Runout analysis of debris flows and avalanches in Hong Kong

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Abstract: In order to assess the hazard and risk from highly mobile landslides it is necessary to estimate their runout motion characteristics and the area which could be affected by landslide debris. At present it is very difficult to make such estimates. This paper reports progress on a study which aims to develop a practical method of landslide runout prediction, based on the calibration of an existing dynamic model. On the basis of back-analyses of a number of actual landslides and slope failures, mass movements will be classified in such a way that each class can be successfully modeled using a specific rheological law and a reasonably narrow set of input parameters. The Geotechnical Engineering Office (GEO) of the Hong Kong SAR Government is interested in the development of a landslide runout model, as part of a risk-based approach to the management of landslide hazards. The authors compiled 25 documented case histories of recent debris avalanches and debris flows in Hong Kong and subjected them to back analysis. Typical results of the back-analyses are presented here and an initial typological classification of the landslides is proposed. The model rheology and corresponding input parameters necessary for analysis of the relatively small-magnitude landslides ($100m^3$ to $1,500m^3$) examined to date provide an interesting comparison with the model inputs used in previous back-analyses of large mass movements in Hong Kong and in British Columbia (up to $100,000m^3$).

Introduction

In order to assess the hazard and risk from highly mobile landslides it is necessary to estimate their runout motion characteristics and the area which could be affected by landslide debris. At present it is very difficult to make such estimates. This paper reports progress on a study which aims to develop a practical method of landslide runout prediction, based on the calibration of an existing dynamic model.

The study involves the development of a typological classification of mobile debris flows and avalanches. On the basis of back-analyses of a number of actual landslides and slope failures, mass movements will be classified in such a way that each class can be successfully modelled using a specific rheological law and a reasonably narrow set of input parameters. It is intended that the different classes of debris movement will then be related to criteria which can be derived from the physical properties of the pre-failure slope, which can be measured or estimated in the field. It should then be possible to choose an appropriate model input for hazard prediction on the basis of pre-failure field observations.

The Geotechnical Engineering Office (GEO) of the Hong Kong SAR Government is developing a risk-based approach to management of landslide hazards (Wong et al. 1997). Landslide hazard modelling and prediction requires the estimation of the travel distance and velocity of potential landslides. A numerical model which can provide such predictions has been developed by Hungr (1995). This dynamic model, 'DAN', solves the equations of motion for a given landslide mass, allowing the user to select from a variety of material rheologies. The model must be calibrated through back-analyses of documented case histories. The material rheology is then selected to provide the best fit with the actual behaviour of a given landslide. The resulting output parameters on which the success of the model is judged include the debris runout distance, velocity, and distribution of landslide deposits.

A pilot project was completed in February 1998 for the Geotechnical Engineering Office. Six case histories were analysed using DAN. The current project is a continuation of this pilot study, involving the back-analyses of an additional twenty landslides from Hong Kong. The majority of these landslides occurred on natural terrain, with the exception of four which involved failure of engineered slopes or quasi-natural terrain (natural terrain affected by excavation, disturbed drainage, or other similar activities). The data were derived partly from original fieldwork carried out in the summer of 1998 and partly from unpublished field data provided by the GEO.

Slope failures in Hong Kong

The majority of slope failures on natural terrain in Hong Kong are relatively small (a few hundred cubic metres), shallow debris avalanches which occur in residual soil and/or colluvial veneer on steep slopes. On average, there are over 300 such failures in Hong Kong every year. Runout distances are usually short. However, given the right combination of slope morphology and rainfall, debris can become channelised in streamcourses or slope declivities, leading to entrainment of additional material and the generation of long-runout debris flows. A channelised debris flow on the slopes of Tsing Shan in the New Territories in 1990 involved a total of 20,000m^3 of debris with a runout of 1,000m.

Increased amounts of water can cause debris to become diluted, and failures which may be classified as debris floods or hyperconcentrated stream flows (Costa and Jarret, 1981) have also been recorded in Hong Kong. Debris floods often follow debris flows, eroding the original deposits. This can result in misinterpretation of the field data, with consequent overestimation of the runout distance of the original event.

