Mobility of Selected Landslides in Hong Kong - Pilot Back-Analysis Using a Numerical Model

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Abstract: Conventional slope stability analyses do not consider runout of debris after failure. However, the travel distance and velocity of landslide debris are key factors in consequence assessment, quantification of risk and design of debris barriers.

A relatively simple and versatile computer model, DAN, was proposed by Hungr (1995) for the assessment of debris mobility. This model simulates the motion of landslide debris and allows the user to select from a variety of material rheological models to simulate different landslide movement mechanisms. Previous calibrations of the model have been carried out for large rock avalanches and for coal mine waste flow slides.

In this paper, the background to the formulation of the model is outlined and its application to back analyse selected landslides in Hong Kong is described. The cases considered covered a wide range of landslides, including natural terrain, fill slope and cut slope failures in different materials. The velocity of the landslide debris was found to be of the order of 20 m/sec in some cases. Useful findings were obtained with respect to the types of material model in the DAN program that best describe the dynamic motion. Areas for further work are discussed in the paper.

INTRODUCTION

In the quantification of landslide risk, there is a need to assess the post-failure runout characteristics of landslide debris. As suggested by Wong et al (1997), there is, on the whole, a lack of a systematic and practical framework for assessment of landslide consequences, in which the quantification of travel distance and velocity of landslide debris is an important component.

This paper briefly reviews the existing empirical and semi-analytical approaches for assessment of mobility of landslide debris. The theoretical background and pilot application of a numerical model to simulate the dynamics of debris movement are described in this paper.

EXISTING METHODS FOR ASSESSMENT OF MOBILITY OF LANDSLIDE

Conventional analytical techniques for slopes have largely concentrated on the assessment of the safety margin against the initiation of failure. In recent years, attention has been given to assessing the travel distance of landslide debris to facilitate quantification of landslide consequence. Based on landslide data from the 1993 landslides in Lantau, Wong & Ho (1996) examined the correlation between the travel angle and volume of landslides, with due consideration of different landslide and debris movement mechanisms. Lau & Woods (1997) also presented a review of the various approaches for assessing debris mobility, including multivariant regression techniques.

The empirical approaches for assessment of landslide runout distances adopted in Hong Kong generally do not provide detailed information on the velocity and distribution of the landslide debris mass. These parameters are needed for the assessment of debris impact on facilities or upon debris barriers (Lo & Ho, 1998). There has only been limited application of advanced analytical techniques for assessing landslide debris behaviour in Hong Kong.

The sled model is a simplified approach to describe rigid body motion of a lumped mass and predicts the runout distance and average velocity of debris. Different rheological models are available for describing different landslide runout characteristics. Sassa (1988) proposed to use apparent friction angle to take into account pore water pressure generation and the intrinsic friction angle of the landslide debris. Sassa et al (1995) and Sassa (1996) used this concept in a simple sled model to explain the phenomena of sliding surface liquefaction and general liquefaction of landslide debris. Hutchinson (1986) and De Matos (1988) considered consolidation of the basal shear zone of the debris in controlling the runout distance and velocity of debris using a sled model. Huang & Wang (1988) also considered the effect of rolling particles in the basal shear zone. However, it is noted that the lumped mass sled models are unable to provide information on thickness and velocity profiles of the landslide debris.

There are various numerical methods available for examining the dynamic continuum behaviour of different types of landslide debris to estimate the time-dependent velocity profile and debris mass distribution along the trail, i.e. the momentum flux of the moving debris. Savage and Hutter (1989) and Norem et al (1990) developed 2-dimensional Lagrangian models for dry sand flows and submarine flowslides respectively. Flood routing models have also been used to determine the run-out and deposition characteristics of debris flow and channelised debris flow (Julien & O'Brien, 1997). Other more complex and sophisticated programs, which simulate the mass of the landslide debris using finite element (Chen & Lee, 1998), or finite different methods such as FLAC (Itasca, 1995), are also available. The application of the distinct element method to model the dynamic behaviour and interaction of landslide debris in terms of discrete blocks (such as UDEC, Itasca, 1991) or particles (such as PFC2D, Itasca 1994 and the CSIRO program, Cleary, 1994), is still under development.

Thus, there is a wide spectrum of techniques of varying complexity which can be adopted to assess the dynamics of debris movement. However, the main difficulty is in the assessment of appropriate input parameters for a meaningful analysis and there is a need to validate the results.

