A study of a flowslide with significant entrainment in loess areas in China

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ABSTRACT: Flowslides are a frequent type of natural disaster in loess areas and may result in the significant loss of properties and/or casualties. The Dagou flowslide is a typical event in a loess area and is accompanied by significant sediment entrainment. To analyze the mechanisms responsible for flowslides and to obtain the parameters for a run-out analysis, a field investigation was conducted. Specimens were sampled on site to carry out laboratory tests, including a triaxial test, sieve analysis, and chemical component analysis. The parameters were used in the runout study employing an energy-based runout model. An analytical entrainment model was adopted to calculate the entrainment after considering physical properties and the mechanism of the entrainment process of the loess. Finally, the entrainment model was incorporated into the runout model to simulate the post-failure process of this case. Energy dissipation due to the deformation of slices was considered as it was thought to be important for a slide with a significant deformation. The simulation results were compared with the measurements, including runout distance, total volume, erosion depth, deposition height at different sections, and velocities at specific locations. The results indicate that the energy-based runout model, together with the entrainment model, can capture the kinematic characteristics of the Dagou flowslide. Therefore, it is feasible to use this model to predict the runout characteristics of flowslides in similar areas. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: flowslide; loess; entrainment; numerical modeling; energy-based runout model

Introduction

Flowslides in loess area are among the most catastrophic of geological and geomorphological processes, causing great fatalities and serious casualties as well as significant economic losses in the Chinese Loess Plateau (Zhang et al., 2013; Zhang et al., 2014). This can be attributed to their high velocity, long run-out distance, and high frequency of occurrence. Most are triggered by rainfall, climate change, and earthquakes, as well as human activity, such as irrigation, slope excavation (Wang et al., 2014b; Xu et al., 2014). Once they occur, these flowslides are more catastrophic (Wang et al., 2015). For example, the Haiyuan earthquake-induced loess landslides killed more than 100,000 people (Close and McCormick, 1922; Huang, 2009; Picarelli, 2010).

Loess flowslides in the Chinese Loess Plateau have been extensively investigated. Zhang and Wang, together with their colleagues, performed detailed shear behavior studies of the loess flowslides triggered by the 1920 Haiyuan earthquake and concluded that their high mobility and long run-out distance were mainly caused by liquefaction during the earthquake (Zhang and Sassa, 1996; Zhang and Wang, 2007; Wang et al., 2015). Wang et al. (2015) also found that air entrapped in the loess is unlikely to be the main contributor to the high mobility of this kind of large-scale landslide and that pore pressure generation in a saturated loess is the main cause of the fluidized loess landslides. Irrigation-induced loess flowslides in the Chinese loess terraces or platforms have received considerable attention (Zhang et al., 2009; Xu et al., 2012a; Xue and Wu, 2012b; Zhang et al., 2013). Many studies have found that irrigation water infiltration raises the groundwater level due to the resultant increase in pore-water pressure and a consequent reduction in shear resistance (Ishihara et al., 1990; Dijkstra et al., 1994; Derbyshire, 2001b; Zhang et al., 2009; Xu et al., 2012a; Xu et al., 2012b; Zhang et al., 2013).

Upto now many studies have been performed to understand the loess flowslides triggered by rainfall, but most of them are limited to shallow ones (Dijkstra et al., 1994; Derbyshire, 2001b; Zhang et al., 2009; Xu et al., 2012a; Xu et al., 2012b; Zhang et al., 2013).
movement with high mobility, hereinafter we term this landslide as Dagou flowslide. Although Peng et al. (2015) studied the mechanism of the Dagou flowslide, and pointed out that liquefaction was the main reason for the high mobility of the Dagou flowslide, the downslope movement, especially the enlargement process due to the entrainment of debris on the traveling path of displaced landslide material had been less examined and remains unclear.