A number of larger and deeper failures involving natural terrain have been documented, triggered by human activities such as excavation, head loading or disturbance of drainage. These failures can be highly mobile and hazardous, and are referred to within the GEO as quasi-natural terrain landslides. One such event, involving 26,000m^3 of debris occurred at Shum Wan Road on Hong Kong Island in 1995 and killed two people.

Some disastrous failures of engineered slopes have also occurred. A 40,000m^3 failure of a cut slope (also involving natural terrain) at Po Shan Road on Hong Kong Island in 1972 caused the death of 67 people. Failures of loose fill slopes in the 1970s also led to serious fatalities.

Further information on the nature of slope failures and landslide hazards in Hong Kong can be found in Lumb (1975) and Evans *et al* (1998).

Case Histories

The pilot study carried out in February 1998 back-analysed the Po Shan Road and Shum Wan Road failures, the Tsing Shan debris flow and an associated debris flood, a debris avalanche on Lantau Island and a rockslide at Fei Tsui Road on Hong Kong Island. The more recent work has involved the analysis of the following events.

Lantau Island

Five landslides were chosen from GEO data obtained following severe rainstorms in 1992 and 1993. These landslides ranged in volume from 100m^3 to 1,500m^3, with corresponding runout distances of 100m to 450m. Only one of these events became channelised. Data for these landslides was obtained from landslide study report SPR 10/96 (GEO, 1996).

New Territories

Five landslides were chosen from a collection of field data provided by the GEO. This data was collected in the New Territories areas of Sha Tau Kok, Shek Au Shan, Kat Tsai Shan Au, Cloudy Hill and Hok Tau Reservoir. As part of the present project, a field survey of the landslide at Sha Tau Kok was carried out. This landslide comprised a channelised debris flow with a volume of 1,500m^3 and a runout distance of 900m. The remaining four landslides were significantly smaller, and ranged in volume from 200m^3 to 400m^3 with corresponding runout distances ranging from 100m to 250m.

Field data was also collected during the present study for four additional landslides, all of which occurred during rainstorms in June of 1998. These included two small, channelised debris flow failures at Luk Keng (170m^3) and Pak Sha Wan (150m^3). Also included was a slightly larger translational sliding failure at Tai Mong Tsai (350m^3) and one debris flow failure at Pat Sin Leng.

The landslide at Pat Sin Leng actually consisted of two distinct events with two very different failure mechanisms. These were analysed in this study as two separate events. It appeared that the first event was a debris flow failure with low mobility and a volume of 300m^3, the debris of which appeared to have reached the main stream channel and stopped. The second event was smaller (50m^3) and probably behaved more like a hyperconcentrated flow failure. This event appeared to have washed away any of the debris of the first event which might have reached the main stream channel. The runout distance of the second event was approximately 600m down the main stream channel.

Liu Pok School

Sometime in September of 1993, a natural terrain landslide occurred on the slopes just west of Lo Wu in the northern New Territories. As described in report DN 2/97 (GEO, 1997a), the resulting debris destroyed part of an abandoned school building. The failure involved approximately 300m^3 of debris which travelled a distance of 200m. This landslide was a small channelised debris flow which occurred during a heavy rainstorm. In spite of its small magnitude, channelisation in a drainage line gave it sufficient energy to partially demolish the school building, demonstrating the potential hazard from these relatively small failures.

Engineered Slopes

Three roadside slope failures and one quasi-natural failure were back-analysed. Data was derived from existing GEO reports. All failures consisted of relatively low-mobility debris avalanches triggered by translational slides (angles of reach ranging from 20° to 30°).

Landslide study report LSR 15/97 (GEO, 1997b) describes a landslide which occurred sometime between the morning of July 2 and the afternoon of July 3, 1997.

This quasi-natural failure had a magnitude of 2,500m^3 and occurred on a natural hillside opposite Shing On Temporary Housing Area, Ma On Shan. The landslide affected an abandoned cut slope and two fill platforms, and the debris accumulated on a gently sloping grassed area adjacent to a footpath at the toe of the slope.

On August 3, 1997, a landslide occurred on a roadside cut slope above Ching Cheung Road, east of Butterfly Valley, Kowloon. The debris completely blocked a 50m section of Ching Cheung Road. The landslide occurred on the central portion of a registered cut slope located beneath a natural drainage line. The slope was cut into highly weathered granite. Following the landslide, the GEO began an investigation into the failure from which data for this analysis was derived. The report (Halcrow Asia Ltd., 1998) describes three phases of the failure on three separate dates, however, only the failure of 3/8/97 with a source volume of 1,800m^3 is analysed in this study.

