Cover letter to Editor:

Dear Prof. Glade,

We acknowledge your time and the reviewers' helpful comments and advice very much, which are valuable for improving the quality of our manuscript. We reworked on the manuscript carefully by incorporating almost all the comments and suggestions that the reviewers suggested into the new version. **Two completely new sub-sections** have been added: subsection 4.1 "Reach angle of channelized rock avalanches" to illustrate the correlation between reach angle (H/L) and other parameters (i.e. volume, runout distance, the slope angle of the source area and the angle of the channel); and the subsection 5.2 "The mobility of channelized rock avalanches" to make a better and more interesting discussion. In subsection 5.2 we compared our data with the worldwide dataset and also the local dataset. In total, **5 new figures and 1 table** have been added. Therefore, to our best knowledge the manuscript has been largely improved. The reviewers' comments are reproduced below, followed by our responses and/or a summary of revisions to the manuscript in italic. A marked-up manuscript version with correction marked in red has also been attached at the end.

Sincerely, on behalf of my co-authors,
Xuanmei Fan

Response to Reviewer Comments on Manuscript NHESS-2016-372:

Manuscript: Empirical prediction for travel distance of channelized rock avalanches in the Wenchuan earthquake area

Weiwei Zhan, Xuanmei Fan, Runqiu Huang, Xiangjun Pei, Qiang Xu, Weile Li

1. Response to Reviewer 1, Prof. Hans-Balder Havenith

Comments in general:

Q1: Some essential aspects about the ratio of volume versus sliding surface are missing in the discussion and conclusions. You mainly considered the relatively classical parameters of volume (alone), slope angle, and total relief. The problem is treated as being almost 1D (linear along the slope) while channeling of rock avalanches is certainly also depending on the channel cross section and the presence of ’turns’ along the channel. Those two aspects should be analysed as well.

R1: *We thank the reviewer for the insightful comments. The correlation between volume vs. H/L, slope angle of the source area (sliding surface) vs. H/L, and the channel angle along the flow path vs. H/L were presented in the new figures 4 and 5. We have focused on the maximum travel distance prediction of the rock avalanches in Wenchuan earthquake area. The effect of channel cross section and the channel direction turns on mass movement has been being always the challenge in landslide runout prediction, due to the factors (e.g. channel geometry, material properties). We have address this issue in Section 5.1 and the new Section 5.2 to explain the channel geometry) in the revised version (see lines 324-346).*

Comments tied to sections:

Q2: the specific conclusion of your work is missing.

R2: *Besides with the prediction models, we have added more discussions on the influences of topography constrain, landslide types, and triggers on the landslide mobility through the comparison with other datasets. These has been added in the newly added Section 5.2 of the revised version, see lines 314-361.*

Detailed comments tied to lines:

Q3: The grammar, terms and other similar details in lines 32, 62,139,156,195,297

R3: *We have corrected the above lines.*

Q4: Line 88-112; this page is the same as the previous one !!! To be deleted

R4: *We are sorry about this mistake. This page has been deleted.*

Q5: Line 139: is that channel referring to the preexisting channel?

R5: *Yes. We have rephrased the ‘channel’ to ‘pre-existing channel’.*

Q6: Line 149: the concept of initiated slope (source area)

R6: *We have rephrased this as the source area means where the materials were initiated.*

Q7: Line 155: repeat reference to fig.3 where alpha and beta should be more highlighted.

R7: *We have highlighted them.*

Q8: Line 167: 'desirous' might not be used in this context. Maybe use 'most important prediction parameter'.

R8: *We have rephrased 'most desirous' to 'most important prediction parameter'.*

Q9: Line 291: 'the travel distance of channelized rock avalanche would increase with the channel angle cut down given the same flow discharge' is not convincing ! The negative correlation with alpha is not logical and I think that it has an indirect effect ... meaning that some other parameter not studied here must explain this 'apparent' negative correlation. I think that the negative effect comes from the fact that the smaller alpha is compared to beta, the deeper is the sliding surface in the source area, - a very deep sliding surface ends up almost horizontal at the toe of the source area. This reduces alpha.

R9: *We agree with the reviewer and has changed this part. See more discussions in section 5.1, lines 297-302, where we explained the reason of the negative correlation between travel distance and channel gradient. While in Equation 4 alpha has negative correlation with travel distance, but beta became positive. The reason for that might be the alpha somehow indirectly implies the depth of the source area and the corresponding volume.*

Q10: Line 293: the cross-section morphology was totally neglected in your analysis – why? Actually, the volume has this positive effect on travel distance as normally with larger volumes the volume-contact surface (reducing mobility due to friction) ratio increases. Additionally, curved cross-section profiles. up to a certain amount of curvature (typical for channels) reduce the total friction. For flat areas, the friction is highest as well as for very narrow channels with vertical walls. For medium curved channels the volume -contact surface ratio is lowest.

R10: *We agree with the reviewer. We have added some new figures to explain the correlation between volume and H/L ratio both from our dataset and world wide dataset* *in the new subsection 5.2. We also would like to point out that the empirical-statistical method that we presented in this study only suits for the rapid assessment of potential runout of channelized rock avalanches in the data-lack situation. The cross-section morphology could be obtained from DEM. However, in most case, DEM is not available. If it is available, numerical simulation using DEM could provide better results with consideration of the detailed morphology than our method.*

Comments on figures:

Q11: Fig.3: (1) do not understand initiated slope. Maybe better: Failed upper part of the slope?

(2) highlight better 'alpha' and 'beta' angles and refer to this figure when you use them in the equations.

R11: *We have revised Fig.3*

2. Response to Reviewer 2, Prof. Theo van Asch

Comments in general:

Q1: This is an interesting paper showing that with a limited amount of factors one is able to predict the travel distance of rock avalanches provided that they occur in the same area, are of the same type and have the same triggering conditions. This was already shown in this paper where the validation with landslides with other triggering conditions and lying in another area gave sometimes poor results. I am wondering why the authors did not mention in the introduction explicitly the use of the energy concept for runout modelling, which gives a simple transparent insight in the most important factors (relief and friction) influencing run-out distance. Interesting question arises also from the introduction about advantages and disadvantages of the use of deterministic physical models and statistical models.

R1: *Thanks for your comments. We have added a new sub-section 4.1 to analyze the application of energy line model on the channelized landslides (see the revised text) and the new figures 4 and 5.*

Comments tied to sections:

Q2: In the introduction, the authors mention examples of important fast landslides but they must more precisely describe triggering condition and type.

R2: *Thanks for your comment. We added a new table to summarize some commonly used empirical-statistical models for landslide runout prediction in Table 1.*

Q3: lines 153-155: This is unclear: what is inclination of slope section and valley section. Why they are obtained. In the next sentence you talk about Slope angle (alpha) and Channel angle (beta) Is that the same as the inclinations mentioned in this highlighted sentence?

R3: *We have clarified this as "The average inclination of the source area and travel path are obtained respectively, while the gradient of valley floor (deposition area) is neglected as it has very little variation", which refer to "α" and "β" in the following sentence (see lines 136-138 in the revised version).*

Q4: lines 164-165: From a theoretical point of view the empirical link between area and volume is very tricky because rock strength of a failing block, and slope angle plays an important role in the depth of sliding and hence the volume.

R4: *It is tricky, but there are a lot of research making efforts on estimating volume using area, landslide type, rock type etc. as indicators to improve the statistic models. We agree that the sliding depth and the volume are affected by the geological structure (like weak zone), topographic condition (like slope angle, location on the slope), groundwater level, ground motion intensity and so on. But there are several publication confirming that power-law equations indeed exists between the area and volume of landslides. Considering the difficulty of obtaining the volume of every rock avalanches due to the lack of pre-quake topographic data, we still regarded as a practical measure the relationship build with accordance to a popular volume-area relationship adapt by Guzzetti et al. (2009), Larsen et al. (2010) and calibrated with the field dataset in the Wenchuan earthquake area by Parker et al. (2011) (see lines 141-142 in the revised version).*

Larsen, I.J., Montgomery, D.R. and Korup, O., 2010. Landslide erosion controlled by hillslope material. Nature Geoscience, 3(4), pp.247-251.

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M. and Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy. Earth and Planetary Science Letters, 279(3), pp.222-229.

Q5: I have great difficulty in presenting the total height (H) as an important factor for the run out distance since it is highly correlated with run-out distance (L) Therefore Equation 2 and 3 are really not useful predictive equations because you need the travel distance L which you have to predict? May be a trial an error procedure for L is a solution when using this equation? It would be nice to test this.

R5: *We agree that travel distance (L) is highly correlated with total relief (H) partly due to the geomorphologic similarity in same area. Yet we suggest there are potential benefits of Eq(2) and Eq(3). As the Eq(2) is developed through a stepwise linear multivariate regression technique to get the best-fit multivariate regression model for travel distance prediction, H is attracted to the equation when taking account of H, Hs, V, beta as input variables. On the physical base, total relief indicates the potential energy difference of the failure mass which control the motion of rock debris. Eq(2) can give a clue to the compare the influence of two important factors, volume and potential energy difference on the travel distance. From the point of practical use of Eq(2), the estimated results using Eq(2) can be a benchmark of the results obtained through other models especially while* ***H can be estimated to close to elevation difference between source area and valley floor for cases with high possibility to reach the valley floor.***

Q6: The authors solved the problem by making a correlation of Hs with H (Eq4) which is a practical solution but has of course no physical meaning and it has to be questioned whether it works in other areas. I want to see comments on this in the discussion paragraph.

R6: *The positive correlation between Hs and L can be explained to be the increasing tendency of Hs with the volume.*

Q7: The energy approach to model run-out (not used in this paper) shows that volume does not play a role. But in that case it is assumed that friction is not influenced by volume, which in practice seems to be the case due to all kinds of physical processes in the mass. Therefore in order to show this, I asked the authors to make also a correlation between H/L (mean friction during run-out) and volume.

R7: *Thanks for your suggestion. We have added one chapter "4.1 Apparent coefficient of friction" to discuss the influence of several factors such volume, effective drop height, slope angle, channel angle on the H/L" (see lines 175-195).*

Q8: The effect of slope angle beta is a bit strange In Eq, 2 and 3 it is negative while in Eq 4 it is a positive factor. The authors should comment on this.

R8: *Thanks for your comment. We have discussed this in Section lines 297-302, as below*

"The channel gradient is highly correlated with the H/L ratio as shown in Figure 5b, which actually represents the apparent friction coefficient along the flow path similar to the definition of angle of reach by Heim (1932). This is probably the reason of the negative correlation between travel distance and channel gradient, as the decrease of channel gradient means the decrease of static friction coefficient, and the increase of landslide volume and mobility (Figure 4a and Figure 12)."

This explains the negative influence of beta (the channel gradient) in Equation 2 and 3. While in Equation 4 beta becomes positive, it is probably due to the fact that alpha and beta together determine the reach angle (H/L). The positive maybe caused by the introduce of source area height and slope angle alpha to the regression model in Equation 4. Though this might be still not so convincing, this is what the data tell us. It is also possible some other site-specific factors played important role in controlling the landslide travel distance, but they could not be considered in the model, please see more discussions in the new section 5.2 (lines 314-361).

Q9: The authors give sometimes unclear and peculiar explanations of their findings regarding the effect of volume on travel distance and the effect of total height and channel angle on run-out distance.

R9: *These have been clarified in Section 5.1*

Q10: A lack of clarity for me sometimes occurred in the text where the authors give no definitions of some terms like flow capacity, projectile motion etc., (see my annotations and comments).

