Assessing Annual Risk of Vehicles Hit by a Rainfall Induced Landslide: A Case Study on Kennedy Road in Wan Chai, Hong Kong

Meng Lu, Jie Zhang, Lulu Zhang and Limin Zhang

Response to Review Comments

The authors are grateful to the reviewer, who offered many constructive suggestions to enhance the manuscript. In this document, specific responses (Regular font) to the review comments (Italic font) are presented in detail and the changes (Regular font) are also shown by referring to the line numbers in the revised manuscript.

Review comment 1*: This manuscript presents a case study on quantifying the risk of landslides hitting vehicles.*

It is my opinion that the manuscript is not at the standard of this journal. There are a number of issues associated with tis manuscript:

- It is mentioned that few attempts have been made to suggest a rigorous assessment framework of vehicles hit by landslides. This is not true. Besides the work you have already referenced, there has been much work done on this regard, including:

Macciotta, R. et al., 2019. Quantitative risk assessment of rock slope instabilities that threaten a highway near Canmore, Alberta, Canada: managing risk calculation uncertainty in practice. Canadian Geotechnical Journal, 37(2), pp.1–17.

Bunce CM, Cruden DM, Morgenstern NR (1997) Assessment of the hazard from rockfall on a highway. Can Geotech J 34:344–356.

Macciotta, R. et al., 2017. Rock fall hazard control along a section of railway based on quantified risk. Georisk, 11(3), pp.272–284.

Corominas, J. et al., 2013. Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment, 9(3), pp.1095–55.

Bunce CM (2008) Risk estimation for railways exposed to landslides. Dissertation, University of Alberta.

Macciotta, R. et al., 2016. Quantitative risk assessment of slope hazards along a section of railway in the Canadian Cordilleraâ˘A Ta methodology considering the uncertainty in the results. Landslides, 13(1), pp.115–127.

- In this regard, the content of the manuscript is not novel and it does not provide a framework for quantitative risk to vehicles from landslides. The manuscript needs to be re-framed. It is a case study, what can be learned from this case study?

Review comment 2*: The paper focuses on rainfall induced landslides, therefore it can not claim to provide a formal framework that can be generally applied to vehicles impacted by landslides.*

Authors' reply to Review comments 1-2: Thank you for the constructive comments. We have carefully revised the literature review and highlighted the novelty of the method suggested in this revised manuscript [Lines 45-64]:

"Previously, many studies have been conducted to study the individual risk associated with the landslide, which is often measured by that the annual probability that a person who frequently uses the highway was killed by the landslide (e.g. Bunce et al., 1997; Fell et al., 2005; Dorren et al., 2009; Michoud et al., 2012; Macciotta et al., 2015; Macciotta et al., 2017). Several studies have also examined the societal risk of vehicles being hit be landslides, in which the societal risk is measured in terms of the annual probability that at least one fatality occurs in one year (e.g. Budetta, 2004; Peila and Guardini, 2008; Pierson, 2012; Ferlisi et al., 2012; Corominas et al., 2013; Macciotta et al., 2019). These studies have provided both useful insights and practical tools for analysis and management of the landslide/rockfall hazards. Nevertheless, it was commonly assumed that the traffic is uniformly distributed in time and space, and that each vehicle had the mean length of all vehicles (e.g. Hungr et al., 1999; Nicolet et al., 2016). In reality, there is randomness associated with the spacing among vehicles on the highway. If such uncertainties are ignored, the resulting uncertainty associated with the number of vehicles being hit by the landslide cannot be considered in the risk assessment process. Also, there might be multiple types of vehicles on the highway, and different types of vehicles may have different lengths and also significant different passenger capacities. If the difference between different types of vehicles is ignored, it might be hard to estimate the number of people being hit by the landslide, which is also an important aspect of risk assessment.

Through a case study on Kennedy Road in Wan Chai, Hong Kong, this paper aims to suggest a new method to assess the risk of moving vehicles hit by a rainfall-induced landslide, in which the possible number of different types of vehicles being hit by the landslide can be investigated."