Landslide Study Report LSR 4/98 (GEO, 1998a) describes a landslide which occurred on July 2, 1997, on a slope approximately 250m south-west of the Kowloon-Canton Railway, Fo Tan Station. The slope on which the failure occurred consisted of a 26m high, densely vegetated, partly modified natural hillside. A concrete footpath lies at the crest of the slope and is positioned on the edge of a cut platform. The failure consisted of two phases which may have occurred successively. The first phase was not very mobile, with most of the debris remaining as a disturbed raft near the source area. Only the second, more mobile phase, of magnitude 85m^3, was back-analysed in this study. Both failures were described in the reports as translational debris slides. However, while a sliding mechanism probably initiated the events, severe internal deformation of the debris had certainly taken place over the runout distances which were greater than 50m. The event was classified as a debris avalanche.

Also on July 2, 1997, a 900m^3 'debris slide' occurred near Lido Beach in the New Territories The failure, which is described in landslide study report LSR 8/98 (GEO, 1998b), occurred on a 15m high, partly modified natural hillside and affected an adjacent fill slope. The crest of the slope formed part of a fill platform which contained gardens and a swimming pool. The slope was heavily vegetated and had no surface protection. Roads at the toe of the slope were blocked. Eight people were injured.

Back Analysis

Dynamic Model

The back-analyses were carried out using the dynamic model, DAN (Hungr, 1995). This shallow-flow, continuum model is an extension of the lumped-mass approach. The model applies a Langrangian finite difference solution to the hydrodynamic equations. The net driving force is calculated as a balance of the weight of material, internal stress and the resistance to flow. Internal stresses are determined based on earth pressure theory (Lambe and Whitman, 1969) and the assumption that the stress increases linearly with depth. The resistance is calculated based on a user-selected rheology and corresponding input parameters. Possible rheologies include frictional flow, Newtonian laminar flow, Bingham flow, Coulomb viscous flow and Voellmy fluid.

Method

Relevant input data were extracted from reports supplied by the GEO or directly from field data. These included source and entrainment volume estimates as well as path longitudinal profile and width data. The runout path of each landslide was plotted by hand on 1:1000 maps based on discrete trail section data. Interpolated longitudinal profiles and width data were then determined from the maps for input into the DAN program.

The dimensions of the source area were adjusted slightly in some cases to match the source volume with reported values. The shape factor (ratio of hydraulic depth and maximum depth) was input as 1.0 for open-slope failures and as 0.67 for channelised failures. Entrainment values were calculated along appropriate path segments according to erosion data supplied or estimates of the final deposition volume. Recent modifications to the dynamic model allow for entrainment along the path.

The choice of an appropriate rheology and corresponding input parameters was based somewhat on previous experience (Hungr, 1998) and somewhat on trial and error. In this study both the frictional model and the Voellmy flow model were used. In general, the frictional model was used for debris avalanche failures while the Voellmy model was used in cases of channelised, debris-flow failures. In the latter cases, the frictional model was usually applied to the initial source failure area, while Voellmy was used once the debris became channelised and began to flow.

In the case of the frictional model, the resisting stresses at the base of the flowing mass are a fraction of the total normal stress (σ_n). This fraction is the tangent of a bulk friction angle, ϕ_b. The material friction is reduced by excess pore pressure (u) which is determined by a constant pore-pressure ratio, r_u, where

[1] $\tan \phi_b = (1-r_u) \tan \phi$, and

[2] $r_u = u / \sigma_n$

and where ϕ is the friction angle of the material.

The Voellmy flow model (Voellmy, 1955) is a combination of friction and turbulent flow. Resistance is defined by a friction coefficient, $\tan\phi$, and a turbulent coefficient, ξ, which has the dimensions of acceleration:

[3] $$T = A[\gamma H (\cos\alpha + a_c/g) \tan\phi + \gamma v^2/\xi]$$

where A is the cross-sectional area of flow, α is the slope angle, γ is the unit weight of material, g is the acceleration due to gravity, a_c is the vertical centrifugal acceleration and v is the velocity of flow. This model is essentially a granular-flow model in an undrained condition, the behaviour of which was studied by Bagnold (1954).