R10: *Thanks for your comment. We explained these definitions in the relevant detailed comments tied to lines, see R32.*

Detailed comments tied to lines:

Q11: The grammar, terms and other similar details in lines 40, 68, 76, 80, 85, 86, 138, 183, 184, 238, 241, 279, 317

R11: *We have corrected the above lines.*

Q12: Line 28: What is the role of water in these rock avalanches?

R12: *The term "rock avalanche" has developed naturally in the literature, as a simplification of the complex "rock slide-debris avalanche", proposed by Varnes (1998). Hungr et al.,2001, suggested that the term "rock avalanche" be reserved for flow-like movements of fragmented rock resulting from major extremely rapid rock slides. This contrasts with the term "debris avalanche", which should be reserved for landslides originating in unconsolidated material. Therefore, the role of water on the motion of rock avalanches is omitted in this study.*

Q13: Line 49: Make it more general: The statistical empirical models enveloped in one region cannot be applied in another region with different geomorphological and geological surroundings. And to be honest: the same holds nearly always for physical models: due to the lag of parametric input data the parametric values have to be back calculated with passed events in a particular area and it has even to be seen whether these parametric values are valid for a next event in the same area

R13: *We fully agree with the reviewer. However, this is the problem of all these kinds of models, we could only wait to see whether it could really work for predicting the future events (even in other similar regions).*

Q14: Three major sub-parallel faults were not marked in the map under this title.

R14: *We are sorry about these mismatches of the sub-parallel faults. We have corrected the fault names in the text as "the Maoxian- Wenchuan fault, the Yingxiu-Beichuan fault and the Jiangyou-Guanxian fault".*

Q15: Line 62: what are highly developed stream systems?

R15: *We agree that the highly developed stream systems is not explicit. We have rephrased this sentence to 'With long-term endogenic and exogenic geological process, this region is characterized by high mountains and deep gorges with extreme rates of erosion'.*

Q16: Line 76: give an idea of the size of the fragments of these rock avalanche deposits.

R16: *These rock avalanches deposits are mainly made up of debris with tens of centimeters as average particle size. As we do not have exact grain size distribution data of all these rock avalanche deposition, we did not explain specific number here.*

Q17: Rephrase the sentence 'When the source mass was detached from the slide bedrock, it may directly move into the channel down slope (see Figure 2b), or access the channel with enter it at some impact transition angle of movement direction (see Figure 2a)'.

R17: *Thanks for this comment. We rephrase this paragraph to "The influence of the local geomorphology on the topography of the rock avalanche depositions can be recognized from remote-sensing images after the earthquake. The source area and the transition area of channelized rock avalanches in the study area were somehow easy to be differentiated, as the source area are normally located at the top or upper part of slope, while the flow path (flow or transition area) is partially or fully confined by channels." (in lines 86-90)*

Q18: Line 88-112: Delete!! Repetition ! These section are a copy of what was printed above.

R18: *We are sorry about this mistake. This page has been deleted.*

Q19: Line 119: Vague! What means Geography in this case: 'Another well-known model is the statistical α–β model in which the maximum runout distance is solely a function of geography'.

R19: *We replaced "geography" with "topography".*

Q20: In the first paragraph after chapter title 3.1 General consideration, namely line 116-127, indicate in the type of landslide which was investigated.

R20: *Thanks for this comment. We added a table of published empirical relations related to landslide travel distance prediction, which summaries the keywords, model formula, type and trigger of landslide samples of different models (Table 1 in the revised version).*

Q21: Line 144-146: Altitude difference determines with mass the potential energy difference. The difference in potential energy is of course related to the travel distance but is not a deterministic factor. What surprises me is that in the fore going no attention was given explicitly to the energy method with the use of a friction lines to predict run-out distances. That brings me to the question why the authors did not consider material type as a surrogate for friction.

R21: *Thanks for your comment. We have added section 4.1 (lines 177-196) to analyze the apparent coefficient of friction of channelized rock avalanches and also done some comparison in the discussion part.*

Q22: Line 164-165: Unclear No idea what you mean: 'Volume of some rock avalanches with detailed field investigation are replaced by the data from published literature.'

R22: *Thanks for the comment. We rephrased this sentence to "For some rock avalanches with field measured volume available, we use field measurement data rather than the estimated volume by area" in lines 147-148.*

Q23: Line 173: But in that case the empirical-statistical methods may miss important factors when one does not knowing the physical processes of the mobility.

R23: *We agree that some fundamental physical processes and principles should be considered during the empirical-statistical method construction. But as there are many unknowns related to the hypermobility of the rock avalanches, using empirical-statistical methods can considerably simplify the travel distance prediction. We rephrased this sentence to 'Empirical-statistical methods have long been used as tools to study the mobility of rock avalanche since they are easy to develop and apply, and not dependent on knowing the complex physical processes involved in the hypermobility of rock avalanches.'*

Q24: Line 193: H is not independent of L.

R24: *We agree with you about H is relevant with L and think it can be a basis of the regression model considering H as a variable at least from statistical view.*

Q25: Line 198: The differences must have something to do with the difference in type of landslides. The here investigated landslides are all? rockslides triggered by the Earthquake fragmented into a rock avalanche

R25: *We have found different datasets considering the landslide classification and then make more specific compare to analyze the influence of landslide types and topographic confinement on the motion ability of landslides. We have analyzed the influence of landslide types on the landslide mobility in the discussion part section 5.2 in lines 324-374.*

Q26: Line 209: It appears that in a basic energy approach for run out, volume is canceled out and does not play a role if we assume that volume has no influence on the friction. But volume does have an influence on friction. Friction is lower at larger volumes which can be explained by all kind of physical processes. So it is nice to make a correlation between volume and H/L.

R26: *We thank for your suggestion. We have made a new figure (Figure 13 in the revised version) to compare our dataset with the dataset of Legros et al. (2002). According this figure, the tendency that apparent friction angle (H/L) decreases with the increase of volume is still steady for channelized rock avalanches in our study. However, more scatters occur when the volume of channelized rock avalanches are less than approximately* $4.0x10^6m^3$*, which indicates topographic confinement may play a more important role than volume in determining the travel distance of landslides when the scale of landslide are relatively small.*

Q27: Line 214 and 218: As the Eq.(2) and Eq.(3) show, if beta increases L decreases ??

R27: *Please see the answer to Q8 in R8.*

Q28: Line 224: It looks to me also difficult to predict the area of rock mass which will fail?

R28: *In our opinion, with adequate deformation premonition and detailed investigation, it is possible to reduce the uncertainty related to the scale estimation of potential slope failures.*

Q29: Line 226: The correlation coefficient between H and alpha is not so high. Why do you want to introduce here alpha? In the foregoing you said that it is not a good correlator. Does it give a slighly better result with alpha in the equation?

R29: *Yes it gives slightly better result.*

Q30: Line 229: Compared with Eq 2 and 3 beta is now positive correlated with L in Eq 4??

R30: *Please see the answer to Q8 in R8.*

Q31: Line 247: The Wenjia gully is of course a very complex one with among others a platform with a main deposition area half way.

R31: *We agree with you. We want to take the Wenjia gully as an example to illustrate the influence of micro topography on the mobility of rock avalanches, especially of the broad depression at the upper end of channels.*

Q32: Line 249: what is meaning of 'projectile motion' ?

R32: *The projection process was a special type of failure mode of earthquake-triggered landslides that was first proposed by Huang et al. (2011).* The projection phenomenon was observed in the Wenchuan earthquake region by Huang et al. (2011), defined us the thrown out or projectile motion of slope material due to site amplification effect of seismic wave causing the PGA large than 1 g (lines 314-316). Several features of the Wenchuan Earthquake had quite different characteristics from those produced under general gravity force. The Donghekou landslide is a good example.

Huang, R.Q., Xu, Q., Huo, J.J, 2011. Mechanism and Geo-mechanics Models of Landslides Triggered by 5.12 Wenchuan Earthquake. J.Mt.Sci 8:200-210

Q33: Line 260: Are these validation landslides all rock slides transforming into debris avalanches?

R33: *No, they are rock avalanches. Even though the last two avalanches were triggered by heavy rainfall, their motion did not have strong relations with water.*

Q34: Line 265: With equation 4 we get large errors especially with the Lushan earthquake and when triggered by rain. Do we get an explanation?

R34: *The significant underestimate of travel distance of rock avalanches triggered by the Lushan earthquake and heavy rainfall was supposed to be related to the decrease of rock strength due to the Wenchaun earthquake.*

Q35: Line 266: I find a 40 % error with Eq (4) a bit cumbersome. Maybe it have something to do with the trigger mechanism (rain) and another area (Lushan area more to the south).

R35: *Yes, we have added some discussion on the effects of triggers on the landslide mobility. But in order to address this issue, further datasets are required, see lines 283-288.*

Q36: Line 267: As for the best-fit regression model, But I am not so happy with the best fit regression model because it requires indirect knowledge of the predicted value (L) in order to obtain H.

R36: *H could be considered as the vertical relief from the landslide source area to the nearest gully floor, which then could be obtained easily in the field or from the topography map. Therefore, the results calculated through Eq.2 are possible used as a preliminary estimation of the rock avalanche travel distance.*

Q37: Line 272: Was there an influence during the Wenchuan earthquake on rock weakening in the Lushan area?

R37: *It is possible but we could not find enough evidence now.*

Q38: Line 277: In Eq 2 and 3 beta is negatively correlated with L while in Eq 4 beta is positively correlated with L. I should expect that beta is always positively correlated with L.

R38: *Please see the answer to Q8 in R8.*

Q39: Line 281-282: I do not see the logic of this. May be you can explain a bit more. It may have also something to do with a decrease in friction of larger volumes.

R39: *'Such a high correlation between landslide volume and travel distance implies that the travel distance of channelized rock avalanche is dominated by the spreading of the slide mass (Davies, 1982; Staron,2009).'*

Q40: Line 283-284: The kinetic energy varies along the track starting with zero to a maximum and ending with zero. The positive relation between H and L is determined by the friction line and the slope profile. The friction line start in the source area and crosses the slope in the lower part where the mass comes at rest A variation of slope profiles and a constant friction line will give a linear positive correlation between H and L The llinear correlation between H and L in Figure 3 shows that the friction is more or less constant around a mean value.

R40: *We agree with the reviewer, see more discussions in sub-section 5.2 an 4.1.*

Q41: Line 285: Unclear, need more explanation.

***R41**: We have clarified this in the revised version.*

Q42: Line 287: the medium negative correlation between travel distance and channel angle was referred in chapter 4.1, but Eq 4 shows a positive correlation!

***R42:** Please see the answer to Q8 in R8.*

Q43: Line 290: the sentence 'the channel could not stop the rock avalanche until it lost fragment flow discharge' is not clear.

***R43:** We have deleted that part, please see the new section 5.2 (line 314-361)*

Q44: Line 291-292: If discharge and flow velocity are the same the crossectional flow area is the same . Width and depth of the crossection can change but what has that to do with a decreasing slope angle leading to a larger run-out distance? More explanation here. What do you mean by flow capacity?

***R44:** We have deleted that part, please see the new section 5.2 (line 314-361)*

Q45: Line 305: I am not so happy with the factor total relief because it is highly dependent on the run-out distance L. ' As the total relief and channel angle act as external factors for the motion of rock avalanche, it seems like it is in essence landslide volume that control the rock avalanche movement.'

***R45:** please see R36, which is the same question.*

Q46: Line 312: 'entrainment volume' is not considered in this paper Can be very important!

***R46:** We agree, however without detailed pre- and post-event DEMs, it is not possible to quantify the entrainment volume.*

Q47: Line 312: you mean in our case Beta Because apart from volume and H nothing was considered in the equation 2 and 3 and in 4 Alpha and Hs. A bit confusing to introduce here the term flow capacity as a factor.

