Role of confinement on spreading of flow-like dry rock avalanches

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ABSTRACT

Typical peculiarities of large-scale bedrock landslides are the intensive comminution of debris and absence of mixing of the lithologies involved in slope failure. Such combination allows classifying most of them as rock avalanches – dry laminar granular flows. Different parameters characterizing rock avalanche mobility such as runout, angle of reach, affected area, and their relationships with volume of failure, height drop, and product of the latter that is somehow proportional to the potential energy released during emplacement, are analyzed based on the rockslide inventory of the Central Asian region. It was found that the regressions of the affected area with volume and with its product with maximal height drop has higher correlation coefficients that those of the angle of reach and runout. Effect of confinement type (frontal, lateral and unconfined) on rock avalanche mobility is analyzed statistically. Interrelations between various parameters characterizing and governing spreading of flow-like dry rock avalanches is demonstrated by use of triple regressions allowing comparison of the influence of two parameters, e.g. failure volume and height drop, on rock avalanches’ mobility.

1 INTRODUCTION

Rock avalanches represent the specific type of flow-like landslides, whose extreme mobility is governed not by the presence of the significant amount of water mixed with rapidly moving debris, as, for example, in debris flows, and not by liquefaction within the sliding zone (e.g. Sassa et al. 2010), but by internal processes evolving during emplacement of these dry granular flows. Various mechanical models were proposed to explain their high mobility (Hsü 1975; Grigorian, 1979; Davies 1982; Melosh 1986; etc.) and the dynamic fragmentation model seems to be the most realistic and well-grounded one (see e.g. Davies et al. 2017). Study of numerous rock avalanches that originated on slopes formed by multiple varicolored lithologies whose mutual position before and after the emplacement can be compared just visually, shows that in most of cases rock avalanche moves as a laminar flow without any turbulence, so that comminuted debris that originated from various types of rocks do not mix and form distinct “layers” or “belts” (see, e.g., Abdakhmatov, Strom 2006; Strom 2006). We want to notice that clear evidence of laminarity can be seen in the deposits of those rock avalanches that form long thin sheets of debris spreading over unconfined surfaces, of those canalized in narrow valleys, and of those that moved across deep narrow valleys forming compact dams. Sometimes it is really difficult to distinguish between what should be classified as “rockslide” and what – as “rock avalanche”. Quite often such division is based just on the deposits’ morphology (compact bodies are caller “rockslide”; thin and elongated bodies – “rock avalanche”), while, considering state of the material, most of large-scale rock slope failures represent flow-like granular flows and, thus, can be classified as rock avalanches.
Unlike many other types of landslides that affect elements at risk located on the deforming slopes mainly, highly mobile rock avalanches in mountainous regions endanger people, buildings and infrastructure at the slopes' feet at most. Extremely high velocity of moving debris that could reach hundreds km/h predetermines hazard of rock avalanches both for people that cannot escape, and for structures due to severe impact force. Besides high velocity, mobility of rock avalanches can be characterized by their geometrical parameters. Those used most commonly are the runout – maximal horizontal distance between headscarp crown and most distant point of the deposits (Kilburn, Sorrencec 1998; Legros 2002), and the angle of reach – ration between height drop and runout (Sheidegger 1973; Hsiü 1975; Davies 1982; Li 1983; Shaller 1991; Kobayashi 1993; Corominas 1996). Li (1983) used the affected area as an additional parameter characterizing rock avalanche mobility. Starting from the pioneering work of Sheidegger (1973) researchers analyze dependence of rock avalanche mobility from its volume.

It is obvious that shape of rock avalanche deposits and their geometrical parameters should strongly depend on the confinement. Following Shaller (1991), all of them be divided, at first approximation, in three groups – unconfined, laterally confined and frontally confined. However, most of relationships mentioned above were derived for the entire data sets. Limited number of case studies prevented statistical analysis of samples selected considering the confinement conditions. Compilation of the Central Asia rockslide database including about 1000 case studies, more than 500 of which were quantified (Strom, Abdrakhmatov 2018) allowed quantitative analysis of the relationships between various parameters of rock avalanche that takes the confinement into consideration.