In addition, we have also explained how the results from the method suggested in this paper can complement those from existing study in the revised manuscript [Lines 139-146]:

"Previously, the individual risk is often used to measure the threat of a landslide to the moving vehicles, which provides information about the probability of a frequent user of the highway to be killed by the landslide. On the other hand, decision makers may also be interested in the annual expected numbers of vehicles/persons being hit by the landslide, which can be obtained using the method suggested in this paper. As will be shown later in the case study, the above framework can be easily extended to calculate the F-N curve for societal risk assessment, which is an important complement to previous methods on social risk assessment relying solely on the probability of at least one fatality per year."

Review comment 3*: Travel distance. The authors justify the application of empirical methods based on convenience. This is not scientific. Should take advantage of the work referenced after this statement to validate this. Were these landslides of a similar type? Under similar moisture conditions?*

Authors' reply: Thank you for your suggestion. We have revised the manuscript as follows [Lines 212-228]:

"In general, the runout distance of a landslide depends on factor like the slope geometry, the soil profile, and geotechnical, hydraulic and rheological properties of sliding mass. The methods to investigate the runout distance of a landslide can be divided into two categories (Hungr et al., 2005): (1) analytical or numerical methods based on the physical laws of solid and fluid dynamics (Scheidegger, 1973), which are usually solved numerically (e.g. Hungr and McDougall, 2009; Luo et al., 2019) and (2) empirical methods based on field observations and geometric correlations (e.g. Dai and Lee, 2002; Budetta and Riso, 2004). The use of the physically-based methods require detailed information on the ground condition as well as the geotechnical and hydraulic properties of the soils. On the other hand, empirical methods based on geometry of the landslide are generally simple and relatively easy to use (e.g. Finlay et al., 1999; Dai et al., 2002). In this study, the empirical method is adopted due to lack of information of geotechnical and hydraulic conditions of the slope. In particular, the following empirical equation is used (Corominas, 1996):

$$\log L = 0.085\log V + \log H + 0.047 + \varepsilon \quad (8)$$

where V is the volume of the sliding mass and H is the height of the slope; ε is a random variable with a mean of zero and a standard deviation of $\sigma = 0.161$. As shown in Finlay et al. (1999) and Gao et al. (2017), Eq. (8) can predict the runout distance of cut and fill slopes in Hong Kong quite well. As mentioned previously, the slope studied in this paper is indeed a cut slope."

Review comment 4*: The methodology does not appear to be comprehensive regarding potential scenarios. It is common that a quantitative analysis of vehicles endangered by landslides include the scenario where the moving vehicle is impacted by a falling landslide, a moving vehicle impacts a blocked section of road, and a static vehicle (traffic jams or vehicles stop because of precursory landslide activity to a larger event) is impacted by falling material or debris.*

Authors' reply: Agree. The focus of this paper is on the scenario of a moving vehicle impacted by a falling landslide. We have provided the following clarification in the revised manuscript [Lines 64-68]:

"In general, quantitative analysis of vehicles endangered by landslides includes three scenarios, i.e., (1) a moving vehicle is impacted by falling materials, (2) a moving vehicle impacts falling materials on highway, and (3) a line of stationary vehicles is impacted by falling materials (Bunce et al., 1997). In this study, our focus is on the risk assessment of moving vehicles impacted by a falling landslide."

Review comment 5: *The manuscript mentions a quantitative risk assessment. Only calculations of probability of a landslide impacting vehicles are presented. No risk calculations are presented in the manuscript.*

Authors' reply: Thanks for the comment. In the revised manuscript, we have used an event tree to illustrate the development of the method, through which the probability and the consequence of different pathways are explicitly shown, as summarized below [Lines 102-120]:

"Fig. 4 shows the event tree model employed in this study to assess the risk of rainfall-induced landslide hitting type j vehicles. As can be seen from this figure, if the slope does not fail in a year, there will be not spatial impact, and the number of type j vehicles being hit is zero. Let $P(F)$ denote the annual probability of slope failure. If the slope fails, its spatial impact, which can be characterized by the width of the landslide mass and the runout distance of the landslide mass, is also uncertain. In general, the spatial impact of the landslide depends on factors like slope geometry, soil profile, soil strength parameters, and water content in the soil mass. The spatial impact can be evaluated using physically-based methods or statistically-based methods, and will be discussed later in this paper. Suppose there are m possible spatial impacts and let $P(\mathbf{S} = \mathbf{S}_i | F)$ denote the probability that the spatial impact is $\mathbf{S}_i$ when the landslide occurs. For a given spatial impact, the number of type j vehicles being hit is also uncertain. Let n_j denote the number of the type j vehicle being hit by the landslide. Let $P(n_j = k| \mathbf{S} = \mathbf{S}_i)$ denote the encounter probability that k type j vehicles will be hit by the landslide when the spatial impact is $\mathbf{S}_i$. If the landslide mass cannot reach the road for the case of $\mathbf{S} = \mathbf{S}_i$, the spatial impact is zero, which can be denoted as $P(n_j = 0| \mathbf{S} = \mathbf{S}_i) = 1$.