***R47:** Please see the answer to Q8 in R8.*

Comments on figures:

Q48: Fig 6, 7: the lateral axis titles are both log(L).

R48: *Thanks for your comment. We have revised these two figures in the revised version.*

3. Response to Reviewer 3, Prof. Martin Mergili

Comments in general:

Q1: Pages 3 and 4 are almost identical – I think that page 4 can just be deleted.

R1: *Thank you for point it out. Page 4 has been deleted.*

Q2: A reference that could be interesting: Mergili, M., Krenn, J., Chu, H.-J. (2015)

R2: *We are sorry for missing this very interesting and relevant paper, which has been cited in the introduction section "Mergili et al. (2015) developed a multi-functional open source tool r.randomwalk, for conceptual modelling of the propagation of mass movements, which combined the empirical model with the numerical model." (lines 44-46)*

Specific comments:

We have done careful copy editing to revise grammar and style errors.

Q3: Line 119: "topography" would be suitable rather than "geography"

R3: *We agree and it has been corrected to "Topography".*

Q4: Line124: please explain what you mean with "slope transition angle"

R4: *We have explained it in the text. The slope transition angle refers to the angle between the failed upper slope and lower slope, which is the definition of Guo et al. (2014), see line 103 in the revised version.*

Q5: Line 130 what is the "angle of impact"?

R5: *We have rephrased the "angle of impact" to most commonly used term "angle of reach" in line 111, which actually represents the relationship between the height of fall* *and maximum run-out distance, also called apparent coefficient of friction by Heim (1932).*

Q6: Line 145 In many cases it is probably hard to clearly delineate the source area from the transition area – maybe you could shortly explain which strategy you applied to do so?

R6: *Thanks for your comments. For the channelized rock avalanches, their source area and transition area are somehow easy to be differentiated, as the source area are normally located at the top or upper part of slope, while the flow path (transition area) is partially or fully confined by channels. We added an explanation in the text: "The source area and the transition area of channelized rock avalanches in the study area were somehow easy to be differentiated, as the source area are normally located at the top or upper part of slope, while the flow path (flow or transition area) is partially or fully confined by channels" (in lines 87-90).*

Q7: Line 148–165: This part does NOT describe the data you use, but defines some terms. It should be moved to the introduction.

R7: *Thank you for your comment, but we think this part fits better to the Data section, because it mainly defines the parameters in Table 1 that we used for building the regression models. Table 1 summarized the data from 38 channelized rock avalanches.*

Q8: Line 159–160: Is L the Euclidean distance, or the distance along the flow path?

R8: *L is the Euclidean distance, which has been specified in the text (line 142).*

Q9: Line 176: You should give some examples or references demonstrating that the existing models did not produce a favourable prediction.

R9: *We thank the reviewer for the nice comment. We have added Fig.13 to show the difference of our dataset with others' models. In addition, a new table (Table 1) has been added to summarize the existing models in the literature.*

Q10: Line 182: You have to explain what "x" is in Eq. 1.

R10: *Thanks for pointing this out. We has specified that x (i= 1, 2, …, n) are the predictors ('independent variables', e.g. total relief, landslide volume etc, see line 170-171.*

Q11: Line 238: Eq. 5 does not exist

R11: *This was a typo, which has been corrected.*

Q12: Line 261: better use 10^3 or 10^6 instead of 10^4.

R12: *We have revised all the units to* 10^3.

Q13: Line 296: What do you mean here with "projection"?

R13: *The projection process was a special type of failure mode of earthquake-triggered landslides that was first proposed by Huang et al. (2011). The projection phenomenon was observed in the Wenchuan earthquake region by Huang et al. (2011), defined us the thrown out or projectile motion of slope material due to site amplification effect of seismic wave causing the PGA large than 1 g (lines 314-316).*

Huang, R.Q., Xu, Q., Huo, J.J, 2011. Mechanism and Geo-mechanics Models of Landslides Triggered by 5.12 Wenchuan Earthquake. J.Mt.Sci 8:200-210

Please check the marked-up manuscript with changed parts marked in red.

Empirical prediction for travel distance of channelized rock avalanches in the Wenchuan earthquake area

Weiwei Zhan, Xuanmei Fan, Runqiu Huang, Xiangjun Pei, Qiang Xu, Weile Li

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, 610059, China

Correspondence to: Xuanmei Fan (fxm_cdut@qq.com)

Abstract. Rock avalanches are extremely rapid, massive flow-like movements of fragmented rock. The travel path of the rock avalanches may be confined by channels in some cases, which were named as the channelized rock avalanches. Channelized rock avalanches are potentially dangerous due to their hardly predictable travel distance. In this study, we constructed a dataset with detailed characteristic parameters of 38 channelized rock avalanches triggered by the 2008 Wenchuan earthquake using the visual interpretation of remote sensing imagery, field investigation, and literature review. Based on this dataset, we assessed the influence of different factors on the runout distance and developed prediction models of the channelized rock avalanches using the multivariate regression method. The results suggested that the movement of channelized rock avalanche was dominated by the landslide volume, total relief, and channel gradient. The performance of both models was then tested with an independent validation dataset of 8 rock avalanches that induced by the 2008 Wenchuan, the Ms7.0 Lushan earthquake, and heavy rainfall in 2013, showing acceptable good prediction results. Therefore, the travel distance prediction models for channelized rock avalanches constructed in this study is applicable and reliable for predicting the run out of similar rock avalanches in other regions.

Keywords: channelized rock avalanches; travel distance; empirical prediction; multivariate regression model; Wenchuan earthquake

1 Introduction

Rock avalanches are extremely rapid, massive flow-like movements of fragmented rock from a very large rock slide or rock fall (Hungr et al. 2014). Hundreds of rapid and long run-out rock avalanches were triggered by 2008 Wenchuan earthquake in Sichuan Province (Zhang et al. 2013), with catastrophic

consequences for residents in the affected areas. For instance, the 15×10^6 m^3 Donghekou rock avalanche in Qingchuan County, near the seismogenic fault, travelled 2.4 km, killing about 780 persons and destroying four villages (Zhang et al. 2013). Rock avalanches can cause incredible damage due to their characteristics of high-speed and unexpectedly long runout, while their transport mechanisms are still considered to be controversial among many researchers (Hungr et al. 2001). Therefore, constructing prediction models for rock avalanche travel distance is meaningful in terms of not only theoretical research on motion mechanisms but also in practical application for risk mitigation of rock avalanches.
Methods for determining the travel distance of landslides can be divided into two categories: dynamic modeling (Heim 1932; Sassa 1988; Hungr et al. 2009; Pastor et al. 2009; Lo et al. 2011;), and empirical modeling (Scheidegger 1973; Lied et al 1980; Corominas, 1996; Finlay et al. 1999; Van Westen et al. 2006; Guo et al. 2014). The dynamic models are able to provide information on landslide intensity, such as velocity, affected area and deposition depth, in addition to travel distance. Nonetheless, dynamic models with a variety of physical bases require accurately quantified input parameters that are difficult to obtain before the events, and many simplified assumptions that are not applicable to the actual situation. Recently Mergili et al. (2015) developed a multi-functional open source tool r.randomwalk for conceptual modelling of the propagation of mass movements, which can combine the empirical model with the numerical model. Empirical models considering the correlations between observational data provide an effective technique to aid in understanding mechanisms of rock avalanche motion and to develop practical models for predicting rock avalanche travel distance. However, the empirical-statistical models set up from samples with different geomorphological and geological surroundings, trigger conditions, or failure modes are not very sufficient to be applied to the Wenchuan earthquake area.

In this study, we compiled a dataset of 38 rock avalanches with flow paths confined by channels (this kind of landslide is hereinafter termed as channelized rock avalanche) from interpretation of remote sensing, field investigations and literature review (see Section 3.1). Statistical correlations were used to determine the principle factors affecting the mobility of the channelized rock avalanches. Then a stepwise multivariate regression model was developed to build a best-fit empirical model for the travel-distance prediction of this kind of rock avalanches in the Wenchuan earthquake area. A derivative multivariate regression model was also constructed. The performance of both models was then tested with an independent validation dataset of 8 rock avalanches in the same area.

2 Rock avalanches in study area

The study area (see Figure 1) is on the northeast-trending Longmenshan thrust fault zone between the Sichuan basin and the Tibetan plateau. Three major sub-parallel faults are: the Wenchuan-Maowen fault, the Yingxiu-Beichuan fault and the Pengguan fault (Fan et al., 2014). With long-term endogenic and exogenic geological process, this region is characterized by high mountains and deep gorges with extreme rates of erosion (Qi et al 2011).

【Fig.1 somewhere here】

This study selected 38 channelized rock avalanches induced by the Wenchuan earthquake to study the relations between travel distance and influential factors. These rock avalanches occurred along the seismogenic Yingxiu-Beichuan fault; the distance to the fault ranged from 0 m ~21,300 m with a mean value of 3,895 m. Another distribution characteristic was that these rock avalanches mainly clustered on the step-overs, bends and distal ends of the seismogenic fault. These distribution characteristics of the large rock avalanches suggested that the occurrence of rock avalanches was associated with very strong earthquake ground motion. The Wolong Station recorded the highest seismic acceleration with the peak ground acceleration reaching 0.948g vertically and 0.958g horizontally (Yu et al., 2009). Locally, the ground motion was high enough to throw rocks into the air.

The lithology of outcropping rock in source areas can be divided to four types: carbonate rock, phyllite, igneous rock and sandstone. The deposit of the rock avalanches in the study area was usually debris with mean particle size as tens of centimeters, which suggests that the sliding masses were intensively fragmented during their movement.

The influence of the local geomorphology on the topography of the rock avalanche depositions can be recognized from remote-sensing images after the earthquake. The source area and the transition area of channelized rock avalanches in the study area were somehow easy to be differentiated, as the source area are normally located at the top or upper part of slope, while the flow path (flow or transition area) is partially or fully confined by channels (Figure 2).

【Fig.2 somewhere here】

3 Data and method

3.1 General consideration

Various statistical methods have been applied to predict travel distance of landslides, and some popular relationships are summarized in Table 1. The most prevalent one is the equivalent friction coefficient model, which only takes account of landslide volume (Scheidegger, 1973). Another well-known model is the statistical α–β model in which the maximum runout distance is solely a function of topographic conditions (Lied et al., 1980; Gauer et al. 2010). Finlay et al. (1999) developed some multiple regression models containing slope geometric parameters like slope height and slope angle for the travel distance prediction of landslides on the artificial slopes upon the horizontal surface. Based on the data of 54 landslides which was relatively open or confined by gentle lateral slope, Guo et al. (2014) established an empirical model for predicting landslide travel distance in Wenchuan earthquake area and suggested that rock type, landslide volume, and slope transition angle (between the failed upper slope and lower slope) play dominant roles on landslide travel distance. And there are increasing sound that the prediction models of travel distance should adapt to different types of landslides (Corominas 1996; Fan et al, 2014).

【Table 1 somewhere here】

Moreover, the shape and mobility of rock avalanches are controlled by the local topography. Heim (1932) firstly mentioned the influence of local morphology that the debris masses will undergo different effects with the angle of reach changing, and rock avalanches has to conform to the local morphology regardless of their scale. Abele (1974) summarized four different possibilities of adaptation of the rock avalanche to local morphology. Hsu (1975) noted that a sinuous pathway can reduced runout distance of rock avalanches. Nicoletti (1991) inferred that local morphology impacts on landslide motion through changing the rate of total energy dissipation along the travel path. To determine the influence of specific channels on the travel distances of rock avalanches, we respectively consider the impacts of gradients of the upper slopes and lower channels.