DAN MODEL

A relatively simple and versatile continuum numerical model to simulate debris movement was proposed by Hungr (1995). This models the motion of landslide debris using a finite difference solution for the governing dynamic equations in a Largrangian framework and allows the user to select from a variety of material rheological models and pre-defined options. The solution is obtained in time steps for a block assembly of elements, representing the landslide debris as a continuum. This model is implemented in a microcomputer program DAN ("Dynamic ANalysis"). A spreadsheet calculation routine has also been set up to perform the analyses.

Once the landslide mass simulated by a number of blocks along a 2-dimensional curve representing the runout path is set up, the net driving force of the blocks can be obtained from the tangential component of the self-weight of the block, the basal resistance force and difference in inter-block normal forces. This out-of-balance driving force is then used to determine the resultant change in velocity through Newton's second law. Time marching numerical integration along the runout path will give the velocity and runout profiles of the landslide debris at different times.

Seven flow resistance functions are available to simulate the different rheology of the landslide debris. Hungr (1995) presents the details of the formulation and application of these different rheological models and flow characteristics.

BACK-ANALYSIS OF CASE HISTORIES IN HONG KONG USING DAN

Previous calibrations of the DAN model have been made for large rock avalanches (Hungr & Evans, 1996 and 1997) and for coal mine waste flow slides (Hungr et al, 1998). In July 1997, the Geotechnical Engineering Office (GEO) commissioned O. Hungr Geotechnical Research Inc. to carry out a pilot study to explore the feasibility of using DAN as a predictive tool to assess the mobility of the debris generated by landslides in Hong Kong. The pilot study involved back-analysing six notable case histories, viz. the 1972 Po Shan Road landslide, 1976 Sau Mau Ping landslide, 1990 Tsing Shan debris flow, a natural terrain landslide on Lantau Island in 1993, and the 1995 Shum Wan Road and Fei Tsui Road landslides, using DAN (Hungr, 1998). As part of the detailed landslide study of the 1997 Lai Ping Road landslide, the GEO also carried out detailed dynamic analyses of two discrete failures of the landslide using spreadsheet calculation of the DAN model (Sun & Campbell, 1998). Salient details of the analyses and findings are reported below.

The general procedure adopted for the back-analyses is as follows:

The centre-line profile of each movement path was digitised using cross-sections or topographic maps. The ground surface of the depletion area prior to failure was also digitised. An array of path widths was compiled for each landslide (except for Sau Mau Ping, which has a path of essentially constant width so that a 2-dimensional analysis would suffice). The dimensions of the initial slide were adjusted so as to correspond to the reported bulked volume of each event.

The initial selection of an appropriate rheological was guided by previous experience with dynamic landslide analysis. The landslide deposits in the cases examined tend to have tapered forward, with the thickest debris accumulation forming in the proximal parts of the deposition area. Different models and input parameters were tried to obtain a reasonable fit with the observed behaviour in the back-analyses. The best-fit in terms of debris mass distribution were obtained using a frictional model. In this model, the resisting shear stress at the base of the flowing mass is taken to be a fraction of the total normal stress and corresponds to the tangent of a "bulk friction angle", ϕ_b. The assumed frictional relationship relates ϕ_b to the effective stress "dynamic friction angle", ϕ_d', which is reduced by dynamic pore water pressure effects, which are represented by a constant pore-pressure ratio, r_u within a given path segment, as follows:

$$\tan \phi_b = (1 - r_u) \tan \phi_d' \qquad (1)$$

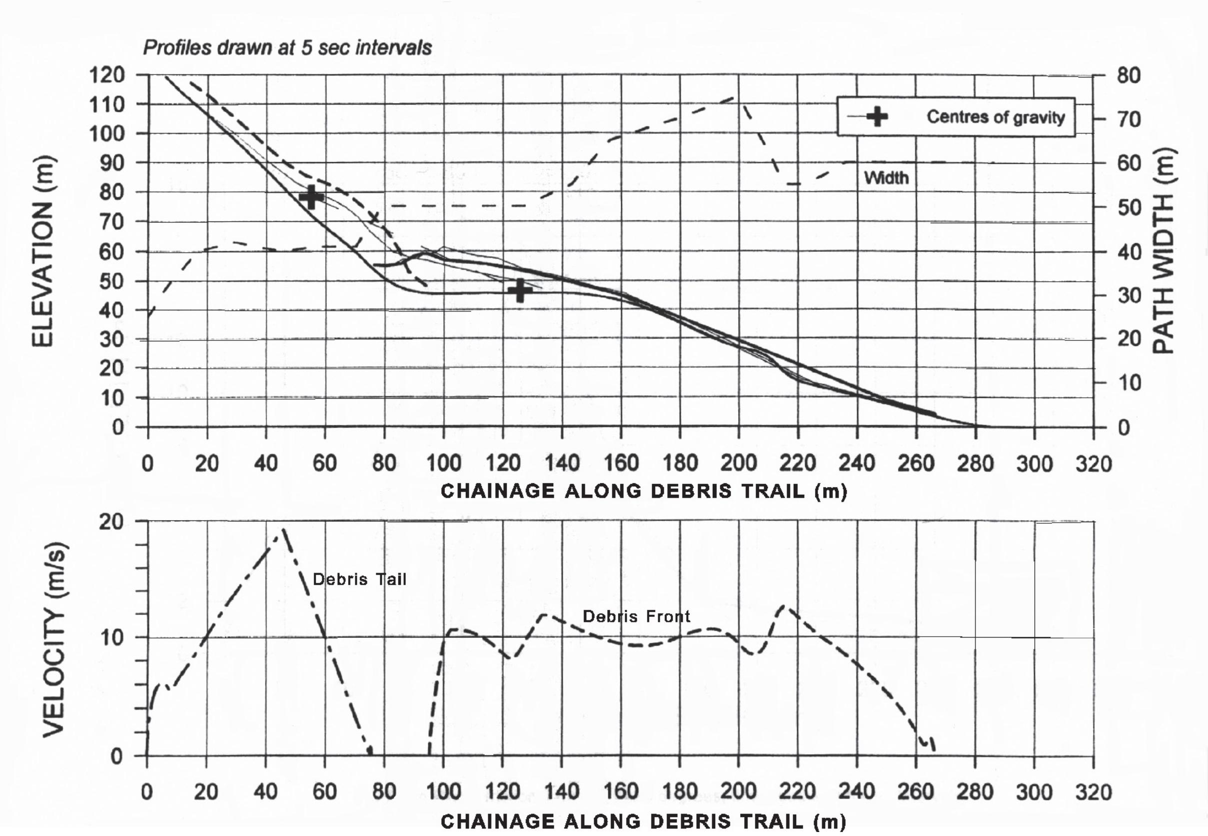

Figure 1. Calculated velocity and debris profiles for the Po Shan Road landslide

PO SHAN ROAD LANDSLIDE (GOVERNMENT OF HONG KONG, 1972)

The analysis of the Po Shan Road landslide considered the main movement episode, starting with the failure of the hillside above Po Shan Road. DAN analyses, using a bulk friction angle (ϕ_b) of 23° produced a good representation of the distribution of the deposits. A total volume of 40,000 m^3 of the landslide debris was modelled. The velocity of the debris reaching Kotewell Road, where the building at 11 Kotewell Road and the Kotewell Court were destroyed, was calculated to be about 10 m/sec. Figure 1 shows the calculated profiles and velocity distributions of the landslide debris at different times.

SAU MAU PING FILL SLOPE FAILURE (GOVERNMENT OF HONG KONG, 1977)

The Sau Mau Ping failure was analysed using a 2-dimensional model, which considers a typical slice of the slope with unit thickness. A frictional model with $\phi_b = 20°$ produced a good representation of debris distribution. The movement velocity at the wall of the affected building calculated by DAN was 12 m/sec. The analysis has neglected any resistance which may be offered by the building.

TSING SHAN DEBRIS FLOW (KING, 1996)

The Tsing Shan debris flow was analysed using a version of the DAN model that is capable of simulating gradual entrainment of debris along the path. The "parent landslide" was represented by an initial volume of 4,000 m^3, which accounts for the trigger landslide as well as the debris mobilised in the main part of the depletion zone. An entrainment "yield rate" of 25 m^3/m was specified in the gorge segment of the path, to increase the debris volume gradually to 13,000 m^3 at the proximal end of the deposition area.

The analysis was carried out with the simplifying assumption that the bulk of the coarse deposits moved in a single surge. The actual event may have consisted of several surges. It may be possible that one of the surges was dominant and that its major parts arrived in a single phase. Such an assumption would be conservative when the model is used as a predictive tool in that it would maximise the discharges and potential impact loads.

King (1996) estimated the movement at elevation 160 mPD as 16.5 m/sec and at 110 mPD as 12.5 m/sec based on observations of the super-elevation and radius of curvature of the debris trail. DAN analysis using the Voellmy model (Hungr, 1995), with a friction coefficient of 0.2 (i.e. ϕ_b of 11.3°) and a turbulence coefficient ξ of 500 m/sec gives a

