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RELIABILITY ANALYSIS OF ROCKFALL NET FENCES CAPACITY

Valerio De Biagi[1], Maddalena Marchelli[1], Daniele Peila[1]

Rockfall protective structures are widely used in hazardous environment to protect inhabited settlements and roads. These infrastructures are provided in kits, i.e., built in parts and assembled onsite and their performance is assessed through EAD 340059-00-0106. The choice of the most appropriate product must follow reliability considerations. Since rockfall is generally modelled as a probabilistic phenomenon, a deterministic analysis on rockfall net fence capacity is inadequate. We propose a reliability based approach for assessing the safety of an installation, based on several variables associated to rockfall phenomenon and to the uncertainties related to the installation of the protection structure.

Keywords: rockfall net fence, reliability analysis, safety factors, energy capacity

INTRODUCTION

Rockfall protective structures, such as rockfall protective barriers (or rockfall net fences), are widely used in hazardous environment to protect inhabited settlements and roads [1]. Such protective devices are provided in kits, i.e., built in parts and assembled onsite, and, due to their easiness of transport and limited installation area, they have been largely employed in the last decades. As structural protective works made as construction protection kits, their performances have to be evaluated in relation to their essential characteristics, e.g. the mechanical resistance and stability with respect to energy absorption capacity and height. In Europe, the criteria for the assessing the performance of such devices is reported in EAD 340059-00-0106 [2], following which a capacity class is assigned to each tested kit. From the results of the propagation analysis, the rock block kinetic energy and passing height at a particular location along the slope are obtained. The most appropriate net fence is chosen among the commercial kits that fulfill design requests. This design procedure, despite simplistic, must consider that all the entities involved in the phenomenon, i.e., rock block mass, velocity, passing height, as well as barrier capacity are nondeterministic quantities. Such problems are common in construction engineering practice, where mathematical and numerical methods have been developed in the framework of the structural reliability to assess the safety of a building. The Authors have proposed an extension of the well-known reliability approaches to the design of rockfall protection structures [3]. The present research focuses on a complete reliability analysis accounting for the uncertainty related to the net fence, expressed through a specific coefficient of variation.

BASICS OF RELIABILITY CALCULATIONS

Structural reliability calculations are based on the following inequality [4]

$$\gamma_A A_k \leq \frac{R_k}{\gamma_R}, \tag{1}$$

where A_k and R_k are the characteristic values of the action and the capacity, respectively. The action is increased and capacity reduced by the partial safety factors γ_A and γ_R, respectively. In the civil structural probabilistic framework, such factors are computed in order to guarantee an

[1] Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy, Phone: +39 011 0904842, valerio.debiagi@polito.it

appropriate level of safety, measured through the reliability index β, with larger values relating to more safe conditions, as reported in EN 1990:2002 [5]. The β is related to the failure probability p_f as $p_f = \Phi(-\beta)$, where $\Phi(\cdot)$ is the cumulative normal standard distribution (zero mean, unit standard deviation). The values of all the partial safety factors suggested by the design codes for various types of actions, materials or structural types are the results of the code calibration procedure.

RELIABILITY CALCULATIONS FOR ROCKFALL NET FENCES

The herein proposed approach for assessing the reliability of a rockfall net fence follows a previous study related to a general procedure for the safety assessment proposed by the Authors accounting for multiple failures related to excessive height or overabundant kinetic energy [3]. Considering the energy capacity failure, only, the state of the protection structure is defined as

$$g(e, m, v) = e - \frac{1}{2} m v^2, \tag{2}$$

where e is the capacity of the barrier, m and v the mass and the velocity of the impacting block. The structure is safe as soon as $g > 0$, i.e., the capacity larger than the impact energy. In a probabilistic framework, the three variables are non-deterministic quantities, i.e., a probability density function can be associated to each of them. A joint probability density $p_{EMV}(e, m, v)$ is associated to each point of the variable space. The failure probability is the integral over the unsafe region, i.e., $p_f = \int_{g<0} p_{EMV}(e, m, v)\, de\, dm\, dv$. Usually, the expression of the joint probability density function is non-trivial and, thus, the integral cannot be solved in a closed form. Various methods have been developed so far to tackle the problem. The First-Order-Second-Moment (FOSM) approach measures the safety through a linearization of the limit state function around the design point [4]. Through the aforementioned approach, it is possible to obtain the design values of barrier capacity, e_d, block mass, m_d, and block velocity, v_d, for which the integral over the unsafe region of the state equation equals the required failure probability.