Rock avalanches triggered by the Wenchuan earthquake usually initiated from top or the higher part of slopes possibly due to the altitude amplification effect of earthquake acceleration, therefore the toes of the rupture surface were commonly found in the source area at the upstream of the pre-existing channel (See Figure 3). When the slope failed, the failed mass travelled a long distance down the channel. The 38 rock avalanches in this study are selected with the criterion that the flow path is partially or fully confined by channels. The volumes of these rock avalanches ranged from 0.4–50 ×10^6 m^3; with horizontal travel distances between 0.58 and 4.00 km. The volume is prior to the area to be put into the travel distance prediction model as it had much more physical meanings. And we introduced total relief as well as the height of source area to probe the influences of the potential energy difference and altitude difference of source mass on the travel distance of the rock avalanches.

【Fig.3 somewhere here】

3.2 Data

The terms and notations of a typical channelized rock avalanche are shown in Figure 3. The local morphology of a rock avalanche can be divided to three sections: initiated slope (source area), channel (main travel path or flow area) and valley floor (deposition area). When the mass moves over the initiated slope section, it is free from lateral constraints, and the moving mass is able to spread laterally. After entering the channel, the flowing mass is constrained by the two lateral slopes. Finally, the mass may reach to a wide valley floor, where it spreads laterally and deposits. The average inclination of the source area and travel path are obtained respectively, while the gradient of valley floor (deposition area) is neglected as it has very little variation. Slope angle (α), denotes the average inclination of the initiated slope section. Channel angle (*β*), denotes the average inclination of the sectional channel. Source area height (Hs), denotes the elevation difference between the crest of the sliding source and the toe of the rupture surface. Total relief (H) is the elevation difference between the crest of the sliding source and the distal end of the debris deposit. Travel distance (L) is the horizontal Euclidean distance between the crest of the sliding source and the distal end of the debris deposit. Landslide area (A) is the source area of the rock avalanche obtained from remote sensing image interpretation. An empirical scaling relationship with different empirical coefficients is frequently used to link the volume and the area of landslides in different areas or with different types, and we chose the one developed by Parker et al. (2011) in the same study area. For some rock avalanches with field measured volume available, we use field measurement data rather than the estimated volume by area. The parameters of 38 rock avalanches are listed in Table 2.

【Table 2 somewhere here】

3.3 Method

Travel distance is the most important prediction parameter in rock avalanche hazard evaluation in mountainous areas. Travel distance prediction of rock avalanche is a complicated issue as it is determined by many different properties of the materials (i.e., grain size distribution and water content), topographical factors, mobility mechanics of failed mass, the confinement attributes of travel path, and so on (Guo et al., 2014). Empirical-statistical methods have long been used as tools to study the mobility of rock avalanche since they are easy to develop and apply, and they are not dependent on knowing the complex physical processes involved in the hypermobility of rock avalanches. Channelized rock avalanches have unique movement paths involving complex, and possibly little-known physical processes such as grain collisions, fragmentation and entrainment of bed material from the channel sides and bottom. Existing empirical models have not produced a favourable prediction. The forecasting index system and the prediction model of channelized rock avalanches should be discussed first.

In this paper, we first selected controlling factors on rock avalanche travel distance through correlation analysis. Then we fitted a stepwise multivariate regression model using all significant correlation variables to obtain a best-fit empirical model for landslide travel distance, and explored which factors were statistically significant at the same time, as expressed in equation (1).

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + ... + b_n x_n + \varepsilon \qquad (1)$$

where y is the predictant ('dependent variable'), e.g. travel distance of rock avalanche, x_i (i = 1, 2, …, n) are the predictors ('independent variables'), b_0 is the intercept, b_i (i = 1, 2, …, n) are the regression coefficients of the corresponding, and ε is the residual error, here assumed to be independently and normally distributed. Predictors were added to the regression equation one at a time until there was no significant improvement in parsimonious fit as determined by the adjusted R^2.

4 Results and validation

4.1 Reach angle of channelized rock avalanches

Reach angle, also called the apparent coefficient of friction, is a well-known index to express the landslide mobility. It is the angle of the line connecting the crown of the landslide source area to the toe of the displaced mass. This angle is firstly conducted by Heim (1932) in the famous energy-line model as the average coefficient of friction of a sliding mass from initiation to rest. The reach angle is supposed to possess the ability of landslide mobility prediction because of its tendency to decrease with the increase of landslide volume as illustrated by many researchers (Scheidegger, 1973; Corominas, 1996).

In this study, the influence of landslide volume, drop height, slope of the source area and flow path (channel) on the reach angle of the channelized rock avalanches are examined respectively (Figure 4 and 5). Figure 4(a) presents Log(volume) vs. Log(reach angle), showing a weak correlation probably due to the limited volume range in our dataset, constrained movement in channel and local morphology of channels. In order to analyse the effect of potential energy on the reach angle, the effective drop height (defined as the total height minus the height of source area) is used instead of the total height to exclude the effect of the superposition of source height and total height. That is especially useful for landslides with large-size initiation but limited travel distance. A significant positive correlation is observed between the reach angle and effective drop height, apart from the four lower scatters in the Figure 4(b). Figure 5(a) and (b) indicate obvious positive correlations between the reach angle with both the slope gradient in source area and channel gradient along the flow path. The large scatter in Figure 4 and 5 suggests that the reach angle of channelized rock avalanches might be controlled by some other factors, such as local topography rather than volume, but this needs to be further studied.

【Fig.4 somewhere here】

【Fig.5 somewhere here】

4.2 Relationships between travel distance and volume, topographic relief of rock avalanche

Correlation coefficients between different variables and travel distance (L) were calculated first, generating the correlation coefficients matrix shown in Table 3. The significant relevant predictors with the 95% confidence for travel distance prediction of channelized rock avalanches are landslide area (A), landslide volume (V), total relief (H), source area height (Hs) and channel angle (β), with correlation coefficient of 0.877, 0.866, 0.857, 0.675, -0.467, respectively.

【Table 3 somewhere here】

Figure 6 illustrates that the travel distance (L) varies exponentially with the volume (V) of rock avalanche with an exponential exponent of 0.377. Compared with a compilation of worldwide rock avalanche data (Legros, 2002), the mobility of rock avalanches in our study area is stronger than other non-volcanic landslides (power exponent is 0.25), but weaker than volcanic landslides and debris flows (both power exponent is 0.39), as shown in Fig.13. The relation between travel distance (L) and total relief (H) is shown in Figure 7. The result suggests that the mobility (travel distance) of rock avalanche has relatively strong linear relationship with total relief (H). The scale factor is close to 2.4, which means that the apparent friction coefficient (H/L) for the rock avalanches is approximately 0.42. This is significantly lower than the commonly observed static coefficient of friction of rock material (~0.6).

【Fig.6 somewhere here】

【Fig.7 somewhere here】

4.3 Multivariate regression model of rock avalanche travel distance

According to the matrix of correlation coefficients (Table 3), the slope angle (α) does not have a significant correlation with travel distance (L) at the 95% confidence level. Thus this variable could be excluded first during development of the best-fit regression model for travel distance prediction. Prior to the landslide area (A), the landslide volume (V) has been considered in the models as it has much more physical meaning. In the end, a stepwise linear multivariate regression technique was applied to find the best-fit travel distance regression model using the significant relevant predictors including landslide volume (V), total relief (H), source area height (Hs) and channel angle (β). The best-fit regression equation for travel distance prediction were derived from the dataset of Table 2 (see equation (2)), and the coefficient of the variables with 95% confidence are shown in Table 4.

$$\log(L) = 0.420 + 0.079\log(V) + 0.718\log(H) - 0.365\log(\tan\beta) \qquad (2)$$

Where log is the logarithm of 10; *L* is the predicted travel distance (m); *V* is the landslide volume (m^3); *H* is the total relief (m); *β* is the mean gradient of the channel (°). Equation (2) can be transformed to equation (3):

$$L = 2.630\,V^{0.079} H^{0.718} (\tan\beta)^{-0.365} \qquad (3)$$

The best-fit travel distance regression equation indicates that the travel distance of channelized rock avalanche is positively correlated with landslide scale (landslide volume) and potential energy loss (total relief), and negatively correlated with channel gradient, which is coherent with the results of correlation analysis in Table 3.

While the total relief (*H*) will be unknown prior to landslide occurrence, the elevation difference of source area will be available through specific field investigation on a potential rock avalanche area. Hence, we introduced Hs and α in replacement of *H* to the regression model as they have relative high correlation with *H* (correlation coefficients are 0.801 and 0.429 respectively). The transformed alternative regression equation is given as equation (4) with the coefficient of the variables with 95% confidence in Table 4.

$$L = 3.6 V^{0.303} Hs^{0.244} (\tan\alpha)^{-0.115} (\tan\beta)^{0.072} \qquad (4)$$

Where L is the predicted travel distance (m); *V* is the landslide volume (m^3); *Hs* is the height of source area (m); *α* is the mean angle of slope segment (°); *β* is the mean gradient of the channel segment (°). The validity of these two models were evaluated through the significance test leading to the highest R^2 value and the lowest residual standard error. Table 4 shows the significance values for the prediction model equations. Adjusted R^2 means adjusted multiple correlation coefficient, which represents the correlation level between the dependent variable and the independent variables. The calculation of adjusted R^2 considers the number of variables and can be used to compare goodness of fit of different regression models. Adjusted R^2 of the two regression equations are high, suggesting that the constructed regression models are reliable. The adjusted R^2 of Equation (2) is higher than Equation (4), implying a higher precision for the best-fit regression model. The significance test results on the regression equation suggest the significance of multiple regression equations (($F=173.5> F_{0.05}(2.883)$ for equation (2), and

F=49.5> $F_{0.05}$(2.659) for equation (4)). Figures 8 (a) and (b) show the distributions of the residuals in relation to the observed travel distance estimated by using equation (2) and (4). Both plots illustrate normality, constant variance and absence of trends in the residuals.

【Table 4 somewhere here】

【Fig.8 somewhere here】

Figure 9 compares the predicted travel distances estimated by using equations (2) and (4) with the observed ones. It suggests that the predicted values of the samples are close to the observed ones. Where L exceeds 2000 m, the predicted travel distance calculated by using two models are lower than actual one, with relatively large residual error.

【Fig.9 somewhere here】

4.3 Validation

The regression equations were tested using an independent sample validation dataset of 8 rock avalanches in the same area induced by three different kinds of triggers: 2008 M_s 8.0 Wenchuan earthquake, 2013 M_s7.0 Lushan earthquake, and heavy rainfall (Table 5). The volume of these samples ranged from 88×10^3–1.5×10^6 m^3, and travel distance from 372–1372 m. The background parameters and the predicted values of each avalanche are listed in Table 5. The relative errors between the predicted values estimated by using equation (3) and observed values of the travel distance of the rock avalanches, $|L_{predicted}-L_{observed}|/L_{observed}\times 100\%$, are between -14.4% and 17.2%, while the relative errors are -44.0% and 17.9% for equation (4). On the whole, these two regression models achieved acceptable prediction accuracy for preliminary forecasting of travel distance of rock avalanches in rugged mountainous areas. The best-fit regression model appeared to provide greater precision than the alternative model. Regarding the influence of triggers on the travel distance of the channelized rock avalanches, those triggered by rainfall and the Lushan earthquake seemed to be more mobile. It is inferred that the former difference is due to the high water content in failed mass induced by rainfall. A possible reason why two rock avalanches triggered in the Lushan earthquake travelled farther may be because of structural weakening of slope rock mass in the 2008 Wenchuan earthquake in the study area.

