

# Prediction of landslide run-out distance based on slope stability analysis and center of mass approach

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**Abstract.** Mitigation of landslide hazard requires the knowledge of landslide run-out distance. This paper presents the application of slope stability analysis and center of mass approach to predict the run-out distance of a rotational landslide model with different soil types. The Morgenstern-Price method was used to estimate the potential sliding zone and volume of landslide material. The center of mass approach used a simple Coulomb friction model to determine the run-out distance. Results of the slope stability analysis showed that the soil unit weight can influence the depth of sliding zone, and the volume of unstable material. The slope model of silty sand and gravel would have the largest volume of unstable mass. From the Coulomb friction analysis, this slope model has higher run-out distance and velocity than other slope models. Thus, the run-out distance will be influenced by soil type and the dimension of unstable soil mass.

## 1. Introduction

Knowledge about physical properties, mechanism and behavior of landslide is essential for hazard mitigation and risk assessment. Analyses of run-out and slope stability are some important parameter in landslide risk assessments. Landslide-related case studies, theories, and technology advancement have been reported in journal articles, conference proceedings as well as books. One of the analytical theories related to the landslide is the slope stability which based on relationship between driving force and resisting force. The driving force acts on the landslide material in downslope movement which depends on gravity, slope angle, slope material, and water. On the other hand, the resisting force acts oppositely of driving force which depends on shear strength of the slope material. The ratio between the resisting forces to the driving forces is one way to define the safety factor in a force equilibrium analysis [1]. Prediction of landslide run-out distance has also been one of the significant topics in the research field. Currently there are several ways to analyze run-out distance using dynamic models; one of them is center of mass (COM) approach. Prediction of run-out distance using dynamic models has been applied in 2D [2, 3] and in 3D [4, 5] and also statistical analysis [6]. Some researchers [6, 7, and 8] have mentioned that the correlation between volume of landslide material and travel distance is linear. There are several commonly used methods to analyze run-out distance, e.g., the COM method, the end of deposit method [2] and cone fall method [5]. Hungr [4] and Devoli [6] analyzed the run-out distance from initial height higher than 10 m. The aim of this paper is to estimates the run-out distance

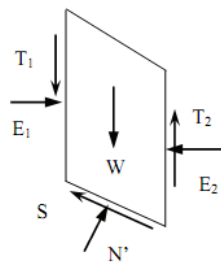


of rotational landslide in the slope model with initial height less than 10 m. In this model, two soil layers of different type are used to find the influence of soil type to the run-out's parameters (apparent friction angle, travel distance, friction coefficient).

## 2. Methods

### 2.1. The Morgenstern-Price Method

There are several methods to determine slope stability. One of the most commonly used methods is the Morgenstern-Price Method (MPM) which firstly proposed by Morgenstern and Price [10]. This method is based on the summation of tangential and normal forces to the base of a slice and the summation of moments about the center of the base of each slice. The relationships for the base normal force ( $N$ ) and inter-slice forces ( $E$ ,  $T$ ) are shown in figure 1.



**Figure 1** Force diagram of inter-slice forces in Morgenstern-Price method [1]

where  $W$  is the weight of a slice,  $S$  is the shear mobility force (friction) on the base of each slice,  $T$  is the vertical inter-slice shear forces,  $E$  is the horizontal inter-slice normal forces, and  $N$  is the total normal force on the base of a slice. The expression of safety factor ( $F$ ) in terms of force ( $F_f$ ) and moment equilibrium ( $F_m$ ) are given as follows:

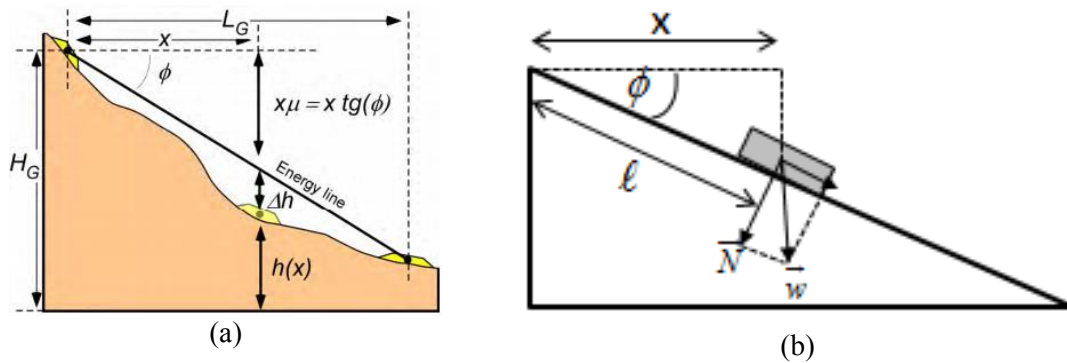
$$F_f = \frac{\sum \left[ \left\{ c' l + (N - ul) \tan \phi \right\} \sec \alpha \right]}{\sum \left\{ W - (T_2 - T_1) \right\} \tan \alpha + \sum (E_2 - E_1)} \quad (1)$$

