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

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The authors are grateful to the reviewers, 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.

Response to Anonymous Referee #1

Review comment 1*: The paper illustrates a methodology for Quantitative Risk Assessment of Vehicles Hit by Landslides in a Kennedy roadway in Hong Kong. It must preliminarily say that not novelty methods at all are consider to the fundamental topic within which the case study proposed by authors evidently falls. The proposed manuscript needs to reach a differential with respect the previous work in this topic. As the manuscript is, it seems like a pragmatic solution (description of an engineering solution) to a case study that still lacks explanation and detail on some questions regarding the geotechnical conditions of the study site.*

However, I think that a good contribution of your research can be to support establishing new guidelines for highways design for purposes of roadway safety in terms of landslide risk reduction hitting vehicles & persons. For this, the methodology must be more detailed looking for include some uncertainties involve in the process providing innovative or novelty assessment processes or methods. The authors should consider that include solutions to the assumptions and uncertainties involve in the processes, omitted in other research can be the innovative level required for a relevant paper.

Authors' reply: Thank you for your constructive advice. We have thoroughly revised the manuscript and highlighted the difference between existing studies and our study in the introduction as follows [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."

We have also explained the new results which can be obtained from the method suggested from the method used in this study, which can well complement those from existing studies in the revised manuscript as follows [Lines 139-146]:

"Previously, the individual risk is often used to measure the threat of a landslide to a moving vehicle, 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."

In addition, we have also illustrated how the results obtained from this study can be used to establish new guideline for design of highway slopes in the revised manuscript [Lines 368-376], [Lines 386-391]:

"Fig. 13 shows the how the societal risk for all types of vehicles changes as the annual failure probability of the slope changes. As can be seen from this figure, when the failure probability of the slope is smaller than 1.0×10^{-4}, the societal risk will be in the ALARP region. If the failure probability of the slope is further reduced to 1.0×10^{-6}, the societal risk will become acceptable. Hence, reducing the annual failure probability of a slope is an effective means to reduce the risk of the slope. In practice, the annual failure probability of a slope under rainfall can be reduced through the use of engineering measures such as structural reinforcement. To assess the effect of such measures on the failure probability of the slope, physically-based methods shall be used for hazard probability analysis."

"As can be seen from Fig. 15, the societal risk also increases as the density of vehicles becomes larger. When density of vehicles is less than 10 vehicles per kilometer, the societal risk will be within the ALARP region. Therefore, depending on the density of the vehicles, the societal risk of a landslide may be acceptable when it is located near one highway but become unacceptable when it is located at another highway. Therefore, in the design of highway slopes, the failure probability of the slope should be decreased as the density of the vehicles increases."

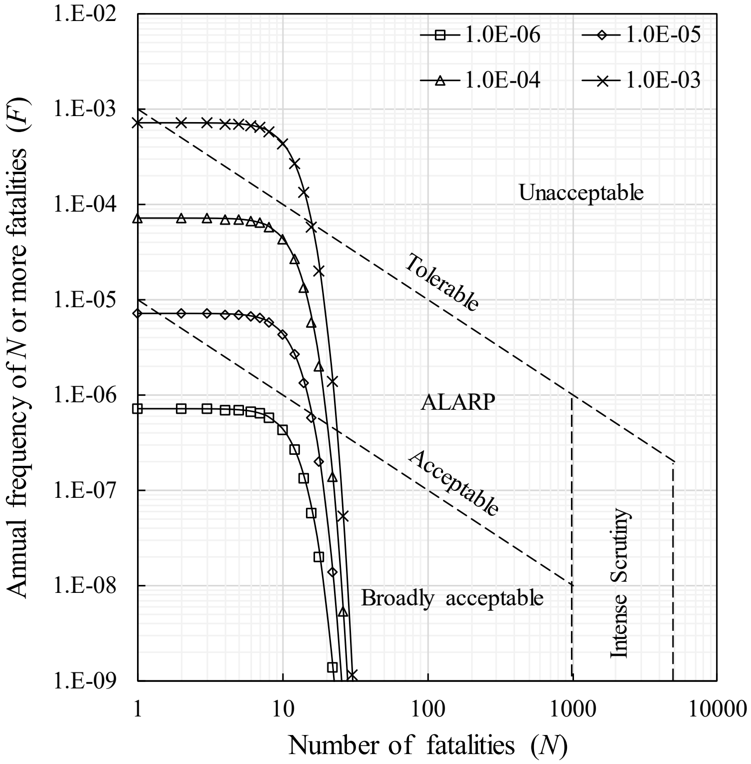

Figure 13. Impact of annual failure probability of the slope on annual societal risk

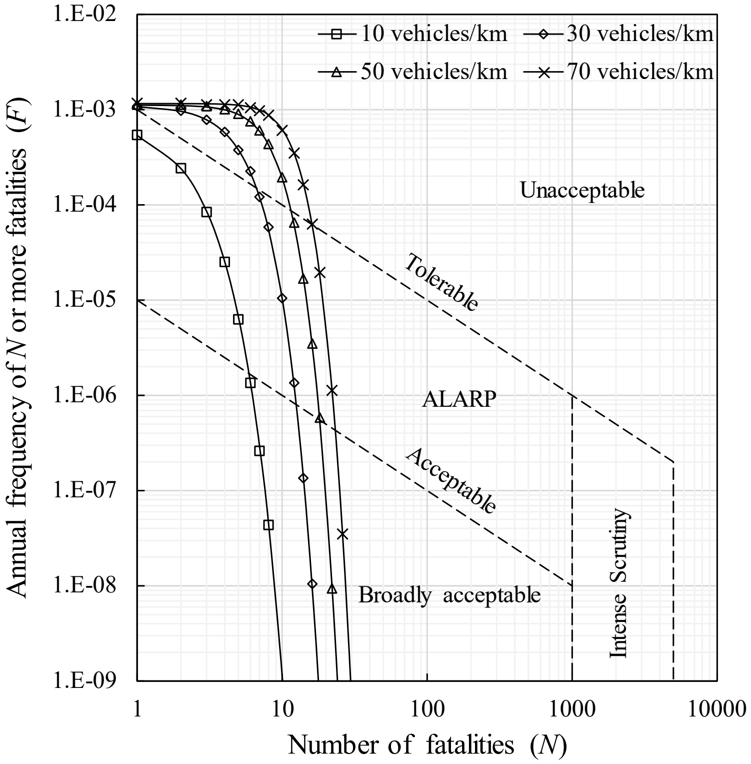

Figure 15. Impact of density of vehicles on annual societal risk

We have also provided a section called "Limitations and Applicability of the Method Suggested in This Study" to clearly address the assumptions 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 are 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 2*: There are clear probabilistic methods, but there are many uncertainties and assumptions that are not clear to the reader. This is because much of the data used for evaluations comes from secondary data obtained from other sources, which are assumed to be true and are not discussed by the authors.*

As mentioned above, part of the data is obtained from secondary sources. Hence, it is not possible to reproduce its acquisition process, even more so when some of these processes are poorly explained. Regarding those results that are obtained or calculated by the authors, if it is possible to reproduce them in part.

Author's Reply: Thank you for your suggestion. In this study, the conditional failure probability for a given type of rainfall is calculated based on results from Zhang and Tang (2009). In the revised manuscript, we have provided the following explanation on how such results were obtained in Zhang and Tang (2009) [Lines 166-178]:

"In Hong Kong, the failure of a slope is highly correlated to the 24-hour rainfall, i_{24} (Cheung and Tang, 2005). Based on i_{24}, the rainstorms in Hong Kong can be divided into three categories, i.e., (1) $i_{24} < 200$ mm/day (small rainfall, denoted as SR), (2) 200 mm < $i_{24} < 400$ mm/day (medium rainfall, denoted as MR) and (3) $i_{24} > 400$ mm/day (large rainfall, denoted as LR) (Zhang and Tang 2009). Through statistical analysis of the slope failure data in Hong Kong during 1984-2002, it is found that the failure probability of a slope in Hong Kong when subjected to small rainfall, medium rainfall and large rainfall are 1.09×10^{-4}, 2.61×10^{-3} and 8.94×10^{-3}, respectively, i.e., $P(F| SR) = 1.09 \times 10^{-4}$, $P(F| MR) = 2.61 \times 10^{-3}$ and $P(F| LR) = 8.94 \times 10^{-3}$ (Zhang and Tang, 2009). In the statistical analysis, it is assumed that slopes in Hong Kong when subjected to the same type of rainfall have the same failure probability, and hence the failure probability obtained should be interpreted as the failure probability of an average slope. Such an assumption is commonly adopted in statistically-based method for evaluating the failure probability of slopes in a region. As noticed by Dai et al. (2002), such a method cannot consider the effect of local geology and soil condition on the site-specific slope stability."

In the runout distance analysis, the empirical equation suggested by Corominas (1996) is used. In the revised manuscript, we have also explained its applicability to runout distance analysis in Hong Kong as follows [Lines 221-228]:

"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):

$$\log L = 0.085 \log V + \log H + 0.047 + \varepsilon \tag{8}$$

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 3*: The conclusions look more like a summary of the work. Additionally, the authors state that "The suggested method can also be potentially used to analyse the* *highway landslide risk in other regions", but if are not clearly established some conditions of applicability in Hong Kong, how do you expect that this method could be used in other regions?*

Authors' reply: Thank you for your advice. We have thoroughly rewritten the conclusions as follows [Lines 434-457]:

"When assessing the risk of landslide hitting the moving vehicles, the number and types of vehicles being hit could be highly uncertain. Using a case study in Hong Kong, this paper suggests a method to assess the risk of vehicles hit by a rainfall-induced landslide with explicit considering of the above factors. The research findings from this study can be summarized as follows.

(1) With the method suggested in this paper, the expected annual number of vehicles/persons hit by the landslide as well as the cumulative frequency-number of fatalities curve can be calculated. These results can provide important complement to those from previous studies on risk assessment of landslide hitting moving vehicles, which mainly focus on the individual risk of a landslide or societal risk assessment relying on the probability of the occurrence of at least one fatality per year.

(2) As the length, density, as well as the passage capacity of different vehicles are different, the annual number of vehicles/persons hit by the landslide for different types of vehicles are not the same. The societal risk associated with different types of vehicles are also different. It is important to consider different types of vehicles in the traffic flow.

(3) The suggested method can be used to examine the effect of factors like the annual failure probability of the slope and the density of the vehicles on the road on the risk of landslide hitting moving vehicles. The proposed method can be potentially useful to determine the target annual failure probability of a slope considering the traffic condition at a highway, which can be used as a new guideline for highway landslide risk management.

In this case study, the annual failure probability of the slope is evaluated based on a statistical model, and the spatial impact of the landslide is analyzed through an empirical equation. While these methods are easy to use, they cannot consider the effect of local geology and soil condition on the failure and post-failure behavior of the slope. Further studies are needed to explore physically-based methods to predict the annual failure probability and runout distance with explicit consideration of the uncertainties involved."

We have also clarified the limitations and applicability of the suggested method in the revised manuscript, which has been presented in our reply to Review comment 1.

Review comment 4*: Some recommendation for authors: I should suggest to include the specific site and region of the case study in the title (see attached document).*

Authors' reply: Thank you for the suggestion. We have revised the title of the paper as suggested.

Review comment 5*: Abstract must be revised once all modification have been made. Some Figures must be re-designed for a relevant scientist paper publication.*

Authors' reply: Thank you for the advice. We have revised the abstract as suggested as follows [Lines 6-21]:

"Landslides threaten the safety of vehicles on highways. In analyzing the risk of landslide hitting the moving vehicles, the spacing between vehicles and the type of vehicles on the highway could be highly uncertain, which are often not considered in previous studies. Through a case study about a highway slope in Hong Kong, this paper presents a 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 this case study, the annual failure probability of the slope is analyzed based on historical slope failure data in Hong Kong. The spatial impact of the landslide is evaluated based on an empirical runout prediction model. The consequence is assessed through probabilistic modeling of the traffic, which can consider uncertainties of vehicles spacing, vehicle types and slope failure time. With the suggested method, the expected annual number of vehicles and persons being hit by the landslide can be conveniently calculated. It can also be used to derive the cumulative frequency-number of fatalities curve for societal risk assessment. With the suggested method, the effect of factors like the annual failure probability of the slope and the density of vehicles on the risk of the slope can be conveniently assessed. The method described in this paper can provide a new guideline for highway slope design in terms of managing the risk of landslide hitting moving vehicles."

In addition, we have also re-designed Fig. 1, 2 and 3, as suggested.

Review comment 6*: Methods must include an innovative formulation proposed by the authors, maybe the key of this could lies in the incorporation of those aspect omitted in other studies. Moreover, the limitations of the proposed model should be more explicit in the main text and discussion of them may be incorporate. A figure containing a graphical workflow is convenient. The authors are suggested to read and take into account more high-quality papers about this particular case.*

Authors' reply: Thank you for your suggestion. We have clarified the novelty of the suggested method in the revised manuscript, as described in our response to Review comment 1. We have also illustrated the limitations of the proposed model, as described in our response to Review comment 1. In addition, we have provided an event tree model to illustrate the workflow, and revised the description of the method suggested in the paper along with the event tree as follows [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 $k \times P(F) \times P(\mathbf{S} = \mathbf{S}_i | F) \times P(n_j = k | \mathbf{S} = \mathbf{S}_i)$."