In the moving process of landslides, the slide process always scours loose material from the channel bed and the banks of the channel as the slide process moves along the gully (Iverson, 1997). The volume of entrained material is sometimes several times larger than the source volume, such as the Tsingshan debris flow (1990) and the Fjærland debris flow (2004) (Lo and Chau, 2003; Breien et al., 2008). The entrained material can enhance or reduce the mobility of the debris flow, which will affect the kinematic characteristics of the landslides. Analytical and empirical approaches have been used to study the entrainment process (Pitman et al., 2003; Sovilla et al., 2006; Medina et al., 2008; De Blasio et al., 2011; Iverson and Ouyang, 2015; Pastor et al., 2014; Han et al., 2015). Entrainment depth or entrainment rate have been calculated. The results are compared with available observations showing a good agreement overall. In addition, a method for directly measuring entrainment has been proposed (McCoy et al., 2006; Medina et al., 2008).

Because it is difficult to predicate the locations and occurrence time of flowslide, and also it is difficult to observe the kinematic characteristics of flowslide on the field, numerical simulation becomes a useful approach for understanding the process and dynamics of flowslide in many cases. Different runout models, based mainly on the Law of Conservation of Momentum and the Law of Conservation of Energy, have been developed to calculate the characteristics of debris flow (Hungr, 1995; and the Fjærland debris flow (2004) (Lo and Chau, 2003; Breien et al., 2008). Numerical experiments have also been carried out to test the effect of entrainment on the characteristics of debris flow (Mangeney et al., 2010; Acharyya et al., 2011; Haas and Woerkom, 2016). Numerical experiments have also been conducted to understand the mechanics of debris flow during its movement (Zhou and Sun, 2013).

Figure 1. Precipitation information in study area. (a) Annular accumulated precipitation. (b) Hourly accumulated precipitation from July 20 to July 22, 2013. [Colour figure can be viewed at Wileyonlinelibrary.com]

Case Description

Since 2010, annual accumulated precipitation in Tianshui region of the Chinese Loess Plateau ranges from approximately 770 to 1350 mm, with an average precipitation more than 1000 mm (Figure 1a). In 2013, a heavy rainfall occurred in the study area. The total precipitation exceeded 240 mm, with the rate ranging from 5 to 22 mm/h on July 20, 2013 (Figure 1b). The rainfall subsequently continued at an average rate of 10 mm/h until accumulating 200 mm in precipitation (Peng et al., 2015). The extreme rainfall event triggered more than 400 landslides (Tianshui Institute of Geological Engineering Investigation [TIGEI], personal communication, 2013). Several of them even formed landslide dams, threatening life and property downstream.

Among these landslides, the most catastrophic one was a loess landslide that transformed from a slide into the flow with high velocity and long runout distance. The flowslide was located in Dagou Village, Tianshui City, Gansu Province, China (referred as the Dagou flowslide, Figure 2). Figure 3 provides an overview aerial image of the Dagou flowslide as well as the main morphological features at different sections. As shown in Figure 3, the flow channel is divided into the following main sections: source area, upper flow track zone, main flow track zone, and deposition area. The elevation of the slope is between 1090 and 1330 m. The average slope angle of the flow channel is about 29.2°, and slope length is around 1300 m. The landslides occurred due to heavy rainfall and occurred at an elevation of around 1210 and 1300 m. The flowslide started with a volume of approximately 1.6 × 10^5 m³, entrained material in flow track zone, and finally stopped with a volume of 2.26 × 10^5 m³ (Peng et al., 2015). The erosion depth of the channel bed is about 1–3.5 m. The source material is mainly composed of weathered mudstone ranging from 20 to July 22, 2013. [Colour figure can be viewed at wileyonlinelibrary.com]
from 2 to 5 m. The material lying on the flow channel mainly consists of Pleistocene loess (Q3) with a thickness of approximately 2–6 m. It has loose structure and developed joint fissures. Holocene loess (Q4) is exposed at the foot of the slope.

**Laboratory Tests**

**Tested samples**

To obtain the physical and chemical parameters, and mechanical behavior, disturbed colluvial soil samples at the bottom of the main scarp of the Dagou flowslide were collected (Figure 3a). The deposits at the sampling site were soils that had traveled from the source area or were mobilized from the flow channel bed which is the colluvium of the slopes in the source area. Therefore, it is considered that the deposits were a part of the displaced materials in the source area, and had almost the same soil as in the source area, as shown in Figure 3d. Thus, the triaxial tests were performed on this sample. The samples in the field had a unit weight of 1.69 g/cm³ with a water content (at sampling time) of 20.25% by weight. The particle size distribution is presented in Figure 4. The main physical properties and chemical compositions of the samples are summarized in Table I.

