Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2539

Runout distance of gravitative debris flow

Distance coulée de flux gravitative de débris

K.T. Law & B.P. Paudel

Department of Civil and Environmental Engineering, Carleton University
1125 Colonel By drive Ottawa, Ontario, Canada K1S 5B6

ABSTRACT

The study in this research consists of a review of two case studies of landslides in natural terrain, parametric study, and a comparison of the computed and observed runout distances of a cluster of landslides. The study leads to the following conclusions. (1) The runout distance increases with the decrease of the angle of friction mobilized or with the increase in the natural terrain inclination. (2) When the natural terrain inclination is approaching the mobilized friction angle, the runout distance is independent of the initial landslide height and is dependent on the natural terrain inclination and debris characteristics. (3) The results of the parametric study have been compared to the observed runout distance of 28 debris flows and reasonable agreement has been obtained.

RÉSUMÉ

Cette étude consiste en une examination de deux études de cas sur des glissements de terrain sur du terrain naturel, une étude paramétrique, et une comparaison des distances coulées calculées et observées d'un groupe de glissements de terrain. Les conclusions en sont les suivantes : (1) La distance coulée augmente avec une diminution de l'angle de friction mobilisée ou avec l'augmentation de l'inclinaison du terrain naturel. (2) Lorsque l'inclinaison du terrain naturel s'approche de l'angle de friction mobilisée, la distance coulée est indépendante de la hauteur du glissement de terrain initial mais dépend de l'inclinaison du terrain naturel et des caractéristiques du débris. (3) Les résultats de l'étude paramétrique étaient comparés aux distances d'infiltrations observées de 28 flux de débris et un accord raisonnable a été obtenu.

1 INTRODUCTION

Landslides cause loss of lives and properties every year around the world. Records show that on an average 50 people lose their lives from landslides every year in the United States (Paula and Elliot 2001). In Canada, between 1840 to 1999, 570 people lost their lives due to landslides (Evans 2000). The impact is more serious in a poor and hilly country like Nepal, where landslide-monitoring system is primitive. In only one monsoon season of 2002, landslides killed 244 persons, displaced 9,063 families, and damaged 3,359 houses in Nepal (Nepal Red Cross Society 2003). The most disastrous form of landslide is debris flow. Hence, an ability to predict the initiation of debris flow and its runout distance in natural terrain is essential for preserving lives and property.

This study is aimed at predicting the runout distance of gravitative debris flows as a function of the various factors such as friction, cohesion, and natural terrain inclination. This has been carried out in several steps. First, by reviewing two landslides, one turned into a debris flow and the other did not, in colluvium of sand, gravel and boulders mixed with different types of fines, the appropriate model for assessing the runout distance is established. Second, the relationship between runout distance and friction and natural terrain inclination for such debris flows is examined through a parametric study. Finally, the study is applied to a cluster of debris flows caused by a single rainstorm event. The application yields a lower bound mobilized friction angle that leads to an upper bound runout distance for landslides in soils similar to those being studied.

2 BRIEF REVIEW

Debris flow formation is a complex process and has been a subject of much study. The research to highlight the importance of different factors in forming debris flows has been conducted by Blackwelder (1928), and , Iverson et al. (1997).

Similarly, many researchers have studied the prediction of runout distance of a debris flow. Voellmy (1955), Salm (1966) and Takahashi and Yoshida (1979) propose that the runout distance might be computed from energy and momentum conservation principles. Johnson and Rodine (1984) proposed that debris flowScould be predicted from the mobility index of sliding mass or historical records of the landslide prone area. O'Brien and Julien (1985) propose the continuum of flow regimes from viscous to turbulent or dispersive flow in their quadratic shear stress model (FLO-2D). Wong et al. (1997) suggest that the relation between the travel angle and the debris flow runout distance could be applicable for estimating runout distance for similar regions. Hungr (1995) proposes a dynamic analysis (DAN) by solving the hydrodynamic equations, which involved inertia, pressure and resistive terms.

Debris flow initiated from landslides (Iverson et al 1997) gives rise to gravitative debris flows as defined by Kang et al. (2003)

This research examines the applicability of some models for estimating the runout distance of two gravitative debris flows involving granular colluvium with some fines, the use of the selected model in a parametric study, and assessment of a cluster of gravitative debris flows.

