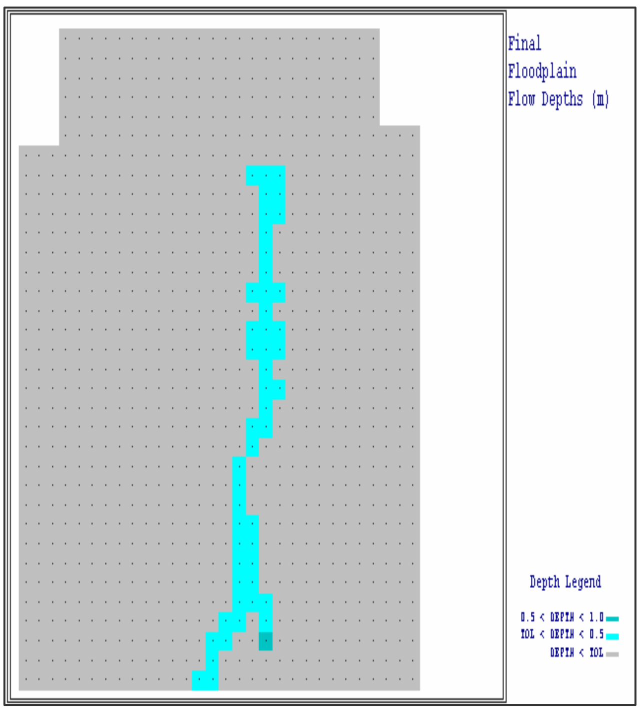

Figure 5 Debris flow plain from FLO-2D

A mesh of 10m x 10m grids is formed for simulating the topography of the flow area. The elevation and roughness factor of each grid are manually input in the grid system. The elevation of the northernmost grids is 230m, which is the highest in the flood plain. Manning's roughness coefficient is taken as 0.03 for the flow course and 0.05 for the course outside the deepest drain. Area reduction factor is applied in some grids, where the whole surface of grids is not available for flow. Evaporation and infiltration are neglected due to the small surface area of flow and the short duration of the event. The Froude number for flow is taken as 1.0 for initiation and is updated with the flow progress in subsequent levels. For shallow flows, Manning's n value is given as 0.2 and the n value adjustment is 0.01 for every update in Manning's n value.

The full dynamic wave equation was used in the analysis. The time interval of 0.01 second was chosen for the successive computation so as to obtain more stable simulation. The minimum flow depth was taken as 0.2m for the change in flood plain depth. The specific gravity of the debris was taken as 2.7. The laminar flow resistance factor was taken as 2000.

The void ratio of soil at the scarp is 0.93. The specific gravity is 2.7. The soil porosity of landslide source mass is 0.48. Based on the saturation condition and surface runoff into the sliding mass, the soil concentration in the landslide soil matrix is approximated to 48%.

The result shows at Chainage 190, the maximum flow depth mark of debris flow was approximately 1.3m. The computed flood depth was, however, 1.0m, as shown in Figure 5. The difference in depth may be due to the involvement of eroded material during flowing, which is not considered in the simulation. The velocity obtained from the simulation in different locations varies from 0.03 to 0.35 m/s. As the velocity was not recorded in the field, it is difficult to assess the computed result. The computation shows the velocity of 0.2 m/s at the point where the maximum depth is 1.0m.

The result also shows that the simulated volume of the landslide mass moves continuously through the given topography. The final deposition is not significant within the simulated region. Therefore the runout distance of debris flow is difficult to predict in this study. The information obtained from the FLO-2D simulation did not closely match the field information. The reason behind the dissimilar result may be due to discrepancies in rheological relation of the yield stress and the viscosity chosen for the simulation.

5. BARABENSI LANDSLIDE

5.1 Description

The landslide area is located at 84 km of Arniko Highway along the bank of Sun Koshi River near Barabensi, a small town northeast of Kathmandu, Nepal. Field information of this landslide is taken from Nepal Engineering Consultancy Services Centre Ltd. (NEC 2002).