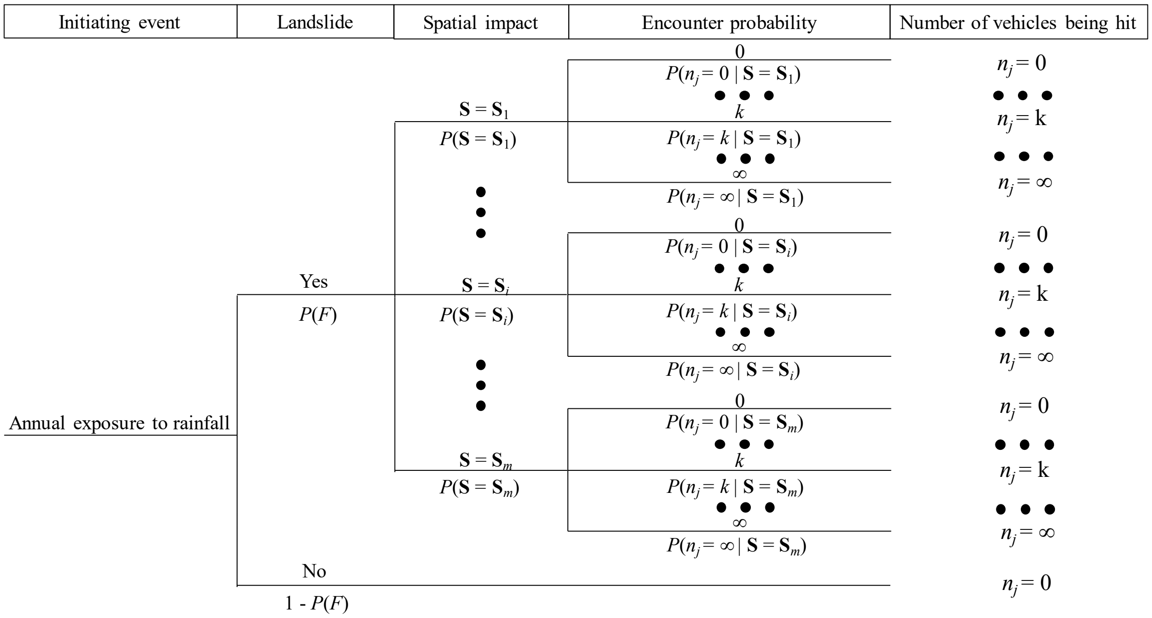

Figure 4. Event tree of evaluating the annual risk of the type j vehicle hit by the landslide

Comments in the supplement:

Review comment 7: *[Page 2, Line 32-34] and what about the probability that the sliding mass reaches the road?*

Authors' reply: Yes, we have corrected this sentence in the revised manuscript as follows [Lines 37-39]:

"There are many uncertainties in the assessment of the hazard of moving vehicles hit by a landslide, such as the occurrence of the landslide, the spatial impact of the landslide, the number of vehicles being hit by the landslide, and the type of vehicles being hit by the landslide."

Review comment 8: *[Page 2, Line 40] "attacked→ affected"; "in that→ because"*
[Page 3, Line 52, Line 63] "how the annual failure probability of the slope is calculated is described→the annual failure probability of the slope is calculated"; "26 m→25m"
[Page 4, Line 79, Line 80] add "and the consequences of the collision"; add "in a landslide critical zone of the road"

Authors' reply: Thank you. We have corrected these typos in the revised manuscript as suggested.

Review comment 9: *[Page 3, Line 56] How is possible to get that the suggested method be adaptable to others territories?*

Authors' reply: To address this question, we have provided a section on "Limitations and Applicability of the Method Suggested in This Study" in the revised manuscript, which has been described in our response to Review comment 1.

Review comment 10: *[Page 3, Line 58, Line 63] It will be more proper: particular conditions of case study or something like that…; This section should provide to reader some information about geological & geotechnical conditions of the slope with the aim to introduce him in the slope stability concepts.*
Authors' reply: Agree, we have changed the title of this section as "Study Slope and Traffic Information". In this case study, the geological and geotechnical conditions of the slope were not reported in GEO (1996). Thus, the empirical method is applied to analyze the runout distance of the slope failure in this study.

Review comment 11: *[Page 4, Line 68-69] This phrase should be in the begin of this section.*
Authors' reply: Agree. We have introduced this sentence at an earlier part of this section as suggested.

Review comment 12*: [Page 5, Line 86] (1) It is not possible 0 spatial impacts? and then, i=0. (2) are there infinite value for types of vehicles?*
Authors' reply: In Eq. (1), *k* denotes the number of vehicles. We have clarified this point in the revised manuscript. In the suggested method, the possibility of 0 spatial impact can also be considered, as clarified in the revised manuscript as follows [Line 112-116]:

"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 $P(n_j = 0| \mathbf{S} = \mathbf{S}_i) = 1$."

Review comment 13*: [Page 5, Line 99-100] It should not be sufficient only a slope failure, because the sliding mass might not reach the road, even a vehicle. Why? because that probability of reach de road depends of slope geometry, geotechnical parameters, etc… then how you could explain and include this consideration in your model?*
Authors' reply: We have explained how we consider such uncertainties in our model using an event tree in the revised manuscript, as described in our response to Review comment 6. In this paper, empirical equations are used to assess the failure probability and runout the distance, which can consider the effect of slope geometry but cannot consider the effect of geotechnical parameters. We have provided a discussion on the limitations and applicability on the suggested method, as described in our response to Review comment 1.

Review comment 14*: [Page 6, Line 106, Line 111] add "physically-based models"; add "or susceptibility"*
Authors' reply: Agree. We have revised the manuscript as suggested.

Review comment 15*: [Page 6, Line 116-118] This FP is obtained by physically-based methods involving uncertainties? These probabilities are related to a which return period of rainfall?*
Authors' reply: The failure probability is also obtained empirically based on statistical analysis of historical slope failure data, which has been described in our response to Review comment 2. Note the probabilities obtained from Zhang and Tang (2009) are conditional

probabilities for a given type of rainfall. To assess the annual failure probability of the slope, the annual occurrence probability of each type of rainfall should be considered through Eq. (6). In the revised manuscript, we have provided the following explanation in the revised manuscript [Lines 198-200]:

*"*With the above equation, the impact of uncertainty of rainfall on the annual failure probability of the landslide is considered. The failure probability obtained is unconditional on the rainfall type and hence does not correspond to a certain return period of rainfall."

Review comment 16*: [Page 7, Line 144] add "and geometric correlationships"*
Authors' reply: We have revised the manuscript as suggested.

Review comment 17*: [Page 7, Line 147] add "and geotechnical, hydraulic and rheological properties of sliding mass"*
Authors' reply: Thank you. We have revised the manuscript as suggested.

Review comment 18*: [Page 8, Line 148] in landslide debris is important water content of sliding mass and geometry slope.*
Authors' reply: Thank you for the comment. We have provided more background about the empirical equation used in this revised manuscript [Lines 212-228]:

"In general, the runout distance of a landslide depends on factors 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):

$$\log L = 0.085\log V + \log H + 0.047 + \varepsilon \tag{8}$$

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."

We have also discussed the limitations of the empirical method in the revised manuscript through a new section "Limitations and Applicability of the Method Suggested in This Study", which has been described in detail in response to Review comment 1.

Review comment 19*: [Page 7, Line 155] this formulation is applicable for back analysis because you know landslide scar but for not occurred events?*

[Page 14, Line 258] It is important to mention that the proposed model applicability is for back analysis of landslides, because you need information about landslide scar to estimate the volume and then L. Otherwise, you need to take into account more suppositions or to consider more uncertainties.
Authors' reply: Thank you. We have provided the following explanation in the revised manuscript [Lines 229-236]:

"To apply Eq. (8), the landslide volume is needed. In general, the volume of a landslide can be estimated through methods based on surface-area volume relationship (e.g. Malamud et al., 2004; Imaizumi and Sidle, 2007; Guzzetti et al., 2008; Guzzetti et al., 2009), slope stability analysis (e.g. Huang et al., 2013; Chen and Zhang, 2014), or morphology-based methods (e.g. Carter and Bentley, 1985; Jaboyedoff et al., 2012). A comprehensive review of such methods can be found in Jaboyedoff et al. (2020). With these methods, the volume of a sliding mass can be estimated both for a slope that has not failed yet and for a landslide that has occurred. In this study, the volume is estimated through the surface-area volume relationship."

Review comment 20*: [Page 8, Line 159] which was the real value?*
Authors' reply: The real value is 500 m^3 (GEO, 1996). We have added it in the revised manuscript.

Review comment 21*: [Page 9, Line 171] This term should be defined earlier to introduce to reader in this terminology.*
Authors' reply: Agree. This term has been defined earlier in the revised manuscript [Lines 203-208]:

"In this study, the spatial impact of the landslide is characterized by the landslide width and the runout distance of the landslide. Let b_l denote the width of the landslide. Let L denote the runout distance of the landslide, which is defined as the distance between the crest of the landslide scar and the toe of the slip. Thus, $\mathbf{S} = \{b_l, L\}$. For simplicity, the uncertainty of the landslide width is not considered. In such a case, the uncertainty associated with $\mathbf{S}$ is fully characterized by the uncertainty associated with the runout distance."

Review comment 22*: [Page 9, Line 185] This relation can be produce fractional numbers….which is the meaning of these values in the context of vehicles number?? It is an affectation degree?*
Authors' reply: Thank you for the comment. We have provided the following clarification in the revised manuscript [Lines 248-257]:

"As shown in Fig. 2, the horizontal distance from the crest of the landslide scar to the side of Kennedy Road close to the slope (l_{ch}) is 35 m. The width of Kennedy Road (b_h) is 10 m. When $L_i > l_{ch}$, the landslide will reach Kennedy Road. When $L_i \geq l_{ch} + b_h$, the Kennedy Road will be totally covered by the sliding mass. When $l_{ch} < L_i < l_{ch} + b_h$, the Kennedy Road will be partially affected. Thus, the percent of vehicles within the affected length of the highway for a given spatial impact, denoted as $\alpha(\mathbf{S} = \mathbf{S}_i)$ here, can be calculated as follows:

$$\alpha\left(\mathbf{S}=\mathbf{S}_i\right)=\begin{cases} 0, & L_i \le l_{ch} \\ \dfrac{L_i-l_{ch}}{b_h}, & l_{ch} < L_i < l_{ch}+b_h \\ 1, & L_i \ge l_{ch}+b_h \end{cases} \tag{10}$$

$\alpha(\mathbf{S} = \mathbf{S}_i)$ can also be interpreted as the degree of affection related to the runout distance. As can be seen from Eq. (10), $\alpha(\mathbf{S} = \mathbf{S}_i)$ is between 0 (the sliding mass does not reach the road) and 1 (the sliding mass totally covers the road)."

Review comment 23: *[Page 11, Line 230] In economic or monetary terms…which the value of potential losses?*

Authors' reply: Thank you for your advice. We have provided the following explanation in the revised manuscript [Lines 133-138]:

"Eq. (2) can be extended to estimate the expected monetary losses of vehicles being hit by a landslide when information regarding the price of different types of vehicles is available. Nevertheless, during the analysis of the risk of vehicles hit by landslides, the social impact, which can be better measured by the number of vehicles than the cost of the vehicles, is often more important than the economic losses. Hence, the risk of vehicles hit by landslides is not measured in terms of monetary losses in this study."

Review comment 24: *[Page 11, Line 232] It is suggested to comment if these values correspond to high or low risk values according some risk scale.*

Authors' reply: Thank you for the suggestion. We have explained in the revised manuscript on whether the risk is acceptable 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 being hit by the landslide can be calculated as:

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

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 $\lambda_p = \lambda(w_1 n_{p1} + w_2 n_{p2} + \dots w_n n_{pn})$ 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 is 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."

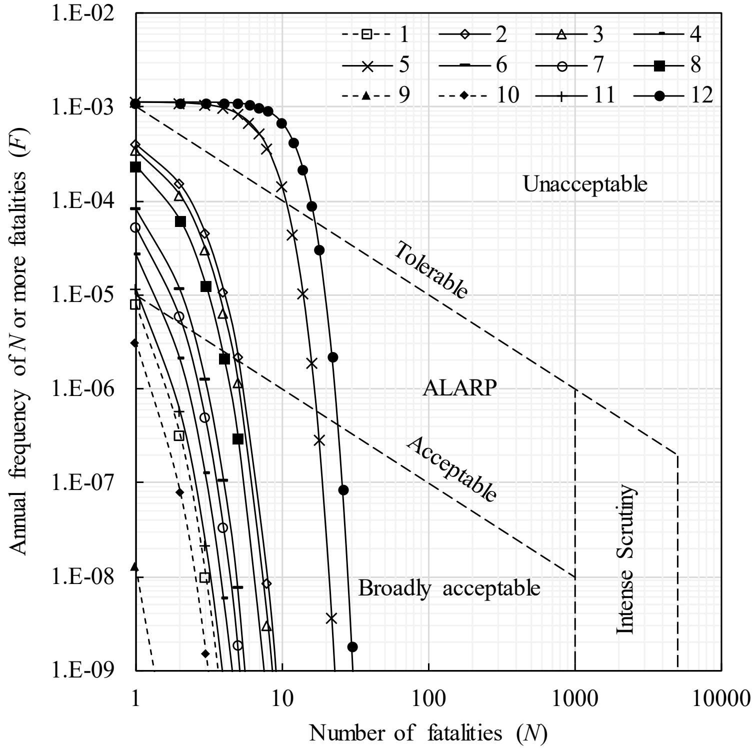

Figure 11. Estimated annual frequency of *N* or more persons hit by the landslide studied in this paper (Tolerable and acceptable F-N curves are those specified by the GEO 1998). (1. Private buses, 2. Non-franchised public buses, 3. Franchised buses, 4. Taxis, 5. Private cars, 6. Public light buses, 7. Private light buses, 8. Goods vehicles, 9. Special purpose vehicles, 10. Government vehicles, 11. Motor cycles, 12. All types of vehicles)

Review comment 25*: [Page 12, Line 251] under which considerations?*
Authors' reply: This has been explained in our response to Review comment 15.