【Table 5 somewhere here】

5 Discussion

5.1 Prediction for travel distance of channelized rock avalanche

The results of our analysis of the data set, indicates that the mobility (travel distance) of channelized rock avalanche is positively correlated with landslide volume and total relief but negatively correlated with channel gradient. As Figure 6 shows, the travel distance of channelized rock avalanche would rapidly increase with volume of rock avalanche enlarged. Such a high correlation between landslide volume and travel distance implies that the travel distance of channelized rock avalanche is dominated by the spreading of the slide mass (Davies, 1982; Staron, 2009). The high positive correlation between total relief and travel distance is for two reasons: the larger the total relief is, the more kinetic energy the slide mass could obtained and the further distance could it travel (Legros, 2002). The channel gradient is highly correlated with the H/L ratio as shown in Figure 5b, which actually represents the apparent friction coefficient along the flow path similar to the definition of angle of reach by Heim (1932). This is probably the reason of the negative correlation between travel distance and channel gradient, as the decrease of channel gradient means the decrease of static friction coefficient, and the increase of landslide volume and mobility (Figure 4a and Figure 12).

The residual analysis result demonstrates that the projection process in the early motion stage will significantly enlarge the travel distance of rock avalanches. The projection phenomenon was observed in the Wenchuan earthquake region by Huang et al. (2011), defined us the thrown out or projectile motion of slope material due to site amplification effect of seismic wave causing the PGA large than 1 g. The nature of this phenomenon is suggested to be involved with transformation of motion mode from sliding to flowing due to collision and fragmentation effects after the projection (Davies et al, 1999). Furthermore, the degree of fragmentation of failed mass should have remarkable influence on the travel distance of rock avalanche, and other factors changing the fragmentation degree should be further study, such as earthquake effect, geologic structure and rock type.

5.2 The mobility of channelized rock avalanches

The mobility of landslides is influenced by a variety of factors, such as topography, landslide size, material type, landslide type and water content. The important role of topographical constrains on the landslide mobility can be referred from the high positive correlation of reach angle with effective drop height, slope gradient and channel gradient (see Figure 4 and 5). Besides, some micro topography like turns (changes of channel flow direction), drop cliff and broad depression along the landslide travel path will influence the motion and deposition of rock avalanches remarkably. The rock avalanches corresponding with the four large bias scatter in Figure 4 (b) are the Wenjia gully, Hongshi Gully, Niumian Gully and Donghekou rock avalanche, whose flow path has cliffs in the upper end of channels with notable drop heights of 260 m, 150 m, 60 m and 160 m respectively according to field investigations. Moreover, fluidization characteristics such as super-elevation near curve transitions can be found in the channel section of these four rock avalanches. This steep micro-topography will enlarge the mobility of rock avalanches because the sliding mass will undergo the drop, collision and fragmentation effects in the early motion stage, which will facilitate motion mode transformation from sliding to flowing. This transformation will enhance the mobility of rock avalanches traveling a much longer distance than predicted. Attention also need to be paid to the broad depression along the channel which is possible to contain a large amount of debris mass and therefore to curb the travel distance of channelized rock avalanches. For example, in the Wenjia Gully almost half of the total volume of the rock avalanche was deposited at the beginning of the channel (see Figure 10(c)), leading to a lower travel distance than expected.

【Fig.10 somewhere here】

To investigate the influence of landslide types on the landslide mobility, we compile our dataset with the dataset created by Guo et al. (2014), as it contains the data of 32 landslides with other types (debris avalanches, rock slides, soil slides) triggered by the Wenchuan earthquake. We plot the relationship between L with V and H respectively for different landslide types (see Figure 11 a and b). As shown in Figure 11, rock avalanches have the strongest mobility while soil slides show the weakest one, and the mobility of rock slides is approximate to the mobility of debris avalanches. While compared with the worldwide datasets by using the reach angle as the mobility index (see Figure 12 and 13), our dataset shows a consist tendency with the worldwide datasets presented by Corominas (1996) and Legros (2002). Our dataset could contribute to the worldwide database by filling the gap of rock avalanches.

【Fig.11 somewhere here】

【Fig.12 somewhere here】

【Fig.13 somewhere here】

The common triggers of landsides are earthquakes and rainfall. The influence of triggers on landslide distribution has been well studied, but the effect of triggers on the landslide mobility is still a scientific gap. Zhang et al. (2013) indicated that rock avalanches triggered by earthquakes have a slightly lower mobility than ones not triggered by earthquakes, and rock avalanches close to the seismic fault do not always have a higher mobility even when a rock avalanche near the seismic fault is subjected to higher ground accelerations. Guo et al. (2014) also mentioned that the seismic acceleration has less influence than rock type, sliding volume, slope transition angle and slope height on landslide travel distance. According to Table 5, two rainfall-induced rock avalanches show stronger mobility than earthquake-induced ones. The rock avalanches induced by rainfall express a stronger mobility than the earthquake-induced ones may due to lubrication effect of water However, detailed study on the influence of triggers on the landslide mobility need further dataset.

6 Conclusion

Channelized rock avalanche refers to a rock avalanche with a flow path confined between valley walls. Relevant detailed data on thirty-eight channelized rock avalanches triggered by Wenchuan earthquake were collected by remote sensing, field investigation and literature review. The results of correlation and regression analysis revealed that the movement of channelized rock avalanches is dominated by spreading of the failed mass. Landslide volume (V), total relief (H) and channel angle (β) had predominant effects played a dominating role in the on travel distance of channelized rock avalanches. Stepwise multivariate regression was used to develop a nonlinear best-fit travel distance prediction model for the channelized rock avalanches. An alternative multivariate regression model was also built. The reliability of the two models was tested on by an independent validation dataset of 8 rock avalanches in the same area and produced good results, meeting the requirements for preliminary evaluation of travel distance for channelized rock avalanches in the Wenchuan earthquake area.

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Zhang, M., and Yin, Y.: Dynamics, mobility-controlling factors and transport mechanisms of rapid long-runout rock avalanches in China, Engineering Geology, 167, 37-58, 2013.

454 **Table 1** Summarization of statistical relationships indicating landslide mobility in the literature

Approach	Keywords to characterize the methods	Landslide types	Triggers	Main references
Reach angle	$\text{Log } H/L=C_1\text{Log } V+C_0$	Rock fall/slide/avalanche and flow-like landslides	Unkonwn	Scheidegger, 1973; Corominas,1996
	$H/L=C_1 \tan S+ C_0$	Soil slides, snow avalanches	Non-seismic	Hunter et al., 2003; Lied et al., 1980
Travel distance	$\text{Log } L=C_1Rt+C_2\text{Log } V+ C_3 \sin S+C_0$	Rock/soil slides and rock/debris avalanches,	Seismic	Guo et al., 2014
	$\text{Log } L=C_1 \text{ Log } H +C_2 \text{ Log } \tan S+C_0$	Soil landslides on artificial slopes	Human activities	Finlay et al., 1999
	$L=C_1V^{C2}$	Debris slides, debris slides	Rainfall	Jaiswal et al., 2011

455 *Note: C0, C1, C2, C3 are the constants. L is the travel distance. H is the total height. V is the volume. S*
456 *is the average slope angle while St is the slope transition angle. Rt is the rock type.*

Table 2 Data of various factors for establishment of prediction model of rock avalanche travel distance

Code	Landslide name	Longitude, (°E)	Latitude, (°N)	Landslide area, A (m^2)	Landslide volume, V (m^3)	Source area height, Hs (m)	Slope angle, α (°)	Channel angle, β (°)	Total relief, H(m)	Travel distance, L (m)	Reference
1	Wenjia Gully	104.140	31.552	3000566	50000000	440	26	7	1320	4000	Xu et al., 2009
2	Shuimo Gully	103.981	31.442	915608	19960000	490	35	10	860	2000	
3	Dawuji	104.196	31.702	792190	16330000	540	29	13	880	1900	
4	Donghekou	105.113	32.410	1283627	15000000	240	25	11	640	2400	Xu et al., 2009
5	Hongshigou	104.130	31.624	687520	13410000	290	37	17	1040	2700	
6	Woqian	104.964	32.308	695672	12000000	330	30	10	560	1600	Xu et al., 2009
7	Xiaojiashan	104.038	31.465	465899	7810000	480	48	24	930	1350	
8	Niumian Gully	103.456	31.044	527700	7500000	320	32	13	800	2640	Xu et al., 2009
9	Liqi Gully	105.207	32.169	355113	5360000	360	37	12	650	1500	
10	Caocaoping	104.139	31.607	354046	5340000	345	31	17	580	1340	
11	Huoshi Gully	104.134	31.616	322155	4680000	270	38	17	700	1320	
12	Shibangou	105.090	32.419	496983	4500000	450	34	9	650	1800	Xu et al., 2009
13	Xiejiadianzi	103.841	31.298	294256	4000000	400	34	15	720	1600	Xu et al., 2009
14	Dashui Gully	103.675	31.199	241874	3150000	320	30	17	560	1400	
15	Changping	103.754	31.259	224645	2840000	290	37	16	500	1200	
16	Xiaomuling	104.102	31.613	218704	2740000	175	45	26	710	1025	
17	Baishuling	104.385	31.807	208968	2570000	335	36	20	620	1200	
18	Dawan	104.536	31.907	203959	2480000	220	28	20	480	1000	
19	Xiaojiashan	104.182	31.486	198165	2385499	340	44	20	650	1135	

20	Shicouzi	104.918	32.243	169540	1920000	260	30	26	640	1200
21	Changtan	104.133	31.508	151094	1640000	400	33	25	1050	1650
22	Hongmagong	104.962	32.301	144683	1540000	195	30	14	330	800
23	Baiguocun	105.088	32.385	139800	1470000	165	26	12	260	800
24	Qinglongcun	105.036	32.342	134079	1390000	90	21	11	200	600
25	Pengjiashan	104.546	31.930	127156	1290000	200	33	28	580	1000
26	Longwancun	104.571	31.922	99821	920000	205	31	28	460	860
27	Zhangzhengbo	105.017	32.333	99726	920000	125	29	15	320	800
28	Dujiayan	105.028	32.336	94769	860000	100	33	17	400	880
29	Madiping	104.996	32.355	94632	860000	140	27	31	395	740
30	Yandiaowo	105.099	32.391	92128	820000	145	30	26	390	800
31	Chuangzi Gully	104.085	31.518	91717	820000	185	35	15	295	670
32	Zhaojiashan	105.041	32.342	82329	700000	115	22	16	280	700
33	Weiziping	105.083	32.387	74661	620000	135	22	18	240	600
34	Maochongshan 2	104.908	32.243	70251	570000	160	38	22	500	740
35	Waqianshan	105.049	32.376	70007	560000	135	24	18	250	620
36	Muhongping	104.982	32.291	68288	540000	175	28	20	420	970
37	Dapingshang	104.542	31.889	65700	520000	160	34	29	365	640
38	Liushuping 2	105.054	32.365	54810	400000	150	29	16	240	580

Table 3 Correlation coefficients of continuous variables listed in Table 2

	A	**V**	**H**	**Hs**	***α***	***β***	**L**
A	1.000	0.982	0.674	0.521	*-0.119*	-0.524	0.877
V	—	1.000	0.713	0.560	*-0.055*	-0.492	0.866
H	—	—	1.000	0.801	0.429	*-0.130*	0.857
Hs	—	—	—	1.000	0.399	-0.323	0.675
α	—	—	—	—	1.000	*0.264*	*0.082*
β	—	—	—	—	—	1.000	-0.467
L	—	—	—	—	—	—	1.000

Note: The number in Italics indicates the two variables are not significantly correlated

Table 4 The regression coefficients and results of significance tests of two multivariate regression models

