A Mathematical Model for the Determination of Debris Deposition Magnitude by a Landslide

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ABSTRACT
The landslide hazard area is not only where it starts but also where its debris deposits. A model is required for the determination of the extent of its deposition. A mathematical model is proposed based on the debris flow concept for the sizing a landslide deposition and it examined for the Seymareh landslide (Seimareh in some other literatures). Seymareh landslide was occurred in the mountainous area of Zagros range in west of Iran in 11000 years ago. The dynamic characteristics of the Seymareh landslide are discussed in this paper. Possible dynamic of the landslide was deliberated based on the limited available data. The landslide triggered from the sharp slope of mountain and its debris progressed kilometers on the inverse mild slope of the plain. A mathematical model is proposed to simulate dynamic and deposition of the debris of the landslide on inverse slope. The model is applied to simulate deposition of debris flow on Seymareh syncline. The result of model denotes that the size of simulated deposition is close to observed one in the Seymareh landslide. Therefore, the capability of the proposed mathematical model is proven by comparing to field data.

Keywords: Mathematical Model, Seymareh Landslide, Zagros Range, Seimareh, Iran, Debris Deposits.

1. INTRODUCTION
Landslides are widespread occurrence in sharp lands of Zagros range, in the west of Iran. Field evidences show a large mass movement in the Seymareh area and Harison and Falcon (1936-8) regarded it as a landslide. Seymareh area is a part of the mountainous area of Zagros range in west of Iran. Harrison & Falcon assessed the volume of the initial landslide of Seymareh as 20 Gm³ has been mentioned in recent papers (e.g. Legros 2002; Hancox & Perrin 2009). About 38 Gm³ of initial rock slid in the Seymareh area. In this regard, it may be considered as one of the largest non-volcanic landslide in the world (Roberts and Evans, 2013). Roberts and Evans (2013) stated the Seymareh Landslide as a rock avalanche which can be questionable its travel-distance as long as 12 on an inverse slope in the absence of water. Therefore, in this paper, its dynamic is examined as debris flow.

Sharp slopes of mountain can slide and creep during storms or sudden melting of snow. In some literature, the phenomenon mentioned as debris slides and rock avalanche. Debris slides are the movement of relatively unconsolidated soil that contains of various kinds of rock rubbles and the other fine earth material. They are usually unsaturated and what distinguished then from debris avalanches is the fact that they have a lower moisture content (Mainali & Rajaratnam 1991). As the material travels down the slope, it accumulates moisture and gets saturated, the ratio of water volume to solid volume rises. In these conditions, it is named debris flow or mudflow (Swanson, 1971 and 1974). Hirano and Moriyama (1993) explained different condition for the occurrence of debris flow. Debris flow occurs on a sharp slope when the soil of the slope is saturated and surface flow appears due to heavy rainfall. Hirano and Moriyama (1993) showed that debris flow will happen when rainfall exceeds a definite value determined by the hydraulic, geological and topographic properties of the slope. Occurrence of debris flow may have various explanations, but after it starts moving, it may be considered as high-concentration flow (Banihabib, 1997). The olumetric concentration of solids in it may exceed 50% (Banihabib, 1997). The high-concentration of fine material increase bulk density of fluid and hence it may carry large stone easily. Many cases have been described that debris flow transported rock blocks up to 1500 cubic meters in size in Tajikistan (Maslov, 1987).
Debris flow flashes down the sharp slope and slow down on a mild slope or inverse slope. Slowing of debris flow on the mild slope or the inverse slope causes deposition of debris. Banihabib (1998) discussed a mathematical model for two-dimensional simulation of debris deposition. Probably the Seymareh landslide occurred between 8710 and 9800 years BP (Roberts and Evans, 2013). It is impossible to get the accurate data that the two-dimensional model need for simulation. In this paper, another model is proposed to determine size of deposition. The model needs a few data to predict the size of the deposition area, and it can be applied for Seymareh area.

2. THE STUDY AREA

First, the geography and geology of Seymareh area is described to have an image of the study area (Shoaei and Ghayoumian, 1997). The study area is in the southeast part of Lorestan Province, at 33° 0’ to 33° 15’ latitude and 40° 30’ to 40° 40’ longitude. The area is bounded by Kabirkuh anticline in South, Dughfurush and Kuh-i-Maleh anticline in North. The study area is part of Seymareh basin. The Seymareh basin is a syncline which Kashkan and Seymareh rivers flow it along aforementioned anticlines. Asmari Limestone of Dughfurush and Kuh-i-Maleh forms northeastern and northwestern walls of the syncline. Kuh-i-Maleh anticline is composed of a series of marl and shale formations. The highest scarps of the anticline are Asmari Limestone. The syncline consists alluvial on Fars series. The Cretaceous limestone of Kabirkuh anticline is the base of southern bound of the syncline. On the flank of Kabirkuh anticline lays a zone of layers in which the upper Cretaceous-Eocene marly body has been more rapidly weathered away. The upper layer of Kabirkuh anticline is weathered Asmari Limestone. The upper layers of the limestone are weathered and may be saturated by longtime storm. In this condition, probably the big landslide had happened.