Review comment 26*: [Page 13, Line 258] do you suggest some kind of measures to reduce the AFP & that it can be consider in your model?*
Authors' reply: We have addressed this point in the revised manuscript as follows [Lines 373-376]:

"In practice, the annual failure probability of a slope under rainfall can be reduced through the use of engineering measures such as structural reinforcement. To assess the effect of such measures on the failure probability of the slope, physically-based methods shall be used for hazard probability analysis."

Review comment 27*: [Page 13, Line 273] What about weather conditions and their relationship to traffic flow and AFP?*
Authors' reply: We have addressed this question in the revised manuscript [Lines 394-400]:

"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."

Review comment 28*: [Page 14, Line 292] "round→runout"; add "on vehicles".*
Authors' reply: We have corrected the typos in the revised manuscript.

Review comment 29*: [Page 14, Line 298] Of course, but with which adjustments or considerations?*
Authors' reply: Thank you. We have included a new section "Limitations and Applicability of the Method Suggested in This Study" in the revised manuscript to discuss the limitation and the applicability of the suggested method, as described in detail in our response to Review comment 1.

***Review comment 30:** I think that a good contribution of your research can be to establish new guidelines for highways design for purposes of roadway safety in terms of landslide risk reduction hitting vehicles & persons. For this, the methodology can be more detailed looking for include some uncertainties involve in the process providing innovative or novelty processes or methods.*
Authors' reply: We have discussed how the suggested method can be used to determine the target failure probability of the slope or the allowable traffic density in the revised manuscript, which has been described in our response to Review comment 1.

In the revised manuscript, we have also explained the novelty of the suggested method, as described in our response to Review comment 1.

Review comment 31*: [Page 23, Line 448] It is suggested a convenient figure, preferently with own authorship. As the figure is, it is not recommended for a scientific publication.*
Authors' reply: Thank you for your advice. The figure has been re-designed in the revised manuscript as follows:

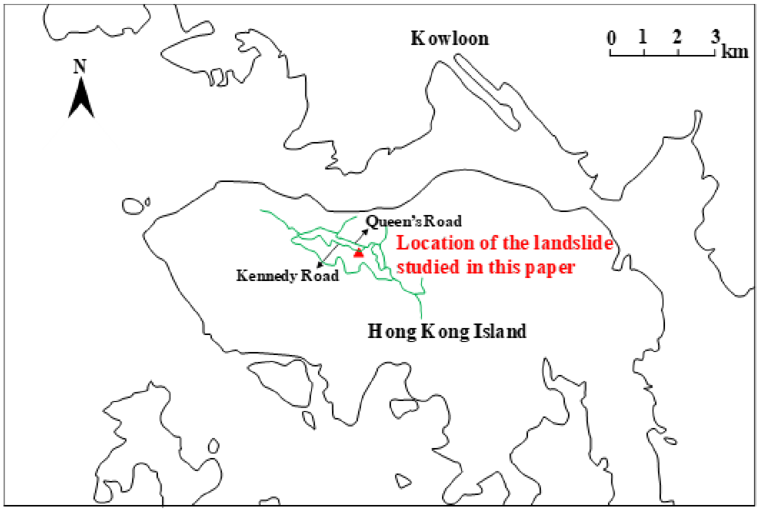

Figure 1. Location of the landslide studied in this paper

Review comment 32*: [Page 24, Line 452], [Page 25, Line 456] It is suggested a better figure. As the figure is, it is not proper for a scientific publication.*
Authors' reply: We have re-designed the figures of the slope based on your advice as follows:

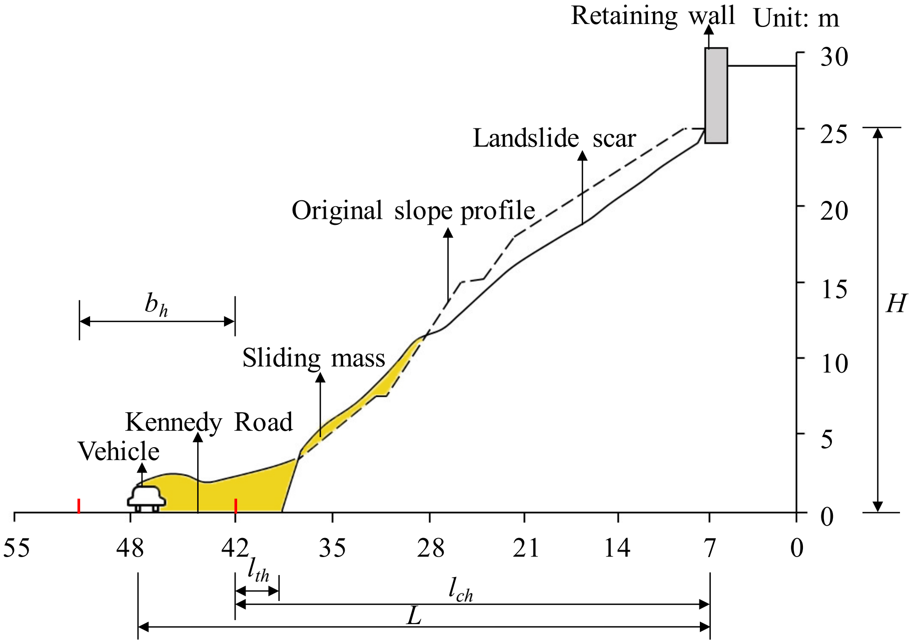

Figure 2. Typical cross section of the slope and the occurred landslide studied in this paper

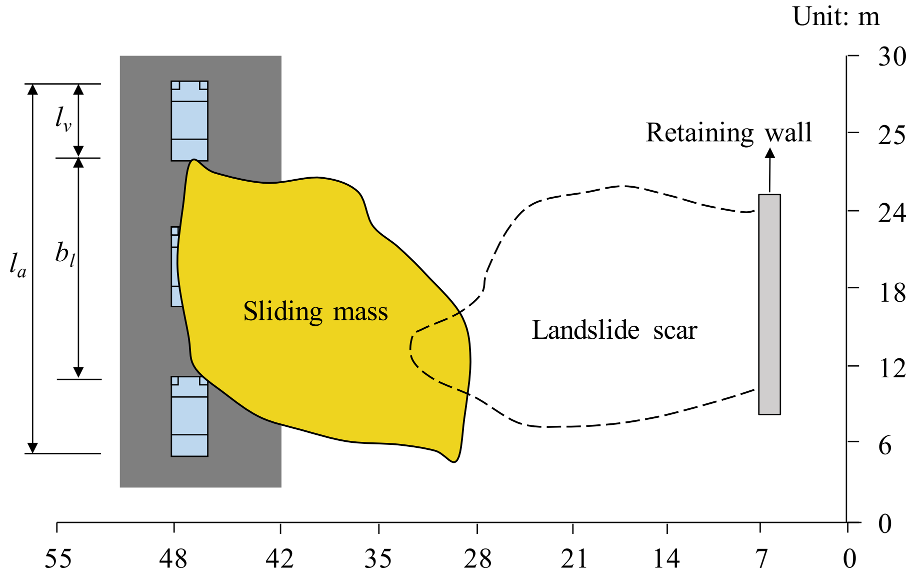

Figure 3. Plan view of the occurred landslide studied in this paper

Review comment 33: *[Page 29-34] This is not adequate symbol.*
Authors' reply: We have corrected the typo in the revised manuscript.

Response to Anonymous Referee #2

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 a moving vehicle, 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 factors 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):

$$\log L = 0.085\log V + \log H + 0.047 + \varepsilon \tag{8}$$

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 $k \times P(F) \times P(\mathbf{S} = \mathbf{S}_i| F) \times P(n_j = k| \mathbf{S} = \mathbf{S}_i)$."

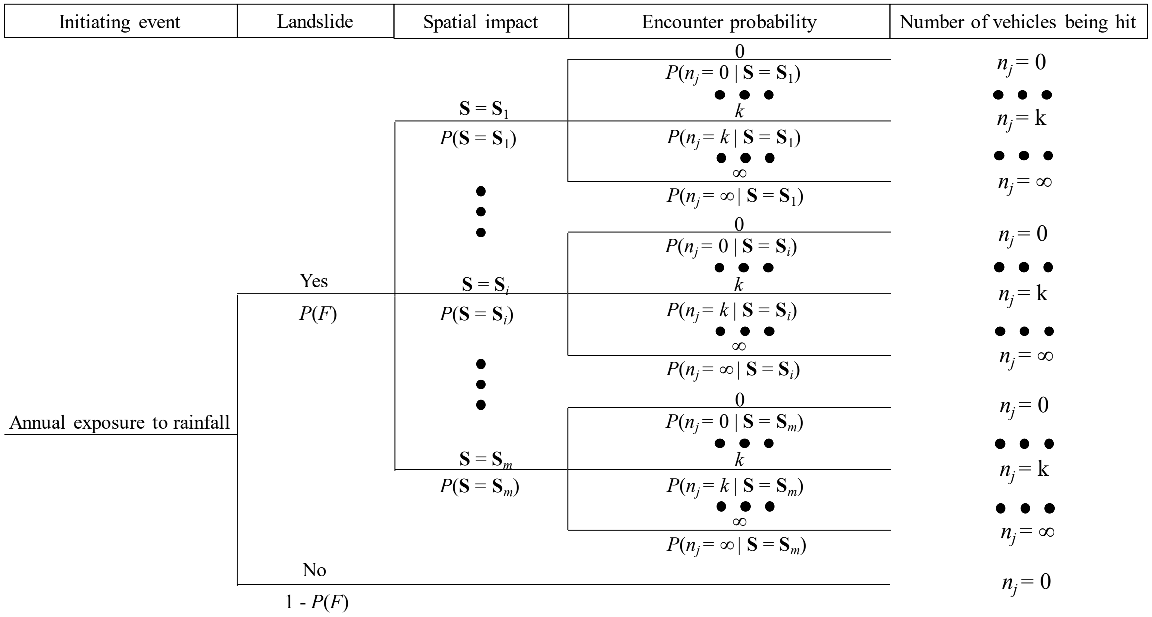

Figure 4. Event tree of evaluating the annual risk of the type *j* vehicle hit by the landslide

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 being 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 $\lambda_p = \lambda(w_1 n_{p1} + w_2 n_{p2} + \dots\ w_n n_{pn})$ 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 is 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."

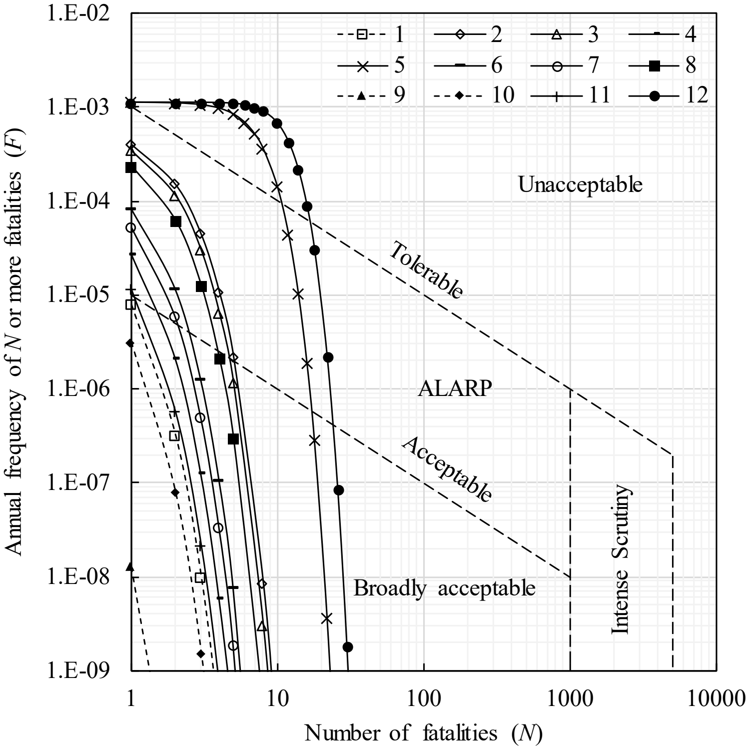

Figure 11. Estimated annual frequency of N or more persons hit by the landslide studied in this paper (Tolerable and acceptable F-N curves are those specified by the GEO 1998). (1. Private buses, 2. Non-franchised public buses, 3. Franchised buses, 4. Taxis, 5. Private cars, 6. Public light buses, 7. 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 are 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.

