Travel Distance of Landslide Debris

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Abstract: The consideration of the travel distance of landslide debris forms an important element in the assessment of the failure consequence of a slope. This paper describes the findings of a systematic study on the travel distance of landslide debris based on reliable data obtained from field inspections. The data have been analysed and important trends have emerged. Useful observations were made in respect of the key factors that govern the travel distance of landslide debris.

1 INTRODUCTION

In dealing with slope stability problems, the main emphasis is often placed on the evaluation of the likelihood of slope failure. A rational assessment of the potential travel distance of landslide debris is rarely carried out, and the consequence of a slope failure is usually gauged on the basis of engineering judgement.

Methods of assessing the travel distance of landslide debris and their application in Hong Kong are reviewed in this paper. Apart from the use of analytical methods, the travel distance of debris may also be assessed with more realistic results by reference to actual field data collected from landslide studies. This approach can reasonably be adopted in Hong Kong given the availability of reliable information.

This paper describes the findings of a systematic study made of the travel distance of landslide debris based on reliable data obtained from field inspections. The data have been compiled and analysed with due regard to key factors which may affect the travel distance of debris, and have been compared with selected case histories with reliable and comprehensive information. The importance of mechanism of failure, landslide geometry and downslope topography is highlighted by the study. Given sufficient good quality data and a proper classification of the type of landslide, a quick assessment of the likely range of debris travel distance can be made with reasonable confidence by means of this empirical approach.

2 CONSIDERATION OF DEBRIS TRAVEL DISTANCE IN LANDSLIDE RISK ASSESSMENT

The assessment of landslide risk involves the consideration of the frequency (or probability) of instability and the consequence in the event of a failure. In appraising the failure consequence, it is necessary to take into account the influence zone of a landslide for facilities located both beyond the crest and toe of the slope. For a facility at the toe, the amount of potential damage caused by a landslide depends principally on the amount of the debris, the possibility for the facility to be struck by debris from above, the momentum upon impact, as well as the resistance of the facility against the impact force.

Clearly, for a given slope of a certain height and gradient, the likelihood and probable degree of damage sustained by facilities at different distances away from the slope will vary. The practice commonly used in Hong Kong is to classify slopes that have potential to affect facilities (i.e. those within the reach of a sizeable amount of failure debris posing a threat to possible loss of life) into three consequence-to-life categories, viz. 'high (Category 1)', 'low (Category 2)' and 'negligible (Category 3)'. Such categories reflect the probability and severity in respect of loss of life in the event of a failure. Different minimum factors of safety are used in the design of new slopes or upgrading of existing substandard slopes for different consequence-to-life categories (GCO, 1984). Typical examples of different consequence-to-life categories are shown in Figure 1.

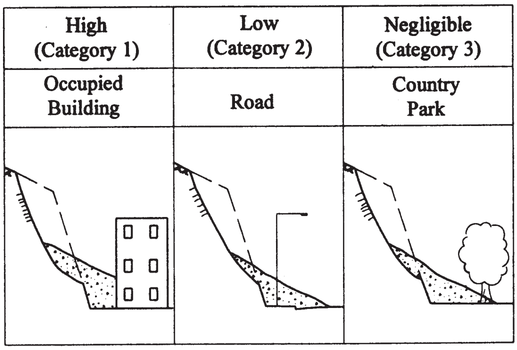

Figure 1. Examples of different consequence-to-life categories

Engineering judgement is generally required as to whether a slope is 'affecting' a facility. In principle, there is scope for downgrading the consequence-to-life category with respect to the proximity of the feature

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(e.g. slope or retaining wall) to the adjacent facility.

For instance, should the facility be judged to be beyond the probable reach of the debris, a high consequence-to-life slope feature may reasonably be downgraded to the 'low' consequence-to-life category. Such an approach would be compatible with the general framework of quantitative risk assessment in that the relative probabilities of damage for facilities at different distances are accounted for. In addition, this can have considerable financial implications because slopes belonging to different consequence-to-life categories are designed to different minimum factors of safety. In practice, it would be useful to develop a suitable framework for assessing the likely travel distance of debris in the event of a failure. On the basis of this rational framework, the engineer can then make a sound judgement on the suitable consequence-to-life category for a given slope.