Equations	Coefficients*	Intercept	Coefficient of log(V)	Coefficient of log(H)	Coefficient of log(tan*β*)	Coefficient of log(Hs)	Coefficient of log(tan*β*)	Adjusted R^2	F_{stat}	$F_{0.05}$
Best-fit regression equation	LCI	0.175	-0.013	0.521	-0.548	—	—	0.933	173.5	2.883
	Mean	0.420	0.079	0.718	-0.365	—	—			
	UCI	0.665	0.171	0.914	-0.182	—	—			
Alternative regression equation	LCI	0.110	0.199	—	-0.165	-0.002	-0.464	0.840	49.5	2.659
	Mean	0.561	0.303	—	0.072	0.244	-0.115			
	UCI	1.012	0.407	—	0.308	0.489	0.233			

Note: "Coefficients" of each variable has three kinds: LCI is lower bound of the coefficients with 95% confidence; Mean is the mean value of the coefficients; UCI is upper bound of the coefficients with 95% confidence;

Table 5 Background parameters and predicted values of 8 rock avalanches in the same area used for validation

Landslide name	Longitude	Latitude	Triggers*	*V* $/10^4m^3$	*α* / °	*B* / °	*Hs* /m	*H* /m	*L* /m	$L'_{(3)}$** /m	Error / %	$L'_{(4)}$*** /m	Error / %
Pianqiaozi	104.370	31.822	WCEQ	8.8	35	19	153	205	372	436	17.2	373	0.3
Yangjiayan	104.328	31.755	WCEQ	25.4	41	23	164	304	518	583	12.5	518	0.1
Shanshulin	103.508	31.181	WCEQ	27.9	34	25	340	433	715	731	2.3	660	-7.6
Fuyangou	103.501	31.422	WCEQ	71.9	38	28	385	530	763	869	13.8	900	17.9

Dayanbeng1	102.762	30.179	LSEQ	100	53	10	254	424	1267	1136	-10.3	781	-38.4
Dayanbeng2	102.761	30.178	LSEQ	110	50	8	237	407	1372	1208	-12.0	787	-42.6
Ermanshan	102.739	29.322	RF	100	33	15	148	635	1370	1303	-4.9	767	-44.0
Wulipo	103.567	30.919	RF	150	30	10	135	377	1260	1078	-14.4	833	-33.9

Note: "Triggers" is the triggering condition of rock avalanches: "WCEQ" represents the 2008 Wenchuan M_s 8.0 earthquake; "LSEQ" represents the 2013 Lushan M_s 7.0 earthquake; "RF" represents the rock avalanche was induced by heavy rainfall. $L'_{(3)}$, $L'_{(4)}$ indicates the predicted travel distance estimated by using equation (3) and (4) respectively.

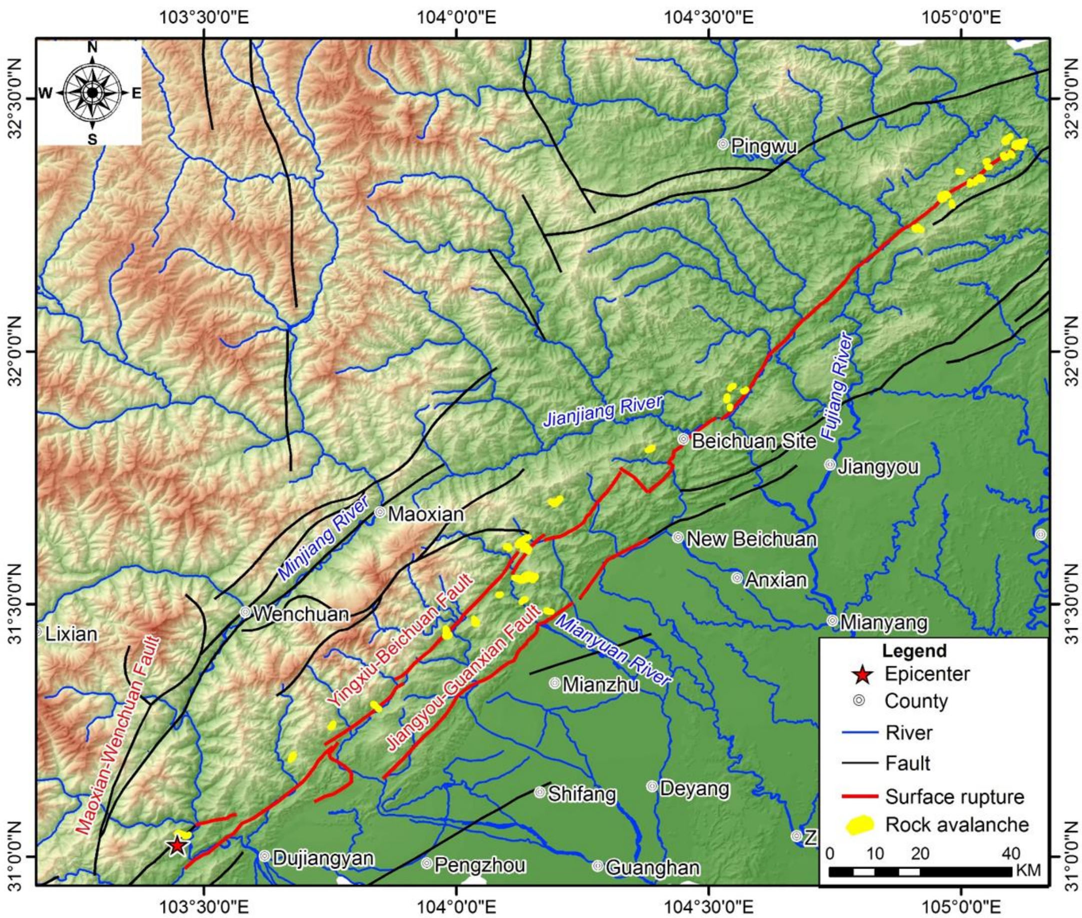

Figure 1. Distribution map of large rock avalanches triggered by the Wenchuan earthquake

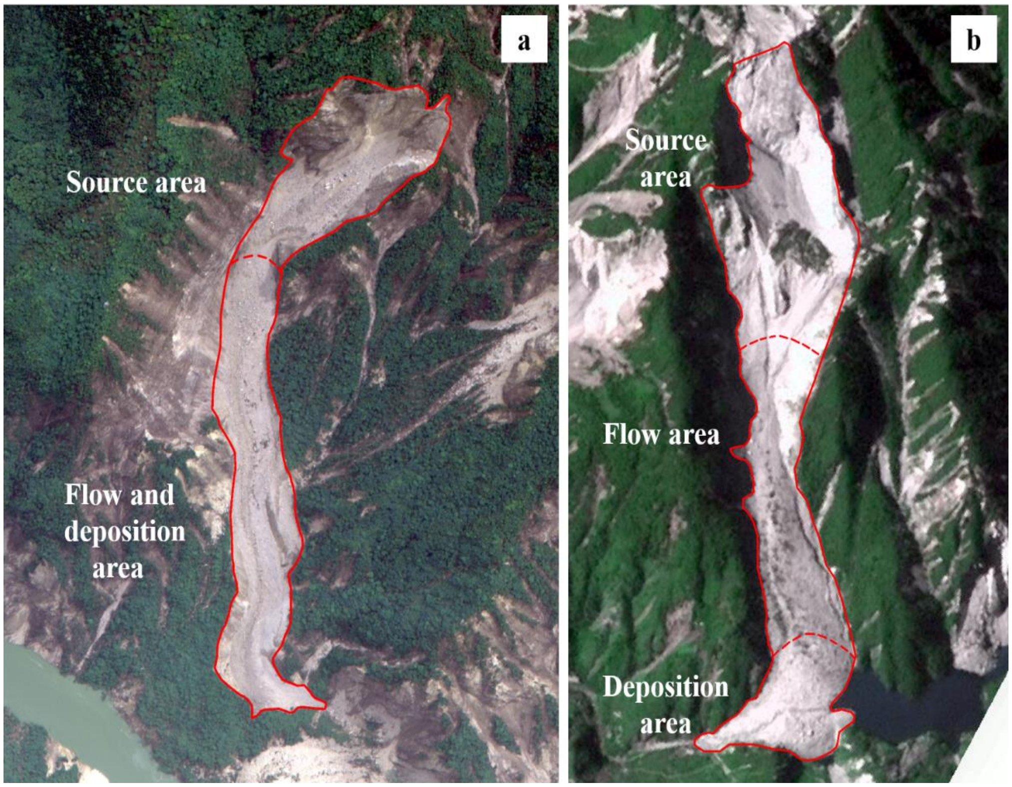

Figure 2. Remote-sensing images of two channelized rock avalanches triggered by the Wenchuan earthquake. a is Changtan rock avalanche (No.21 in table 2); b is Laoyingyan rock avalanche, which is river-blocked

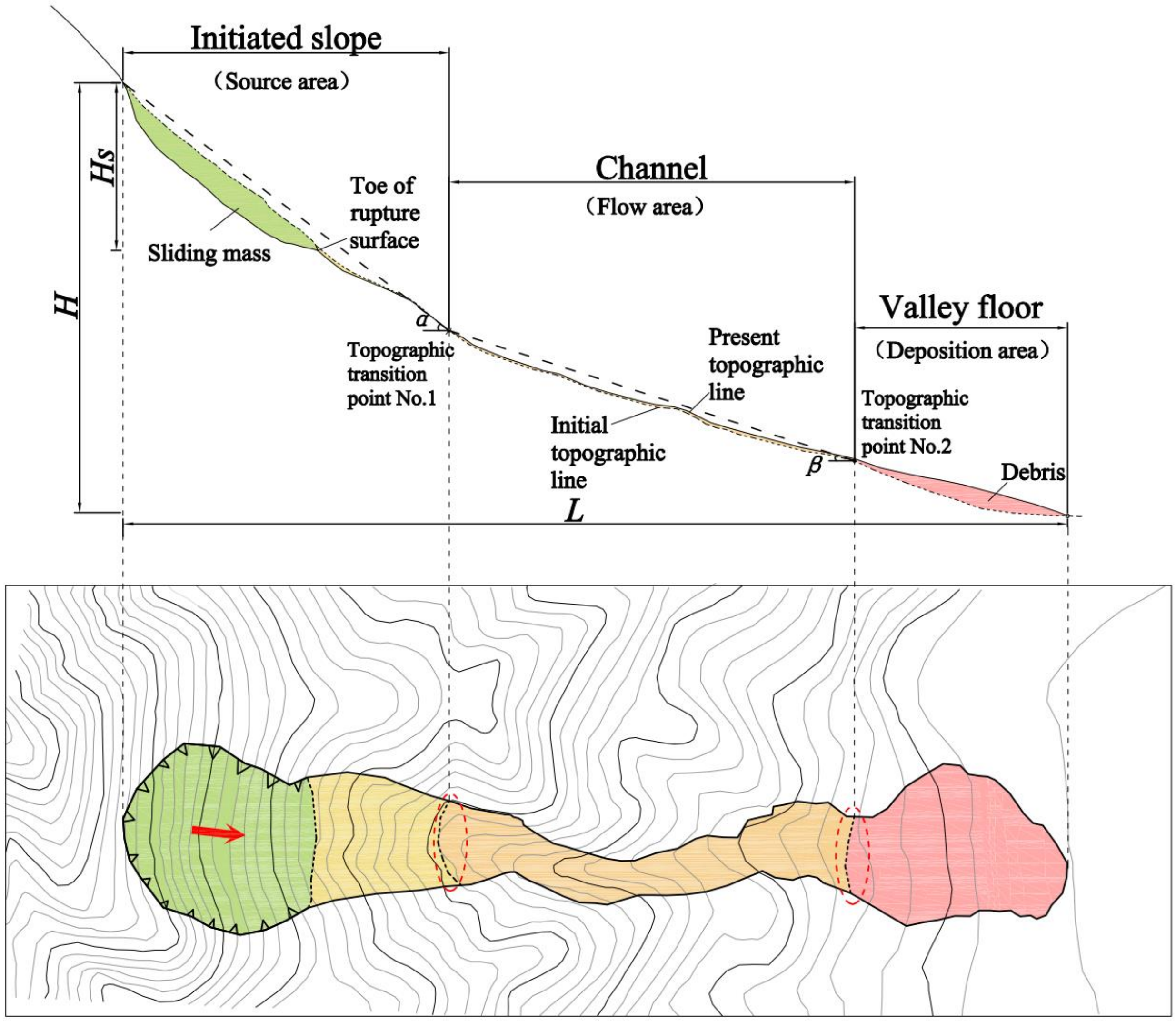

Figure 3. Sketch map of a channelized rock avalanche defining geometric parameters. The red-dashed ellipse indicates the topographic transition dividing the initiated slope, channel and valley floor. The red arrow represents sliding direction of source mass