The distribution of debris along the path was used as a measure of the success of the rheological model chosen. The accuracy of the back-analysis was also based on the total runout distance of the debris which was compared to values supplied in the reports or directly from field evidence.

Results of the Pilot Study

Two representative results of the pilot study, those of Po Shan Road and Shum Wan Road are discussed below.

The analysis of the Po Shan Road failure included only the main movement episode, starting with the failure of the steep slope above Po Shan Road. The frictional analysis, with a bulk friction angle equal to 23°, produced an excellent representation of the distribution of deposits. The results of the analysis are shown in Fig. 1.

The Shum Wan Road failure can be modelled satisfactorily with the frictional model using a bulk friction angle of 20°. However, the Voellmy model with a bulk friction coefficient of 0.2 (11.3°) and a turbulence coefficient of $200 m/s^2$ gave a somewhat more accurate representation of the debris distribution. The results of the back analysis are presented in Fig. 2.

Results of the Current Study

The results of three representative cases are discussed in detail. Landslide '5A/2' from Lantau Island was a debris flow with a source volume of $1,500 m^3$ and a final volume of $2,300 m^3$. This failure was accurately modelled using the Voellmy rheology, the results of which are presented in Fig. 3, with a friction coefficient of 0.1 (5.7°) and a turbulence coefficient of $500 m/s^2$.

Landslide '6A1', also from Lantau, is a typical example of a low volume ($110 m^3$), high gradient debris avalanche. This category of failure required exceptionally high friction angles along the runout path in order to achieve realistic total runout distances. Landslide 6A1, represented in Fig. 4, required a bulk friction angle along the path of 41°. However, to initiate motion, the friction angle on the source was set at 27°. A lower friction angle at the source can be justified based on the fact that some source of weakness such as joints or bedding planes must exist at the source area in order to initiate failure. At the same time, obstacles in the path would result in an increase in the effective friction angle, particularly for small landslides.

The Ching Cheung Road landslide had a source volume of $400 m^3$. The frictional model provided a good representation of the runout characteristics using a bulk friction angle in the source area of 23° and that along the path of 29°. Graphical output is presented in Fig. 5. A summary of all results of the current study is presented in Table 1.

Fig. 1. Back analysis results of the Po Shan Road debris avalanche; frictional model, ϕ_b=23°. Source volume = $40,000 m^3$; initial profile is indicated by the heavy dashed line. Final deposit profile is indicated by the heavy solid line. Profiles are drawn at 2 second intervals. '+' indicates the center of gravity of initial and final volumes.

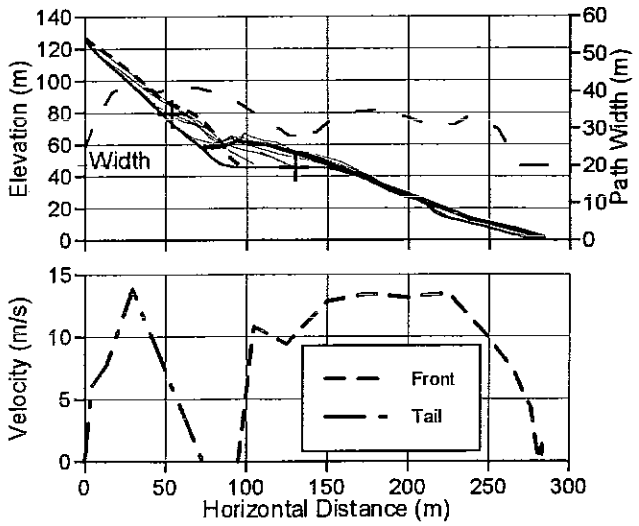


Fig. 2. Back analysis results of the Shum Wan debris avalanche; Voellmy model, ϕ=11.3°, ξ=200m/s^2. Source volume = $25,000 m^3$. Profiles are drawn at two-second intervals. Normal depth is exaggerated five times. For symbol descriptions refer to Fig. 1.