3 FACTORS AFFECTING THE TRAVEL DISTANCE OF DEBRIS

An adequate understanding of the generic factors that can significantly affect the travel distance of debris is of paramount importance before deciding on a suitable assessment method. The range of relevant parameters may be grouped as follows :

(a) characteristics of the slope - these include the slope height and gradient, nature of slope-forming material, position of feature with respect to slope height, and the extent uphill beyond the crest of a cut face that may be involved in a failure,

(b) mechanism of failure and mode of debris movement - these include collapse of meta-stable or loose soil structure leading to possible generation of excess pore water pressure during failure and reduction in soil shear strength (e.g. liquefaction failure of loose granular fill slopes), degree of disintegration of the failure debris during motion, fluidity of the debris and effects arising from convergent flow of surface water (e.g. wash-out action), nature of debris movement (e.g. sliding, rolling, bouncing, viscous flow, etc), and characteristics of ground surface on which the debris travels (e.g. susceptibility to depletion, response to rapid loading as a result of the weight of the debris, type of vegetation, etc).

(c) condition of downhill slope - gradient of the downslope area, possibility of channelisation of debris, drainage condition of the downslope area, extent of catchment which collects and discharges into the downslope area, potential for ponding, etc.

It is apparent from the above summary that a multitude of factors can affect the travel distance of debris. In view of the uncertainties involved, suitable conservatism needs to be incorporated in the framework for predicting the probable runout distance of debris.

4 METHODS FOR ASSESSING THE TRAVEL DISTANCE OF DEBRIS

A range of methods has been developed for assessing the travel distance of debris. These can be broadly classified as follows :

(a) single body models,
(b) continuum models based on numerical methods, and
(c) observational approach.

Single body models consist of models based on rigid body motion of the failed mass. Different models have been proposed, e.g. Sassa (1988), Fang & Zhang (1988) and Aydan et al (1991).

Of the above models, the 'sled' model as proposed by Sassa (1988) has been commonly used as a convenient means for the assessment of debris travel distance. The formulation of the 'sled' model is based on energy principles. In this model, it is assumed that all the energy losses during the motion of a landslide mass will be dissipated through 'friction'. Various assumptions can in turn be made regarding the nature and distribution of 'friction' during landslide motion, which can affect the prediction of travel distance of debris. As the nature of 'friction' is poorly understood, it is generally referred to as the apparent angle (or coefficient) of friction. In essence, the apparent angle of friction is a measure of the fluidity of the debris and the amount of energy loss during debris movement. Sassa (1988) suggested that the apparent friction angle reflects the combined effect of the intrinsic internal friction angle and pore pressures induced during motion. High-speed ring shear tests have been adopted to determine the apparent friction angle (Sassa, 1988). More complicated models involving the assumptions of rigid and fluid friction coefficients have been proposed in the literature, e.g. Egashira & Ashida (1985).

Sassa (1992) noted the difference in behaviour as related to the landslide volume in that a large landslide is more likely to induce undrained loading, resulting in a sliding surface in the deposit due to generation of high excess pore pressure, and hence large travel distance. In the case of a small landslide, the loading may not be undrained and the corresponding runout distance is likely to be less.

Hutchinson (1986) proposed a consolidation model for the motion of a flow slide, which is generally consistent with the principles of the 'sled' model. He further suggested that a two-phase or three-phase effective stress model may offer a better means of studying flow slides than viscous models, in which an empirical fit is sought to the usually unmeasured viscosity of a hypothetical single-phase material.

