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Additional insights to EC7 from the application of reliability-based design methods: the case of debris flow protection structures

F Vagnon[1], AM Ferrero[1], L Alejano[2]

[1]Department of Earth Sciences, Università di Torino, Torino, Italy
[2]Department of Natural Resources and Environmental Engineering, University of Vigo, Vigo, Spain

federico.vagnon@unito.it

Abstract. Debris flows are dangerous natural processes that cause extensive damages to infrastructures and urbanized areas and can lead to loss of human lives. Their unpredictability, their extremely high motion and their magnitude are the main causes of these harms. Mitigation measures are fundamental for reducing the associated risk and protecting infrastructures in mountainous areas. Their design is still an open issue: there are many formulations to evaluating impact pressure. Moreover, the uncertainties in the determination of flow characteristics (velocity and thickness) are significantly high and difficult to quantify. In the European Union, the design of any type of structures involved in rock mechanics field must comply with EN-1997 Geotechnical Design (CEN 2004) (EC7). For debris flow countermeasures, EC7 requirements are very difficult to apply in practice since partial safety factors are not provided for these phenomena. However, the basic philosophy of reliability-based design (RBD), as defined in EN1990 (CEN 2002) may be a suitable and complementary approach to provide geotechnical structures with a uniform probability of failure. Reliability Based Design (RBD) can provide additional insights to EC7 design and can be applied when partial factors have still to be proposed (by EC7) to cover uncertainties of less common parameters, as in case of debris flow countermeasures. This paper presents an analysis of the advantages and limitations on the applicability of RBD approach to debris flow countermeasures, by using the first-order reliability method (FORM). In particular, data availability, the possibilities for analysing data in a statistical framework and the choice of performance function are the main limitation of the method, which force to make assumptions regarding statistical distribution of the considered parameters. A sensitivity analyses, comparing different equations, commonly used for debris flow impact pressure estimation, were performed for quantifying the effect of the selected performance function on the RBD results.

1. Introduction

The unpredictability, the total absence of premonitory signals, the high velocities and the long travel distances make debris flow one of the most destructive gravitational movements on Earth. Moreover, the climate change will increase in the next future the frequency and the magnitude of these phenomena increasing the associated risk of economic damages and loss of human lives. As a result, it is crucial to strengthen the prevention design of debris-flow disasters.

Many mitigation strategies have been developed in recent years and both active and passive measures are used to change the vulnerability of debris flow basins and to protect infrastructures in mountainous areas. Although passive measures (hazard mapping and correct land-use planning) are more advisable than active ones (protection structures), the latter are often essential in order to reduce risk [1].

Each countermeasure has its own peculiarity, in terms of components, drainage capacity and construction methodology. From the point of view of their design requirements, they must be able to counteract the impact forces of the flow by dissipating totally (in case of rigid structures) or partially (in case of filtering or cable/net structures) its kinetic energy and by retaining the flowing material. However, the engineering design of debris-flow barriers is still challenged and practice-based in current stage. There are few specific national standards that provide guidance for the reliable design of these types of countermeasures. For instance, the Geotechnical Engineering Office of the Government of Hong Kong introduced the first technical basis for the design of standardized debris-resisting barrier modules [2]. In 2011, the Austrian Standard Rule [3] (included in [4]) provided loading scenarios for debris flow protection structures, specifically giving information on limit state design and failure mode for check dams, as well as partial safety factors for structural (STR) and geotechnical (GEO) limit state actions.

Hong Kong and Austrian standards provide a great contribution, but the recent reports of structures destroyed by debris flow [5-7] rise many doubts on their efficiency and leave many unsolved open questions. No information about the probability of failure is provided since uncertainties regarding all debris flow phases are difficult to quantify [1, 8]. Moreover, many formulations were developed for evaluating debris flow impact pressure on structures [9], but none of them is universally recognized.

In the European Union, the design of any type of structures involved in rock mechanics field must comply with EN-1997 Geotechnical Design [10]. The design of debris flow countermeasure is only dealt with in passing in EC7 code. Its requirements are very difficult to apply in practice since partial safety factors are not provided for these phenomena. Some authors [11-17] have highlighted how applying the same partial safety factors in problems with different levels of uncertainty may not result in the same target failure probability. However, the basic philosophy of reliability-based design (RBD), as defined in EN1990 ([18]) may be a suitable and complementary approach to provide geotechnical structures with a uniform probability of failure [16].