3. MATERIALS AND METHODS

Mechanism of Seymareh Landslide is explained to clarify how it could be started about 11800 years ago. Rainfall could infiltrate weathered material on sharp slope of Kabirkuh anticline. It is difficult to say the degree of saturation of the material just before landslide. The saturation ratio depends on duration of rainfall and meteorological condition. Field observation shows that the toe of the sharp slope of Kabirkuh anticline scoured by river flow. A sharp slope has less stability when its toe is cut. Regarding these facts, two cases are possible. The first possibility is that duration of rainfall was enough long to saturate upper layer of sharp slope and to have surface flow. Cutting of the toe of sharp slope made instability and landslide started. The second possibility is that saturation of material and cutting of the toe was not sufficient to make instability and earthquake caused instability. Then, landslide is initiated. After landslide started and the material flowed down the slope, it gathered moisture and got saturated. Then the ratio of water volume to solid volume gradually increased and soil movement changed to debris flow.

The dimensions of the deposited are described to provide field data for comparison by the proposed model. Roberts and Evans (2013) appraised the debris volume of Seymareh landslide as 44 Gm³ which it initialized from about 38 Gm³ of initial rock. The plan of the landslide is drawn based of stereoscopic study of aerial photos and field investigation (Fig 1). A slid with length of 5000m and width of 16000m moved down sharp slope of Kabirkuh anticline (Shoaei and Ghayoumian, 1998). The thickness of slide varies from 300m to 400m. The average angle of the slope is 18°. The mass of slid moved down and changed to debris flow by getting moisture. It crossed Seymareh River and transported debris more than 12000m. The average width of deposited area is about 18000m. In debris flow direction, the Seymareh syncline has inverse slope of about 3°. The deposited materials are loamy material with inclusions of crushed rock and large rock fragment.

4. RESULTS AND DISCUSSION

4.1. THE FEATURES OF SEYMAREH LANDSLIDE

Since thousands years have been passing from Seymareh Landslide occurrence, limited characteristics of it may be investigated. However, data and evidences can be described and discussed in three classes: Geography and geology of the area, Mechanism of the landslide, Dimensions and the material of the landslide. The most part of investigation for collecting data has been done by field study and examining possible conditions of the landslide.

4.2. THE PROPOSED MODEL

As a debris flow leaves sharp slope and come into inverse slope, it reduces speed and deposits debris. Debris flow parameters may change in three directions. Thus, debris flow should be considered as a three-dimensional phenomenon. But, since accelerated flow by sharp slope debris flow has dominant velocity in the sharp slope direction, it usually extents in that direction and variation of flow parameter may be ignored in vertical and transversal directions. Also, debris flow accelerates in the direction of sharp slope. In the case, one-dimensional model may be used to apply model practically.
The process of the debris flow on an inverse slope is shown schematically (Fig 2). Debris flow may be defined by a velocity in slope direction and depth when it leaves sharp slope. On the inverse slope, flow depth varies in flow direction. Thus, it may be modeled by trapezoidal shape.

The control volume of I-II is used for the study of momentum balance (Fig 2). Upstream bound of control volume is the vertical line on the point of slope variation. Using the control volume, conservation of mass may be expressed as:

\[
\frac{d}{dt} \left[ \frac{h + h_f}{2} x B_d \right] = u_s h_s B_s
\]

or,

\[
\frac{h + h_f}{2} x B_d = u_s h_s B_s t
\]

where \( t \) is time, \( h \) is depth of flow, \( h_f \) is depth of front of a debris flow front, \( x \) is distance traveled by the debris flow, \( B_d \) flow width on inverse slope, \( u_s \) is flow velocity at upstream of the change slope, \( h_s \) is flow depth at upstream of the change slope, \( B_s \) flow width on at upstream of the change slope.