3 THE TWO CASE RECORDS

The first case record is the Lei Pue Street landslide in Hong Kong that occurred during heavy rainfall at an upper part of a hill with a slope angle of 41^o. It consisted of an initial landslide that turned into a debris flow. The initial slide was 17m high, the volume of failure mass 250m^3 and the failure surface being in highly to moderately decomposed colluvium with a friction angle of 41^o and zero cohesion. The runout distance of the debris flow reached 282m.

The factor of safety of the initial slide calculated using Morgenstern and Price method at zero pore pressure, 41^o friction angle and zero cohesion is 1.08. With the pore pressure ratio (r_u defined as the ratio of the pore pressure to the total vertical stress in the failure mass) rising to 0.04, the factor of safety drops to 1. These calculations show that the stability of the initial slope was marginal.

The runout distance of this landslide debris flow is computed using friction and Voellmy rheology models in DAN (Hungr 1995). Appropriate parameters of soil behaviour for the models were estimated from existing literature for use with the models as described by Paudel (2004). The friction angle ϕ_m mobilized during the debris flow process is an important parameter that is hotly discussed in the literature (e.g., Tika and Hutchinson 1999). In this case, ϕ_m has been obtained from triaxial tests conducted on soft saturated debris samples taken from the field within 24 hours of the failure (Maunsell 2002). At this state the soil is considered to be remoulded and at the residual state. This ϕ_m was found to be 26^o. The computed runout distances are 235m and 120m using the friction model and the Voellmy model, respectively.

The debris mass movement was also modeled in the FLO-2D (O'Brien and Julien 1985) software. The debris flow simulation shows that there was no final deposition point within the debris flow surface, which implies that the runout distance is extremely long.

By comparing the computed results with the observed value in the field (282m), it is evident that the friction model in DAN produces the most agreeable result for assessing debris flows in this type of soil and therefore it is used in the parametric study in the next section.

The second case record is the Barabensi landslide in Nepal, a slow moving landslide. The general slope of the right side of the sliding area is about 34^o and on the left the slope is about 30^o. The slope heights of these two sides are 91m and 72m, respectively. The main slide mass is colluvium, which is boulder mixed with plastic silty clay soil.

The movement of the landslide was slow at about 1m or less per year. The landslide mass had moved about 1.5 m to 8 m at different locations since the landslide started to move. Joints are developed on the moving soil mass. The groundwater table in the slide area near the crown is relatively deep. Perennial seepage was found at the toe of the landslide mass, interfacing with bedrock. With zero pore pressure, 30^o friction and 6-kPa cohesion, the calculated factor of safety using Morgenstern and Price method was 1.08 in the right side (34^o) of the landslide slope. A pore pressure ratio of 0.07 was sufficient to reduce the factor of safety to 1.0 for this slope.

This landslide has also been analyzed using the friction model in DAN. The model does not show that the landslide mass would turn into a debris flow as the computed movements are only approximately 20 m for the right side of the slope and 18 m for the left side. These movements do not constitute a debris flow compared to the fairly large slope heights and are generally agreeable to the field observations.

Therefore this second case record supports the use of the friction model in DAN for assessing the occurrence potential of debris flows in this type of soil.

4 PARAMETRIC STUDY ON RUNOUT DISTANCE

Figure 1 shows a sketch of the profile of the landslide and the subsequent debris flow, and the symbols used in the study. In Figure 1, R is the runout distance of the debris flow, H the total height of natural terrain (including the height of the initial landslide) down to the horizontal ground, H_s the height of the initial landslide, θ the natural terrain inclination, and α the slope of the initial landslide, L the horizontal distance from the initiation point to the meeting point of the horizontal ground and the sloping terrain, L_s the initial landslide length, R' the modified runout distance of the debris flow (R'= (L-L_s)). The initial friction angle is denoted by ϕ_i, the mobilized friction angle by ϕ_m, and the pore pressure parameter by r_u. In this study the initial friction angle (ϕ_i) is used during landslide initiation and the mobilized friction angle (ϕ_m) during debris flow. The volume of the debris is 250 m^3 and the width of the debris trail is 15m. Table 1 shows the different combinations of parameters for the study.

The effect of cohesion is first studied. The results are shown in Figure 2, which show that cohesion is an important parameter. The runout distance drops rapidly with the presence of cohesion as small as 1kPa. Therefore debris flows are seldom found associated with soils with some cohesion. The second case record, the Barabensi landslide, is one such example.