Reliability Based Design (RBD) can provide additional insights to EC7 design and can be applied when partial factors have still to be proposed (by EC7) to cover uncertainties of less common parameters [12] as in case of debris flow countermeasures. Moreover, as stated by [11], reliability calculations provide a means of evaluating the combined effects of uncertainties, and a means of distinguishing between conditions where uncertainties are very high (evaluation of debris flow impact pressure is a clear example).

This paper presents an analysis of the advantages and limitations on the applicability of RBD approach to debris flow countermeasures, by using the first-order reliability method (FORM). In particular, data availability, the possibilities for analyzing data in a statistical framework and the choice of performance function are the main limitation of the method, which force to make assumptions regarding statistical distribution of the considered parameters.

A sensitivity analyses, comparing different equations, commonly used for debris flow impact pressure estimation, were performed for quantifying the effect of the selected performance function on the RBD results.

2. FORM procedures

In RBD methods, the probability of failure can be expressed using the following equation:

$$P_f \approx 1 - \Phi(\beta) = \Phi(-\beta) \quad (1)$$

where Φ is the normal cumulative probability function and β is the reliability index [19]. The evaluation of β allows to define the coordinates of the most probable failure point that is called the design point, x^*. It physically denotes the tangency of the expanding dispersion ellipsoid with the failure domain surface (figure 1).