2 RUNOUT VERSUS AFFECTED AREA

Runout (L) as well as its inverse ratio with height drop (H/L) (height drop H is defined as altitude difference between headscarp crown and the deposits' tip) are not the only, and, likely, not the optimal parameters characterizing rock avalanche mobility, especially for the purpose of risk assessment that requires knowledge of the exposure of elements at risk (Corominas et al. 2015). Indeed, rock avalanche debris can move not only forward, but also sideward, forming fan-shaped or the pancake-shape bodies that, despite they might spread not as far as those moving straightly forward, could affect much larger area, thus increasing the exposure.

Considering needs of landslide risk assessment, Strom and Abdrakhmatov (2018) analyzed total affected area defined as a polygon embracing source, transition and deposition zones whose area is measured in plan view (A_{total}). Indeed, there is no big difference for an element at risk if ground would sank under its feet, if it would be swept out by rapidly moving debris or would be buried by the deposits. As it was shown by the statistical analysis (ibid), correlation coefficients of the relationships between rock failure volume (V) and the affected area (A_{total}) and of its inverse ration with height drop (H/A_{total}) are much higher than of those between volume (V) and angle of reach (H/L) or volume (V) and runout (L) (Table 1).

<table>
<thead>
<tr>
<th>Confinement</th>
<th>L×V</th>
<th>H/L×V</th>
<th>L×V×H_{max}</th>
<th>A_{total}×V</th>
<th>H/A_{total}×V</th>
<th>A_{total}×V×H_{max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontally confined</td>
<td>0.7335</td>
<td>0.3008</td>
<td>0.8160</td>
<td>0.9008</td>
<td>0.8006</td>
<td>0.9258</td>
</tr>
<tr>
<td>Laterally confined</td>
<td>0.7301</td>
<td>0.4497</td>
<td>0.051</td>
<td>0.8833</td>
<td>0.8686</td>
<td>0.9267</td>
</tr>
<tr>
<td>Unconfined</td>
<td>0.8066</td>
<td>0.3962</td>
<td>0.8824</td>
<td>0.9151</td>
<td>0.8330</td>
<td>0.9361</td>
</tr>
</tbody>
</table>

Correlation coefficients R^2 of the L×V and A_{total}×V regressions are slightly less for laterally confined cases than for other types of confinement, and, contrariwise, are slightly higher for H/L×V and H/A_{total}×V regressions.

Similar effect was found when we analyzed dependence of runout and of total affected area from the product of rock failure volume and maximal height drop (H_{max}) defined as difference of altitude between the headscarp crown and the lowermost part of the deposits along the profile where it is measured. For unconfined and laterally confined rock avalanches H_{max}=H; for frontally confined features H_{max}>H. This product is somehow proportional to the potential energy released during the emplacement. More strict definition of the potential energy requires knowledge of height drop of the center of mass and of rocks' unit weight. However, considering poor accuracy of the localization of the center of gravity and high uncertainty of volume estimates (about ±30% if not more) that is higher than variation of the unit weight of different types of rock, in the first approximation this value (V×H_{max}) seems to be sufficient. R^2 of such correlations are higher than of correlations between L, H/L, A_{total} and H/A_{total} just with volume only, except the only one – L×V×H_{max} for
laterally confined rock avalanches that is extremely low (see Table 1). Thus, both general considerations and the statistical analysis demonstrate preferability to characterize the mobility of large-scale flow-like rock avalanches by the total affected area rather than by the runout or angle of reach.

4 EFFECT OF CONFINEMENT

Effect of the confinement conditions on rock avalanches’ mobility is quite evident: lateral confinement prevents debris spreading in the transverse direction; frontal one forces debris to form compact dams and to rise on the opposite slope, sometimes for hundreds meters. Such up slope motion means that part of the kinetic energy and momentum gained by rock avalanche body during initial descent is consumed by work against gravity force, along with its consumption by work against basal and internal friction and by crushing, while at unconfined and laterally confined cases energy is consumed by basal friction and internal processes only.

Interesting and somehow surprising results were obtained when we analyzed relationships between runout and total affected area that characterizes transverse spreading of rock avalanche debris. $A_{\text{total}}=L$ regression curves for unconfined and frontally confined cases appeared to be almost the same, while that for laterally confined cases lies parallel but their affected areas are about 2 times less for the given runout. It can be described by the exponential equations in the form: $A_{\text{total}}=aV^{b}$. While coefficient “b” for three confinement types is almost equal (from 1.7594 to 1.7764), coefficient “a” for frontally confined cases is 0.4134, for unconfined cases is 0.4222, and for laterally confined cases is 0.2238 only. Similarity of such regressions for unconfined and frontally confined cases allows assumption that lateral spreading due to collision with an opposite slope provide same effect as lateral spreading of debris moving over the unconfined surface. We must consider, however, that another parameter indirectly affecting these relationships is rock avalanche volume. Relative importance of volume and runout for the affected area derived from the triple correlation $\log(A_{\text{total}}) = ax\log(V) + bx\log(L) + c$ is demonstrated by Table 2.