The proposed reliability framework is applied for the evaluation of the design values. Once the characteristic values of the variables have been defined, the partial safety factors of the action, i.e., the impacting energy, and of the capacity of the barrier can be defined. Various hypotheses on the shape of the probability distributions of mass, velocity and capacity must be made. Referring to the mass, following the uncertainties related to the estimation of a rock block volume with a given return period, a normal distribution is supposed. Such distribution is described through its mean value, m_{50}, and the coefficient of variation of the mass, namely, COV_m that is the ratio between the variance and the mean value. In the present approach, the characteristic value of the mass is its mean value. The empirical distribution of block velocities at a precise location along a slope (obtained through a probabilistic rockfall propagation software) can be approximated with a normal distribution that correctly fits the right tail described through the 95th and 99th percentiles, namely, v_{95} and v_{99}. The characteristic value of the velocity is the 95th percentile of its distribution [3]. The capacity of the barrier, differently from the previously published research, is assumed to follow a normal distribution. In the research herein proposed, the mean value of the capacity of the barrier (its characteristic value) coincides with its nominal capacity obtained from the testing procedure described in the EAD 340059-00-0106. The coefficient of variation of barrier capacity, COV_e, relates to the uncertainties due, e.g., to installation difficulties or rock/soil-foundations interactions.

Referring to the general reliability inequality reported in Eqn. (1), considering that the design value of the action is, $A_d = \frac{1}{2} m_d v_d^2$, while its characteristic value is $A_k = \frac{1}{2} m_{50} v_{95}^2$, the corresponding safety factor is

$$\gamma_A = \frac{m_d v_d^2}{m_{50} v_{95}^2}. \tag{3}$$

Similarly, the design value of the capacity is $R_d = e_d$, that is smaller than the characteristic value, e_{50}; the corresponding safety factor is

$$\gamma_R = \frac{e_{50}}{e_d}. \tag{4}$$

It can be demonstrated that the values of γ_A and γ_R are independent from m_{50} and v_{95}; on the contrary, they are affected by the ratio $\frac{v_{99}}{v_{95}}$ and the coefficients of variation of the mass and the capacity, COV_m and COV_e, respectively. The first ratio identifies the shape of the right tail of the distribution of the velocities: the larger the ratio, the fatter the tail. The safety factors have been estimated for different values of $\frac{v_{99}}{v_{95}}$, COV_m and COV_e. Figure 1 shows the resulting of γ_A and γ_R for three selected values of COV_e, i.e., 0.05, 0.10 and 0.15. The factors have been studied for $\frac{v_{99}}{v_{95}}$ in the range 1-1.4 and COV_m in the range 0.1-0.4.