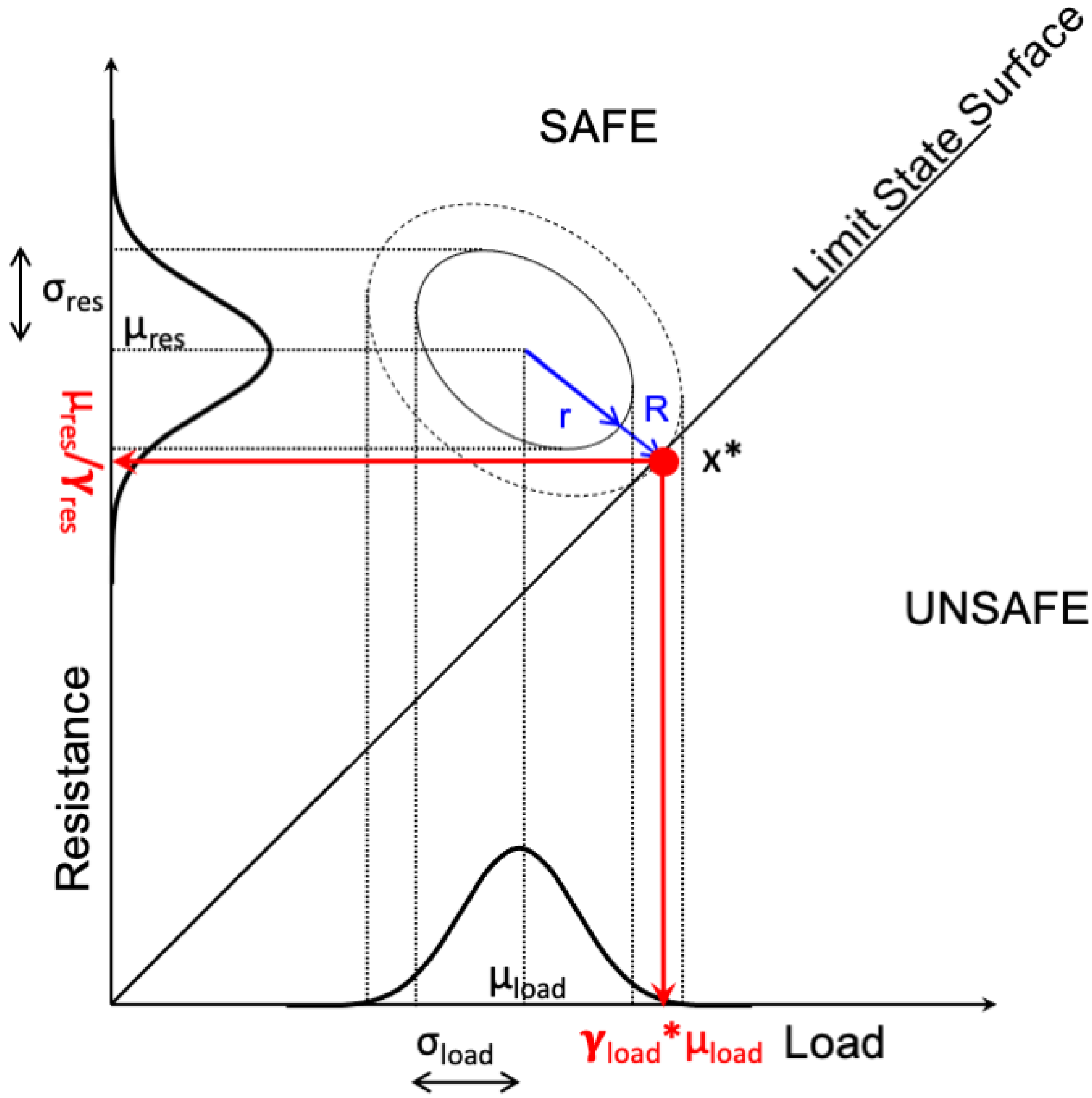

Figure 1. Illustration of the reliability index in a plane with two negatively correlated random variables (modified after [9]).

The most consistent RBD approach is based on FORM, in which β is given by the following equation:

$$\beta = \min_{x\epsilon f} \sqrt{\vec{n}^T [R]^{-1} \vec{n}} \quad (2)$$

where $\vec{n}$ is a dimensionless vector defined as $\vec{n} = (x-\mu N)/\sigma N$, x is a vector representing the set of random variables, **μN** and **σN** are the vectors of normal mean and normal standard deviation evaluated using [20] equations, R is the correlation matrix, and f is the failure domain.

Equation 2 allows taking into account the non-normal distribution of leading variable in debris flow phenomena [9]. Moreover, it can be easily solved in an Excel spreadsheet [21]: for each value of n_i trialed by the Excel Solver, a short and simple Excel VBA code automates the computation of x_i from n_i, for use in the constraint performance function g(x) = 0, via $x_i = F^{-1}\Phi[(n_i)]$, where Φ is the standard normal distribution and F is the original non-normal distribution.

Moreover, the β definition allows back calculating the partial safety factors useful for LSD approach by fixing characteristic values for the random variables and by assessing the design point coordinates (see figure 1).

FORM approach requires the introduction of a performance function g(x) = 0 that, according to LSD principles, reflects the difference between resistances and the effects of actions.

In this study, three equations were used:

$$g(x) = R - \rho\alpha v_f^2 h_f B \tag{3}$$

$$g(x) = R - \rho g k h_f^2\, B \tag{4}$$

$$g(x) = R - \rho h_f B\left(\alpha v_f^2 + g k h_f\right) \tag{5}$$

where R is barrier resistance in N, ρ is flow density in kg/m^3, B is channel width in m, h_f is the flow thickness in m, v_f is the flow velocity in m/s, g is the gravity equal to 9.81 m/s^2, α and k are respectively the dynamic and the static coefficient. For a detailed explanation of the available debris flow impact models, refer to [16].

For what it concerns variable statistical distributions, in a previous work [9] the authors have demonstrated that h_f, v_f and α can be approximated using a GEV (generalized extreme value) distribution, while R can be simulated using normal distribution and k with a lognormal distribution. The GEV distribution has been frequently used to model flood event frequencies: since, channelized debris flows have many analogies with flood processes, it could be also possible to assume probabilistic extreme distributions for debris flows. Further analyses should be done by increasing the processes datasets for confirming or refusing this assumption. However, the fact that laboratory data and field data follow the same statistical model, namely the GEV distribution, for all the considered variables [9] support and strengthen this hypothesis.

3. RBD and EC7

Partial safety factors (γ in figure 1) are applied to characteristic parameter values in Limit State Design (LSD) approaches for addressing uncertainties and providing designs with a uniform probability of failure. The LSD is at the basis of the EC7. In order to verify that the design resistance is greater than the effect of action, three different design approaches, described in detail in Section 2.4.7.3.4 of EC7 [10], are used. This approach is consolidated in civil engineering but its efficacy in the geotechnical field has raised many doubts [16, 21-23] since the variability of the considered materials is extremely high and no information on the probability of failure of the designed structures is provided. Moreover, as stated above, many geotechnical problems, such as rockfalls and debris flows, are not adequately treated and the application of the same partial safety factors in problems with different levels of uncertainty may not result in the same target failure probability [12, 24].