<table>
<thead>
<tr>
<th>Confinement</th>
<th>No of cases</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R-squared</th>
<th>Relative importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>294</td>
<td>0.34</td>
<td>0.91</td>
<td>1.47</td>
<td>0.95</td>
<td>0.51</td>
</tr>
<tr>
<td>Lateral</td>
<td>68</td>
<td>0.34</td>
<td>0.99</td>
<td>0.49</td>
<td>0.97</td>
<td>0.49</td>
</tr>
<tr>
<td>Unconfined</td>
<td>71</td>
<td>0.38</td>
<td>0.90</td>
<td>1.00</td>
<td>0.96</td>
<td>0.50</td>
</tr>
</tbody>
</table>

We must notice that that larger runout of laterally confined rock avalanches of the given volume than of those in other confinement conditions (Strom, Abdrakhmatov 2018) does not compensate impossibility of lateral spreading of debris that result in smaller affected area (and exposure) of laterally confined features in comparison with unconfined rock avalanches.

We also analyzed dependence of the runout and of the affected area from both V and $H_{\text{max}}$ ($\log(L; A_{\text{total}}) = ax\log(V) + bx\log(H_{\text{max}}) + c$ (Tables 3 and 4). Actually, these parameters are not absolutely independent. Larger failures usually occur on higher slopes that can be described by the exponential regression: $V = 1.0089e^{0.0037H_{\text{max}}}$ with large scatter ($R^2 = 0.5018$).

<table>
<thead>
<tr>
<th>Confinement</th>
<th>No of cases</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R-squared</th>
<th>Relative importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>294</td>
<td>0.15</td>
<td>0.57</td>
<td>1.20</td>
<td>0.87</td>
<td>0.49</td>
</tr>
<tr>
<td>Lateral</td>
<td>68</td>
<td>0.14</td>
<td>0.94</td>
<td>-0.65</td>
<td>0.90</td>
<td>0.43</td>
</tr>
<tr>
<td>Unconfined</td>
<td>71</td>
<td>0.22</td>
<td>0.56</td>
<td>0.25</td>
<td>0.91</td>
<td>0.53</td>
</tr>
</tbody>
</table>

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<tr>
<th>Confinement</th>
<th>No of cases</th>
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<th>b</th>
<th>c</th>
<th>R-squared</th>
<th>Relative importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>294</td>
<td>0.48</td>
<td>0.53</td>
<td>2.52</td>
<td>0.92</td>
<td>0.65</td>
</tr>
<tr>
<td>Lateral</td>
<td>68</td>
<td>0.47</td>
<td>0.95</td>
<td>-0.23</td>
<td>0.94</td>
<td>0.57</td>
</tr>
<tr>
<td>Unconfined</td>
<td>71</td>
<td>0.58</td>
<td>0.49</td>
<td>1.26</td>
<td>0.94</td>
<td>0.65</td>
</tr>
</tbody>
</table>
This analysis explains lack of correlation between runout (L) and V×H\text{max} for rock avalanches that moved in laterally confined conditions while for other types of confinement such correlation is quite significant (see Table 1). It is caused by very poor dependence of runout from maximal height drop (Strom, Abdakhatmov, 2018) and much higher relative importance of H\text{max} for runout of laterally confined rock avalanches than for rock avalanches with other confinement conditions (see Table 3). On the contrary, total affected area depends on failure volume much more than on maximal height drop, regardless of the confinement conditions, though for laterally confined cases role of volume is less than for other samples (see Table 4).

3 CONCLUSIONS

Statistical analysis of rather large database of Central Asian bedrock landslides most of which can be classified as rock avalanches provides quantitative validation of the preferability to use total affected area as a parameter characterizing rock avalanches’ mobility. It also allows estimating role of the confinement conditions and proves the assumption that relationships between various parameters of rock avalanches must be analyzed for unconfined, frontally confined and laterally confined case studies separately.

REFERENCES