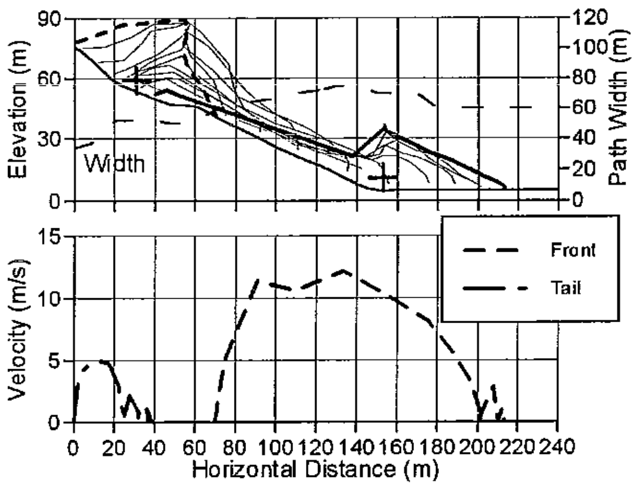


Fig. 3. Back analysis results of the Tung Chung debris flow '5A/2'; Voellmy model, ϕ=5.7°, ξ=500m/s^2. Source volume = 1,500m^3. Profiles are drawn at 2 second intervals. Fine dashes indicate erosion along the path. For description of other symbols refer to Fig. 1.

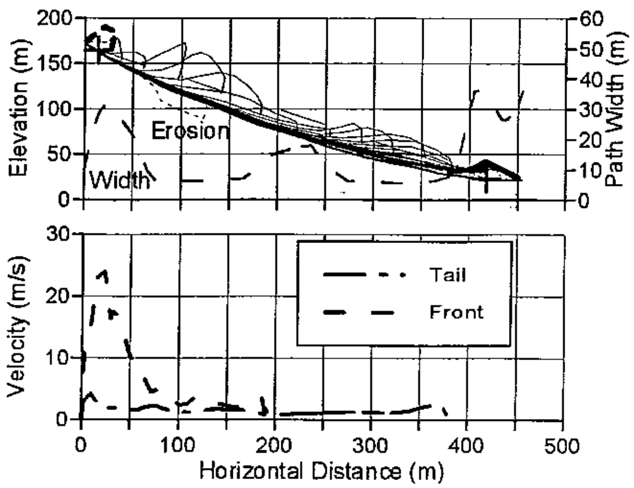


Fig. 4. Back analysis results of the Tung Chung debris avalanche '6A/1'; frictional model, ϕ_{source}=27°, ϕ_{path}=41°. Source volume = 110m^3. Profiles are drawn at two-second intervals. Normal depth is exaggerated five times. For symbol descriptions refer to Fig. 1.

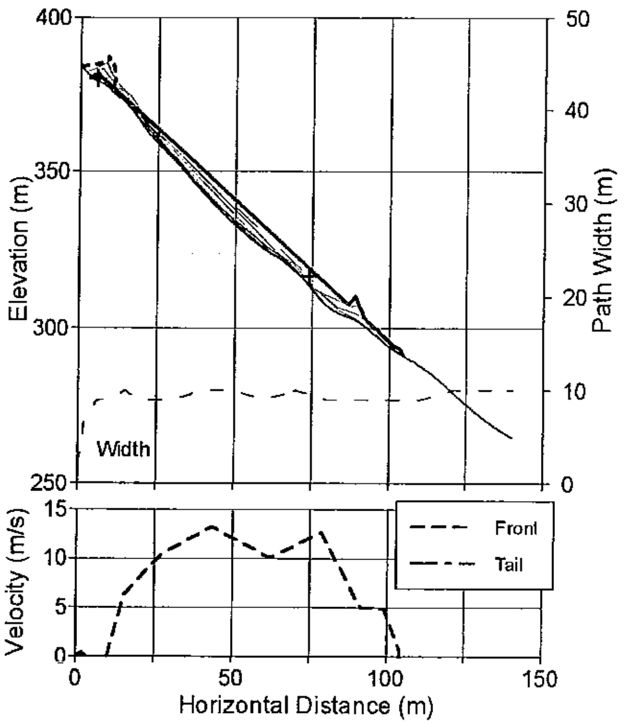
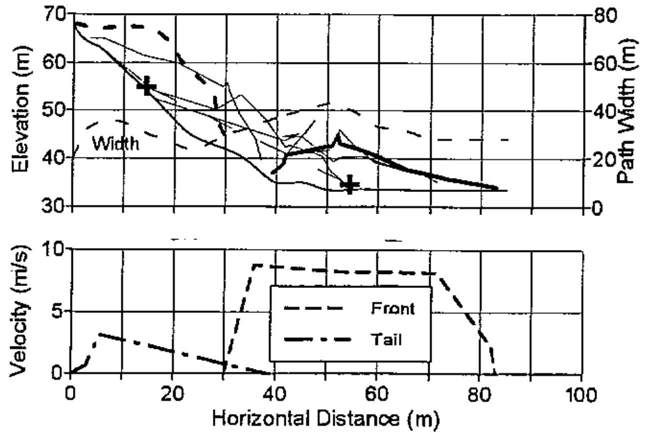