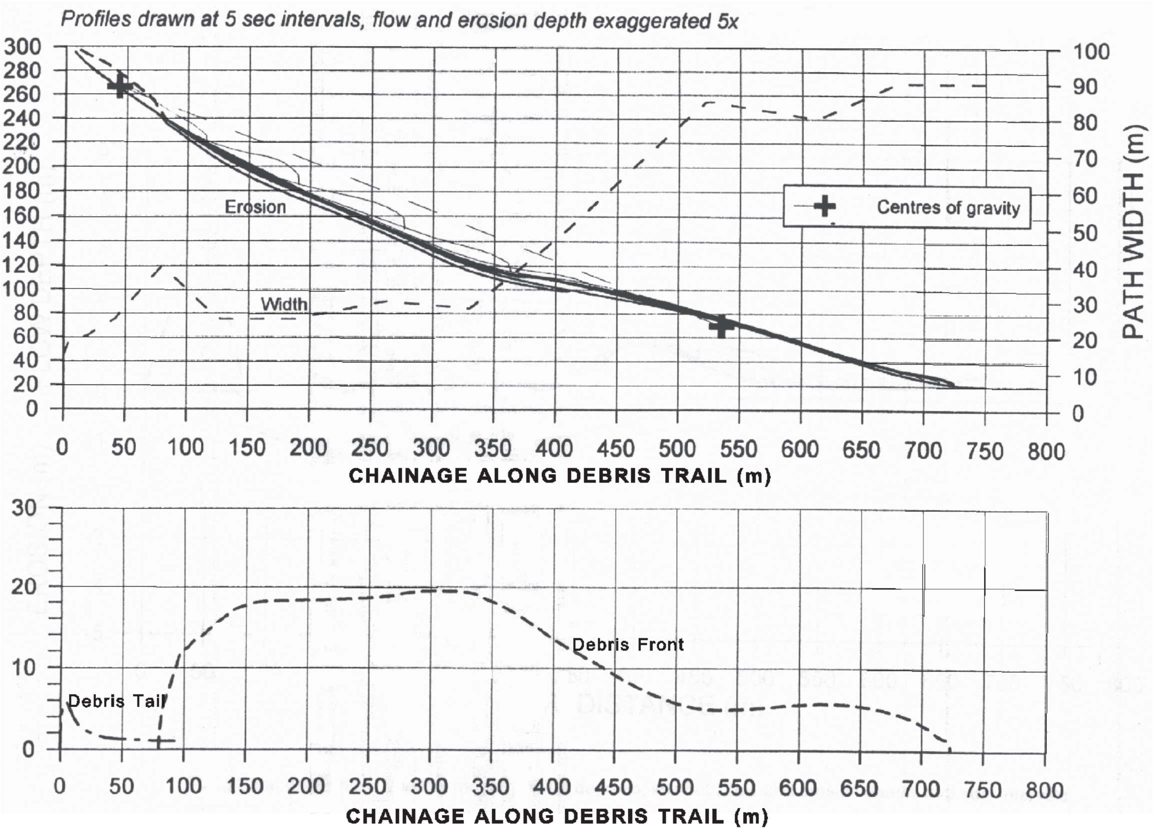

Figure 2. Calculated velocity and debris profiles of Tsing Shan debris flow

reasonable representation of the debris distribution and the calculated velocities at 18 m/sec and 17 m/sec at elevations 160 mPD and 110 mPD respectively (Figure 2).

NATURAL TERRAIN LANDSLIDE C1, LANTAU (WONG ET AL, 1996)

This landslide was modelled satisfactorily by DAN with the frictional model assuming ϕ_b of 23°. The analysis appears to have successfully simulated the forward tapering profile of the landslide debris.

SHUM WAN ROAD LANDSLIDE (GEO, 1996)

This failure was modelled satisfactorily by DAN with the frictional model assuming ϕ_b of 20°. However, using the Voellmy model with a bulk friction coefficient of 0.2 (i.e. ϕ_b of 11.3°) and a turbulence coefficient ξ of 200 m/sec gave a better representation of the debris distribution in this case.

FEI TSUI ROAD LANDSLIDE (GEO, 1996)

This failure was deep-seated and strongly structure-controlled. The best representation of the observed behaviour was obtained using the frictional rheology. The value of ϕ_b was taken as 24° on the rupture surface underneath the slide mass, corresponding to the effective stress shear strength parameters and pore water pressure prevalent at the time of the failure as determined by slope stability analysis. The analyses suggest that the slide mass could have travelled over the paved road surface essentially as a dry frictional granular flow. The distribution of deposits was better simulated by setting the ϕ_b value to 36° on this distal part of the path.

LAI PING ROAD LANDSLIDE (SUN & CAMPBELL, 1998)

The landslide comprised five relatively shallow and mobile landslides and a deep-seated unstable landslide mass of 100,000 m^3 with limited travel. The mobility of debris from landslide scars 1 and 4 (volumes of 1250 m^3 and 2250 m^3 respectively) was modelled using a spreadsheet calculation routine based on DAN.