$$F_m = \frac{\sum \left( c' l + (N - ul) \tan \phi \right)}{\sum W \sin \alpha} \quad (2)$$

where  $c'$ ,  $\phi$ ,  $\alpha$ ,  $l$  is cohesion, friction angle, inclination of slip surface, and slice base length respectively in effective stress terms of each slice base.

### 2.2. Center of mass (COM) approach to predict run-out distance

In this study, we combine the COM approach with the end of deposit method to predict the run-out distance of landslide material which also characterized by the slope stability analysis. Landslide movement can be determined using a simple geometric rule known as energy budget calculation from starting point based on a simple Coulomb frictional model as implemented in this study. This principle was modified and applied without volume dependency. The detail about this approach can be seen in figure 2a. The variables used to calculate velocity and run-out distance are  $H_G$  (the altitude of COM of the starting zone),  $h(x)$  (the altitude of the topography at the distance  $x$  from the start zone),  $m$  (the mass),  $\mu$  (the friction coefficient),  $\phi$  (the internal friction angle), and  $L_G$  (the deposit distance from starting zone).



**Figure 2.** (a) Variables used to calculate velocity and energies based on the energy line concept [11]. (b) A simple Coulomb friction model

In simple Coulomb friction model (figure 2b), the friction is proportional to the normal force  $N$  which also related to the weight  $w$  by:

$$|\vec{N}| = |\vec{w}| \cdot \cos(\phi) \quad (3)$$

and the energy loss by friction is given by,

$$\mu = \tan(\phi) \quad \cos(\phi) = \frac{x}{l} \rightarrow l = \frac{x}{\cos(\phi)}$$

$$E_f = \mu |N| l = \mu m \cdot g \cos(\phi) \cdot \frac{x}{\cos(\phi)} = m \cdot g \cdot x \cdot \tan(\phi) \quad (4)$$

Hence, the balance of energy at point  $x$  of landslide from an elevation  $H$  is given by [2]:

$$mg(H - h(x)) = \frac{1}{2} mv_x^2 + mgx \tan(\phi) \quad (5)$$

Velocity expression for any  $x$ -position can obtained from equation (5):

$$\frac{1}{2} mv_x^2 = mg(H - h(x) - x \tan(\phi)) \rightarrow \text{Let: } \Delta h(x) = (H - h(x) - x \tan(\phi))$$

$$v(x) = \sqrt{2g\Delta h(x)} \quad (6)$$

where  $g$  is gravity acceleration and  $v(x)$  is the velocity at point  $x$ .

Rearranging equation (5) to estimate the stopping point horizontal distance (run-out distance)  $x_{stop}$  by selecting  $v(x) = 0$ , and using  $\mu = \tan(\phi)$ , we obtain the expression of run-out:

$$L = x_{stop} = \frac{H_G - h(x_{stop})}{\tan(\phi)} \quad (7)$$

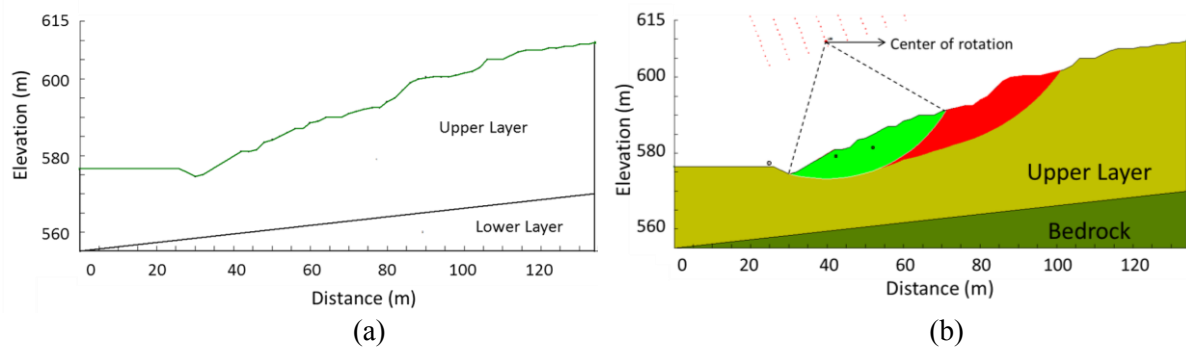
In general form, the equation (7) can be simplified as,