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

Meng Lu[1], Jie Zhang[2*], Lulu Zhang[3] and Limin Zhang[4]

Abstract: Landslides threaten the safety of vehicles on highways. In analyzing the risk of landslide hitting the moving vehicles, the spacing between vehicles and the type of vehicles on the highway could be highly uncertain, which are often not considered in previous studies. Through a case study about a highway slope in Hong Kong, this paper presents a 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 this case study, the annual failure probability of the slope is analyzed based on historical slope failure data in Hong Kong. The spatial impact of the landslide is evaluated based on an empirical runout prediction model. The consequence is assessed through probabilistic modeling of the traffic, which can consider uncertainties of vehicles spacing, vehicle types and slope failure time. With the suggested method, the expected annual number of vehicles and persons being hit by the landslide can be conveniently calculated. It can also be used to derive the cumulative frequency-number of fatalities curve for societal risk assessment. With the suggested method, the effect of factors like the annual failure probability of the slope and the density of vehicles on the risk of the slope can be conveniently assessed. The method described in this paper can provide a new guideline for highway slope design in terms of managing the risk of landslide hitting moving vehicles.

Key words: Risk assessment; Uncertainty; Landslide; Hit; Vehicles

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1 Introduction

With a total land area of about 1100 km^2, Hong Kong is one of the most densely populated regions in the world with a population of about 7.5 million (GovHK, 2019). Throughout the territory of Hong Kong, there are more than 57, 000 registered man-made slope features (Cheung and Tang, 2005). With an average annual rainfall of about 2400 mm, rainfall induced landslides are one of the major natural hazards threatening the public safety in Hong Kong (GEO, 2017). In particular, slope failures along highways have resulted in serious fatalities and damaged vehicles. For example, in August 1994, a public light bus on the Castle Peak Road was hit by landslide debris, causing three persons trapped inside the bus and one man killed. In August 1995, due to the intense rainfall, the landslide along Shum Wan Road resulted in two fatalities and five injuries, and the landslide along Fei Tsui Road resulted in one fatality and one injury (GEO, 2017). Similar phenomena has indeed also been reported in many other parts of the world (Bil et al., 2015), such as Italy (Donnini et al., 2017) and India (Negi et al., 2013).

There are many uncertainties in the assessment of the hazard of moving vehicles hit by a landslide, such as the occurrence of the landslide, the spatial impact of the landslide, the number of vehicles being hit by the landslide, and the type of vehicles being hit by the landslide. Risk assessment is a framework in which both the uncertainties and the consequence of a hazard can be addressed, which has now increasingly been used for landslide risk management (e.g. Lessing et al., 1983; Fell, 1994; Dai et al., 2002; Remondo et al., 2008; Erener, 2012; Vega and Hidalgo, 2016). Indeed, landslide risk assessment has been accepted as an effective tool for the planning of land use in Hong Kong. Nevertheless, the risk assessment of moving vehicles affected by landslides is special because the elements at risk are highly mobile. 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 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. The structure of this paper is as follows. Firstly, the annual failure probability of the slope is calculated based on historical data in Hong Kong. Then, the spatial impact of the landslide is analyzed based on the runout distance analysis. Thereafter, the consequence of the landslide is analyzed via a probabilistic model of traffic. Finally, the annual expected numbers of vehicles and persons being hit by the landslide are calculated, and how it can be used to develop the F-N curve for societal risk assessment is also illustrated. Factors affecting the risk of vehicles hit by the landslide are also discussed. The method suggested in this paper can support establishing new guidelines for highways design for purposes of roadway safety in terms of landslide risk reduction hitting vehicles and persons.

2 Study Slope and Traffic Information

The study slope is located on Kennedy Road in Wan Chai district of Hong Kong as shown in Fig. 1. Wan Chai is one of the most traditional cultural areas in Hong Kong and attracts many tourists around the world every year. In addition, Kennedy Road is a major road with three lanes in this area, linking with the Queen’s Road in Wan Chai (TDHK, 2018). On 8 May 1992, the slope failed during an intense rainfall, which hit a car travelling along Kennedy Road and killed the driver (GEO, 1996). The slope is an old cut slope formed in 1967 and 1968, which was covered by trees before the occurred landslide event. Fig. 2 shows a typical cross section of the slope and the occurred landslide event. As shown in this figure, the rainfall infiltration triggered the failure of the soil mass below the retaining wall and the sliding mass hit the vehicle. The height of the slope, H, is 25 m. The horizontal distance from the crest of the landslide scar to the side of Kennedy Road close to the slope, l_{ch}, is 35 m and the horizontal distance from the slope toe to the side of Kennedy Road close to the slope, l_{th}, is 3 m. The width of Kennedy Road, b_h, is 10 m. Fig. 3 shows the plan view of the occurred landslide event. The width of the slope is 18 m and the volume of the landslide is 500 m^3 (GEO, 1996). According to Transport Department of Hong Kong (TDHK) (2018), vehicles in Hong Kong are composed of private buses, non-franchised public buses, franchised buses, taxis, private cars, public light buses, private light buses, goods vehicles, special purpose vehicles, government vehicles and motor cycles. The percentage of each type of vehicle with respect to total numbers of vehicles is shown in Table 1 (TDHK, 2018). Additionally, the typical length of each type of vehicle and the passenger capacity of each type of vehicle are also shown in Table 1 (TDHK, 2018). The purpose of this case study is to analyze the annual risk of different types of vehicles hit by the landslide if the slope fails again due to rainfall.

3 Methodology

There are multiple types of vehicles on a highway. In a landslide critical zone of the road, the longer the vehicle, the greater the probability that it will be hit by a landslide. 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 $k \times P(F) \times P(\mathbf{S} = \mathbf{S}_i| F) \times P(n_j = k| \mathbf{S} = \mathbf{S}_i)$. As the pathways are mutually exclusive, the annual expected number of type j vehicles being hit by the landslide, E_{vj}, is the summation of expected numbers corresponding to all the pathways in Fig. 4, which can be written as follows:

$$E_{vj} = P(F) \times \sum_{i=1}^{m} \left[P(\mathbf{S} = \mathbf{S}_i \mid F) \times \sum_{k=0}^{\infty} kP(n_j = k \mid \mathbf{S} = \mathbf{S}_i) \right] \tag{1}$$

Let n denote total types of vehicles. The total expected number of vehicles being hit by the landslide considering all types of vehicles, i.e., E_v, can then be calculated as follows:

$$E_v = \sum_{j=1}^{n} E_{vj} \tag{2}$$

Let n_{pj} denote the passenger capacity in a type j vehicle. The expected number of people in type j vehicles being hit by the landslide, E_{pj}, can be calculated as follows:

$$E_{pj} = P(F) \times \sum_{i=1}^{m} \left[P(\mathbf{S} = \mathbf{S}_i \mid F) \times \sum_{k=0}^{\infty} kP(n_j = k \mid \mathbf{S} = \mathbf{S}_i) \right] \times n_{pj} \tag{3}$$

The total expected number of people being hit by the landslide considering all types of vehicles, E_p, can be calculated as follows:

$$E_p = \sum_{j=1}^{n} E_{pj} \tag{4}$$

Eq. (2) can be extended to estimate the expected monetary losses of vehicles being hit by a landslide when information regarding the price of different types of vehicles is available. Nevertheless, during the analysis of the risk of vehicles hit by landslides, the social impact, which can be better measured by the number of vehicles than the cost of the vehicles, is often more important than the economic losses. Hence, the risk of vehicles hit by landslides is not measured in terms of monetary losses in this study.

Previously, the individual risk is often used to measure the threat of a landslide to a moving vehicle, 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.

As indicated by Eq. (1), the keys for the annual risk associated with the type j vehicle are to evaluate: (1) the annual failure probability of the landslide, i.e., $P(F)$, (2) the possible spatial impact of the landslide, i.e., $P(\mathbf{S} = \mathbf{S}_i | F)$ and (3) the encounter probability that possible number of the type j vehicle being hit by the landslide for a given spatial impact, i.e., $P(n_j = k | \mathbf{S} = \mathbf{S}_i)$. How the above elements are assessed will be introduced in the following sections.

3.1 Evaluation of annual probability of the landslide, $P(F)$

The estimation of annual landslide probability or landslide susceptibility is fundamental in landslide hazard assessment. Since almost slope failures in Hong Kong are caused by rainfall infiltration (e.g. Lumb, 1975; Brand, 1984; Finlay et al., 1999), assessing annual probability of rainfall-induced landslides is important. In general, there are two types of methods for evaluating the likelihood of slope failure, i.e., physically based methods through slope stability analysis (e.g. Christian et al., 1994; Fenton and Griffiths, 2005; Huang et al., 2010) and empirical methods through statistical analysis of historical slope failure data (e.g. Chau et al., 2004; Tang and Zhang, 2009). Currently, landslide probability analyses via slope stability analyses mainly focus on the likelihood of slope failure for a given rainfall. In reality, the occurrence of landslides in a year is highly uncertain. Currently, how to calculate the annual failure probability of a landslide using physically-based models considering rainfall uncertainty is still not well established. Hence, the statistical methods are adopted in this study to estimate the annual landslide probability.

In Hong Kong, the failure of a slope is highly correlated to the 24-hour rainfall, i_{24} (Cheung and Tang, 2005). Based on i_{24}, the rainstorms in Hong Kong can be divided into three categories, i.e., (1) $i_{24} < 200$ mm/day (small rainfall, denoted as *SR*), (2) 200 mm $< i_{24} < 400$ mm/day (medium rainfall, denoted as *MR*) and (3) $i_{24} > 400$ mm/day (large rainfall, denoted as *LR*) (Zhang and Tang 2009). Through statistical analysis of the slope failure data in Hong Kong during 1984-2002, it is found that the failure probability of a slope in Hong Kong when subjected to small rainfall, medium rainfall and large rainfall are 1.09×10^{-4}, 2.61×10^{-3} and 8.94×10^{-3}, respectively, i.e., $P(F| SR) = 1.09 \times 10^{-4}$, $P(F| MR) = 2.61 \times 10^{-3}$ and $P(F| LR) = 8.94 \times 10^{-3}$ (Zhang and Tang, 2009). In the statistical analysis, it is assumed that slopes in Hong Kong when subjected to the same type of rainfall have the same failure probability, and hence the failure probability obtained should be interpreted as the failure probability of an average slope. Such an assumption is commonly adopted in statistically-based method for evaluating the failure probability of slopes in a region. As noticed by Dai et al. (2002), such a method cannot consider the effect of local geology and soil condition on the site-specific slope stability.

In Zhang and Tang (2009), the conditional failure probability of a slope for a given type of rainfall is provided. To calculate the annual failure probability of a slope, the uncertainty associated with the rainfall should be analyzed. In this study, the uncertainty associated with rainfall can be represented by the uncertainty associated with i_{24}. To characterize the uncertainty associated with i_{24}, we collected yearly maximum i_{24} measured at Hong Kong Observatory Headquarters during 1969 and 2018 as shown in Figure 5 (HKO, 2018). As can be seen from Fig. 5, the maximum i_{24} in a year in Hong Kong is mainly in the range of 100 to 350 mm. The generalized extreme value distribution (Hosking et al., 1985) with the following probability density function (PDF) seems to fit the histogram with reasonable accuracy:

$$f\left(i_{24}\right)=\frac{1}{\beta}\left[1+\gamma\left(\frac{i_{24}-\mu}{\beta}\right)\right]^{-\frac{1}{\gamma}}\exp\left\{\left[1+\gamma\left(\frac{i_{24}-\mu}{\beta}\right)\right]^{-\frac{1}{\gamma}}\right\} \tag{5}$$

where β, μ and γ are the scale parameter, the location parameter and the shape parameter of the generalized extreme distribution, respectively. The values of β, μ and γ can be calculated based on maximum likelihood method and they are equal to -0.17, 66 and 188, respectively. Fig. 6 shows the cumulative distribution function (CDF) of i_{24} obtained based on the fitted generalized extreme value distribution. As can be seen from this figure, the probability that the rainfall with yearly maximum i_{24} belongs to small rainfall, medium rainfall and large rainfall is 0.44, 0.55 and 0.01, respectively, i.e., $P(SR)$ = 0.44, $P(MR)$ = 0.55 and $P(LR)$ = 0.01. Based on the total probability theorem, the annual probability of a rainfall induced slope failure can be computed as follows:

$$P(F) = P(F \mid SR)P(SR) + P(F \mid MR)P(MR) + P(F \mid LR)P(LR) \quad (6)$$

With the above equation, the impact of uncertainty of rainfall on the annual failure probability of the landslide is considered. The failure probability obtained is unconditional on the rainfall type and hence does not correspond to a certain return period of rainfall.