The accumulation of mass within the control volume equals to mass entering inverse slope (Equation 1). The rate of accumulation of momentum within the control volume equals to summation of net rate of momentum entering control volume and the result of forces acting on control volume. The conservation of momentum may be expressed as:
\[
\frac{d}{dt} \left( \frac{h + h_r}{2} \rho u B_d \right) = \rho q_{i} B_d u_{i} \cos (\theta_{i} + \theta_{d}) - \frac{h + h_{r}}{2} x B_d \rho g \sin \theta_{d} + \frac{1}{2} \rho g h_{i}^2 \cos \theta_{i} \cos (\theta_{i} + \theta_{d}) - \rho \frac{u^2}{\phi} x B_d.
\]

where the left-hand side of Equation (3) is rate of momentum accumulation in control volume, the first term of the right-hand side expresses the input of momentum to control volume, the second is force due gravity, and the fourth is the friction at the bottom; \(u\) is flow velocity on inverse slope, \(\rho\) is apparent density of debris flow, \(q_{i}\) is debris flow discharge per unit width, \(\theta_{u}\) is slope angle of upstream channel, \(\theta_{d}\) is slope angle of downstream channel, acceleration due gravity, \(\phi\) is flow velocity coefficient of debris flow and it is defined as:

\[
\phi = \frac{u}{u_{*}}
\]

Substituting Equation (2) in Equation (3) one obtains:

\[
\frac{d}{dt} \left( u_{*} B_d \rho u t \right) = \rho q_{i} B_d u_{i} \cos (\theta_{i} + \theta_{d}) - u_{*} B_d \rho g \sin \theta_{d} + \frac{1}{2} \rho g h_{i}^2 \cos \theta_{i} \cos (\theta_{i} + \theta_{d}) - \rho \frac{u^2}{\phi^2} x B_d.
\]

or,

\[
\frac{du}{dt} + u = \frac{\rho q_{i} B_d u_{i} \cos (\theta_{i} + \theta_{d})}{\rho u_{*} B_d} - u_{*} B_d \rho g \sin \theta_{d} + \frac{1}{2} \rho g h_{i}^2 \cos \theta_{i} \cos (\theta_{i} + \theta_{d}) - \rho \frac{u^2}{\phi^2} x B_d.
\]

Using quasi-steady assumption and Equation (2), Equation (6) may be written a:

\[
\frac{du}{dt} + u = \frac{u_{*} \cos (\theta_{i} + \theta_{d})}{t} \left[ 1 + \frac{g h_{i} \cos \theta_{i}}{2 u_{*} B_d} \right] - 2 g \sin \theta_{d}.
\]

This differential equation may be integrated as:

\[
u = \frac{u_{*} \cos (\theta_{i} + \theta_{d})}{t} \left[ 1 + \frac{g h_{i} \cos \theta_{i}}{2 u_{*} B_d} \right] - 2 g \sin \theta_{d}\]

The distance traveled by the debris flow may be determined by integration of Equation (8) as:

\[
x = -\frac{1}{2} g \sin \theta_{d} + u_{*} \cos (\theta_{i} + \theta_{d}) \left[ 1 + \frac{g h_{i} \cos \theta_{i}}{2 u_{*} B_d} \right] t.
\]

The maximum distance traveled by the debris flow may be determined using following condition:

\[
x = \frac{u_{*} \cos^2 (\theta_{i} + \theta_{d})}{4 g \sin \theta_{i}} \left[ 1 + \frac{g h_{i} \cos \theta_{i}}{2 u_{*} B_d} \right]^2.
\]

The maximum distance traveled by a debris flow is determined by Equation (11). Since deposited area may be estimated as same as flow area, Equation (11) may be used to determine the length of deposition area.

4. 3. DETERMINATION OF DEBRIS DEPOSITION MAGNITUDE

Equation (11) is used to estimate length of debris flow deposition area in Seymareh. The parameters of right side of Equation (11) should be estimated. The angles of upstream and downstream slopes are estimated as 18° and 3° by using Topographical map of the area, respectively.

The thickness of debris flow in sharp slope of Kabirkuh anticline can be estimated as 350m based on field observation. The velocity of debris flow in sharp slope may be estimated by Equation (4). The velocity coefficient is estimated by using the field data of observed debris flow (Banihabib 1996).

Therefore, the length of deposition area is estimated by Equation (11) as 12165m. The estimated length of deposition area is close to length of deposition in Seymareh area.

5. CONCLUSION

A possible mechanism of occurrence of landslide in Seymareh area is discussed and explained that after starting landslide, it may change to a debris flow. A
One dimensional model is proposed for stoppage of debris flow on the Seymareh syncline. The proposed model is practical and requires a few data to simulate deposition of debris flow and it is proper for landslides which a few data is available. The simulated area of deposition is close to observed one in the field. It may be concluded that the proposed model is proper to determine deposition of landslide in similar case.

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