Effect of rockfall fragmentation on exposure and subsequent risk analysis

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Rockfalls are frequent natural processes in mountain regions with the potential to produce damage. The quantitative risk analysis (QRA) is an approach increasingly used to assess risk and evaluate the performance of mitigation measures. In case of the fragmentation of the falling rock mass, some of the hypothesis taken in the QRA estimation for rockfalls have to be modified since a single block or rock mass can produce several fragments thus modifying the runout probability, the impact energies and exposure of the elements at risk. In this contribution, we present a procedure to account for the exposure in QRA analysis along linear paths using the fragmental rockfall propagation model RockGIS (Matas et al. 2017). The procedure is applied at the "Monasterio de Piedra", Spain as part of a QRA.

1 INTEGRATING FRAGMENTATION IN QRA

Risk is estimated as the product of the annual probability of a block reaching a reference location, the spatio-temporal probability of the exposed element and vulnerability of the element for a certain intensity level (Corominas et al. 2014). In case of rockfalls without fragmentation, the runout probability is usually estimated by stochastic computer simulations: some blocks are released from expected sources, then the runout probability at each reference location is computed by dividing total number of blocks reaching the site by total simulated blocks. When considering fragmentation this approach has to be modified since one single rockfall may lead to multiple fragments reaching the location and thus obtaining runout probabilities mathematically higher than one. For the estimation of exposure, fragmentation will also have a significant effect since one single rockfall may produce a number of fragments with divergent trajectories, thus increasing the width of the area affected by the rockfall. Consequently, the probability of any trajectory intersecting the exposed element will increase.

To integrate fragmentation in QRA analysis we have modified the formulation presented by Agliardi et al. (2009). We calculate the probability that a certain number of fragments *"f"* produced during an event of magnitude *"i"* could reach the exposed element *"j"* and then, integrate it for all number of possible fragments reaching the element. Thus, instead of having a single runout probability for each event magnitude we have a probability distribution that a certain number of fragments could reach the element. Equation 1 shows the modified expression to estimate the Risk.

$$R=\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{f=1}^{F} N_i \,.\, P_f(S/D)_i \,.\, P_f(T/S)_j \,.\, V_{ijf} \qquad (1)$$

Where: ***R*** is the risk due to the occurrence of a rock fall of magnitude (volume) *"i"* that produces *"f"* fragments during its propagation on an exposed element *"j"* located at a reference distance S from the source; $\boldsymbol{N_i}$ is the annual frequency of rockfalls of volume class *"i"*; $\boldsymbol{P_f(S|D)_i}$ is the probability that *"f"* fragments generated by the detached rock mass of the size class *"i"* reach a point located at a distance S from the source; $\boldsymbol{P_f(T|S)_j}$ is the exposure or the probability that an element *"j"* be in the trajectory of the "f" fragments generated by the rock fall at the distance S, at the timing of the event; $\boldsymbol{V_{ijf}}$ the vulnerability of a exposed element *"j"* in the case of being impacted by *"f"* fragments generated by the block of magnitude *"i"*.

Fragmentation modifies the exposure of the elements, since the affected width of the linear structure may increase. Equation 2 shows the expression considered for the exposure (modified from Nicolet et al., 2016).

$$P_f(T/S)=\frac{f_p\,.\,(w_f+l_p)}{24\,.\,1000\,.\,v_p} \qquad (2)$$

Where: $\boldsymbol{f_p}$ is the flow of visitors (persons/day); $\boldsymbol{W_f}$ is the width of the rockfall debris front depending on number of impacting fragments *"f"* computed in the simulation (m); $\boldsymbol{l_p}$ is the width of the person (m) and $\boldsymbol{v_p}$ is the mean velocity of persons (km/h).