$$L = \frac{H}{\tan(\phi)} \quad (8)$$

### 2.3. Soil Layers Model

Safeland [12] generally classified run-out model for landslide hazard and risk mapping into two main models, i.e., empirical models and rational models. In rational model there are sub-models such as a continuum models (3D models based on mixture theory, velocity-pressure models, depth integration model) and a discrete models, where in this study we used the discrete models. The soil layers model

was constructed based on the assumptions that there are two different layers. The first one is the upper layer which is an unstable zone that acts as sliding mass and the second one is the lower layer which is the stable zone and more consolidate than upper layer. In this study, it is assumed that each layer is composed by homogeneous soil type, and the slip surface is assumed circular which is suitable to be used in the MPM. The difference of soil type is indicated from unit weight/bulk weight ( $\text{kN/m}^3$ ). The elevation model is based on an unpublished work which varies between 576 m a.s.l at the toe and 610 m a.s.l at the top (figure 3a). After the model was constructed, the parameters are then used (bulk weight, cohesion, angle of shearing) in measuring the safety factor using MPM to obtain the most critical safety factor. In figure 3b, green indicates the slide mass and red indicates the safe zone.



**Figure 3.** (a) Slope model used in the slope stability analysis. (b) The detailed model depicting the center of rotation. The upper layer is composed by homogenous soil type.

### 3. Results and Discussion

#### 3.1 Safety factor analysis

The unit weight of soil type used in this study is based on an existing geotechnical data and the parameters to determine the safety factor such as angle of shearing is assumed constant and the variation of the cohesion is used to obtain the most critical factor (see table 1). Using model in figure 3 (b), the prediction of run-out distance as well as the velocity can then be carried out.

**Table 1.** Parameters used in the safety factor analysis

Parameters	Units	Soil type (upper layer)		
		(a) silty sand	(b) sand, dense, uniform	(c) silty sand and gravel
Total Volume	[m <sup>3</sup> ]	267.290	267.290	308.150
Total Resisting Moment	[kNm]	48.887	57.856	$1.19 \times 10^5$
Total Activating Moment	[kNm]	45.020	55.765	$1.14 \times 10^5$
Total Resisting Force	[kN]	1196.900	1418.200	2350.200
Total Activating Force	[kN]	1102.400	1367.100	2240.500
Unit Weight $\gamma$	[kN/m <sup>3</sup> ]	13.91	17.23	24.5
Angle of Shearing	[°]	10	10	10
Cohesion	[kPa]	15	17	25
Safety factor	-	1.086	1.037	1.049

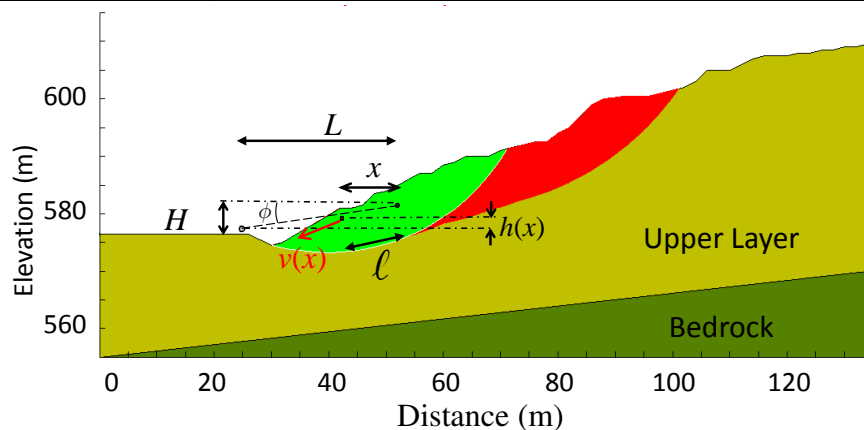
Based on model in figure 3 and the corresponding parameters in table 1, the volume of the landslide material of soil type (a) and (b) are equal and smaller than soil type (c). The results show that the unit weight is strongly affects the slope stability: the heavier unit weight is associated with the greater driving force.

### 3.2 Run-out prediction

Based on figure 3 (b), the center of mass position of the green zone can be estimated. The center of mass is then applied on the simple Coulomb friction model to predict the landslide run-out. The parameters used in the run-out analysis are listed in table 2. Figure 4 visualize the run-out analysis, and the prediction of run-out distance as well as the velocity can also be obtained from these images.