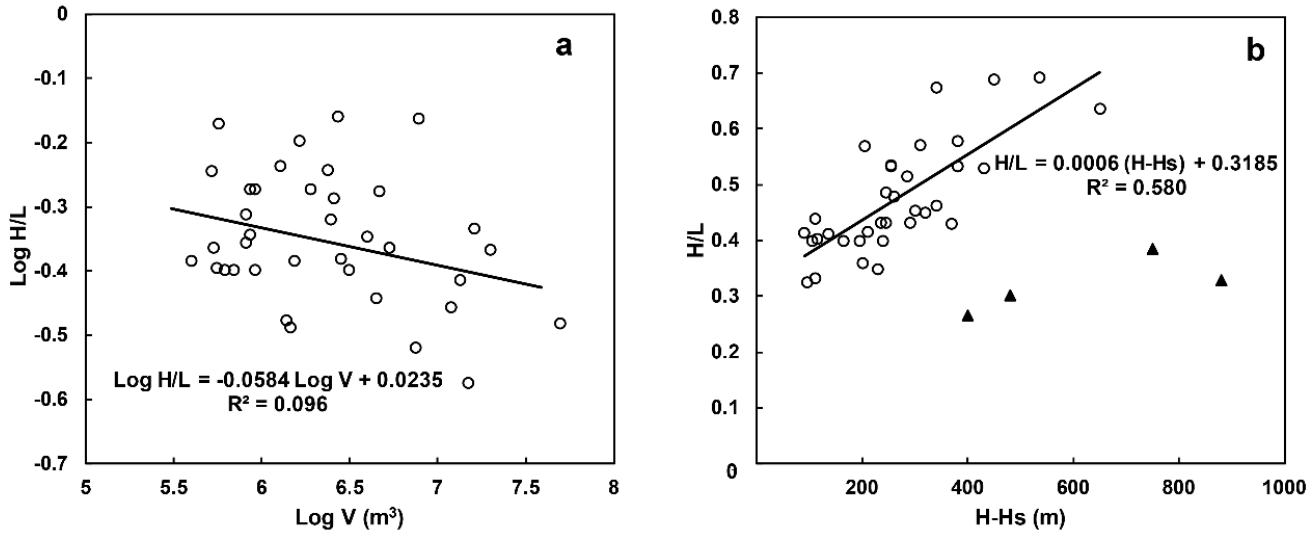

Figure 4. (a) Relationship between reach angle (H/L) and volume (V); and (b) Relationship between H/L and effective drop height of channelized rock avalanches (H-Hs).

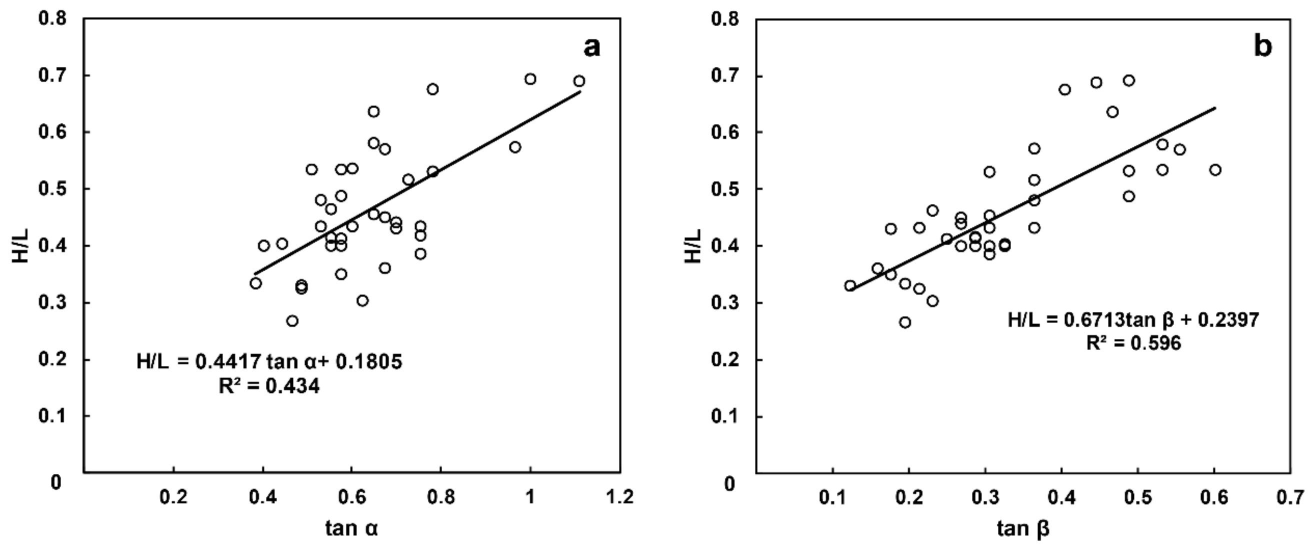

Figure 5. (a) Relationship between reach angle (H/L) and slope angle (tan α); and (b) Relationship between H/L and the channel gradient (tan β) of the rock avalanches

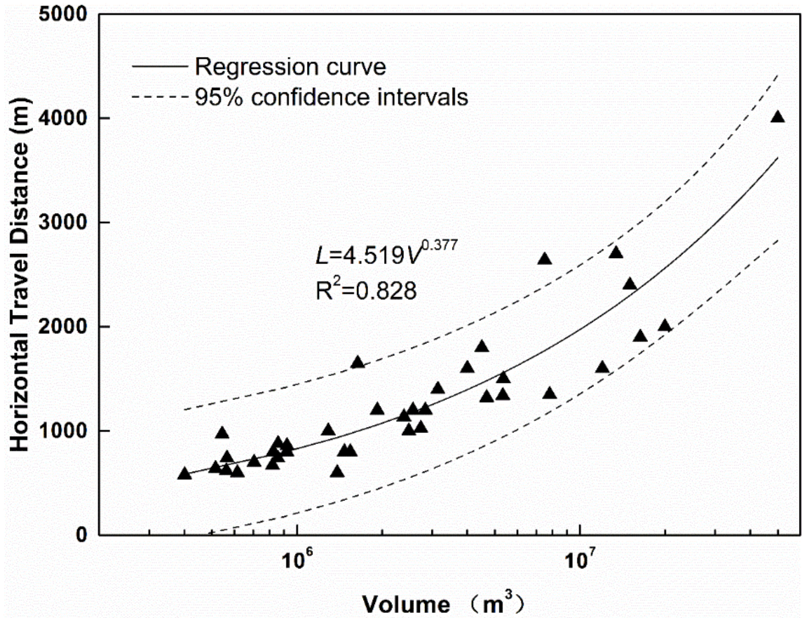

Figure 6. Relationship between horizontal travel distance and volume of channelized rock avalanches

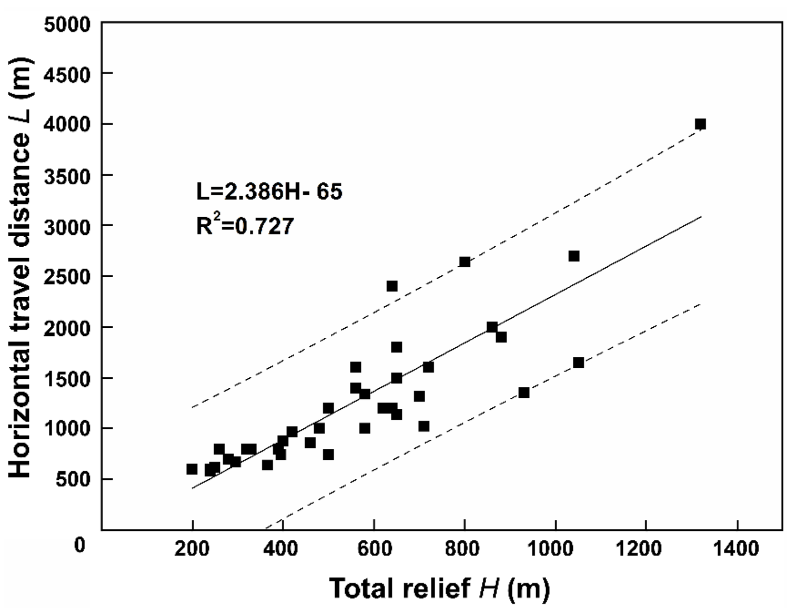

Figure 7. Relationship between horizontal travel distance and total relief of channelized rock avalanches

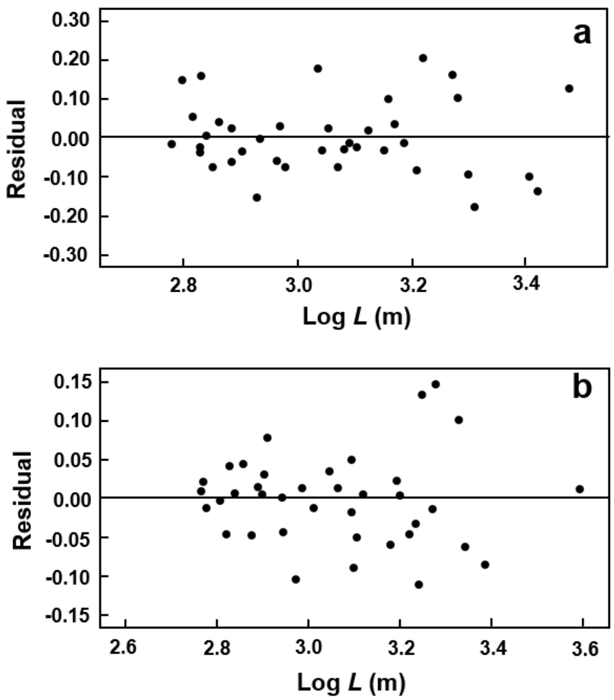

Figure 8. Residual plots for the two multivariate regression models: Figure 9a is for equation (2); Figure 9b is for equation (4).