Fig. 5. Back analysis results of the Ching Cheung quasi-natural debris avalanche; frictional model, ϕ_b=20°. Source volume=1,800m^3. Profiles are drawn at 2 second intervals. For symbol descriptions refer to Fig. 1.



Discussion

The selection of an appropriate rheological model must be made based on comparing predicted and actual behaviour of the landslide. Factors to be considered include velocity and distribution of deposits. In general the frictional model predicts somewhat exaggerated velocities and deposits the bulk of the debris proximally with gradual thinning away from the source. The deposition area tends to be short. The Voellmy rheology results in lower velocities, uniformly-distributed deposits, and fairly short deposit areas with accumulation on the flatter parts of the slope. As the friction coefficient is increased, the Voellmy model approaches the frictional model.

Once the appropriate model is selected based on the above observations, the corresponding resistance parameters are determined based on the runout distance of the slide front.

In all cases examined in the pilot study, the single parameter frictional model produced reasonable velocity profiles and realistic distributions of deposits. The two-parameter Voellmy model performed somewhat better in the case of the Shum Wan landslide, where its use resulted in a smaller quantity of debris remaining on the rupture surface of the original slide. In the case of the Tsing Shan debris flow, the Voellmy model produced somewhat more correct velocities at two control points on the path.

Field estimates of velocity in the current study were not available. Therefore, the choice of rheological model and corresponding input parameters was based entirely on the total runout distance and the distribution of debris. As in the pilot study, only the frictional model and Voellmy flow model were used, either individually or in combination.

Table 1. Input and Output Results of the Current Study vs. Reported Values

Slide Name	Data Source (GEO report numbers unless otherwise indicated)	INPUT: Rheological Model	INPUT: *Input Parameters (deg)	OUTPUT: Runout Distance (m)	OUTPUT: Angle of Reach (deg)	OUTPUT: Max Velocity (m/s)	REPORTED VALUES: Runout Distance (m)	REPORTED VALUES: Angle of Reach (deg)
L-6A/1 *source* L-6A/1 *path*	SPR 10/96	Friction Friction	$\phi_b = 27$ $\phi_b = 41$	104	42	13.3	86	40
L-5A/10	SPR 10/96	Friction	$\phi_b = 34$	69	34	8.3	74	30
L-5A/13	SPR 10/96	Friction	$\phi_b = 25$	140	25	10.2	122	24
L-5A/2	SPR 10/96	Voellmy	$\phi = 5.7$	450	18	23.9	312	26
L-A6 *source* L-A6 *path*	SPR 10/96	Friction Friction	$\phi_b = 23$ $\phi_b = 29$	136	26	9.8	111	31
Sha Tau Kok *source* Sha Tau Kok *path*	field survey	Friction Voellmy	$\phi_b = 29$ $\phi = 5.71$	852	21	18.2	1000	18
NT-419 *source* NT-419 *path*	field data (J. King)	Friction Friction	$\phi_b = 30$ $\phi_b = 43$	242	38	12.0	190	35
NT-515 *source* NT-515 *path*	field data (J. King)	Friction Friction	$\phi_b = 23$ $\phi_b = 28$	117	26.5	9.7	120	29
NT-529 *source* NT-529 *path*	field data (J. King)	Friction Voellmy	$\phi_b = 23$ $\phi = 22$	182	32	22.0	227	32
NT-410 *source* NT-410 *path*	field data (J. King)	Friction Friction	$\phi_b = 25$ $\phi_b = 31$	244	30	12.9	257	34
Luk Keng	field survey	Friction	$\phi_b = 24$	129	23	10.2	150	22
Pak Sha Wan	field survey	Voellmy	$\phi = 11.3$	84	21	9.0	80	22
Tai Mong Tsai	field survey	Friction	$\phi_b = 25$	81	24	9.0	100	22
Pat Sin Leng 1 Pat Sin Leng 2	field survey field survey	Friction Voellmy	$\phi_b = 28$ $\phi = 11.3$	145 614	29 18	12.9 14.0	100 600	32 21
Liu Pok	DN 2/97	Voellmy	$\phi = 11.3$	196	21	13.4	194	24
Lido Beach	LSR 8/98	Friction	$\phi_b = 23$	63	21	11.8	64	20
Ma On Shan	LSR 15/97 (draft)	Friction	$\phi_b = 23$	95	24	12.1	75-105	26
Ching Cheung Road	Halcrow Asia Report	Friction	$\phi_b = 20$	83	22	16.3	45-80	20
KCR Fo Tan *source* KCR Fo Tan *path*	LSR 4/98	Friction Friction	$\phi_b = 14$ $\phi_b = 26$	43	30	13.9	40	30