These EC7 limitations support the need of an RBD analysis for certain complex geotechnical applications, including the design of debris flow protection structures. The reliability index provide design with the same probability of failure that remains independent from the problem type and the level of parametric uncertainties.

On the other hand, the limited dataset for performing reliable statistical analyses may reduce the diffusion of an RBD approach. This is especially true in the case of debris flow, for which databases for the main parameters involved (velocity, vf, thickness, hf, and the dynamic coefficient, α) are difficult to obtain.

4. RBD of debris flow barriers

In this section, an RBD approach is presented considering EN1990 Annex C Table C1. The table proposes a list of reliability index values, β, as a function of probability of failure, Pf. Using those values, a RBD approach is here proposed, based on a hypothetical barrier designed for protecting from debris flow events.

The considered variables are listed in table 1.

Table 1. Input variable values used in the RBD approach.

Variable	Mean value	Standard deviation
Density, $\boldsymbol{\rho}$ [kg/m$_3$]	2155	[-]
Barrier width, B [m]	36	[-]
Flow velocity, v_f [m/s]	10	3
Flow height, h_f [m]	1.6	1.3
Dynamic coefficient, $\boldsymbol{\alpha}$ [-]	1.36	1.24
Static coefficient, k [-]	3.52	2.47

Flow density was assumed to be constant and was represented by a mean value for the solid and fluid components. Even if correlation between variables were demonstrated [9] in this example the leading diagonal terms and the off-diagonal terms of correlation matrix [R] were considered respectively equal to 1 and 0.

Considering the β values listed in Table C1 (EN1990 Annex C), design points for each variable were identified and their distance from the corresponding mean was evaluated (table 2).

Table 2. Design parameters evaluated for a reliability-based design approach as a function of reliability index values proposed in EN 1990 Annex C Table C1 considering three different performance function (The asterisk symbols (*) represents the design parameters obtained after FORM computational approach).

β	Pf	Equation 3				Equation 4			Equation 5				
[-]	[%]	R* [N]	v_f* [m/s]	α* [-]	h_f* [m]	R* [N]	k* [-]	h_f* [m]	R* [N]	v_f* [m/s]	α* [-]	h_f* [m]	k* [-]
1.28	1E-01	5.7E+07	12.2	2.22	2.2	2.6E+07	4.34	2.8	7.0E+07	11.8	2.06	2.5	3.22
2.32	1E-02	1.6E+08	14.2	3.29	3.1	9.0E+07	6.47	4.3	1.9E+08	13.7	2.99	3.5	3.46
3.09	1E-03	3.2E+08	15.6	4.28	4.0	2.1E+08	8.99	5.6	3.6E+08	15.0	3.87	4.5	3.64
3.72	1E-04	5.4E+08	16.6	5.24	4.8	4.1E+08	11.90	6.8	6.0E+08	16.1	4.72	5.4	3.79
4.27	1E-05	8.2E+08	17.3	6.20	5.6	6.1E+08	14.21	7.5	9.0E+08	16.9	5.58	6.3	3.87
4.75	1E-06	1.2E+09	18.0	7.15	6.5	1.2E+09	19.64	8.9	1.3E+09	17.5	6.40	7.3	4.12
5.2	1E-07	1.6E+09	18.5	8.12	7.3	1.8E+09	24.84	9.9	1.7E+09	18.0	7.23	8.2	4.32

RBD results are directly correlated with the partial safety factor concept introduced in EC7. Partial safety factor can be directly calculated from the coordinates of the design point, x*: in fact, knowing the probability distribution of variables, characteristic values can be back-calculated assuming the ith-percentile of the probability distribution. Consequently, the partial safety factor is the ratio between the characteristic value and the design parameter value.

Figure 2 shows flow barrier partial safety factor trends γ for each parameter as a function of the probability of failure, Pf. Partial safety factors were calculated considering the 90th percentiles.