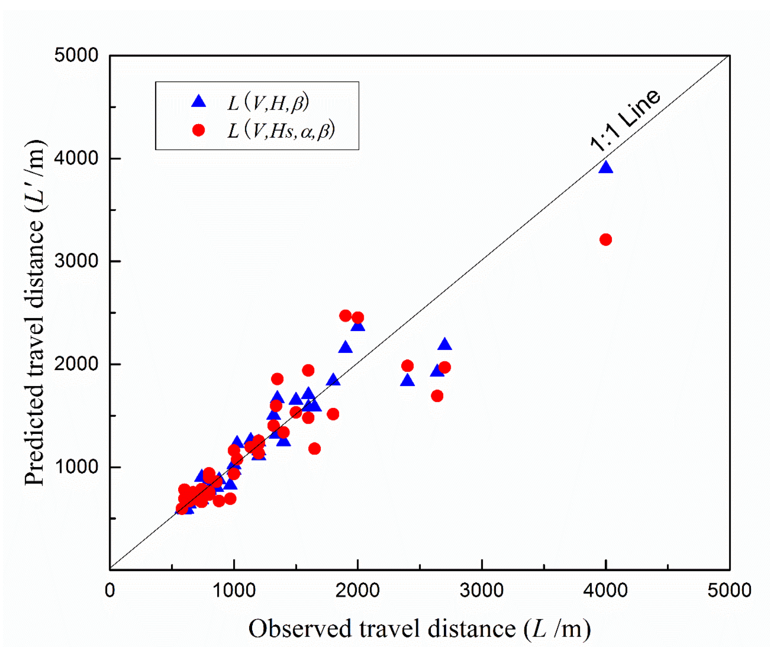

Figure 9. The comparison between observed and predicted travel distance for the two multivariate regression models

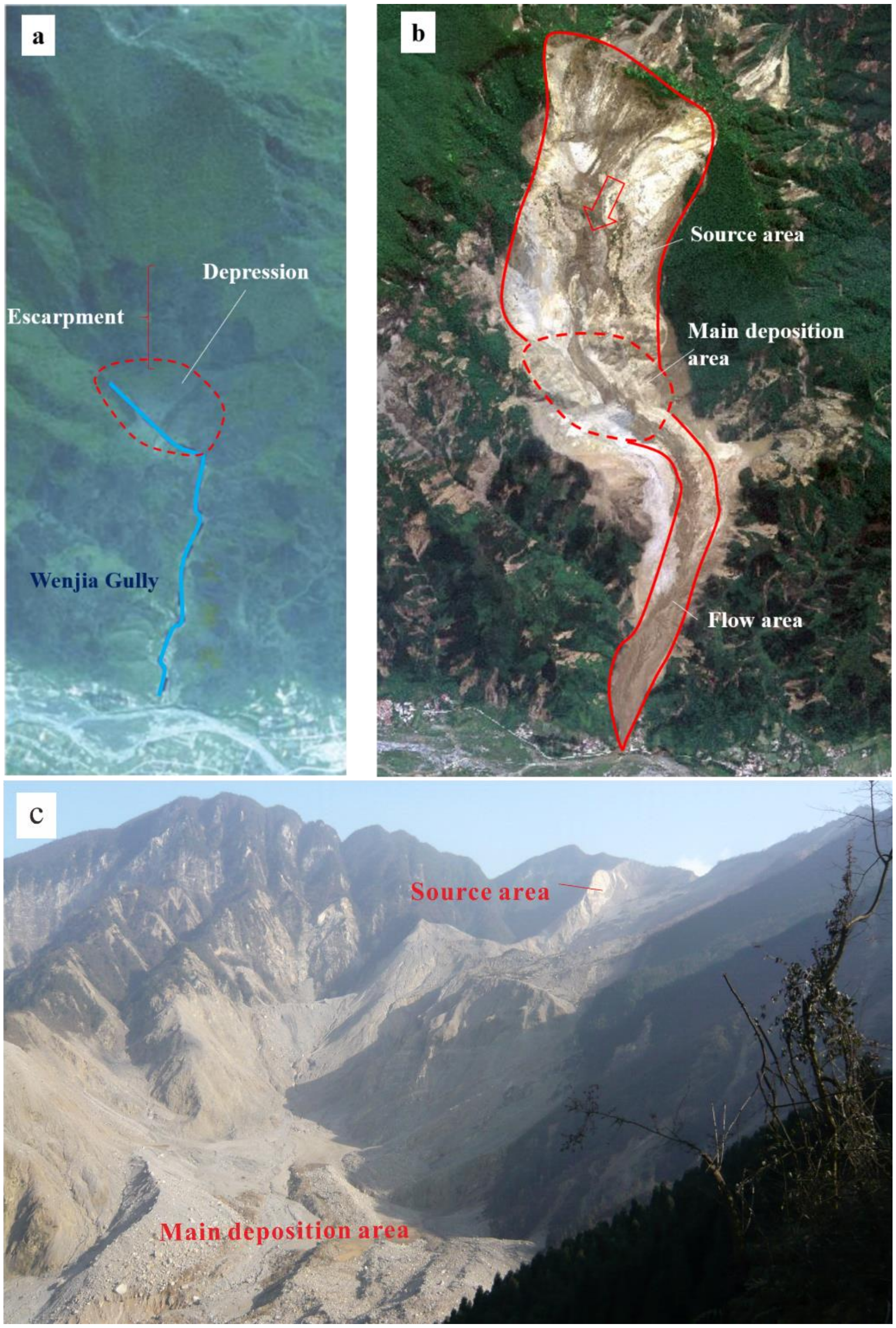

Figure 10. Sketch map of flow capacity of channel affecting on the travel distance of the Wenjia Gully channelized rock avalanche: (a) before the earthquake, (b) after the earthquake, (c) photo taken on deposition platform after the earthquake. The red arrow shows the sliding direction of source mass. The red

dotted line in (a) indicates the original depression on the travel path of the rock avalanche, in where debris deposition of about 30 million m3 was stored after the earthquake (shown in (b)), and more detailed information is shown in (c)

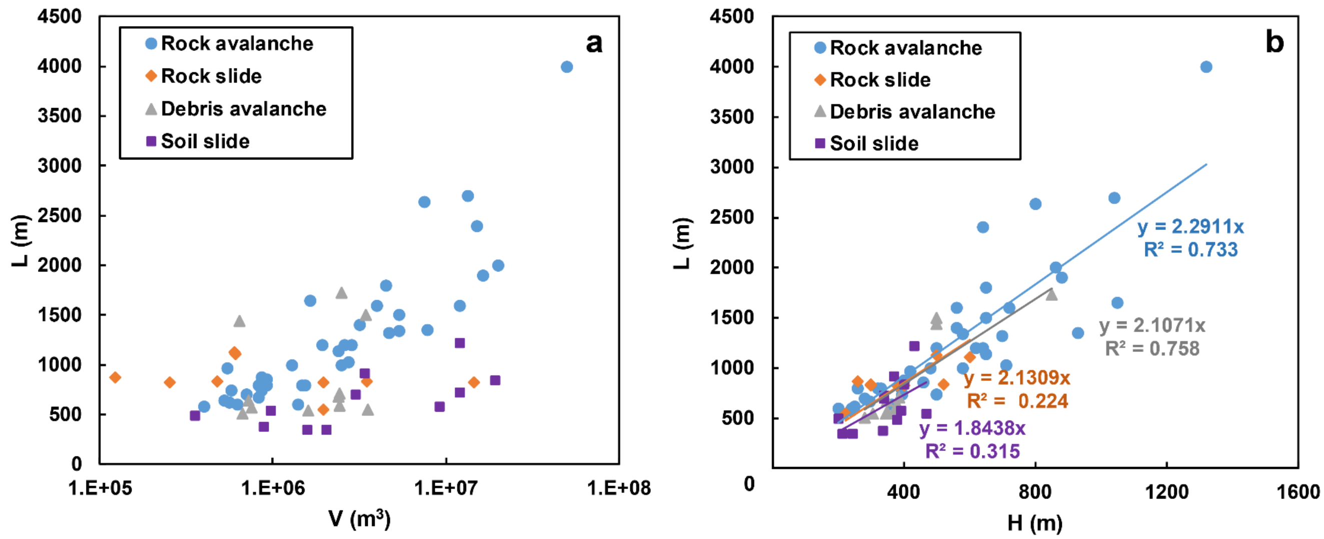

Figure 11. Relationship between the volume and travel distance (a), as well as relationship between the total height and travel distance (b) of different-type landslides triggered by Wenchuan earthquake (rock slides, debris avalanches and soil slides data are from Guo et al, 2014).

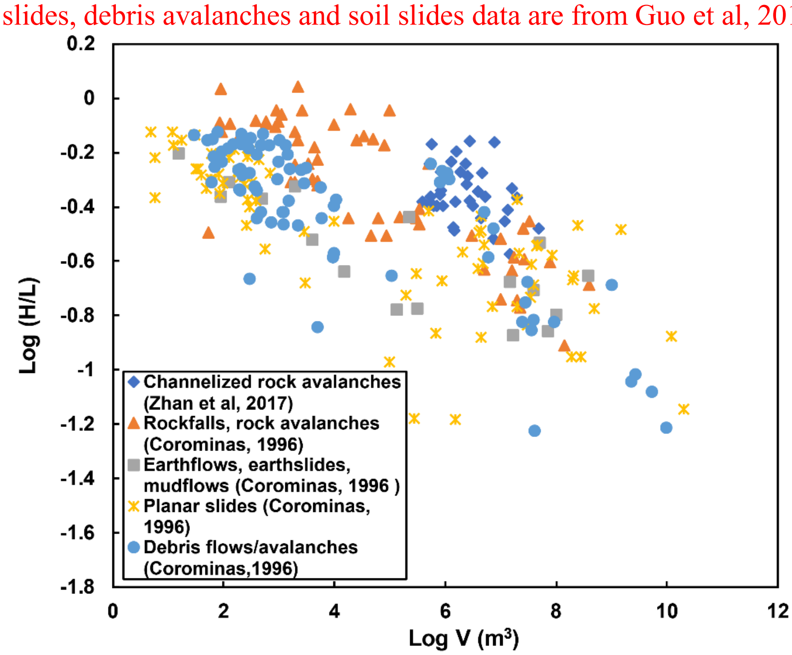

Figure 12. Relationship between the volume and H/L ratio of different-type landslides from the worldwide dataset (Corominas, 1996)

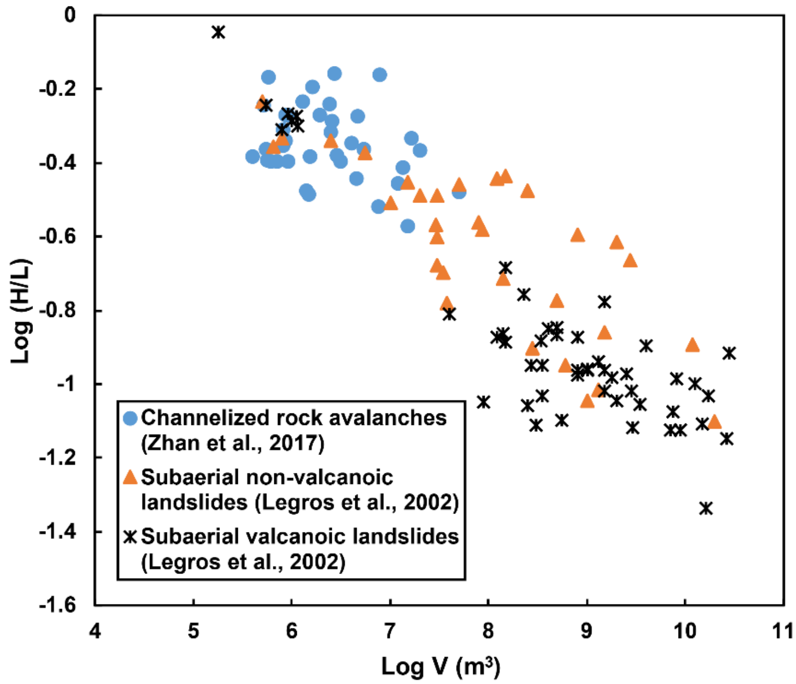

Figure 13. Relationship between the volume and H/L ratio of different-type landslides from the worldwide dataset (Legros, 2002)