Figure 6 shows the physical features of the landslide area. At the beginning of the landslide incident, 100 m length of the highway had subsided. This portion of the landslide continuously sank every year. The landslide mass moved 1.5 m to 8 m in total during the time of the field observation. There were several tension cracks in the sliding mass and seepage water at the toe and rock outcrops at some scarp portion of the landslide.

The general slope of the sliding area is about 34°. On the left portion of the slide, the slope is more gentle at about an angle of 30°. The cut slope for the road is steep at an angle of 41° from the horizontal.

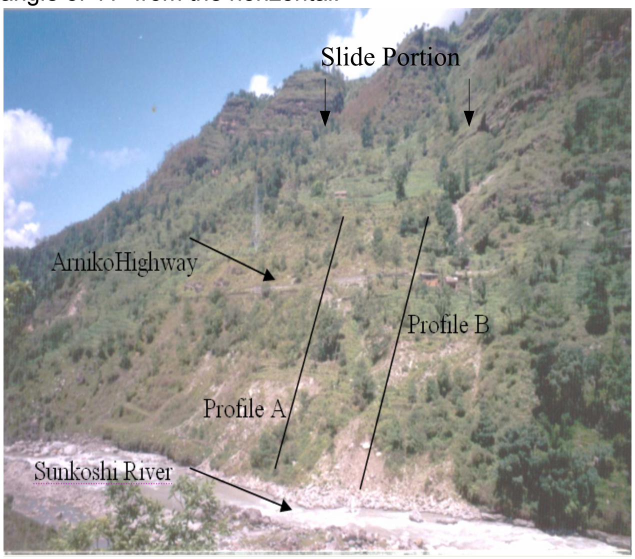

Figure 6 Barabensi Landslide, profile A and profile B (NEC 2002)

5.2 Geotechnical Investigation

Sub-surface investigation was carried using test pits and hand auguring up to the possible depth in eight test pit locations by NEC (2002). Clayey layers were also found in the moving mass. The clayey material possessed a plastic limit up to 29% and a liquid limit up to 40%. A cohesion up to 10 kPa was observed. Considerable amount of fines was observed in the moving mass.

5.3 Field Observation

The landslide mass is colluvium, which consists of boulder, mica particles, and grey color low plastic silt. Engineering properties of the sliding soil mass are shown in Table 3. The soil in most of the test pits was non-plastic silty sand and gravel. On the other hand, soil in Test Pits (TP) 1/Station Number (SN) 4, TP3/SN1, TP3/SN3, TP4/SN2, TP6/SN2, and TP7/SN2 exhibited some plastic characteristics.

5.4 Analysis

5.4.1 Initiation

Stability analysis of both profiles, Profiles A and B were carried out. Profile A is for the steeper slope (34°) and profile B is for the gentler slope (30°).

Based on the observed soil strength parameters by NEC (2002), the cohesion of the sliding mass ranges from 2.0 kPa to 10.0 kPa except for TP1/SN2, where there is high friction and zero cohesion. The operational value of cohesion is taken as the average of 6.0 kPa. The operational friction angle of the soil is taken as 30°.

For Proifile A at zero pore pressure, the F is 1.09 using Janbu's method and 1.10 with Morgenstern and Price method. This result shows that Profile A is in limit equilibrium condition.

There is a discontinuous layer of impervious clay between the bedrock and the landslide mass. The bedrock with low permeability and non-uniformly distributed clay layer along the failure surface cause pore pressure built-up during rainy seasons.

Stability analyses have also been carried out using different pore pressure conditions. At a pore pressure ratio (r_u) of 0.07, Janbu's method provides a F of 0.99 and Morgenstern and Price's method 1.0.

The input parameters for FLAC software are given in Table 4. Pertinent properties are selected from NEC (2002), and other parameters not measured are taken from the literature for similar soils. The Mohr-Coulomb failure criterion is used in this analysis.