**Tested procedure**

A series of consolidated-undrained triaxial compression tests was conducted on the disturbed samples. The remolded samples in the triaxial tests were sieved through a 2-mm sieve to eliminate friable mudstone fragments. The soils were packed into a special sample compaction container to get the desired density and water content; then, with the help of compression, specimens were compressed into a container 10 cm in height and 5 cm in diameter.

The initial confining pressure was 20 kPa. All the specimens were saturated with the assistance of carbon dioxide (CO₂) and de-aired water. The degree of saturation was checked by using the calculation of the B value (Skempton, 1954), which was greater than 0.95 in our test. The specimens were normally consolidated before the test. After that, they were sheared by the strain-controlled method under a loading rate of 0.2 mm/min in normal direction under the undrained condition. The confining stresses for the consolidation and test were 50, 100,
150, 200, and 300 kPa. When the axial strain reached 20%, the tests were terminated.

Tested results

Figure 5 presents the undrained triaxial compression test results from the saturated disturbed loess samples at different cell pressures, including the variation of deviator stress versus pore water pressure versus axial strain and effective stress path. A high pore pressure was generated and resulted in a remarkable decrease in effective stress during compression (Figure 5b). However, the deviator stress of all the specimens increased with the increasing axial strain (Figure 5a). The effective stress paths show that all specimens suffered limited liquefaction with phase transfer because they showed softening tendency at the beginning of shearing, followed by strengthening with further shearing (Figure 5c). Based on the tested results, the disturbed sample showed an effective cohesion of 13.8 kPa and an effective frictional angle of 18° calculated from the Mohr–Coulomb criterion. In addition, the disturbed samples showed a clear shear-strengthening behavior and were typical shear expansive soils. The expansive soils manifest a relatively slow repeated slip episodes during failure, and the contractive failure soils present a catastrophic acceleration due to fully or partially liquefaction (Iverson et al., 2000). Although the difference in the porosity of the same soil is very small, the landslide motion patterns are quite different; it depends on whether liquefaction of the soil can occur (Iverson et al., 2000; Wang and Sassa, 2001, 2003). However, field evidence and laboratory results showed that the expansive soils have a potential to be liquefied (Fleming et al., 1989; Wang and Sassa, 2002). This has been attributed to soil pore volume adjustment during continuous shear deformation (Fleming et al., 1989) and grain crushing with increasing shear displacement (Wang and Sassa, 2002). Essentially, this is related to the changes in the physical nature and the physical state of the soil. Meanwhile, previous research has shown that curing is more likely to occur in coarse sandy particles (Hardin, 1984; Wang and Sassa, 2002; Coop et al., 2004). Therefore, it can be speculated that a state transformation occurred in the loess deposits and ultimately resulted in the liquefied Dagou flowslide. The shear strength parameters from the triaxial compression test should be used in the simula-

Table 1. Physical properties and chemical compositions of sample used in this study

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.73</td>
</tr>
<tr>
<td>Initial moist bulk density (g/cm³)</td>
<td>1.69</td>
</tr>
<tr>
<td>Initial water content (%)</td>
<td>20.25</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>38.02</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>24.25</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>13.77</td>
</tr>
<tr>
<td>Chemical compositions (weight %)</td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.15</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.74</td>
</tr>
<tr>
<td>SiO₂</td>
<td>50.92</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>13.08</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>5.80</td>
</tr>
<tr>
<td>MnO</td>
<td>0.13</td>
</tr>
<tr>
<td>MgO</td>
<td>4.70</td>
</tr>
<tr>
<td>CaO</td>
<td>12.15</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.72</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.32</td>
</tr>
<tr>
<td>LOI</td>
<td>8.51</td>
</tr>
<tr>
<td>Total</td>
<td>99.85</td>
</tr>
</tbody>
</table>

Figure 5. Undrained triaxial compression test results from saturated disturbed loess samples at different cell pressures. (a) Variation of deviator stress versus axial strain; (b) pore water pressure versus axial strain; (c) effective stress path. [Colour figure can be viewed at wileyonlinelibrary.com]
tion with careful calibration.