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2 APPLICATION

This methodology has been applied at the "Monasterio de Piedra", Spain. For this initial estimation just 1m³, 10m³ and 100m³ rockfall events have been considered. Calibration of the model was performed considering historical inventoried events which also allowed to estimate an annual frequency curve to compute N_i. For the trajectory computation of all generated fragments we used the rockfall propagation model RockGIS (Matas et al. 2017) to obtain $P_f(S|D)_i$ from the cumulative probability function shown in Figure 1 and W_f as a proportion of the maximum expected width W_{fmax} depending on number of impacting fragments. Since the exposed elements are visitors we assumed V_{ijf}=1 as a conservative hypothesis. To evaluate the effect of account for fragmentation or not, we also carried out simulations without breakage as seen in Figure 2.

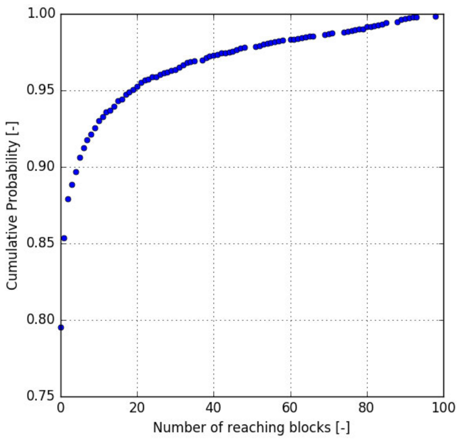

Figure 1: Cumulative probability for each number of reaching fragments

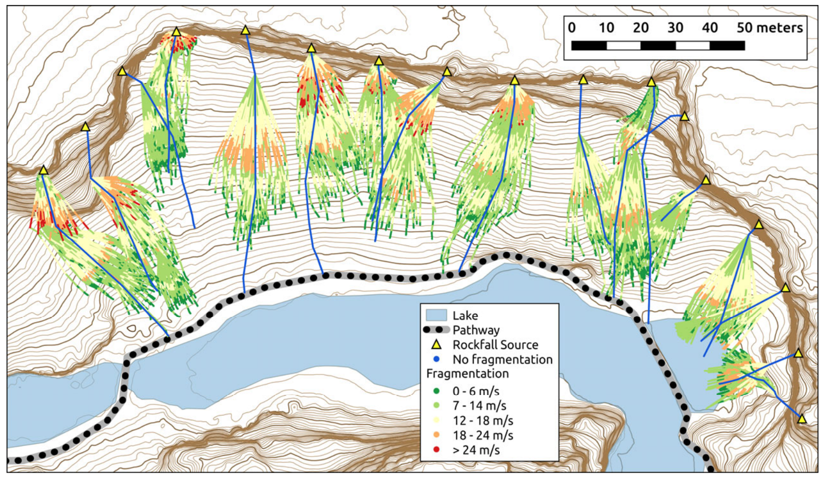

Figure 2: Trajectories with and without considering fragmentation for 10m³ blocks. Just one block released from each source for visualisation purposes.

Risk values obtained with this methodology for rockfall volumes of 1m³, 10m³ and 100m³ are respectively $4.5\cdot10^{-4}$, $1.3\cdot10^{-4}$, $3.52\cdot10^{-5}$ in case of no fragmentation, and $4.35\cdot10^{-5}$, $1.19\cdot10^{-4}$, $1.07\cdot10^{-4}$ when fragmented. This results show that for small-size rockfalls (<1m³), fragmentation reduces risk to the visitors. For rockfall events >100 m³, fragmentation increases the overall risk due to the generation of multiple divergent trajectories and higher exposure of the elements at risk. For 10m³ size rockfall events, the shorter run-out and smaller kinetic energy compensates the increase of width by divergent trajectories.

CONCLUSION

The proposed methodology allows the integration of fragmentation effect into QRA in linear paths but is also extensible to non-linear elements. Risk increment or reduction when considering fragmentation is controlled by the relative position of the elements along the slope. The effect of fragmentation in runout and exposure may have opposite effect in the final risk.

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