3.2 Evaluation of spatial impact of the landslide, $P(\mathbf{S} = \mathbf{S}_i \mid F)$

In this study, the spatial impact of the landslide is characterized by the landslide width and the runout distance of the landslide. Let b_l denote the width of the landslide. Let L denote the runout distance of the landslide, which is defined as the distance between the crest of the landslide scar and the toe of the slip. Thus, $\mathbf{S} = \{b_l, L\}$. For simplicity, the uncertainty of the landslide width is not considered. In such a case, the uncertainty associated with **S** is fully characterized by the uncertainty associated with the runout distance. In principle, the runout distance is a continuous random variable. For ease of computation, it can be discretized into a discrete variable. Let L_i denote the ith possible value of L. Then, $P(\mathbf{S} = \mathbf{S}_i \mid F)$ can be calculated by

$$P(\mathbf{S} = \mathbf{S}_i \mid F) = P(L = L_i) \quad (7)$$

In general, the runout distance of a landslide depends on factors 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):

$$\log L = 0.085\log V + \log H + 0.047 + \varepsilon \tag{8}$$

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.

For the slope as shown in Fig. 2, the height is 25 m, i.e., $H = 25$ m. To apply Eq. (8), the landslide volume is needed. In general, the volume of a landslide can be estimated through methods based on surface-area volume relationship (e.g. Malamud et al., 2004; Imaizumi and Sidle, 2007; Guzzetti et al., 2008; Guzzetti et al., 2009), slope stability analysis (e.g. Huang et al., 2013; Chen and Zhang, 2014), or morphology-based methods (e.g. Carter and Bentley, 1985; Jaboyedoff et al., 2012). A comprehensive review of such methods can be found in Jaboyedoff et al. (2020). With these methods, the volume of a sliding mass can be estimated both for a slope that has not failed yet and for a landslide that has occurred. In this study, the volume is estimated through the surface-area volume relationship. Let A_s denote the landslide scar area. The volume of the landslide in this case study is estimated with A_s using the following equation (Parker 2011):

$$V = 0.106 \times A_s^{1.388} \tag{9}$$

Based on Fig. 3, the landslide scar area is estimated to be 450 m^2. Based on Eq. (9), the volume is estimated about 510 m^3, which is close to the volume of sliding mass (500 m^3) reported in GEO (1996). Substituting the values of H and V into Eq. (8), it can be obtained that the travel distance of the landslide is lognormally distributed with a mean of 50.7 m and a standard deviation of 12.6 m. Fig. 7 shows the PDF of the travel distance of the landslide. As can be seen from this figure, the travel distance of the landslide is mainly in the range of 20 m to 150 m.

3.3 Evaluation of encounter probability, $P(n_j = k| \mathbf{S} = \mathbf{S}_i)$

As shown in Fig. 2, the horizontal distance from the crest of the landslide scar to the side of Kennedy Road close to the slope (l_{ch}) is 35 m. The width of Kennedy Road (b_h) is 10 m. When $L_i > l_{ch}$, the landslide will reach Kennedy Road. When $L_i \geq l_{ch} + b_h$, the Kennedy Road will be totally covered by the sliding mass. When $l_{ch} < L_i < l_{ch} + b_h$, the Kennedy Road will be partially affected. Thus, the percent of vehicles within the affected length of the highway for a given spatial impact, denoted as $\alpha(\mathbf{S} = \mathbf{S}_i)$ here, can be calculated as follows:

$$\alpha\left(\mathbf{S}=\mathbf{S}_i\right)=\begin{cases} 0, & L_i \leq l_{ch} \\ \dfrac{L_i - l_{ch}}{b_h}, & l_{ch} < L_i < l_{ch} + b_h \\ 1, & L_i \geq l_{ch} + b_h \end{cases} \tag{10}$$

$\alpha(\mathbf{S} = \mathbf{S}_i)$ can also be interpreted as the degree of affection related to the runout distance. As can be seen from Eq. (10), $\alpha(\mathbf{S} = \mathbf{S}_i)$ is between 0 (the sliding mass does not reach the road) and 1 (the sliding mass totally covers the road). For a given runout distance, the number of vehicles hit by the landslide highly depends on the length of road affected by the landslide as well as the density of vehicles. Let l_a denote the length of road affected by the landslide. Let l_v denote the length of vehicles. As shown in Fig. 3, when the head or the rear of a vehicle contacts with the landslide mass, the vehicle will be hit by the landslide, i.e., the length of affected road, l_a, is equal to the sum of the width of the landslide (b_l) and the length of the vehicles (l_v) as follows:

$$l_a = b_l + 2l_v \tag{11}$$

In this study, the width of the landslide is assumed to equal to the width of the slope, i.e., $b_l = 18$ m (GEO, 1996). In transportation, the presence of the vehicles on a highway can be modeled as a Poisson process with a mean arrival rate of λ, which is equal to the density of vehicles on a highway (Paxson and Floyd, 1995). Let q denote the number of vehicles passing a given cross section of a road per unit time. Let v denote the average speed of the vehicles. The mean rate of occurrence of moving vehicles (λ) can be calculated as follows (Lighthill, 1995):

$$\lambda = \frac{q}{v} \tag{12}$$

Let w_j denote the proportion of type j vehicle in the traffic flow. The mean rate of occurrence of type j vehicles can be then written as follows:

$$\lambda_j = w_j \times \frac{q}{v} \tag{13}$$

In general, the presence of vehicles also depends on the periods in a day. As an example, Table 2 shows the data about q and v of the Kennedy road for the morning peak, normal period and evening peak, respectively (TDHK 2018). Then, the mean rate of occurrence of each type of vehicle is obtained for different periods of a day, as shown in Figs. 8(a)–(c), respectively. It can be seen that the mean rate of occurrence of the vehicles during the morning and evening peaks is significantly larger than that in the normal period. Among all types of vehicles, the mean rate of private cars in the affected road is the greatest, followed by goods vehicles, motor cycles and taxis.

Let T_1, T_2 and T_3 denote the morning peak, the normal period and the evening peak, respectively, and let l_{aj} denote the length of affected road for type j vehicle. Based on the property of a Poisson process, if the spatial impact is $\mathbf{S}_i$ and the slope fails during period T_i, the encounter probability that k type j vehicles will be hit by the landslide can be computed by

$$P\left(n_j = k \mid t \in T_i, \mathbf{S} = \mathbf{S}_i\right) = \frac{\left[\alpha_j\left(\mathbf{S} = \mathbf{S}_i\right)\lambda_j l_{aj}\right]^k}{k!} \exp\left[-\alpha_j\left(\mathbf{S} = \mathbf{S}_i\right)\lambda_j l_{aj}\right] \tag{14}$$

Eq. (14) provides a probabilistic model of the number of vehicles hit by the landslide, which can consider uncertainties of vehicles spacing, vehicle types and slope failure time. As an example, Figs. 9(a)–(c) show the probability distributions of the number of private cars being hit by the landslide during the morning peak, normal period and evening peak when the spatial impact is $\mathbf{S}_i$ and $\alpha_j(\mathbf{S} = \mathbf{S}_i) = 1$, respectively. As can be seen from these figures, the most probable number of private cars being hit by the landslide during the morning peak and evening peak is both about 3 and its probability is both about 0.20. The most probable number of private cars being hit by the landslide during the normal period is about 1 and its probability is about 0.37.

In reality, the slope can fail during any period of a day. Based on the total probability theorem, the probability that k type j vehicles will be hit for the case of $\mathbf{S} = \mathbf{S}_i$ can be computed by

$$P\left(n_j = k \mid \mathbf{S} = \mathbf{S}_i\right) = \sum_{i=1}^{3} P\left(n_j = k \mid t \in T_i, \mathbf{S} = \mathbf{S}_i\right) P\left(t \in T_i\right) \tag{15}$$

As an example, Figs. 9(d) shows the probability distribution of the number of private cars being hit by the landslide considering the uncertainty of the failure time when the spatial impact is $\mathbf{S}_i$ and $\alpha_j(\mathbf{S} = \mathbf{S}_i) = 1$. As can be seen from this figure, the most probable number of private cars hit by the landslide considering the uncertainty of the failure time is about 1 and its probability is about 0.32.

3.4 Risk calculation and evaluation

In the above analyses, equations for evaluating $P(F)$, $P(\mathbf{S} = \mathbf{S}_i | F)$ and $P(n_j = k | \mathbf{S} = \mathbf{S}_i)$ are introduced. Substituting these equations into Eq. (1), the expected number of each type of vehicles being hit by the landslide can then be calculated, as shown in Figs. 10(a). As can be seen from this figure, the expected number of private cars being hit by the landslide is the greatest with a value of 1.67×10^{-3} vehicles per year, followed by the goods vehicles, motor cycles and taxis. The expected number of each type of vehicles being hit by the landslide is highly correlated with the proportion of vehicles in the traffic flow. The private cars have the greatest proportion in the traffic flow and hence it is natural to be associated with the greatest expected number. In reality, the vehicle that was hit by the studied slope on 8 May 1992 was indeed a private car. With Eq. (2), the total expected number of vehicles being hit by the landslide considering all types of vehicles can be also calculated, which is about 2.48×10^{-3} vehicles per year.

Submitting the passenger capacity of each type of vehicle into Eq. (3), the expected number of persons being hit by the landslide associated with each type of vehicle can be computed and the results are shown in Figs. 10(b). As can be seen from this figure, the expected number of persons being hit by the landslide for private cars is the greatest with a value of 8.37×10^{-3} persons per year, followed by non-franchised public buses, franchised buses and goods vehicles. The expected number of persons being hit by the landslide for each type of vehicles highly depends on the proportion of vehicles in the traffic flow and the passenger capacity of vehicles. The non-franchised public buses have the higher proportion in the traffic flow and the largest passenger capacity hence it is natural to be associated with the greater expected number. Based on Eq. (4), the total expected number of persons being hit by the landslide considering all types of vehicles can be also calculated, which is about 1.36×10^{-2} persons per year.

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 being 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 is 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.

4 Discussions

4.1 Effect of annual failure probability of the slope

In the above analysis, the annual failure probability of the slope only represents the failure probability of an average slope in Hong Kong. To investigate the effect of the failure probability of the slope, Fig. 12 shows the how the annual expected number of vehicles and people being hit by the landslide for all types of vehicles changes with the annual failure probability of the slope. As can be seen from this figure, the expected number of vehicles hit by the landslide increases linearly as the annual failure probability of the slope increases. When the failure probability of the slope increase from 1.0×10^{-4} to 1.0×10^{-2}, the expected number increases from 1.57×10^{-4} vehicles being hit per year to 1.57×10^{-2}

vehicles being hit per year. A similar observation can also be found for the annual expected number of persons being hit by the landslide. Fig. 13 shows the how the societal risk for all types of vehicles changes as the annual failure probability of the slope changes. As can be seen from this figure, when the failure probability of the slope is smaller than 1.0×10^{-4}, the societal risk will be in the ALARP region. If the failure probability of the slope is further reduced to 1.0×10^{-6}, the societal risk will become acceptable. Hence, reducing the annual failure probability of a slope is an effective means to reduce the risk of the slope. In practice, the annual failure probability of a slope under rainfall can be reduced through the use of engineering measures such as structural reinforcement. To assess the effect of such measures on the failure probability of the slope, physically-based methods shall be used for hazard probability analysis.

4.2 Effect of traffic density

The density of vehicles may vary from one road to another. To investigate the effect of density of vehicles, the annual expected number of vehicles and people being hit by the landslide and the annual societal risk for all types of vehicles are investigated when the density of vehicles on the highway increases from 0 to 300 vehicles per kilometer and the results are shown in Fig. 14 and Fig. 15, respectively. As can be seen from Fig. 14, there is a linear increasing trend of the expected number of vehicles and persons as density of vehicles increases. When the density of vehicles is equal to 300 vehicles per kilometer, the expected number can reach 1.01×10^{-2} vehicles being hit per year and 5.52×10^{-2} persons being hit per year, respectively. As can be seen from Fig. 15, the societal risk also increases as the density of vehicles becomes larger. When density of vehicles is less than 10 vehicles per kilometer, the societal risk will be within the ALARP region. Therefore, depending on the density of the vehicles, the societal risk of a landslide may be acceptable when it is located near one highway but become unacceptable when it is located at another highway. Therefore, in the design of highway slopes, the failure probability of the slope should be decreased as the density of the vehicles increases.

5 Limitations and Applicability of the Method Suggested in This Study

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 are 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.

6 Summary and Conclusions

When assessing the risk of landslide hitting the moving vehicles, the number and types of vehicles being hit could be highly uncertain. Using a case study in Hong Kong, this paper suggests a method to assess the risk of vehicles hit by a rainfall-induced landslide with explicit considering of the above factors. The research findings from this study can be summarized as follows.

(1) With the method suggested in this paper, the expected annual number of vehicles/persons hit by the landslide as well as the cumulative frequency-number of fatalities curve can be calculated. These results can provide important complement to those from previous studies on risk assessment of landslide hitting moving vehicles, which mainly focus on the individual risk of a landslide or societal risk assessment relying on the probability of the occurrence of at least one fatality per year.

(2) As the length, density, as well as the passage capacity of different vehicles are different, the annual number of vehicles/persons hit by the landslide for different types of vehicles are not the same. The societal risk associated with different types of vehicles are also different. It is important to consider different types of vehicles in the traffic flow.