Model Description

Runout model

To assess the extent of damages caused by a debris flow event, numerical modeling and debris flow analysis were conducted. Several approaches in debris flow runout modeling exist, including the empirical approach, the discontinuum approach, and the continuum approach. In the empirical approach, calculations of the kinematic characteristics of debris flow are based on the statistical data of historical events (Fannin et al., 2012; Moffat et al., 2011). In the discontinuum method, debris is abstracted into small elements that interact with each other (Cundall and Strack, 1979). The third approach is based on continuum models in which the body of the slides is considered to be a continuum.

Continuum modeling includes two approaches to formulating the equations for debris flow runout analysis, which are derived based on the Law of Conservation of Momentum and the Law of Conservation of Energy. The Dynamic Analysis Model (DAN), developed by Hungr (1995), employs the Law of Conservation of Momentum to simulate the runout of debris flow. The energy-based runout model considers the internal energy dissipation due to deformation during the movement of debris flow (see Wang et al., 2010).

In the slice-based model, the energy model determines the motion of each slice based on the energy conservation equations using the Lagrangian difference scheme (Figure 6). The change in kinetic energy of a sliding mass consists of changes in potential energy, work done by resistance forces along the base of the sliding mass, and work due to internal deformation of the debris (Wang et al., 2010). Lateral pressure and basal resistance on individual slices can be calculated using the Rankine and Mohr–Coulomb equations. The governing equation of the runout model is:

\[
\frac{d}{dt} \left( \frac{1}{2} m \vec{u}^2 \right) = mg \theta \sin \theta + \frac{1}{2} \rho g \theta_{zz} + P_L \theta \cos \theta_L - P_R \theta \cos \theta_R - T \tau_{ij} \frac{\partial u_{ij}}{\partial V}
\]  

where \( m \) is the mass of the slice, \( \vec{u} \) is the mean velocity of the slice along the base of the slice, \( g \) is gravity acceleration, \( \theta \) is the inclination of the base of the slice with respect to the horizontal, \( P_L \) and \( P_R \) are interslice forces exerted on the left and right sides of the slice which is calculated based on the Rankin equation, \( T \) is the shear force acting along the base of the slice, \( \tau_{ij} \) is the components of the stress tensor, and \( e_{ij} \) is the component of the strain rate tensor. Saturated loess deforms easily during movement; thus, the energy-based runout model is considered the most reasonable model for simulating the movement of the Dagou debris flow. The runout model is converted into a numerical scheme, and energy is conserved in each computational time step.

Constitutive model

It is essential to adopt an appropriate constitutive law in the modeling and prediction of debris flow behavior. Many constitutive models have been proposed to describe the rheological properties of the equivalent fluid. According to dominant factors in momentum exchange, constitutive models of debris flow can be classified as the Newtonian fluid model, non-Newtonian fluid model, dilatant fluid model, Coulomb friction model, Coulomb friction model, and Voellmy fluid model (Wang et al., 2010).

The Voellmy fluid model initially developed for the modeling of snow avalanche motion with the assumption that shear resistance at the base of an avalanche is given by the summation of a Coulomb-type friction and a turbulence term. As the Voellmy model is more appropriate for the flowslides with a significant amount of liquefied material, it is used in this study (Hungr, 2008), given by

\[
\tau = \sigma \tan \phi + \gamma u^2 / \zeta
\]  

where \( \tau \) and \( \sigma \) are shear and normal stresses, respectively; \( \phi \) is the basal friction angle; \( u \) is longitudinal velocity; \( \gamma \) is the unit weight of the material, and \( \zeta \) is a turbulence coefficient with the dimension of acceleration.