Table 3 Summery of test results

Sample No.	Cohesion, kN/m^2	Friction Angle Degree	Dry Unit Wt KN/m^3
TP-1/SN2	0.00	36.5	12.81
TP-1/SN3	4.00	14.0	13.87
TP-1/SN4	4.00	28.0	15.61
TP-3/SN1	10.00	32.0	13.85
TP-3/SN2	2.0	29.5	13.94
TP-3/SN3	2.0	20.0	15.02
TP-4/SN2	4.0	25.5	13.06
TP-9/SN2	3.0	29.0	12.30

The F for Profile A without pore pressure is 0.97 from FLAC, which is less than the F of 1.10 calculated from Morgenstern and Price method and 1.09 from Janbu's method. FLAC gives an F of 0.95 for a phreatic surface equivalent to r_u of 0.07.

Table 4 Input parameters for FLAC (Barabensi Landslide)

Parameters	Value
Friction Angle	30°
Cohesion	6.0 kPa
Cohesion of Bedrock	500 kPa
Bulk Unit Wt	18.8 kN/m^3
Bulk Modulus	66.7 MPa
Shear Modulus	40 Mpa

The F for Profile B calculated without pore pressure is 1.12, which is slightly less than the F of 1.18 calculated from Morgenstern and Price method and 1.15 from Janbu's method for profile B. FLAC gives an F of 0.99 for a phreatic surface equivalent to r_u 0.07.

These analyses show that Barabensi landslide slope was marginally stable without pore pressure. Development of positive pore pressure at some locations caused local movement at these locations.

5.5 Dynamic Analysis

The dynamic analysis does not show significant movement of the landslide mass as compared to the size of the landslide. The movement of the slide soil mass is given in Figure 7 and Figure 8. The horizontal distance of Profile A is 135.0 m and profile B is 125.0 m. The result shows that front and back portion 8.0 m and 20.0 m in Profile A and 8.0 m and 18 m in Profile B. These movements do not constitute a debris flow.

The soil is predominately colluvium, which could experience matric suction leading to development of cohesion. The sliding mass does not change into a deberis flow due to existing cohesion of the soil, which was taken as 6 kPa. The relative intact cohesive strength, insignificant decrease in frictional resistance and the mild slope angle are the factors in preventing the initial landslide from transforming into a debris flow. This is in agreement with the field observation.

Similar analaysis using the Voellmy rheology also show that no debris flow will occur in this case.

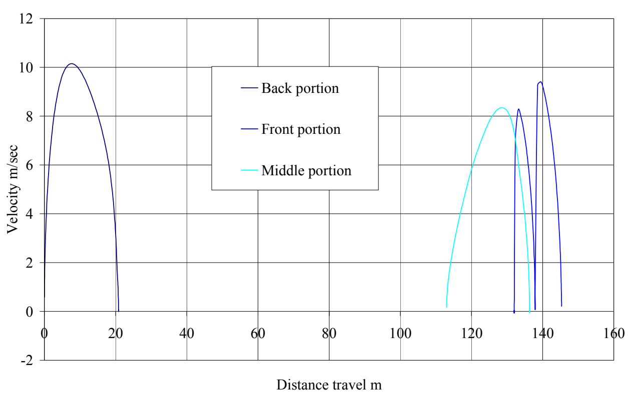

Figure 7 Runout distance from DAN for Barabensi Landslide profile A

6. DISCUSSION

In this research, two different landslide case histories are analyzed. The first case record involved different stages of a fast moving landslide at Lei Pue Street, Hong Kong. This landslide mass changed into a debris within a few seconds. Back analyses was conducted to investigate the initial failure condition of the landslide. The results show that the friction angle is 41^{o} and pore pressure ratio 0.04, and zero cohesion at failure.

The DAN numerical model Hungr (1995) was used to simulate the debris flow movement. In the simulation, the initial soil strength parameters were used within the source region and the mobilized friction angle was applied after the source region. The runout distance of the debris flow estimated with the friction rheology in DAN was 235m. This is in agreement with the field observation. The Voellmy rheology in DAN model, however, produced a runout distance of 130m, much shorter than the measured value in the field. The friction rheology was, therefore, considered as more appropriate for the simulation of debris flow movement in this case.