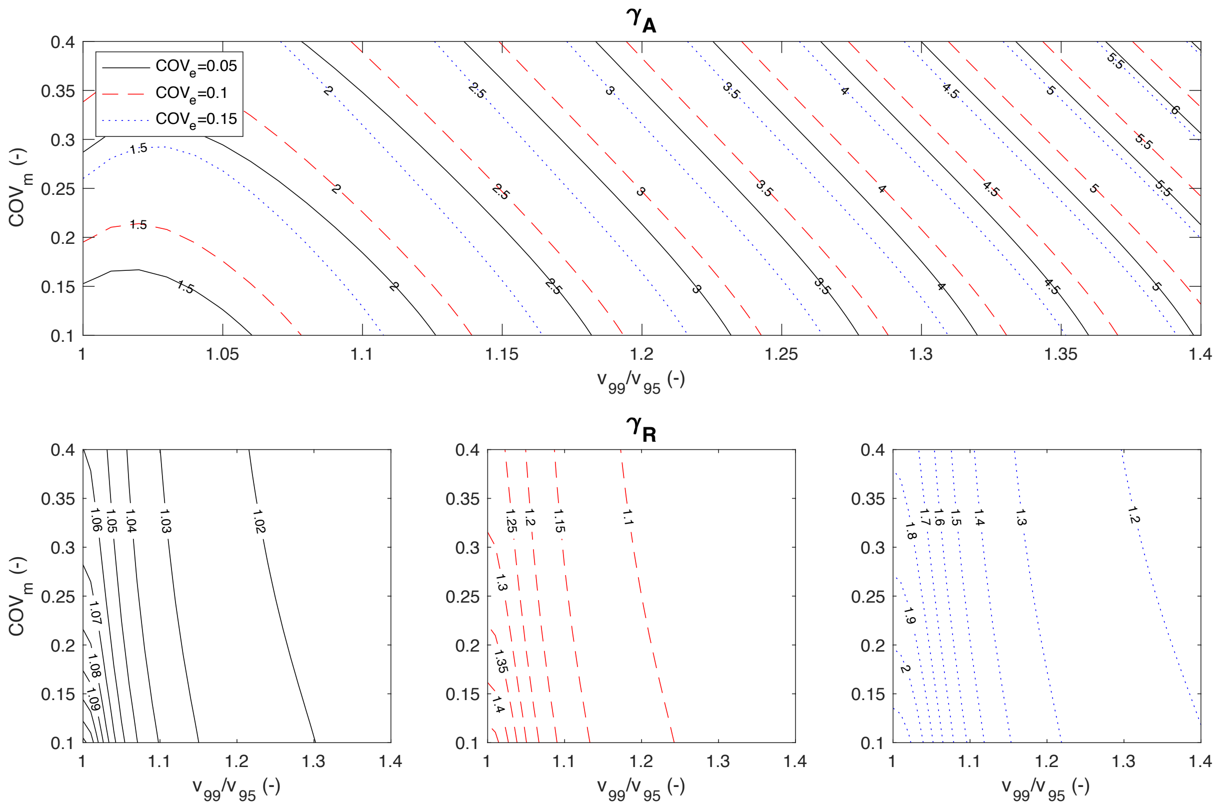

Fig. 1 On the top: contour plot of the values of the safety factor γ_A related to the action for various values of $\frac{v_{99}}{v_{95}}$ and COV_m. The three colors and line types correspond to different values of COV_e. On the bottom: contour plots of the values of the safety factor γ_R related to the capacity. Each plot relates to a different value of COV_e, with reference to the color legend of the top plot.

DISCUSSION AND CONCLUSIONS

The reliability method proposed in the previous sections allows to design a rockfall protection structure that accounts for the variability of the major parameters of the natural phenomenon (mass and velocity) and the uncertainties related to the net fence, itself. A deep analysis of the results of the computed safety factors, plotted in Fig. 1, allows to state some considerations. First, as already observed, the safety factor related to the action, γ_A, depends more on the value of v_{99}/v_{95}, rather than on COV_m. In parallel, it results that the value of γ_A is affected by the COV_e since various curves can be observed on the plot of Fig. 1. Considering that the scale of the axes of the top plot of Fig. 1 differs, it clearly emerges that the ratio v_{99}/v_{95} and the value of COV_e largely affect the value of γ_A. For a given v_{99}/v_{95} and COV_m, the larger the COV_e, the smaller the value of γ_A. This reflects the fact that the uncertainty is spread across all the quantities involved in the design.

Referring to the value of the safety factor related to the capacity, γ_R, it can be noted that the range of the values is wide and is largely affected by the coefficient of variation of the capacity, COV_e. It clearly emerges that for small values of COV_e, i.e., $COV_e < 0.05$, the γ_R is limited to 1.1 for small uncertainties on velocity and mass. On the contrary, increasing the spread on the distribution of the capacity, i.e., for larger COV_e, it results that the safety factor γ_R increases. Comparing the trends for various COV_e, it can be stated that they are similar, i.e., more dependent on the ratio v_{99}/v_{95}, rather than on the value of COV_m.

To conclude, a practical use of the obtained curves is proposed. Given a slope along which a rockfall hazard is present, a propagation analysis provides a set of velocities at a precise location, i.e., upstream the element at risk, where a possible protection structure can be installed. From the empirical cumulative distribution of the velocities, the 95th and 99th percentiles can be determined. The rockfall volume frequency law can be estimated and the related uncertainties computed. Thus, given a reference return period, the corresponding block volume m_{50}, and its variability COV_m are derived. Depending on the type of barrier and the similitude to the tested configuration (with reference to the EAD 340059-00-0106), a variability COV_e is assigned. The safety factor are then evaluated through Fig. 1 and the characteristic value of barrier capacity, useful for the choice among the available sets, is computed as $e_{50} = \gamma_A \gamma_R \frac{1}{2} m_{50} v_{95}^2$. The computed term accounts for the uncertainties related to the phenomenon, i.e., mass and velocity, and to the installed product.

REFERENCES

[1] Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., Dorren, L.K., Gerber, W., Jaboyedoff, M., “Rockfall characterisation and structural protection – a review”, Natural Hazards and Earth System Sciences, Vol. 11, pp. 2617-2651, 2011.

[2] EAD 340059-00-0106, “Falling rock protection kits”, EOTA – European Organisation for Technical Assessment, 2018.

[3] De Biagi, V., Marchelli, M., and Peila, D., “Reliability analysis and partial safety factors approach for rockfall protection structures”, Engineering Structures (under review).

[4] Melchers, R.E., and Beck, A.T., “Structural reliability analysis and prediction”, John Wiley & Sons, 2018.

[5] EN 1990:2002, “Eurocode 0 – Basis of structural design”.