Entrainment model

Some efforts have been made to describe the entrainment process numerically and incorporate basal entrainment. They can be briefly classified as analytical and empirical models. For analytical models, Newton’s Law of motion or the force equilibrium equation is adopted to obtain the entrainment rate or depth. Failure is considered to occur at the interface between moving debris and erodible bed. Newton’s Law of motion is applied to the erodible material. In this approach, shear stress and shear resistance play major roles in the entrainment estimation. The diffusion process due to the difference of sediment concentration between the erodible channel bed and flow is also considered one possible mechanism of entrainment. For empirical models, the entrainment rate is empirically related to flow velocity or shear stress exerted on the erodible bed. The coefficient of correction is often adopted to calibrate the model.

The properties of soil material are based not only on the internal friction angle but also on the cohesion between micro-scale particles. This is also true for loess. Very few works have been carried out to study the entrainment process in a loess area; this is probably caused by the special geotechnical features of the loess and entrainment process of flowslides in the loess area, which is not very common in these areas. As no entrainment model can be used to simulate the entrainment process of flowslide in a loess area, the entrainment model proposed by Medina et al. (2008) is used to calculate the rate of erosion.

In the model proposed by Medina et al. (2008), the rate of erosion is determined based on shear failure at the surface; the material is removed from the surface based on the velocity of the flow of the main body of the debris. The model is given by
Table II. Summary of the parameters used in the Dagou debris flow simulation.

<table>
<thead>
<tr>
<th>Run-out model parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (kN/m³)</td>
<td>19</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>7</td>
</tr>
<tr>
<td>Basal friction angle (°)</td>
<td>9</td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>6</td>
</tr>
<tr>
<td>Turbulent coefficient (m/s²)</td>
<td>2000</td>
</tr>
<tr>
<td>Bulking factor</td>
<td>1.2</td>
</tr>
</tbody>
</table>

\[
\frac{\partial z}{\partial t} = \frac{1}{\rho V} (\tau_b - \tau_{res}) 
\]  

where \(\frac{\partial z}{\partial t}\) is the rate of erosion, \(\rho\) is the bulk density of debris, \(\tau_b\) is the shear stress applied to the channel bed, and \(\tau_{res}\) is basal resistance.

Entrainment occurs when the bed shear stress is greater than the shear resistance. The entrainment rate is equal to the net shear force in the same direction of debris movement divided by the density and average velocity of the moving debris. Thus, the entrainment model was converted into a numerical scheme and incorporated into the runout model to calculate the kinematic characteristics of the Dagou flowslide.

**Numerical Simulation**

**Modeling setup**

To clearly understand the flowing behavior and the entrainment process of Dagou debris flow, numerical simulation is carried out using the new runout model with entrainment included. From the test results of soil density sampled at different spots in the channel of Dagou debris flow, unit weight of the Dagou debris flow is set as 19 kN/m³ in the calculation. Since the density of the erodible bed and the flowing slides is different, the bulking factor is incorporated into the new model based on the Law of Mass Conservation, which is the ratio between the density of erodible bed and the flowslide.

The effective friction angle measured from undrained triaxial shear tests were equal to 18°. The water content in the soil was larger than the water content when the soil was just saturated after the debris flow occurred. In addition, due to heavy rainfall before the event, runoff was generated when the rainfall intensity was larger than the infiltration intensity. This part of the water could lubricate the channel bed. Therefore, the internal friction angle and residual friction angle, smaller than the angles obtained from the undrained triaxial tests, were used to calculate the resistance from the basal material in the entrainment model and the basal friction to the flow in the runout model, respectively. Adhering to the theoretical analysis, the internal friction angle and basal friction angle were determined in the calibration process.

The turbulent coefficient in Voellmy’s fluid model is a function of Chezy coefficient which can be estimated using Manning’s equation that is closely related to the hydraulic radius and Manning’s roughness coefficient. Hydraulic radius was calculated based on the cross-section area and depth of flow. Manning’s roughness coefficient is an empirical coefficient that is dependent on the roughness of flow channel. For Dagou flowslide, the flow channel is composed of loess material. Therefore, a smaller Manning’s roughness coefficient should be adopted. Since turbulent coefficient is negatively proportional to Manning’s roughness coefficient, a larger turbulent coefficient is used in the Voellmy’s fluid model.