Based on the event tree as shown in Fig. 4, the annual probability of k type j vehicles being hit by the landslide is $P(F) \times P(\mathbf{S} = \mathbf{S}_i| F) \times P(n_j = k| \mathbf{S} = \mathbf{S}_i)$ when the spatial impact of the landslide is $\mathbf{S}_i$, and expected number of type j vehicles being hit corresponding to such a scenario is $k \times P(F) \times P(\mathbf{S} = \mathbf{S}_i| F) \times P(n_j = k| \mathbf{S} = \mathbf{S}_i)$."

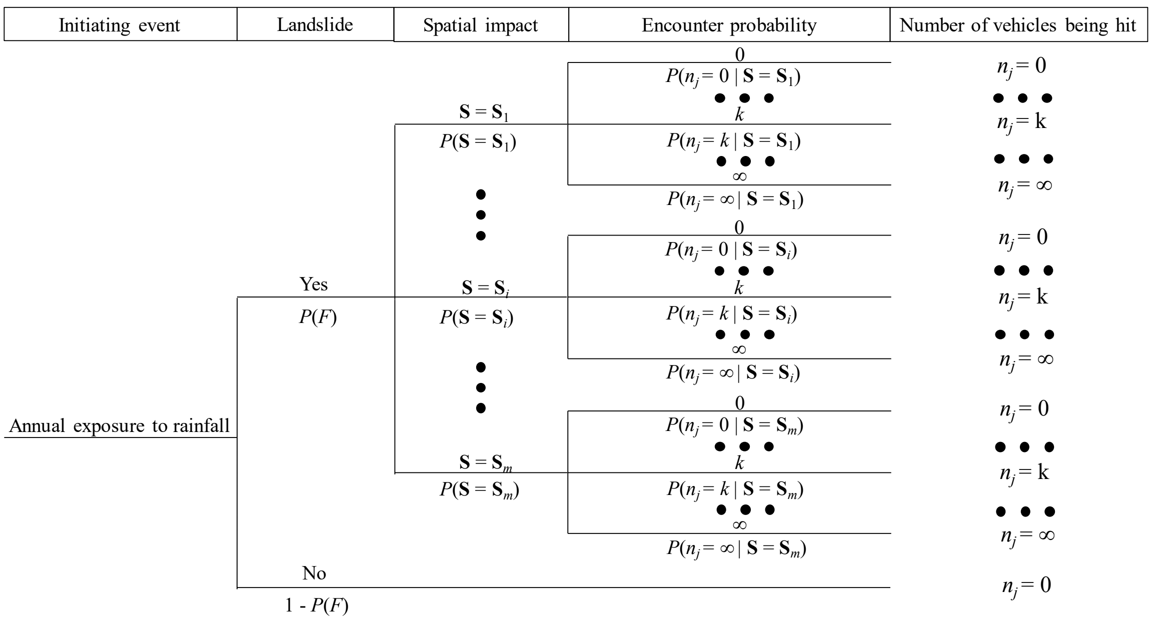

Figure 4. Event tree of evaluating the annual risk of the type j vehicle hit by the landslide

Review comment 6: *No assessment through evaluation against acceptance criteria is presented.*

Authors reply: In the revised manuscript, we have assessed the risk against the acceptance criteria as follows [Lines 325-356]:

"The society is less tolerant of events in which a large number of lives are lost in a single event, than of the same number of lives are lost in a large number of separate events, which can be measured through societal risk (Cascini et al., 2008). In Hong Kong, the societal risk is measured through F-N relationship (GEO, 1998), as shown in Fig. 11. In this figure, the horizontal axis denotes the number of fatalities, and the vertical axis denotes cumulative annual frequency of the number of fatalities. There are four regions in this figure, i.e., the region in which the risk is unacceptable, the region in which the risk is broadly acceptable, the region in which the risk should be made as low as reasonably practicable (ALARP), and the intense scrutiny region. To assess the societal risk of the landslide, the relationship between the number of fatalities and the probability of such an event should be established. When the traffic flow is a Poisson process, the passengers in the traffic flow can also be modeled through Poisson process. For example, the mean rate of occurrence of passengers in type j vehicle is $\lambda_{pj} = n_{pj}\lambda_j$ where n_{pj} is the passenger capacity of type j vehicles and λ_j is the mean rate of occurrence of type j vehicles. Let n_{jp} denote the number of people being hit by the landslide. Using equations similar to Eqs. (14) and (15), the chance of k passengers in type j vehicles hit by the landslide for a given spatial impact can also be calculated, which is denoted as $P(n_{jp} = k| \mathbf{S} = \mathbf{S}_i)$. The annual chance of k passengers in type j vehicles hit by the landslide can be calculated as:

$$P\left(n_{jp} = k\right) = P(F)\sum_{i=1}^{m}\left[P\left(n_{jp} = k \mid \mathbf{S} = \mathbf{S}_i\right)P\left(\mathbf{S} = \mathbf{S}_i \mid F\right)\right] \quad (16)$$

Fig. 11 shows the relationships between the number of people being hit by the landslide and the annual probability such an event occurs for different types of vehicles. As can be seen from this figure, the risk associated with type 5 vehicles (private cars) is greatest and unacceptable. The risk associated with type 1 vehicles (private buses), type 9 vehicles (special purpose vehicles), and type 10 vehicles (government vehicles) are in the acceptable region. The risk associated with the rest types of vehicles are in the ALARP region. Indeed, the people being hit by the landslide on 8 May 1992 was a person in the private car.

As the flow of all vehicles on the highway is modeled as a Poisson process, the flow of people on the highway considering all types of vehicles can also be modeled as Poisson process with a mean rate of $\lambda_p = \lambda(w_1 n_{p1} + w_2 n_{p2} + \ldots\ w_n n_{pn})$ where w is the proportion of each type of vehicle in the traffic flow, n is the number of vehicle types and λ is the mean rate of occurrence of all vehicles. Using an equation similar to Eq. (16), the annual probability of k persons in the traffic flow considering all types of vehicles can also be calculated, and the obtained F-N curve considering all types of vehicles are also shown in Fig. 11. As can be seen from this figure, the social risk considering all types of vehicles is greater than that of any individual type of vehicles and hence is also unacceptable."

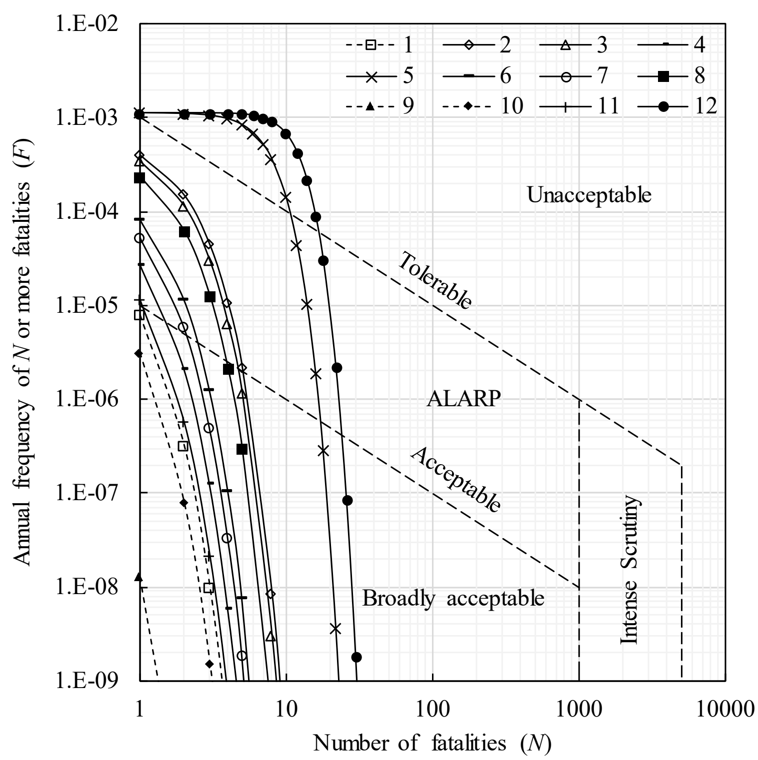

Figure 11. Estimated annual frequency of N or more persons hit by the landslide studied in this paper (Tolerable and acceptable F-N curves are those specified by the GEO 1998). (1.