**Table 2.** Parameters used in the run-out analysis and the calculated results ( $L$  and  $v$ ).

Soil Type of Upper Layer Model	Fall of Height ( $H$ )	Friction Angle ( $\phi$ )	Friction Coefficient ( $\mu$ )	Run-out ( $L$ )	Velocity ( $v$ )
(a) Silty Sand	4.6 m	$10^\circ$	0.176	26.09 m	3.08 m/s
(b) Sand, dense, uniform	3.5 m	$13^\circ$	0.141	24.90 m	2.47 m/s
(c) Silty sand and Gravel	5.4 m	$13^\circ$	0.141	38.42 m	4.59 m/s



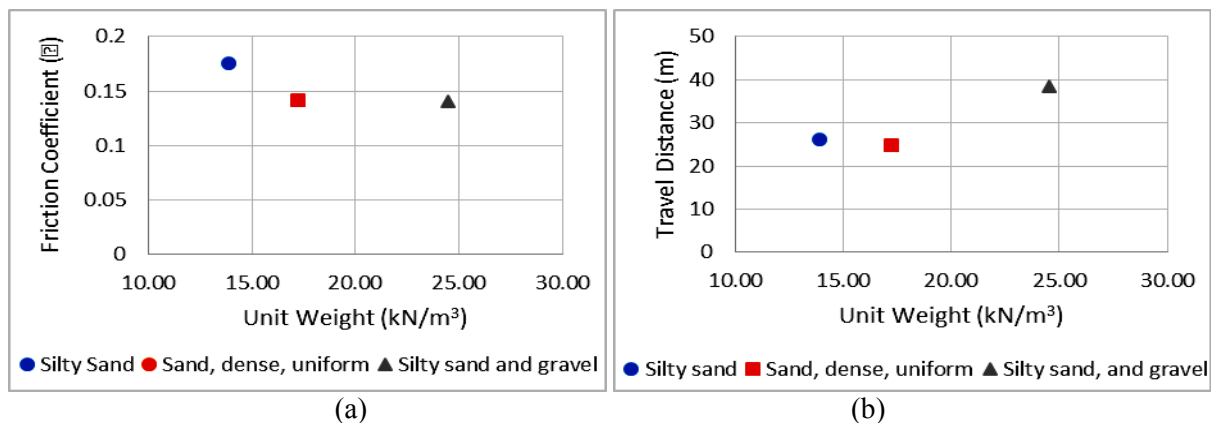
**Figure 4.** Geometrical parameters used in run-out and velocity analysis.

Based on table 2, soil type (a) and (b), the predicted run-out distance are equal but smaller than type (c). However, these results depend on the determination of center of mass position. From these results, the slide mass of third soil type is larger than the other ones, which can cause greater damage to the surrounding environment. From calculation of the run-out distance, it is predicted that the third soil type can reach further than the other ones about 38.42 m from the initial point of center of mass.

This center of soil mass is predicted to reach velocity of 4.59 m/s, which is faster than other soil types. Soil type of silty sand at point  $x$  is predicted to reach velocity about 3.08 m/s and soil type of sand, dense, uniform at point  $x$  is predicted to reach velocity about 2.47 m/s. These predictions of the velocity are considered very low compared to the results from several previous researches [3, 4]. This might be caused by initial height of center of mass which is lower than 10 m and other parameters such as apparent friction angle and friction coefficient. However the results indicate that unit weight is influence velocity and run-out distance. The correlation between unit weight and run-out's parameters are shown in figure 6. Based on figure 6a, friction coefficient ( $\mu$ ) will decrease when unit weight ( $\gamma$ ) increase, it is consistent with the previous results [6, 7, 8, 9]. From figure 6b, we find that heavier landslide material produce larger value of the run-out distance.

### 4. Conclusions and future work

From the analyses, we can conclude that soil type and the dimension of unstable soil mass can influence run-out distance ( $L$ ) of rotational landslide in the soil slope model which the biggest of unit weight and the largest of volume of unstable soil mass in this study (silty sand and gravel) has higher velocity and further run-out distance than the other soil type.



**Figure 5.** The correlation between parameters (a) unit weight and friction coefficient; (b) unit weight and travel (run-out) distance.

The analyses above are based on the situation where a failure occurs caused by a certain value of cohesion which produces the most critical safety factor, and the approaches used in this study could not estimate the distribution of landslide material. Future work will use geotechnical analysis (laboratory test) to obtain actual data of physical properties of soils. We also devise a research plan to predict the deposit distribution and to estimate the instantaneous velocity of the landslide movement from the beginning of the slide until it is fully deposited.

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