The cohesion is used to calculate the lateral earth pressure and the resistance from the basal material, which is obtained from the undrained triaxial tests. It was adjusted as the soil structure had already been destroyed when the debris started to move. The parameters used in the simulation are summarized in Table II.

Figure 7 shows the longitudinal profile used in the simulation. The flow path was divided into three sections: source zone, track zone, and deposition zone. The Dagou flowslide started from the source zone after the slice failed. The failed mass then converted into flowslides and moved along the flow channel. During the movement, the debris entrained soil mass from the channel bed, and some of the debris was deposited on the channel bed. Eventually, the slides stopped when it reached a relatively flat area – namely, the deposition zone shown in Figure 7.

**Simulation results**

The shape of the slides in the calculation is shown in Figure 8, in which the shape of the slides and adjusted channel bed were plotted at 10-second intervals before it fully stopped. Original ground surface shows the terrain before the debris flow. Debris surface and channel bed after erosion demonstrate the surface of debris and ground surface after erosion. To clearly present the profile of debris in movement, the vertical height of debris was enlarged five times. The results show that the flowslides stopped in the flat area of the channel when the rear part of the debris was still almost in the initial location.

Figure 9 shows the calculated velocities of the Dagou debris flow at 10-second intervals in the simulation. The rear and front velocities are also plotted in Figure 9. Since moved distance of the first slice close to the crest of the slope is very small, the rear velocities in Figure 9 overlapped each other. After 40 seconds, velocities of slices behind \(x = 580\) seconds are approximately zero. Frontal velocity decreases to zero at \(t = 46\) seconds. The average velocity was approximately \(19.9\) m/s. The velocities observed from field evidence were smaller than those.
calculated, which was probably due to the simplification of the longitudinal channel shape and the parameters used in the simulation. In the calculation, the shape of the flow channel in the plane view was assumed to be a straight slope that curved in the field. More kinetic energy is dissipated when debris moves along a curved channel than along a straight channel given the longer distance traveled by the slides. Furthermore, using uniform frictional parameters in the simulation caused limited energy to be consumed when the debris reached the section with greater resistance than that...
calculated using the frictional parameters. Both of the factors could cause larger velocities.

The entrainment rates underneath each slice in the simulation are shown in Figure 10. Dashed lines are regression lines of the entrainment rates at different times in the simulation. It is evident that the entrainment detected concentrates on the slices at the front of the debris. Entrainment can then be detected on more slices after a few seconds. The maximum entrainment rate is always observed at the front of debris and moves along the flow path. This is identical to the analysis and observations from other tests (Mangeney et al., 2010).

Theoretically, the debris at the source area starts to spread after it detaches from the original position. It converts into fluid if the solid concentration in the debris is low enough. Figure 11 indicates the maximum flow height and the maximum entrainment rate in the simulation. It is obvious that the maximum flow height decreases in the simulation. The main reason for this decrease is that the velocity of the slide is larger than that behind, which causes the longitudinal spread of the slides.

The maximum entrainment rate appears when \( t = 11 \) s when the net shear stress calculated from the Voellmy model reaches the maximum value. The rate of erosion gradually decreases when the debris reaches a relatively flat area, at which point the velocity and height of the debris start to decrease.

Figure 12 shows the entrainment depth after simulation. The maximum entrainment depth is approximately 2 m. The average entrainment depth between \( \chi = 170 \) m and \( \chi = 730 \) m is approximately 1.8 m, which is very close to the estimated entrainment depth at the track zone at approximately 2 m (Peng et al., 2015).

Since the variation of channel width is not large, it was considered in the calculation that the width of the channel was constant along the longitudinal profile. The width was estimated based on the volume and cross-section area of the source material. The volume is equal to the cross-section area multiplied by the width of the flow channel. The maximum entrained volume, 2.31 \( \times 10^3 \) m\(^3\), appeared when the front of the debris reached \( \chi = 422 \) m (Figure 13). Thus, the curve showing the total volume has a maximum slope at this position. After that point, the rate of increase of total volume gradually decreased until the debris stopped. The total volume calculated is 213 \( \times 10^3 \) m\(^3\), which is very close to the estimated total volume of the debris, 226 \( \times 10^3 \) m\(^3\), including the volume of the debris at the deposition zone – namely, the track zones based on Peng et al.’s (2015) description.