(3) The suggested method can be used to examine the effect of factors like the annual failure probability of the slope and the density of the vehicles on the road on the risk of landslide hitting moving vehicles. The proposed method can be potentially useful to determine the target annual failure probability of a slope considering the traffic condition at a highway, which can be used as a new guideline for highway landslide risk management.

In this case study, the annual failure probability of the slope is evaluated based on a statistical model, and the spatial impact of the landslide is analyzed through an empirical equation. While these methods are easy to use, they cannot consider the effect of local geology and soil condition on the failure and post-failure behavior of the slope. Further studies are needed to explore physically-based methods to predict the annual failure probability and runout distance with explicit consideration of the uncertainties involved.

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Figure 12. Impact of annual failure probability of the slope on annual expected number of elements being hit by the landslide

Figure 13. Impact of annual failure probability of the slope on annual societal risk

Figure 14. Impact of density of vehicles on annual expected number of elements being hit by the landslide

Figure 15. Impact of density of vehicles on annual societal risk

Table 1. Percent, length and passenger capacity of vehicles in Hong Kong

Vehicles types	Percent (%)	Length (m)	Passenger capacity (persons)
Private buses	0.08	10	55
Non-franchised public buses	0.82	10	55
Franchised buses	0.72	10	55
Taxis	2.30	5	5
Private cars	71.41	5	5
Public light buses	0.50	9	33
Private light buses	0.39	9	33
Goods vehicles	13.77	12	2
Special purpose vehicles	0.23	5	1
Government vehicles	0.74	5	5
Motor cycles	9.24	2	1

Table 2. Number of vehicles passing a given cross section of road per hour and average speed of vehicles on Kennedy Road in a day

Periods in a day	Morning peak (7–9 am)	Normal period	Evening peak (5–7 pm)
q (vehicles per hour)	3000	1500	2800
v (km per hour)	15	30	15

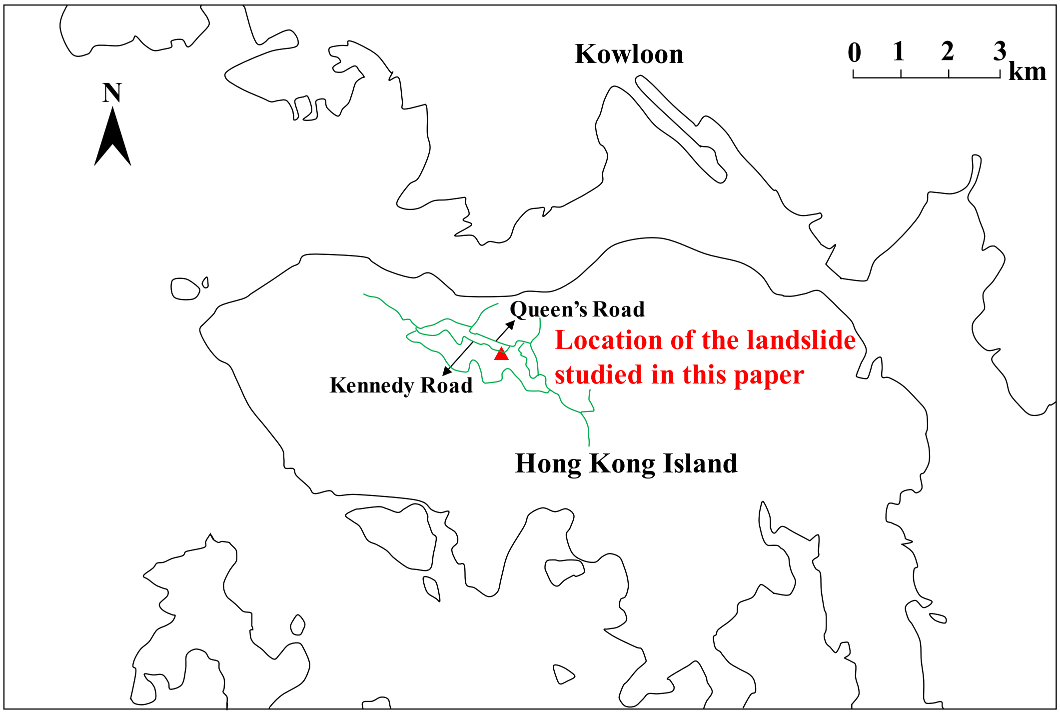


Figure 1. Location of the landslide studied in this paper

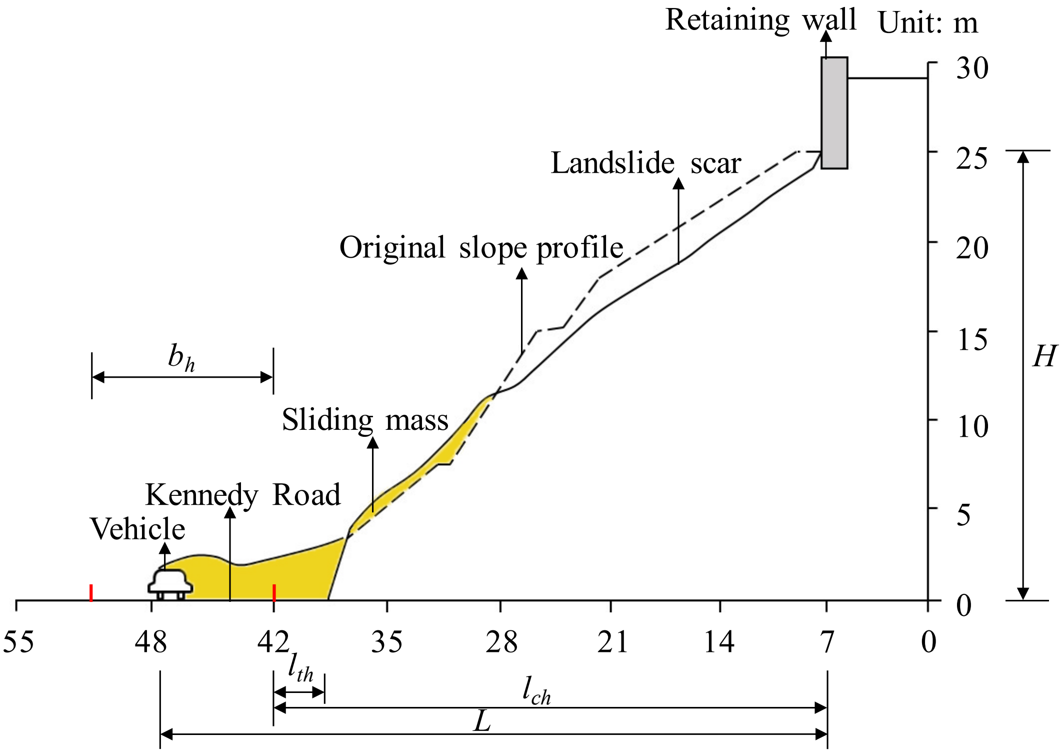
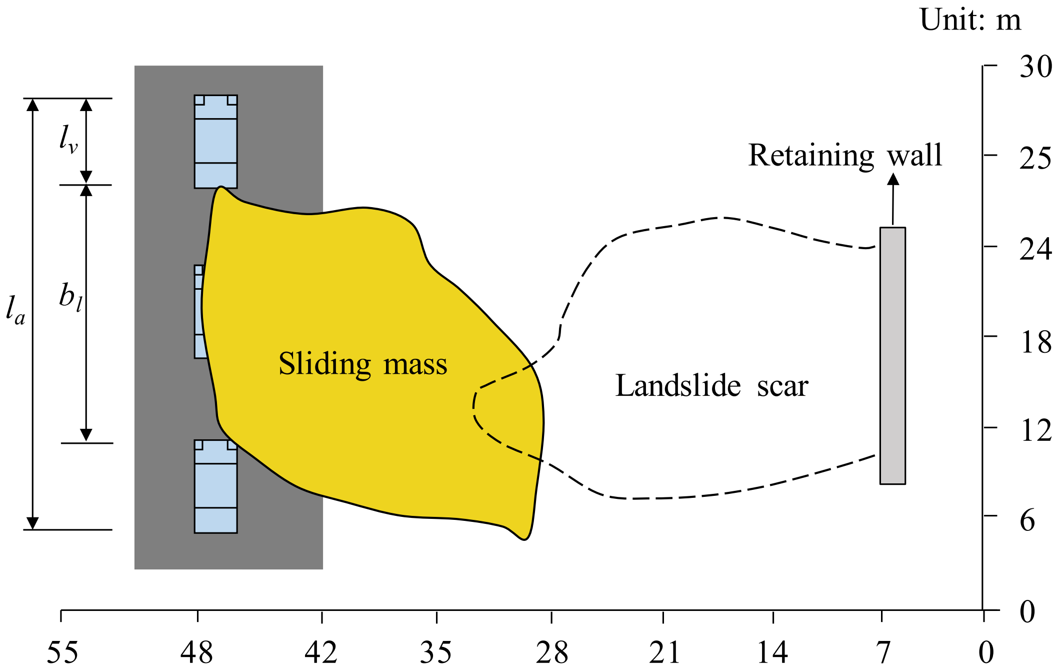


Figure 2. Typical cross section of the slope and the occurred landslide studied in this paper



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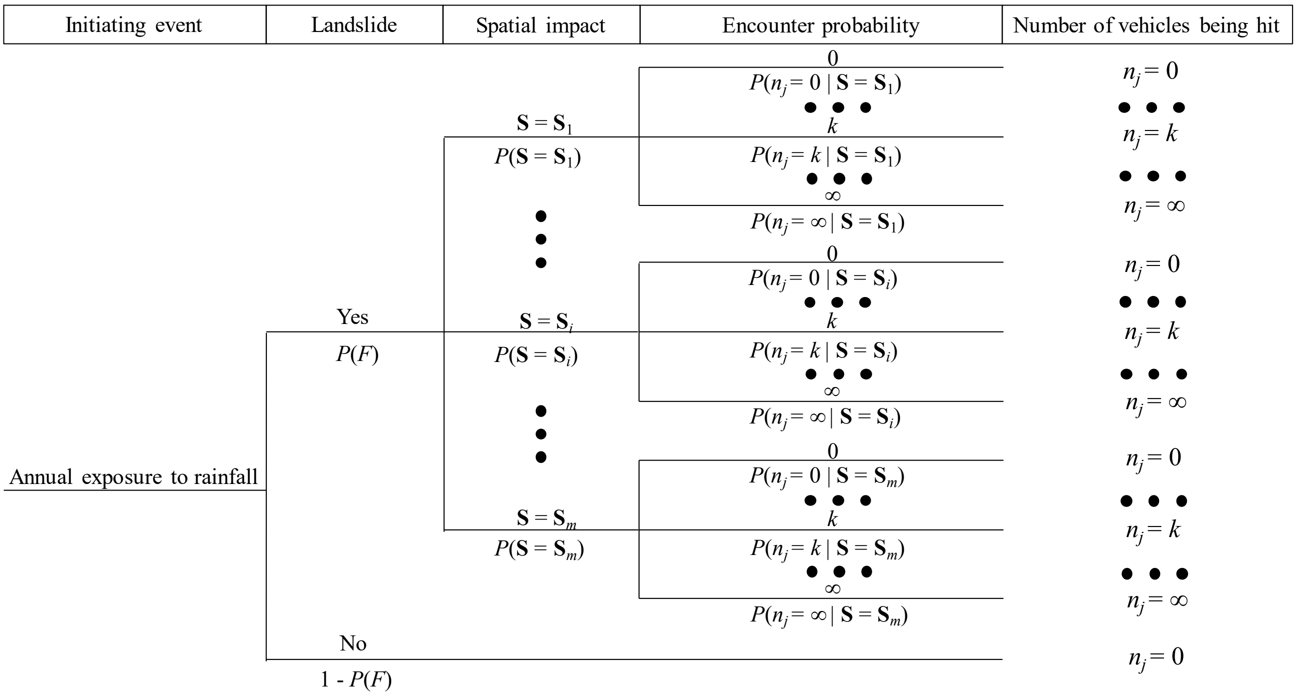


Figure 4. Event tree of evaluating the annual risk of the type *j* vehicle hit by the landslide