Table 1 Summary of parameters for the study
*parameters being varied

S. N.	ϕ_i deg	ϕ_m deg	r_u	C kPa	α deg	θ deg	H m	H_s M	L m	L_s m
1	41	26	0.	*	41	25	933	17	2000	20
2	41	*	0.	0.	20	20	116	17	318	20
3	41	*	0.	0.	30	30	184	17	318	20
4	41	*	0.	0.	40	40	267	17	318	20
5	41	*	0.	0.	50	50	379	17	318	20
6	38	38	*	4	30	30	184	17	318	20
7	40	26	*	4	41	41	276	17	318	20
8	41	*	0.	0.	41	*	*	17	*	20
9	41	*	0.	0.	41	*	*	40	*	46
10	41	*	0.	0.	41	*	*	80	*	92

Figures 3 shows the relationship between modified runout distance and mobilized friction angle (ϕ_m) at natural terrain inclination (θ) ranging from 20^o to 50^o. The parameters for these cases are given in Rows (S.N.) 2 through 5 in Table 1.

The results show that for a given initial slide, the modified runout distance increases with increase in θ or decrease in ϕ_m. More specifically, debris flow will start to occur at θ substantially smaller than ϕ_m because of the conversion of potential energy into kinetic energy from the initial slide. For instance, the runout distance starts to take off at θ as low as 20^o for ϕ_m equal to 26^o.

Figure 4 shows the effect of the pore pressure parameter, r_u, on the runout distance with other parameters listed in S.N. 6 and 7. For the case of S.N. 6, there is hardly any runout distance as no debris flow occurs as computed with the model. This is due to the high assumed ϕ_m of 38^o and cohesion of 4 kPa. For the case of S.N. 7, where ϕ_m equals to 26^o, and cohesion of 4 kPa, the slope will only start to move significantly at r_u exceeding 0.25. Even for r_u reaching 0.5, the runout distance is still relatively low compared to the cases with zero cohesion and zero r_u. This also shows the significant effect of cohesion in reducing the runout distance.

Figure 5 shows the effects of initial slide height (H_s) on runout distance at different ϕ_m and θ and with zero cohesion and zero pore pressure. The data show that, besides the general relationship between runout distance and ϕ_m and θ as noted above, there is some relationship between runout distance and H_s. For the same ϕ_m and θ, the runout distance increases with H_s until θ approaches ϕ_m. Shortly before θ reaching ϕ_m, the runout distances for different H_s merge together and take off to very large values. Therefore beyond this point, the runout distance is no longer dependent on the initial landslide height.

5 APPLICATION TO A CLUSTER OF DEBRIS FLOWS

Approximately 800 landslides occurred in a single rainstorm event in Lantau Island, Hong Kong, between November 4 to 5, 1993. Some details of 56 of them have been reported by Wong et al. (1996). Among them, 28 developed into debris flows. All the landslides were shallow, most being less than 3m thick. Most of the landslide masses were composed of young colluvium consisting of sand, gravel, cobbles and boulders mixed with silt. The young colluvium overlay old colluvium or saprolitic soil. The source length varied from 6m to 40m and the width varied from 3m to 20m. The height of the initial slides ranged from 3.4m to 30m with an average of about 16.7m.

The runout distance of the debris flow was influenced by the size of the catchment area just above the landslide scarp and temporary drainage and permanent drainage outlets near the debris flow surface. These drainages provided more water that could mix with the landslide mass traveling downslope. This could change the mobilized friction angle and the fluidity of the debris. Consequently, Wong et al. (1996) further classified these gravitative debris flows into three groups in order of fluidity: hydraulic, mixed and gravitational.

Since the runout distance no longer depends on the initial landslide height at natural terrain inclination approaching the mobilized friction angle ϕ_m, and since the average H_s is approximately equal to 17m, the runout distances of these 28 debris flows have been plotted on Figure 6 for comparison with the computed values using DAN with H_s of 17m. The values of ϕ_m range from 20^o to 40^o. The cohesion and pore pressure are all zero. The comparison shows the following:

a) The ϕ_m values are different in the different groups of debris flow. The ranges of values are 20^o to 35^o, 34^o to 38^o and 35^o to 40^o for the hydraulic, mixed and gravitational groups, respectively.
b) It appears the use of ϕ_m of 26^o can provide an upper bound estimate of the runout distance for this type of soil under the given climatic conditions and slope geometry.