The results of the calculation show that, although soil mass was still left at the source zone, the slides in this zone were thin compared to the height of debris at the deposition zone (see Figure 14). The average deposition heights in the deposition zone and track zones varied significantly, but the average heights of the debris in these zones were very close to what was observed: approximately 8 and 5 m, respectively.

To test the effect of entrainment on debris flow in the loess area, a new runout analysis was carried out for the Dagou debris flow. The analysis employed the same parameters as those used in the previous section. When the entrainment of debris flow was taken into account, the debris flow moved faster and farther; although the difference was not so large, it affected the kinetic energy of the flow (Figure 15).

The available measurements, including super-elevation, runout distance, maximum entrainment depth, and deposition height as well as the total volume of the flowslide after it stopped, were used to verify the simulation results. According to the super-elevations detected at different locations, as shown in Figure 16 (labeled in Figure 3a), the corresponding velocities

Figure 12. Entrainment depth along the flow channel after simulation.

Figure 13. Variation of the total volume and entrained volume along the flow path.

Figure 14. Final debris height along the flow path and mean height of debris at transition zone and deposition zone.
were estimated using the equations proposed by Henderson (1966) and Scheidl et al. (2014). The results shown in Figure 9 also indicate that overall the calculated velocities are in a reasonable range and the velocities calculated at \(x=400\) m and \(x=1000\) m are very close to the velocities estimated from Scheidl et al. (2014) and Henderson (1966), respectively. Total volume, maximum entrainment depth, and deposition height, as well as runout distance, were also used to verify our model, as was shown in previous sections. The calculated results are very close to those observed in the field.

**Discussion**

Dagou loess flowslide is a special case in loess area with significant entrainment. Since the occurrence of the flow slide coincides with a rainfall process, it was considered that this flowslide was triggered by the rainfall which also has a significant effect on post-failure process of this flowslide. After the slope failed, the soil collapsed and mixed with overflow leading to liquefaction of loess resulting in a high velocity and runout distance. The high velocity, in turn, has a potential to cause a high shear stress applying on flow channel which leads to the erosion of material lying on the flow channel (Medina et al., 2008; Luna et al., 2012; Kang et al., 2017).

Different runout models have been used to study kinematic characteristics of landslides (Miao et al., 2001; McDougall and Hung, 2004). However, most of them only consider the Law of Conservation of Momentum and do not take the energy dissipation into account (Wang et al., 2010). The model used in this study is an energy-based runout model with energy dissipation considered which can reduce the discrepancies in the calculation of kinematic characteristics. The model considers soil properties including cohesion, internal friction and basal friction angles which are obtained from corresponding laboratory results. In the calculation, the source material was divided into slides, and the Law of Conservation of Energy was applied on each slide. Sensitivity analysis of slice number has been carried out using the longitudinal profile of Yigong Rock Avalanche (Kang et al., 2017). The results indicated that increasing the number of slices from 30 to 50 only causes differences of 0.6%, 0.1% and 1% in runout distance, velocity, and total volume, respectively. After evaluating the calculation time and the differences in the results, 30 slices were adopted in this study.

Different relationships have been proposed to describe the relationship between shear rate and shear stress. Among them, Voellmy fluid model was mostly used to estimate the shear stress exerted on the flow channel (Hungr, 2008; Luna et al., 2012). Therefore, in this study, the authors incorporated the Voellmy model into the runout model. The parameters affecting the calculation results mainly include basal friction angle and turbulent coefficient. The tested samples can give a reference value for the selection of basal friction angle. The friction angle was then modified and reduced in the model calibration process. The turbulent coefficient is a function of the Chezy coefficient that is negatively proportional to the roughness of the flow channel. Luna et al. (2012) and Hungr (2008) set the turbulent coefficient to 500 m/s² in the calculation of kinematic characteristics of rock avalanches. However, Dagou flowslide occurred in a loess area where the flow channel is smooth. Therefore, a larger value should be used. Based on the analysis of channel properties, a value of 2000 m/s² is used as the turbulent coefficient.