Attention needs to be drawn to the importance of momentum transfer in the dynamics of mass-wasting processes. The runout distance of a landslide also depends upon the shape of the deposit and the rate of deposition. Deposition of mass during motion can have a marked influence on the runout. It is important to note that if a landslide with changing mass is modelled as a sliding block with constant mass, the runout will be grossly underestimated. Modifications can be made for the different modes of debris deposition (Hungr et al, 1984; Hungr & McClung, 1987; Cannon & Savage, 1987; Van Gassen & Cruden, 1989). However, the predictions are sensitive to the assumptions made. For instance, Van Gassen & Cruden (1989)'s analysis has shown that the runout distance according to the assumption of an exponential mass-changing model may be more than three times that calculated from the linear mass-changing model.

The 'sled' model has been adopted in Hong Kong for the purposes of ranking of old fill slopes for upgrading works (Kwan, 1994). The determination of the priority order for action is based on an assessment of the likely travel distance and profile of debris in the event of failure. The typical topographic conditions of Hong Kong urban areas that are considered in the assessment are shown in Figure 2.

One of the limitations of the 'sled' model is that the debris is effectively considered as a lumped point mass at its centre of gravity, and careful interpretation of the results of analysis is required. The calculated position of the centre of gravity as being on an intermediate road does not necessarily guarantee that the sliding mass would stay entirely on the road (Figure 2). In the presence of a road barrier or other objects which could retain landslide debris, the volume of landslide debris should be considered in assessing whether the area further downslope might be affected. Besides, the use of an apparent angle of friction to lump the diverse modes of possible energy loss, such as friction, impact and rolling, is a simplification, and quantification of such parameters for general application to all types of slope can be frought with difficulties.

In summary, the travel distance may be conveniently assessed by the 'sled' method based on a number of simplifying assumptions. However, complex modes of failure and topographic conditions cannot be easily accounted for. Extreme care is also needed in choosing the appropriate apparent angle of friction for the slope as well as for the downslope area, with due regard to the mechanism of failure and mode of debris movement, together with the properties of the material involved.

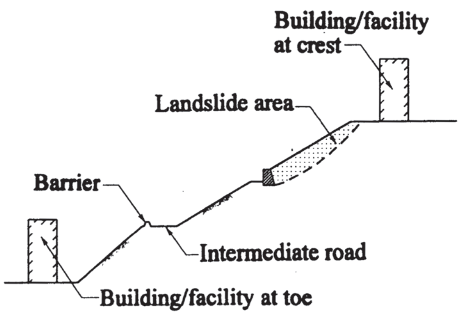

Figure 2. Typical topographic conditions for assessment of debris travel distance (Kwan, 1993)

Modelling by advanced numerical method is an alternative approach, and can prove particularly useful for more complicated cases. Typically, though not necessarily being restrictive, this involves the discrete element method using advanced computer program codes, such as UDEC or FLAC. In this approach, complicated stress-strain relationships and different contact conditions, including visco-elasto-plastic behaviour, separation, sliding and rolling of the individual blocks, can be modelled. However, this approach is as yet not amenable to being a general design office tool due to the specialised nature of the modelling techniques involved and the difficulties in parameter selection for the constitutive relationships.

Assessment of travel distance of debris by means of the advanced numerical modelling approach has been made in the investigation of major landslides in Hong Kong. An example of the results of the assessment is given in Figure 3. In the assessment, the Universal Distinct Element Code (UDEC) was adopted. The landslide debris was modelled as small discrete elements, amongst which sliding, impact and separation were allowed to take place. Energy losses through sliding, impact and viscous damping were also considered.

Alternatively, the travel distance of debris may be assessed by empirical methods by reference to actual field data. Given proper classification of the types of landslip, a quick and realistic assessment of the likely range of debris travel distance may be made. The empirical data may also be used for calibrating the input parameters and analytical results of single body models and those of numerical modelling.