The FLO-2D model (2003) was used for case history I to simulate debris flow inundation in the flow surface. The parameters proposed by Kang and Zang (1980) for similar conditions were used for the simulation. The flow velocity using the FLO-2D simulation was found to be smaller than the velocity obtained from DAN. The debris flow depth obtained from FLO-2D was similar to the flow depth observed in the field for the lower portion of the debris flow surface. The debris flow simulation shows that there was no final deposition point within the debris flow surface. In other words, the runout distance is way beyond the observed value.

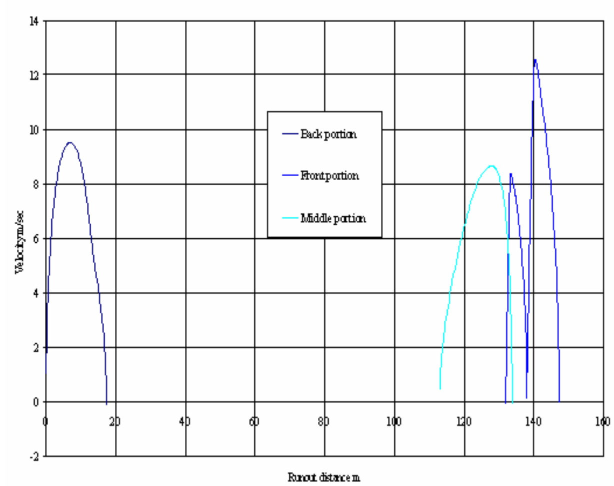

Figure 8 Runout distance from DAN for Barabensi Landslide profile B

The second case history involved the slow moving Barabensi Landslide in Nepal. The initial failure condition was obtained using Slope/W and FLAC. The simulation showed that the friction angle of 30^{o}, pore pressure ratio of 0.07, and cohesion of 6 kPa were operational at failure. The results show that the slope failed following the soil mass experiencing a pore pressure ratio of 0.07.

The small movement of the landslide mass was caused by the generation of pore pressure along discontinuous clay layer at the failure surface. In every rainy season, the pore pressure increases, lowering the soil strength and resulting in soil mass movement in specific locations. Due to differential deformation, the soil mass breaks up and develop cracks, allowing the pore pressure to dissipate. The differential deformation was evident with the presence of horizontal and vertical cracks in the failure soil mass.

The friction rheology and the Voellmy rheology of DAN have been used to analyze the Barabensi landslide. The results show relatively small movement in the soil, implying no debris flow could occur, which is in agreement with the field data.

6.1 Conclusion

The Lei Pui Street landslide turns into a debris flow mainly because of the steep natural terrain and the soil being cohesionless. This allows the initial failure to move down the slope with significant kinetic energy that reduces the initial friction angle to the lower mobilized value. This causes the landslide to transform into a debris flow. The friction model in the dynamic analysis (DAN) is found to give reasonable estimate of the runout distance of this debris flow.

The Barabensi landslide occurs in a mild slope and in a cohesive–frictional soil. Observations show that the cohesion was not significantly reduced during the landslide movement. The analysis suggest that cohesion being intact is the most important factor for reducing the chance of debris flow formation from the failure soil mass.

Based on comparison of computed and observed runout distance, and on the analysis of whether or not a debris flow formed, it is concluded that the friction rheology model in DAN is more appropriate than the other rheology model in DAN and the FLO-2D method.

7. ACKNOWLEDGEMENT

Authors would like to appreciate Geotechnical Office Hong Kong for granting permission to use DAN and field observation report for Lei Pui Street landslide and Mr. Shiva Raj Adkhari, Department of Roads, Nepal, for providing valuable information for Barabeni landslide, Nepal. Authors would also like to thanks J. Locat and B. Wang for their review of this paper

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