6 CONCLUSIONS

In this research, landslide initiation and the runout distance of debris flow are studied. Two different landside case records are analyzed; a parametric study on runout distance is conducted; and a cluster of debris flows is examined. The study shows the following:

a) Both case records involved granular colluvium but with different degrees of fines content. Both were at marginal state of stability and failed during rainfall or in the wet season.
b) The colluvium in the first case, the Lei Pue Street landslide, has small fines content such that the cohesion is zero and the initial slide turned into a debris flow.
c) The colluvium in the second case, the Barabensi landslide, possesses some cohesive fines and the initial slide did not turn into a debris flow.
d) Application of the friction model in DAN (Hungr 1995) to both cases reveals correctly that the first case would turn into a debris flow and the second would not. The model also gave a computed runout distance agreeable with field observation.
e) Other models, the Voellmy model in DAN and FLO-2D, were found not to produce agreeable runout distance for the first case study.
f) The friction model of DAN has been applied to a parametric study on runout distance. The study reveals the various effects on runout distance of parameters including cohesion, pore pressure, initial landslide height, natural terrain inclination and mobilized friction angle. Of particular interest is that cohesion has a substantial effect on reducing runout distance; the runout distance increases with the decrease of the mobilized friction angle or with the increase in the natural terrain inclination; and when the mobilized friction angle approaches the natural terrain inclination the runout distance becomes very large and independent of initial landslide height.
g) Field observations on 28 landslide-induced debris flows caused by a rainstorm event are compared with the estimated values. The comparison shows that a mobilized friction angle of 26^o provides an upper bound estimate of the runout distance from all the different groups of gravitative debris flows involving granular colluvium.

ACKNOWLEGEMENTS

The authors would like to acknowledge the support for this study by the Natural Science and Engineering Council of Canada. The DAN software was provided for use in this study by the Geotechnical Engineering Office, Hong Kong SAR Government.

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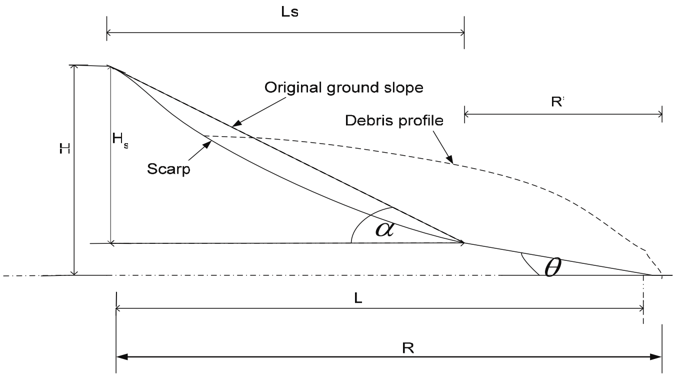