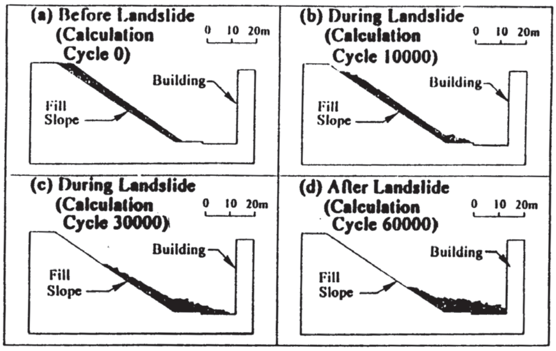

Figure 3. Numerical modelling of debris movement for a major fill slope failure in Hong Kong

Other approaches have also been adopted to assess the debris travel distance and the key parameters that affect the landslide motion, e.g. fixed frame and tilting

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frame model tests using blocks of wood to simulate a slope composed of rock mass were conducted by Aydan et al (1991). However, such laboratory investigations by means of small-scale models have not been attempted in Hong Kong.

5 FIELD OBSERVATIONS OF TRAVEL DISTANCE OF LANDSLIDE DEBRIS

Lantau Island, Hong Kong, was subjected to a severe rainstorm on 5 November 1993, with a maximum 24-hour rainfall in excess of 700 mm. Landslides occurred at about 250 soil cut slopes alongside roads and catchwaters. The large number of landslips provided useful information on the performance of these slope features under severe rainfall conditions, and permitted a systematic study of the characteristics and mechanisms of slope failure.

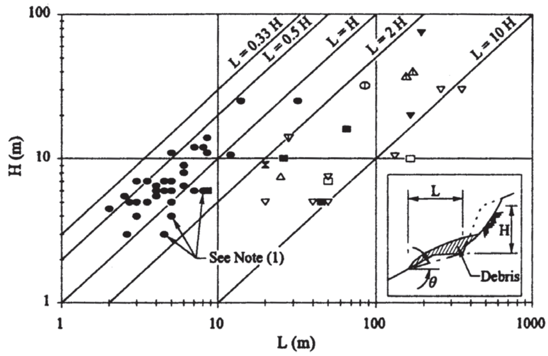
Accurate data on the profile and travel distance of debris were recorded for 42 landslides during the study. It was not possible to obtain reliable data on the travel distance of debris in the other cases because of the speed with which the debris had to be cleared to re-open the affected roads to traffic, disturbance of the debris by the action of surface water, or debris having been trapped in the catchwater. This emphasizes the importance of compiling a high-quality database of reliable field data to safeguard an assessment of debris travel distance with similar setting with reasonable confidence.

The relationship between the height of the cut face (H) and the travel distance of debris (L), as measured from the toe of the failed slopes, is shown in Figure 4(a). The landslides involved weathered volcanics and granite, as well as colluvial deposits which originated from these materials. The causes of the landslips were assessed, and a distinction made as to whether or not the failure mode involved wash-out action due to convergent surface water flow. In addition, the ranges of average angle of inclination (i.e. θ) of the area downslope of the cut face that failed have been grouped. Data from selected case histories elsewhere in Hong Kong with reliable documentary information on the landslip and debris travel distance have also been included in Figure 4(a) for comparison.

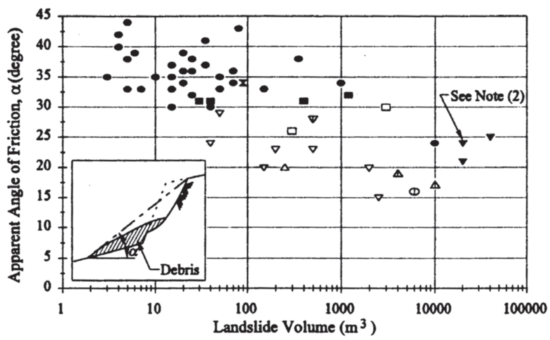
It can be seen from Figure 4(a) that :

(a) for typical rain-induced landslips involving mainly shallow (generally < 3 m) failure of the cut face with a relatively flat ground surface in front, i.e. θ within 5°, L is generally between 1/3 H and H, with a mean of about 0.7 H,

(b) if the landslip involves a substantial portion of the slope uphill of the cut face, such as in some of the failures of thin colluvium overlying weathered rocks caused by the development of perched water pressure at the interface, L could be as large as 1.5 H,