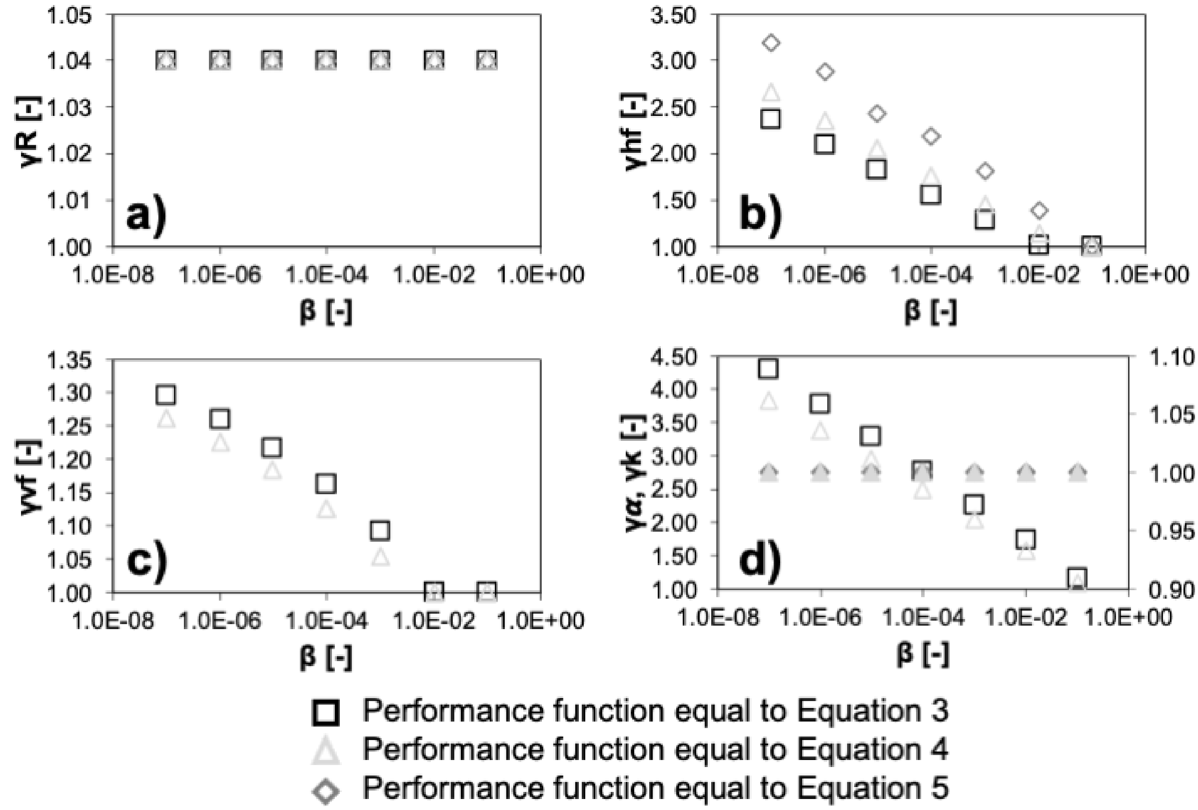

Figure 2. Partial safety factor dependence on resistance (a), thickness (b), velocity (c), and dynamic and static coefficient (d) as a function of probability of failure considering as performance function respectively equation 3 (black squares), 4 (light grey triangles) and 5 (dark grey diamonds).

As expected, partial safety factors increase as the requested probability of failure decrease for all the considered variable, except for resistance and static coefficient k, where they remain constant, independently from probability of failure. Moreover, partial factors are not sensibly sensitive to the impact model used as a performance function.

Even though the velocity and dynamic coefficient partial safety factors are different, their trend is the same. In fact, those two figures suggest that characteristic values for v_f and α should be increased and that α should be increased more than v_f.

5. Conclusions

EC7 is the referencing standard for civil engineering geotechnical design, including complex geotechnical problems, such as the design of debris flow protection barriers. However, the mandatory requirements of LSD approach are not completely applicable to this type of geotechnical problem, since the probability of failure should be used as an indicator for evaluating structure residual risk.

In lieu of LSD philosophy, RBD approach has been demonstrated suitable for facing the design of debris flow barriers. Its main limitations are the data availability and the possibilities for analysing data in a statistical framework. However, experimental test and numerical models for forecasting propagation characteristics might be useful for overcoming these limitations.

Moreover, the RBD approach allows back-calculated partial safety factors to be applied in the LSD method proposed by EC7. These partial safety factors have the advantage that they are associated with a known target failure probability. The results of sensitivity analysis by changing performance function do not highlight relevant differences in partial safety factor trends (see figure 2).

In conclusion, the RBD method provides insights into EC7 design for debris flow countermeasures and is a useful design approach for protection structures based on determining an associated probability of failure.