The distribution of the landslide debris was found to be best simulated using the frictional model with ϕ_b of 19° and 22° for landslides 1 and 4 respectively. The maximum velocity is calculated to be about 7 m/sec for landslide 1 and about 11 m/sec for landslide 4.

DISCUSSION OF THE RESULTS

In the cases examined in the pilot analyses, the frictional model tended to produce reasonable velocity profiles and realistic distributions of the debris deposits. This model predicts fairly high velocities (a maximum of typically over 10 m/sec), deposits that are relatively thick in the proximal part of the deposition area and thinning towards the distal margin.

For the cases investigated, the bulk friction angles back-calculated from DAN analyses ranged between 19° and 23°. Assuming that the effective stress dynamic friction angle of the poorly sorted debris is of the order of 32°, Equation 1 indicates that the overall average pore pressure ratio during motion was in the range of 0.32 to 0.45. It is of interest to note that similar values of the bulk friction angle have also been obtained from back-analyses of flow slides in coal mine waste from south-eastern British Columbia in Canada (Hungr et al, 1998).

Using the frictional model, three of the cases (i.e. Sau Mau Ping, Shum Wan Road and Lai Ping Road) required fairly low "bulk friction angles" corresponding to high average pore water pressure along the runout path. This relates well with the observation of liquefaction failure of the loose fill at Sau Mau Ping. At Lai Ping Road, the high mobility and r_u values were probably due to a combination of high groundwater pressure condition and effect of undrained loading as the 1997 landslide debris impacts on the previous failure debris along the runout path (possibly exacerbated by the prevailing failure debris being in a wet and loose condition). The relative high r_u value for the Shum Wan Road failure may correspond to the high groundwater level in the natural hillside which formed a major part of the runout path.

Po Shan Road, Fei Tsui Road and the Lantau C1 natural terrain failure were simulated well with the frictional model using relatively moderate to high "bulk friction angles", corresponding to moderate to low average pore water pressure condition along the runout path.

The two-parameter Voellmy model performed better in the case of the Shum Wan Road landslide, where its use apparently resulted in a more realistic distribution of the landslide debris. In the case of Tsing Shan debris flow, the Voellmy model produced reasonable velocities compared with the two observation points along the runout path. The Voellmy model is generally able to simulate landslide motion involving a high proportion of water where the debris distributes uniformly over fairly short deposition areas on the flatter part of the runout path. With an increasing bulk friction coefficient, the Voellmy model changes gradually to a frictional model.

FURTHER DEVELOPMENT AND APPLICATIONS

The DAN model remains, at this stage, a suitable tool for the back-analysis of landslide events. The profile of the runout path taken by the debris is obtained by digitising the actual ground surface. In order to improve numerical stability, the shape of the cross section and the runout path are simplified and smoothed using curve fitting techniques. Some experience is required for the correct digitisation from the topographical information. If one were to use the DAN model for prediction of landslide runout, the geometry of the failure zone must be estimated beforehand, which may be done based on conventional stability analyses. The path width function can be established based on the expected width of the initiating landslide and the contours of the potential debris path. On open, unconfined slopes, an angle of lateral spreading of the path margins has to be estimated, based on past observations.

Further back-analyses using DAN covering a wider spectrum of about 30 landslides in Hong Kong of different slope types, sizes and failure mechanisms have been completed recently. The results of this further study are contained in the report produced by Ayotte & Hungr (1998). These analyses further confirm the applicability of the DAN model, particularly for failures of smaller volumes (<800 m^3). Details of this further study are presented in Ayotte et al (1999).

DAN has the potential to be the basis for a classification of debris movement for landslide hazard assessment in Hong Kong. In addition, the application of step-wise dynamic analyses would also improve fundamental understanding of landslide debris impact on barriers. Through consideration of the compatibility of the deformation of the landslide debris and deflection of the barrier, the dynamic equations of the combined debris-barrier system can be solved numerically and used to examine the dynamic behaviour of different debris barrier systems.

CONCLUSIONS

The successful use of the relatively simple numerical model DAN to simulate the dynamics of landslide debris motion has highlighted its potential as a tool in landslide hazard assessment.

The pilot studies described in this paper show that a number of different types of landslides in Hong Kong can be well simulated with a reasonably narrow range of rheological models and dynamic properties. The landslide types considered included debris slides in weathered rocks, flow slides due to liquefaction of loose fill and debris flows in steep gullies involving colluvium and weathered rocks. Most of these events can be simulated realistically with the frictional rheological model, using a bulk friction angle ranging from 19° to 23°.

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