Figure 1 Definition of terms for the geometry of the slope

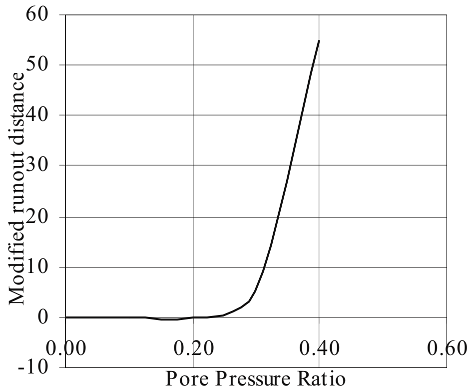

Figure 4 Modified runout distance vs pore pressure

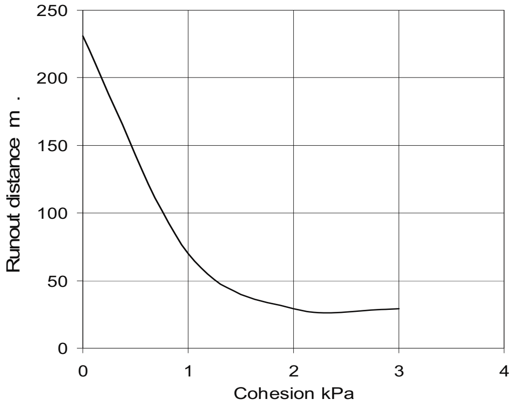

Figure 2 Runout distance vs cohesion

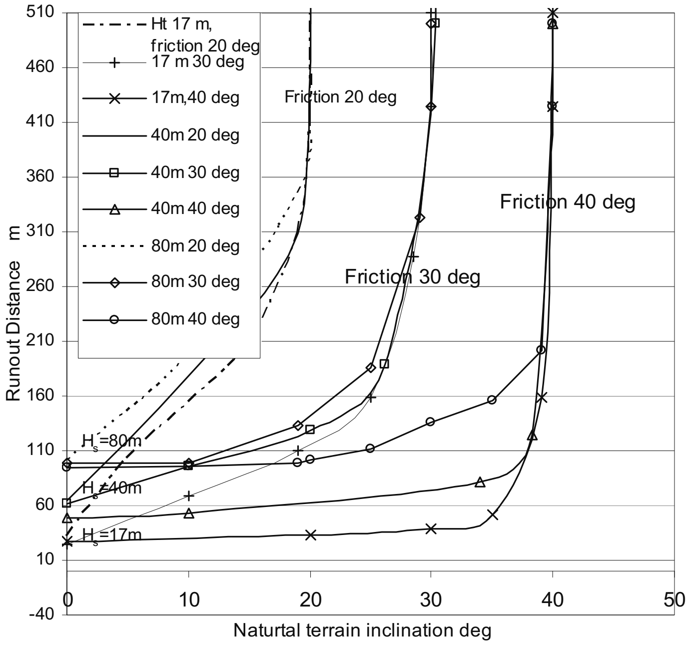

Figure 5 Runout distance vs natural terrain inclination for H_s=17m, 40m, 80m

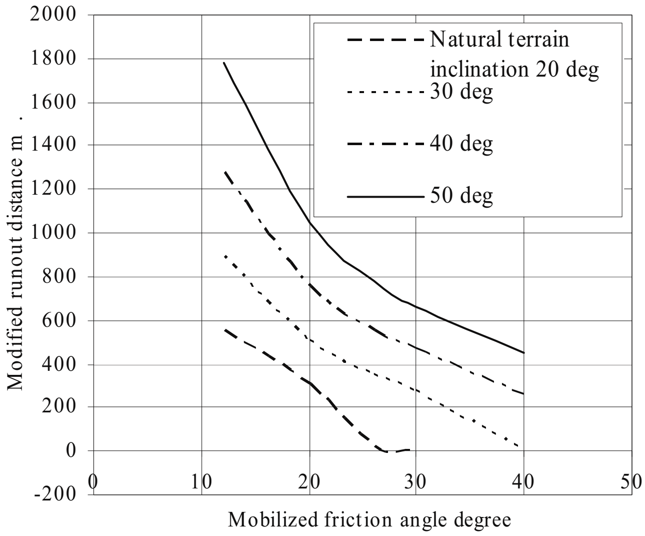

Figure 3 Modified runout distance vs. ϕ_m, θ

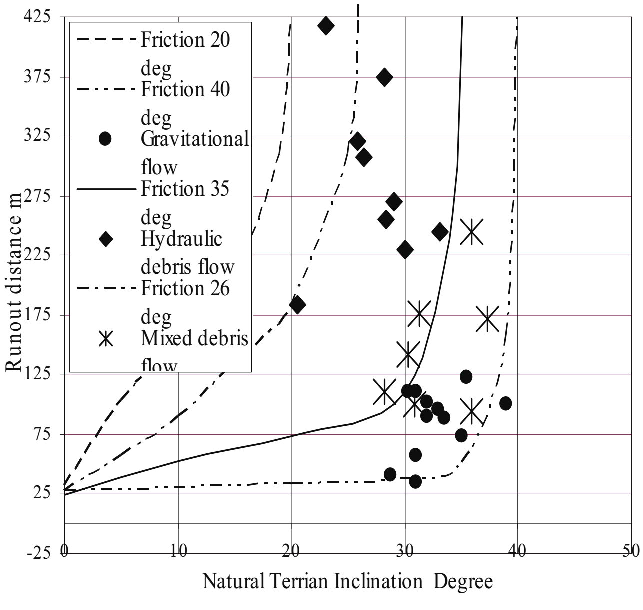

Figure 6 Comparison of observed and estimated runout distances of the November 1993 debris flow on Lantau Island H_s =17m