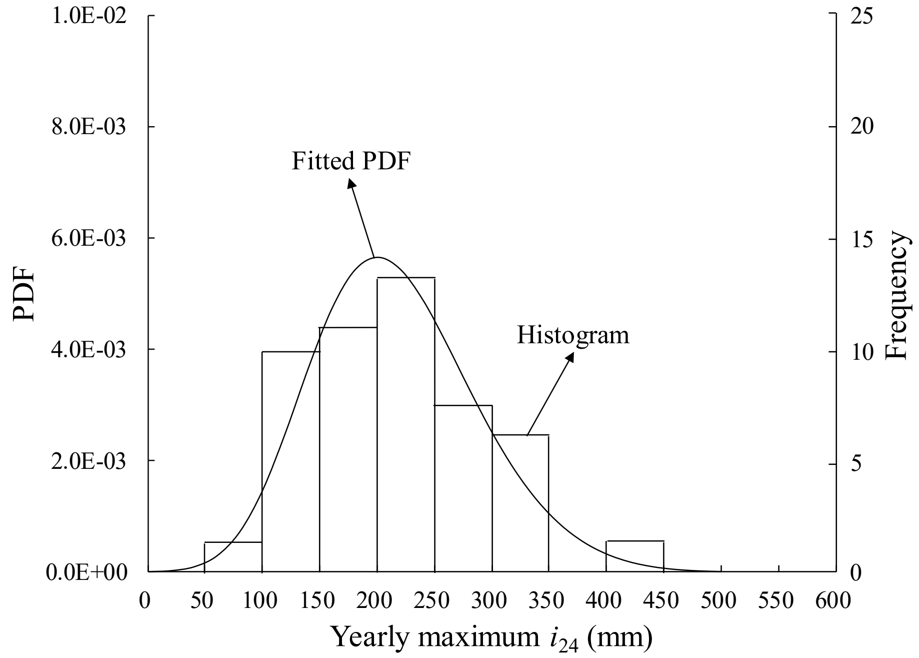


Figure 5. Histogram and fitted PDF of yearly maximum i_{24} in Hong Kong

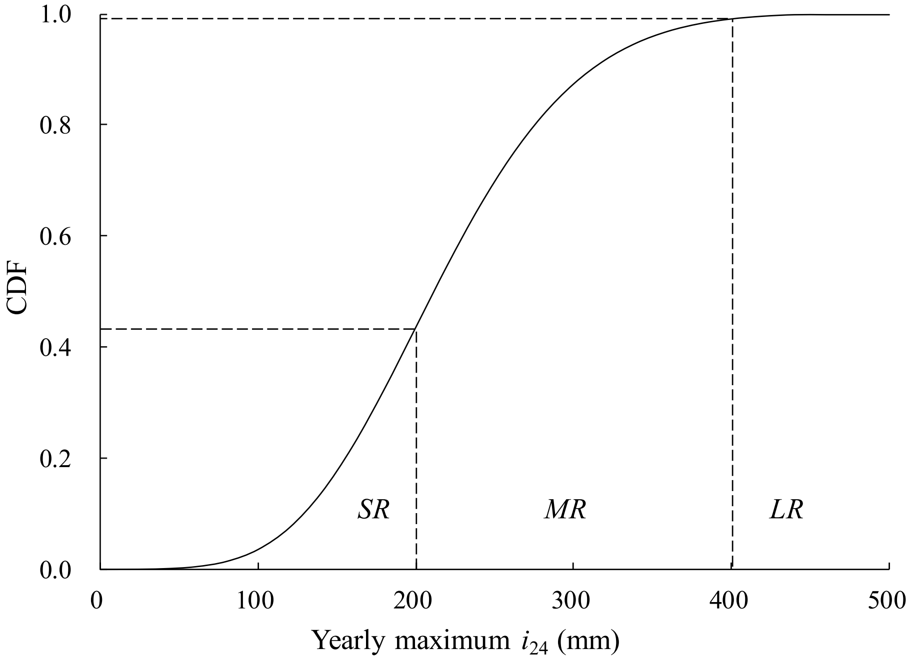
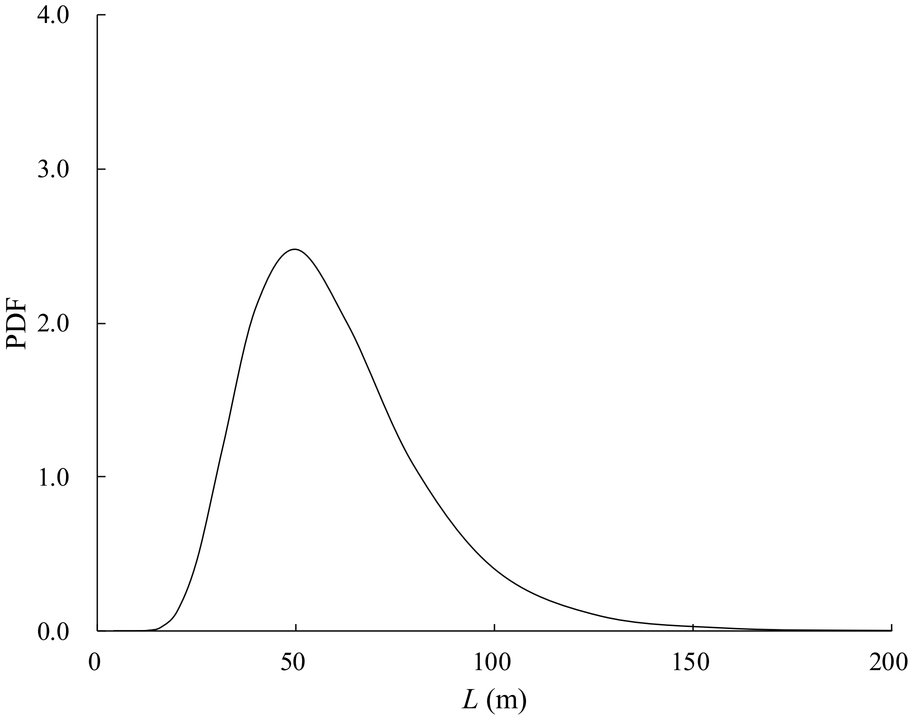


Figure 6. CDF of yearly maximum i_{24} in Hong Kong



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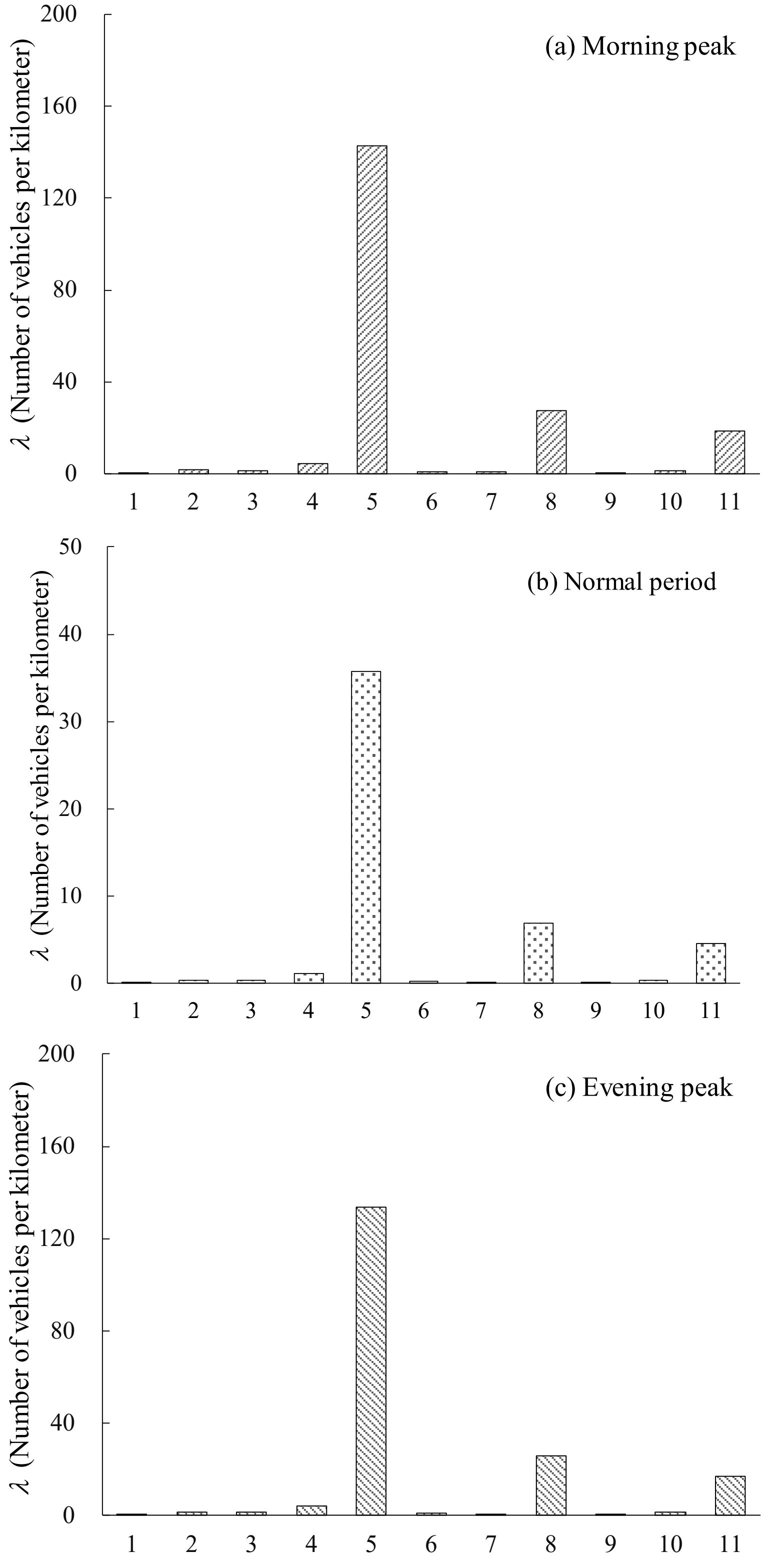

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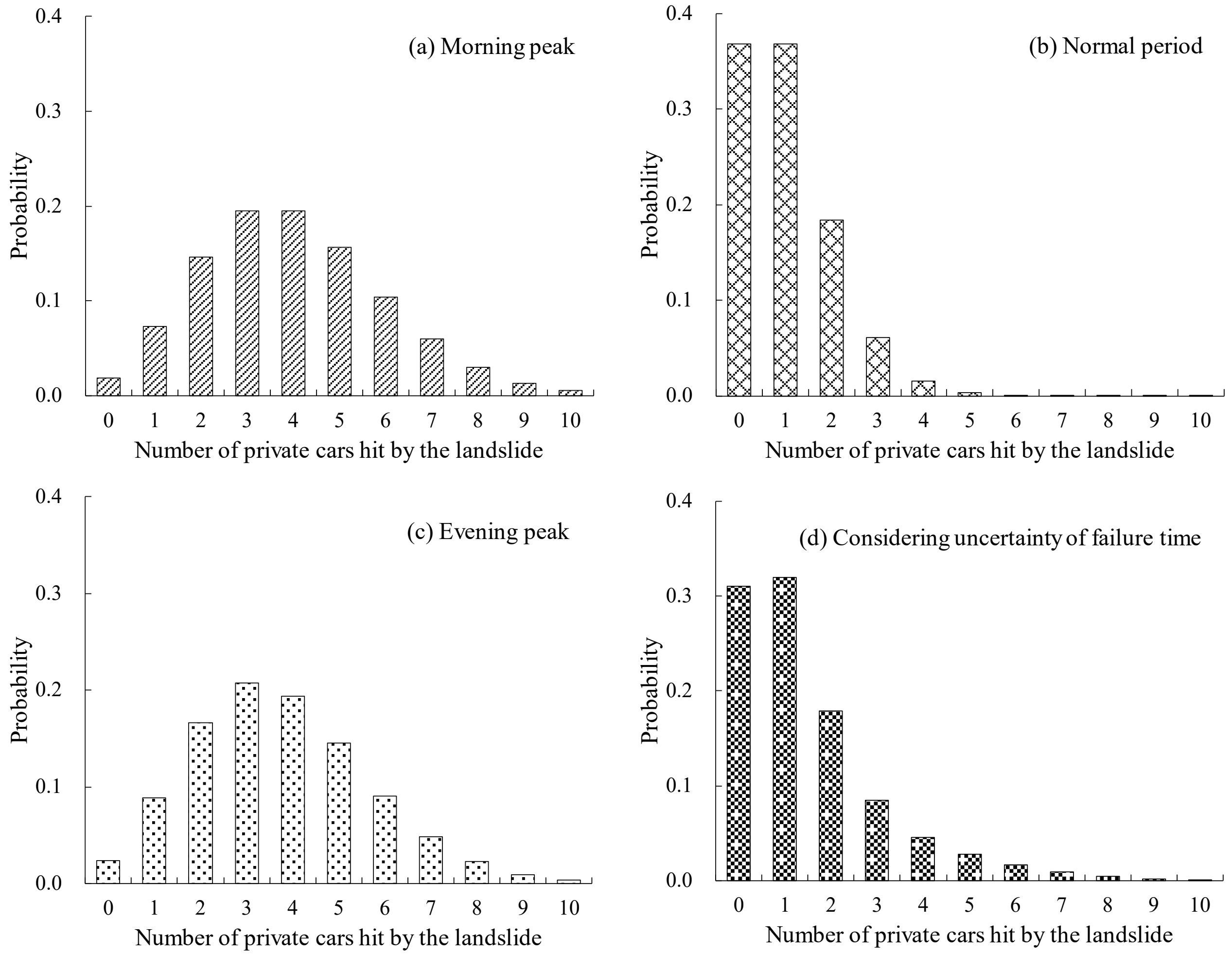