Private buses, 2. Non-franchised public buses, 3. Franchised buses, 4. Taxis, 5. Private cars, 6. Public light buses, 7. Private light buses, 8. Goods vehicles, 9. Special purpose vehicles, 10. Government vehicles, 11. Motor cycles, 12. All types of vehicles)

Review comment 7: *Major revisions would be required, including proper calculation of risk, assessment against adopted criteria.*
Authors' reply*:* We have thoroughly revised the manuscript as suggested.

Review comment 8: *Clear statement and discussion of assumptions and simplifications.*
Authors' reply: Thank you for the advice. We have provided a section called "Limitations and Applicability of the Method Suggested in This Study" to clearly address assumptions and simplifications made in this study [Lines 394-431]:

"The rainfall condition may affect the failure probability of the slope as well as the traffic density and hence affect the risk. In this case study, the effect of rainfall condition on the annual failure probability of the slope is considered through Eq. (6), based on which both the chances of different types of rainfall as well as the failure probabilities of the slope under different types of rainfall are considered. The traffic condition may also vary with the rainfall condition. However, data on the impact of rainfall condition on the traffic density is rarely available. In this study, the impact of rainfall condition on the traffic flow is not considered in the risk assessment.

The method used for case study consists of three components, i.e., the hazard probability model, the spatial impact assessment model, and the consequence assessment model. The annual failure probability of the slope is calculated based on statistical analysis of past failure data in Hong Kong. It represents the failure probability of an average slope in Hong Kong, which is a common assumption adopted in empirical methods. When the method is applied in another region, the failure probability should be estimated using data from the region under study. Alternatively, to reflect the effects of factors like slope geometry and local ground conditions on slope failure probability, the failure probability can also be estimated using physically-based methods. As mentioned previously, current physically-based methods mainly focus the failure probability of a slope during a given rainfall event. It is important to also examine how to incorporate the uncertainty of the rainfall condition into the slope failure probability evaluation in future studies.

In this study, the spatial impact is estimated based on an empirical runout distance prediction equation based on the data of different types of landslides from several countries. When applying the method suggested in this paper in another region, the empirical equation should be tested that whether it can better fit landslides in the region under study or one should estimate the runout distance based on empirical relationships developed in the region under study. The spatial impact of the landslide may also be estimated using physically-based models. In recent years, large deformation analysis methods have been increasingly used for runout distance analysis. It should be noted that, during the runout distance analysis, the uncertainties in the geological condition and soil properties should be considered. Currently, the large deformation analysis is often carried out in a deterministic way. It is highly desirable to combine the large deformation analysis with the reliability theory such that the spatial impact of the landslide can also be predicted probabilistically.

The consequence assessment model is generally applicable and can be used assessment the impact of landslides on moving vehicles in other regions. Therefore, after the hazard probability model and the spatial impact model are replaced with models suitable for application in another region, the suggested method in this paper can also be used for assessing the risk of moving vehicles hit by a rainfall-induced landslide in another region.

There are multiple scenarios for a landslide to impact vehicles on the highway. The focus of this paper is on the impact of falling materials on moving vehicles. In future studies, it is also worthwhile to develop methods to evaluate the effect of uncertainty in the number and types of vehicles on risk assessment of the impact of a landslide on vehicles in other scenarios."

Review comment 9*: Development of other vehicle-landslide impact scenarios.*

Authors' reply: This is a good question. The focus of this paper is on the scenario of moving vehicles hit by a falling landslide. We have stressed the importance of considering other scenarios in future studies in the revised manuscript as follows [Lines 428-431]:

"There are multiple scenarios for a landslide to impact vehicles on the highway. The focus of this paper is on the impact of falling materials on moving vehicles. In future studies, it is also worthwhile to develop methods to evaluate the effect of uncertainty in the number and types of vehicles on risk assessment of the impact of a landslide on vehicles in other scenarios."

Review comment 10*: Justification and discussion regarding the criteria adopted and the need for mitigation.*

Authors' reply: We have provided the justification and discussion regarding the criteria used and the need for mitigation in the revised manuscript as suggested, which has been described in our reply to Review comment 6.