(a) Travel Distance (L) for Slopes with Different Height (H)



(b) Apparent Angle of Friction

Legend :

Mechanism of Failure	θ				
	< 5°	5° - 15°	16° - 25°	26° - 35°	> 35°
Typical rain-induced landslide	●		▼	■	⧗
Liquefaction of loose fill	⊕	▵ (dotted)	▿ (dotted)		
Wash-out by convergent water flow		△	▽	□	

Notes: (1) Landslides involving failure of a substantial portion of the slope uphill of the cut face.
(2) This is a natural slope failure involving channelised debris flow.
(3) Unbulked landslide volume is used.

Figure 4. Field data on travel distance

(c) large runout distance, of much larger than 2 H, is possible for landslips involving liquefaction of loose fill or wash-out action due to convergent flow of surface water, and

(d) runout distance exceeding 2 H is likely if the topography below the landslide location is steep (say, θ larger than 15°) .

The apparent angles of friction for the landslip cases, defined as the inclination of the line joining the far end of the debris to the crest of the landslide scarp, have been calculated. These are plotted against the landslide volume in Figure 4(b), in which the mode of failure is also indicated. It is noted from Figure 4(b) that :

(a) the apparent angle of friction for typical rain induced landslips involving small to medium-scale failure (viz. landslide volume < 2000 m^3), generally ranges from 30° to 40°,

(b) for landslips involving liquefaction of loose fill or wash-out action, the apparent angle of friction reduces to 15° to 30°, and

(c) the apparent angle of friction reduces with increase in landslide volume, irrespective of the mode of failure. The observed trend is generally consistent with observations reported by Hutchinson (1988).

As may be observed from Figures 4(a) & 4(b), the use of the apparent angle of friction to denote the travel distance of landslide debris appears to be less sensitive to the downslope topography than the use of L/H ratio.

In summary, for typical small to medium-scale landslides, the mean apparent angle of friction is about 35°, with a lower bound of 30°. However, there seems to be a trend of increase in the mobility of the debris with increasing landslide volume, and for large-scale failures, the apparent angle of friction could drop to about 20°. The mobility of the debris is also critically dependent on the failure mechanism. For landslides involving wash-out or liquefaction of loose fill, large runout distance corresponding to an apparent angle of friction of as low as 15° has been observed.

6 DISCUSSIONS AND CONCLUSIONS

It is suggested that the empirical approach developed by reference to actual landslide data and based on a proper classification of the modes of landslip and debris movement, as described in this paper, will offer a practical and realistic means for the assessment of the travel distance of landslide debris. The empirical data also constitute a valuable source of information for deriving realistic input parameters, for use in analytical approaches and for calibrating the results. This empirical approach is particularly useful for areas such as Hong Kong, where a large number of landslip data is available, or can be made available, from systematic field data collection.

The present study has highlighted some key factors that can have a profound effect on the travel distance of debris, namely the failure mechanism, extent of the uphill slope involved in the failure, downslope gradient and volume of failure. It is essential that due account is taken of these factors in analysing the observational data and applying the empirical approach. Otherwise, the scatter of the data could be so large as to render the outcome of future predictions of little practical value, or even misleading, when applied to landslide consequence or risk assessment.

The empirical assessment presented in this paper provides some preliminary correlations which can be readily used in a rational assessment of the likely debris travel distance in the event of failure of typical soil slopes in Hong Kong. It is cautioned that the data should not be extrapolated for application to landslide scenarios that are significantly different to those contained in the database.

Further work is required to extend the database by inclusion of further reliable and comprehensive landslide data covering different mechanisms of landslide and modes of debris movement. Given further efforts in careful collection and analysis of landslip data, a more extensive database can be built up, which will enhance the confidence in practical applications. When combined with an adequate understanding of the influence of the various key parameters, the empirical method of assessing debris travel distance can be further refined, and detailed guidelines on the prediction of debris travel distance can be formulated for application in landslide consequence assessment.

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