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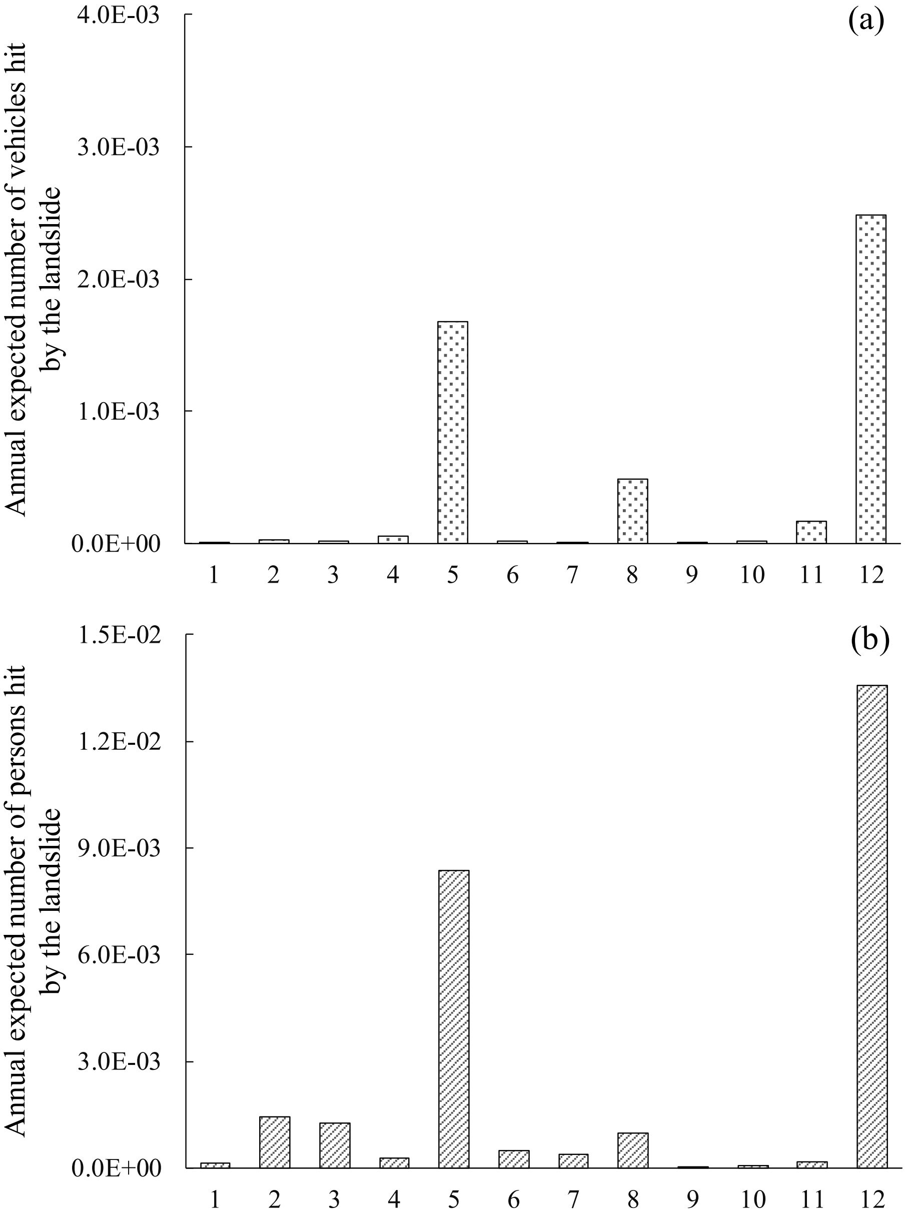

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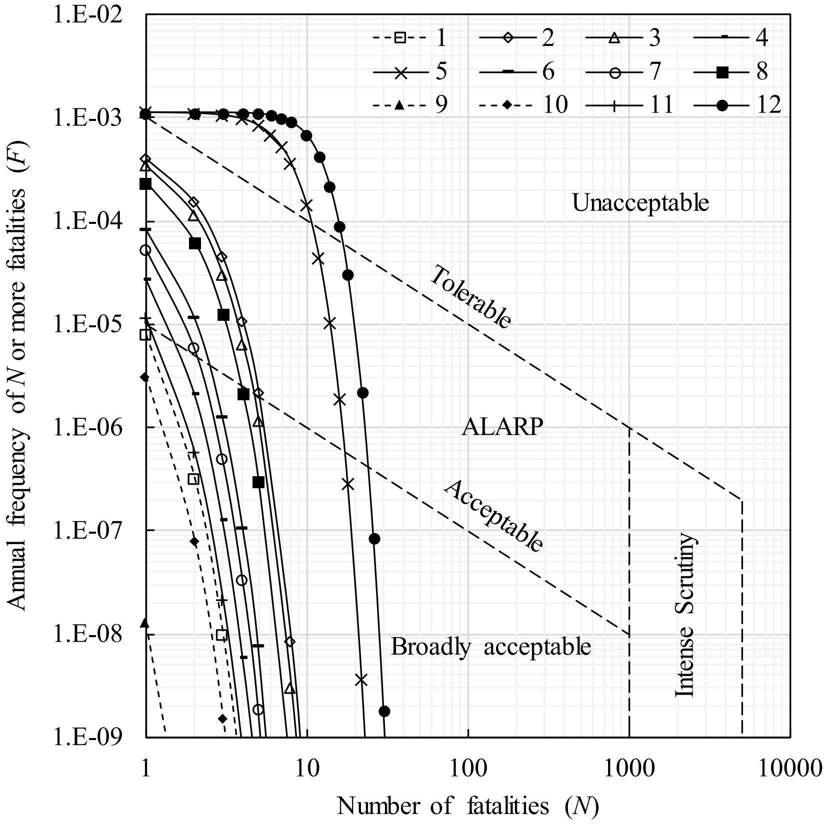

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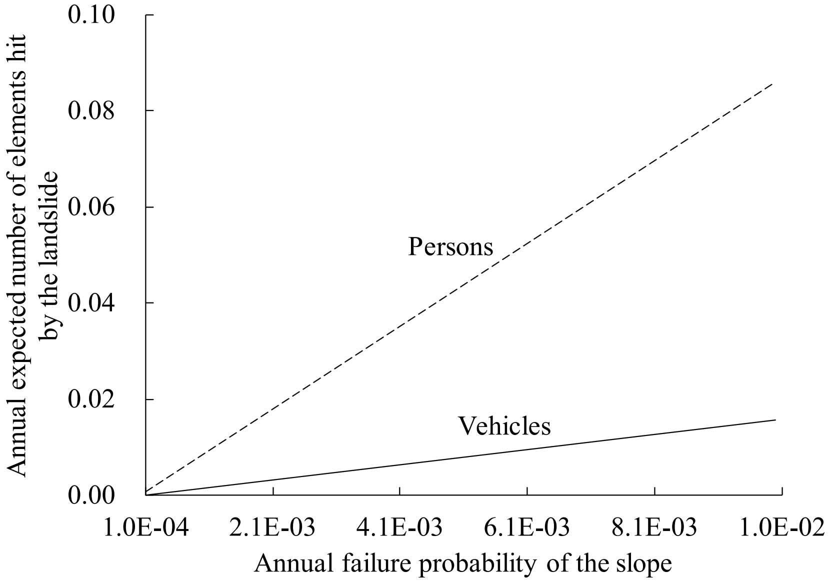


Figure 12. Impact of annual failure probability of the slope on annual expected number of elements being hit by the landslide

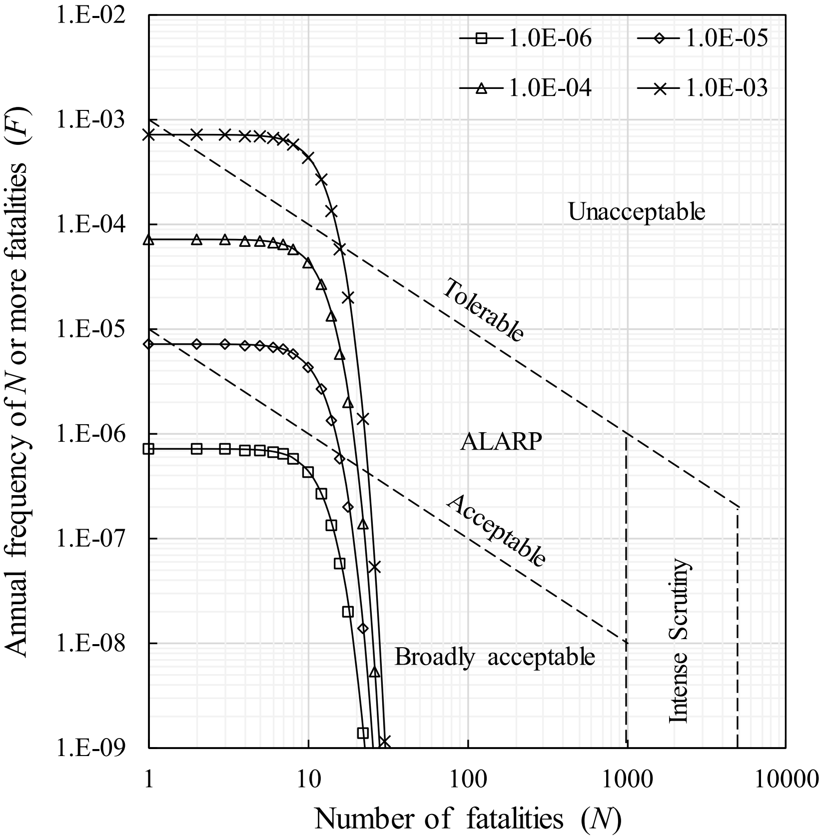


Figure 13. Impact of annual failure probability of the slope on annual societal risk

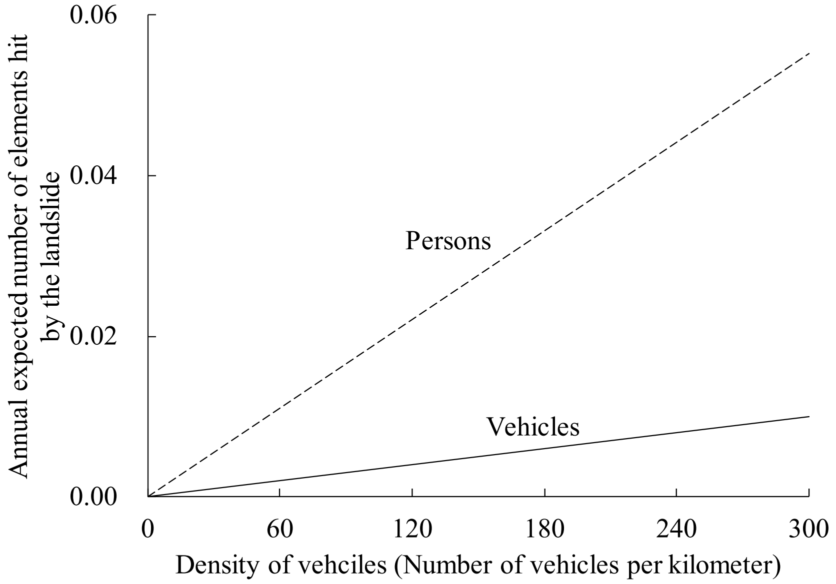
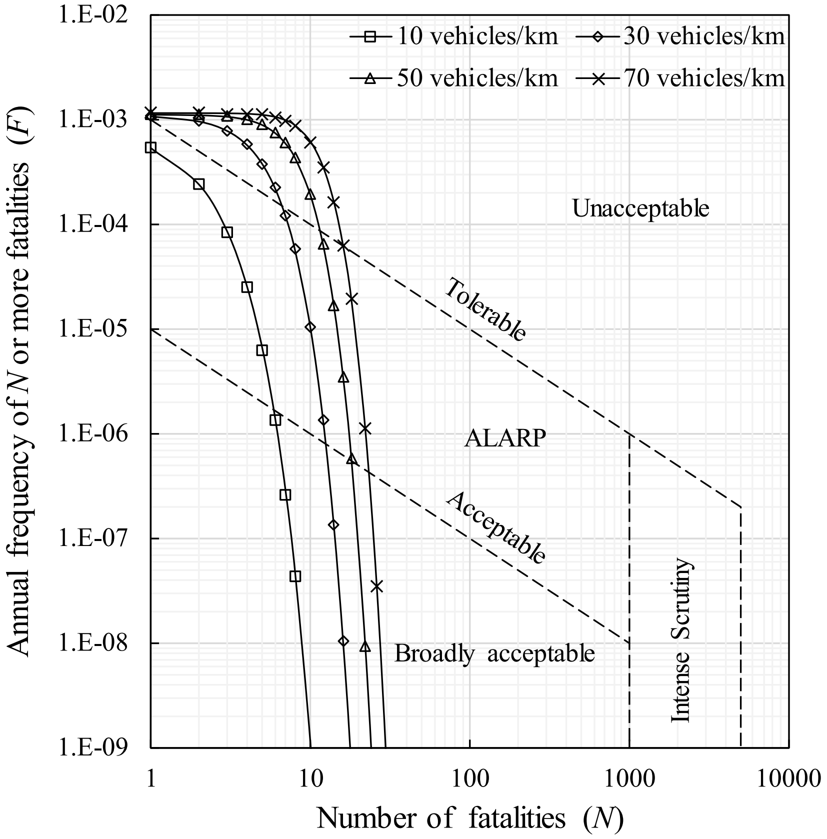


Figure 14. Impact of density of vehicles on annual expected number of elements being hit by the landslide



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