The physical mechanisms of entrainment models mainly include shear failure of the erodible layer, diffusion process between moving material and erodible bed, and progressive scouring process (Medina et al., 2008; Egashira et al., 2001; Kang et al., 2017). Since shear failure is a possible mechanism in the loess area during the entrainment process, the dynamic...
The kinematic characteristics obtained from the runout model included runout distance, flow velocities, entrainment depth, deposition height, entrained volume and total volume. Field observations and investigations are used to verify the results. The calculated results were mostly in accordance with our observations, meaning that the new coupled model has the ability to calculate the kinematic characteristics of debris flows in similar loess areas.

**Acknowledgements**—This study was partially supported by the National Key Basic Research Development Plan of China (No. 2014CB744703) funded by Ministry of Science and Technology of the People's Republic of China, the National Natural Science Foundation of China (No. 41102240) funded by National Natural Science Foundation of China and the Natural Science and Engineering of Canada Discovery grant funded by the Natural Sciences and Engineering Research Council of Canada.

**References**


The entrainment model is used. The static entrainment model is also based on the shear failure process. However, it is easily affected by time steps in the calculation (Medina et al., 2008). The calculation of entrainment rate in the dynamic model is based on the difference between shear stress applied by moving material and shear strength of the erodible material, which are related to basal friction and internal friction angles, respectively.

For most of the landslide, when the moving material reached the deposition fan, channel width suddenly increases resulting in a decrease of flow height and velocity. Most of the time, a three-dimensional (3D) model should be adopted in the calculation. According to Peng et al. (2015), the width of Dagou flowslide did not vary a lot along the flow channel. Therefore, it is reasonable to use a two-dimensional (2D) runout model in the calculation of kinematic characteristics of Dagou flowslide. In the calculation, runout distance was used to calibrate the model. Flow velocities and entrainment depth were compared with the observation. Since no monitoring system existed when the Dagou flowslide occurred, maximum flow velocities were estimated from filed observation. Therefore, super-elevations at several locations of the channel were investigated.

The calculated velocities overall are larger than that estimated from field observation. This is due to parameter selection in the runout model and entrainment model. In the track zone, the velocities estimated using the method proposed by Scheidl et al. (2014) overall are close to the velocities calculated using Henderson’s (1966) method. The average difference between the results calculated using these two methods is around 6.7%. However, in the deposition zone, the velocity calculated using the runout model at approximately x = 1000 m is close to the velocity calculated using the method proposed by Henderson (1966) which is larger than that estimated using the method proposed by Scheidl et al. (2014). The average deposition heights in transition and deposition zones were calculated by dividing the cross-section areas by the longitudinal lengths of each section. The observed and calculated heights in both zones show a good agreement although small discrepancies exist. The comparisons of frontal velocity and runout distance between the calculations with and without erosion process also indicate that when entrainment is involved, the debris moves with a higher velocity and will move longer. This is due to the increase in potential energy.

**Conclusion**

This paper describes a loess flowslide that occurred in July 2013, which was mostly triggered by an extreme rainfall event. The landslide changed to a flowslide due to the liquefaction of loess, which is also the main reason for the high velocity and long runout distance of the flowslide.

To understand the soil characteristics in the study area, soils were sampled from source and deposition zones. Undrained triaxial tests were carried out to determine shear strength and frictional angles. Soil density and particle size were also tested and were considered in the simulation and study of the mechanism. After careful analysis of the situation when the flowslide occurred, the parameters used in the simulation were adjusted accordingly.

As the flowslide moves with a large deformation, an energy-based runout model that considers the energy dissipated due to the deformation of the slides was coupled with an analytical entrainment model to simulate this case. The entrainment model considers shear failure mechanism of an erodible layer which is considered as the main erosion mechanism of cohesive soil.