References

[1] Jakob M and Hungr O 2005 Debris-flow hazards and related phenomena *Springer-Verlag* Berlin Heidelberg
[2] Sun HW, Lam TTM, Tsui HM, Hong Kong Geotechnical Engineering Office 2005 Design basis for standardised modules of landslide debris-resisting barriers *Geotechnical Engineering Office* Civil Engineering and Development Department
[3] ONR 24802:2011 01 01 Protection works for torrent control - Design of structures Austrian technical rules
[4] ONR 24800:2009 02 15 Protection works for torrent control - Terms and their definitions as well as classification Austrian technical rules
[5] Dai ZL, Huang Y, Cheng HL, Xu Q 2017 SPH model for fluid–structure interaction and its application to debris flow impact estimation *Landslides* ***14*** **(3)** pp 917–928
[6] Remaître A, van Asch TWJ, Malet JP, Maquaire O 2008 Influence of check dams on debris-flow run-out intensity *Natural Hazards & Earth System Sciences* ***8*** **(6)** pp 1403–1416
[7] Huang Y and Zhang B 2020 Challenges and perspectives in designing engineering structures against debris-flow disaster *European Journal of Environmental and Civil Engineering*
[8] Vagnon F, Ferrero AM, Pirulli M, Segalini A 2015 Theoretical and experimental study for the optimization of flexible barriers to restrain Debris Flows *GEAM* **145 (2)** pp 29-35
[9] Vagnon F 2020 Design of active debris flow mitigation measures: a comprehensive analysis of existing impact models *Landslides* **17** pp 313–333
[10] EN 1997-1 (2004) Eurocode 7: geotechnical design—part 1: general rules CEN Brussels
[11] Duncan JM 2000 Factors of safety and reliability in geotechnical engineering *J Geotech Geoenviron* **126(4)** pp 307–316
[12] Low BK and Phoon KK 2015 Reliability-based design and its complementary role to Eurocode 7 design approach. *Comput Geotech* **65** pp 30–44
[13] Vagnon F, Ferrero AM, Segalini A 2016 EC7 design approach for debris flow flexible barriers: applicability and limitations. In: Proceedings of EUROCK 2016 ISRM international symposium—rock mechanics and rock engineering: from the past to the future. Cappadocia
[14] Vagnon F, Ferrero AM, Segalini A, Pirulli M 2016 Experimental study for the design of flexible barriers under debris flow impact. In Aversa et al. (Eds) Landslides and engineered slopes. Experience, theory and practice. Associazione Geotecnica Italiana, Rome
[15] Vagnon F, Ferrero AM, Umili G, Segalini A 2017 A factor strength approach for the design of rock fall and debris flow barriers. *Geotech Geol Eng* **6** pp 2663–2675
[16] Vagnon F, Ferrero AM, Alejano LR 2020 Reliability-based design for debris flow barriers. *Landslides* **17** pp 49–59.
[17] Vagnon F, Bonetto SBMR, Ferrero AM, Harrison JP, Umili G 2020 Eurocode 7 and rock engineering design: The case of rockfall protection barriers *Geosciences* **10(8)** p 1-16
[18] EN 1990 (2002) Eurocode—basis of structural design CEN Brussels
[19] Hasofer AM, Lind NC 1974 An exact and invariant second-moment code format *J Mech Div ASCE* **100(1)** pp 111–121
[20] Rackwitz R, Fiessler B 1978 Structural reliability under combined random load sequences *Comput Struct* **9(5)** pp 484–494
[21] Low BK, Tang WH 2007 Efficient spreadsheet algorithm for first-order reliability method *J Eng Mech ASCE* **133(12)** pp 1378–1387
[22] Harrison JP 2014 Eurocode 7 and rock engineering: current problems and future opportunities. In Proceedings of EUROCK European regional symposium—rock engineering and rock mechanics: structures in and on rock masses, Vigo, Spain pp 1531–1537

[23] Lamas L, Perucho A, Alejano LR 2014 Some key issues regarding application of Eurocode 7 to rock engineering design. In Proceedings of EUROCK European regional symposium—rock engineering and rock mechanics: structures in and on rock masses, Vigo, Spain pp 1459–1465
[24] Callisto L 2010 A factored strength approach for the limit states design of geotechnicalstructures *Can Geotech J* **47** pp 1011–1023