Notes: A turbulence coefficient of $500 m/s^2$ was used in all cases where the Voellmy rheology was used.
Data Sources: NT = New Territories, L = Lantau Island

In this study, debris avalanches were modelled using the frictional rheology. In addition, the frictional model was used in all cases of the road-side and quasi-natural failures, as well as for the intact sliding-translational failure at Tai Mong Tsai. The frictional model provided an accurate representation of the failure behaviour for these events.

In all cases of long-runout, channelised debris flows, the Voellmy model was used. The friction angle in the majority of cases was 11.3°, indicating a possible trend for failures of this type and of similar magnitude. In some cases, a combination of the frictional model and the Voellmy model was used. In particular, the failure at Sha Tau Kok began as an open-slope debris avalanche, then entered a stream channel where it was channelised and became saturated, forming a debris flow. The frictional model was therefore applied to the source up to the point of entry into the stream channel and the Voellmy model was then used for flow in the channel.

Many of the landslides studied were of relatively low volume compared to any previous back-analyses performed with DAN. Realistic back-analyses for these low-volume, open-slope, high-gradient failures could be realised only through the application of exceptionally high friction angles. For example, the bulk friction angle of the Tung Chung debris avalanche '6A/1', with a volume of $110 m^3$, was 41°. This corresponds to an effective friction angle of 60° at r_u = 0.5, which is extremely high. As the analyses were completed, a trend in the bulk friction angle with source volume became apparent. Fig. 6 shows the relationship between these two variables for several small-magnitude landslides back-analysed in the current study. The debris of these landslides came to rest on relatively steep slopes (30° to 40°) with no apparent topographic control on the runout.

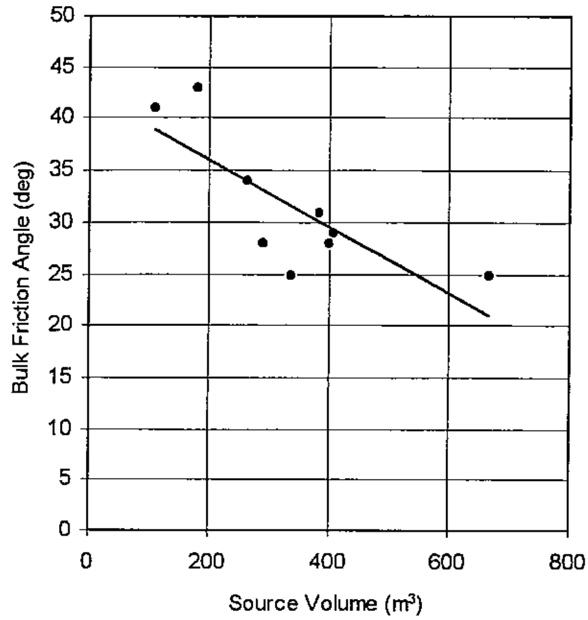
The low mobility of these debris avalanches and resulting application of extremely high friction angles can probably be explained with respect to the relatively low source volumes combined with specific slope properties. These properties may include drainage, vegetation and degree of weathering as well as the presence of obstacles in the runout path. The energy of such low volumes of debris would quickly be lost due to obstacles such as large cobbles or boulders, shrubs, small trees or woody debris which would hinder the movement of small-magnitude failures. In contrast, an event of greater magnitude would probably entrain these 'obstacles' into the debris. Thus, even on steep slopes, the debris of small-magnitude failures would be dispersed along the path and would quickly come to a halt. Corominas (1996) demonstrated that the angle of reach of all types of slope failures is dependent not only on landslide volume, but also on obstacles in the path of flow such as vegetation and scree deposits.

Vegetation not only provides obstacles in the runout path but might also act to reduce entrainment by providing soil erosion resistance. Well-drained slopes may also result in failures of relatively low mobility if they reduce the degree of soil saturation. The degree of weathering of bedrock and the thickness of any colluvial layer are probably major factors in controlling landslide source volume, which also has a direct impact on potential debris mobility. Degree of weathering and presence of superficial deposits also control the erodibility of material along the debris path, again affecting potential mobility. Further investigation into the pre-failure characteristics of the cases back-analysed in this study is necessary to provide evidence for a correlation between debris mobility and pre-failure slope properties.

In many cases, the distribution of debris and total runout distance could be matched to actual values only through the application of bulk friction angles, which were lower on the source than on the path. In most of these cases, a topographic "lip" existed at the base of the source which hindered the movement of the source material. Thus, if the friction angle were too high, all debris would remain at the source. However, if the friction angle was reduced such that 100% mobilisation of the debris was achieved, the total runout would be too high. The use of a lower friction angle on the source scar is realistic since in many cases it is probable that weak planes exist at the source along which the failure took place. Thus, the source friction angle would in fact be lower than the friction angle of the debris along the path.

Field observations indicated that the debris of the first event at Pat Sin Leng ended at the main stream channel. At this location it appeared to be cut off by the debris of the second event. Furthermore, some remoulded debris was observed on the channel banks further downslope which was not consistent with the hyperconcentrated stream-flow failure assumed for the second event. It appeared that the later event had entrained and washed away any debris from event 1 which might have made it to the stream channel. Thus, a realistic estimate of the runout distance for Pat Sin Leng 1 could not be obtained. Attempts at modelling the first failure using the Voellmy rheology resulted in runout which continued a long way down the stream channel, well past the observed extent of the debris in the field. Thus, the frictional rheology was chosen as a more realistic representation of the failure. However, even with the frictional model, the results indicate that the debris may have run out as far as 50m along the stream channel prior to the later debris flood.

Fig. 6. Source volume vs. bulk friction angle along the path for small volume (<800m^3) debris avalanches with non-topographically constrained runout. A preliminary linear regression is shown with R^2=0.612.



Conclusions

The frictional model is capable of producing reasonable simulations in most cases, particularly where the slide mass is not completely saturated. In more saturated flows, the Voellmy model is probably more realistic.

The results of this study indicate that the dynamic model, DAN, can provide accurate results with respect to the back-analyses of landslides of the type occurring in Hong Kong. This study presents the analyses of failures of very small magnitudes never before attempted with DAN. As discussed above, in many cases it was necessary to increase the friction angle to unrealistically high values in order to accurately model the runout distance and debris distribution of these failures. This leads to some interesting results with respect to the development of a typological classification system. These open-slope, small, high-gradient failures form a typological class of their own. While a greater sample size is necessary in order to improve the significance of the correlation presented in Fig. 6, these preliminary results indicate that it may be possible to predict the runout characteristics of this type of failure using such a correlation.

The results of this study also indicate that the dynamic model has excellent potential for predictive use. Further analyses of the physical properties of pre-failure slopes (for example, morphology and surface 'roughness') might allow correlations to be made between these properties and the rheological models and corresponding input parameters used in the back analyses. Typological classifications could be used to classify potentially unstable slopes based on physical slope properties observed in the field, and the dynamic model could then be used to predict the runout characteristics and the resulting hazard.

The results presented in this paper are part of an on-going study aimed at developing a typological classification system for mobile mass movements. This study will involve the back-analysis of a large number of slope failures ranging in failure type from debris flows and debris avalanches to rock avalanches. These preliminary results indicate that calibration of the dynamic model through back-analysis will allow the improvement of our predictive capabilities with respect to the runout characteristics of mobile mass movements.

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