Geotechnical risk management as a basis for quality assurance

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Abstract

Quality assurance is an important topic in the construction industry, both in Spain and elsewhere. The concept of “quality” of a constructed facility has evolved over the years, and it is now generally accepted that following design standards, guidelines, and recommendations is not always a guarantee for quality. In this paper we use our recent experience in the construction quality control industry in Spain to propose a definition of quality as “the capacity to satisfy the needs of different entities involved in the process in the best possible way”, and we argue that risk management should serve as a basis for construction quality control in the future. Furthermore, we also discuss some specific examples of risk quantification and hazard evaluation with state-of-the-art computational tools that can be used for risk management in the context of quality assurance.
Keywords: risk management, quality assurance, construction insurance, design codes, decision-making.

1 Introduction

The concept of construction quality in Spain has evolved in time. Initial efforts in quality assurance were focused toward “assuring constructions with zero defects”, and they relied on assuring that design codes were followed, assuring the quality of materials, and assuring the quality of construction procedures. In the last fifteen years (1990–2005), however, the concept of construction quality in Spain has evolved toward a performance-based approach, in which the quality of the construction is given by the quality of the end result (considering collapse, serviceability, and functionality, among others)—hence introducing the need for quality assurance of the overall process.

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At present, the trend is toward assuring quality by means of prevention and risk management methodologies, which help the designer to make decisions under conditions of uncertainty. Within that context (see Fig. 1), risk can be defined as the product of the "hazard" (i.e. probability of unsatisfactory performance) times the "consequences" of such failure, which are computed as a function of the "vulnerability" of the element of interest. (In some cases the vulnerability of the element is included within the consequences term; we separate both terms to further clarify the concept of risk.)

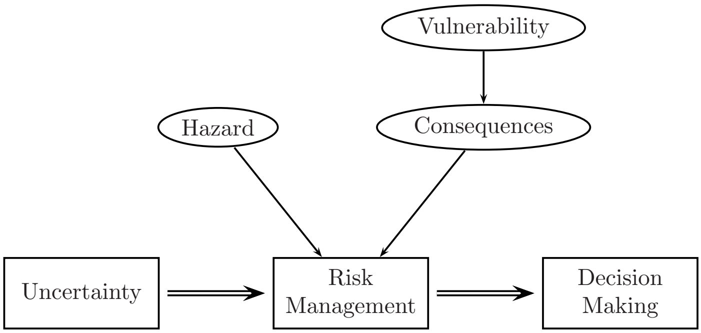

Figure 1: The process of decision-making under uncertainty (modified from [1]).

We propose a definition of quality in which we consider the perception of quality that different agents have. In that sense, we consider quality as "the capacity of satisfying in the best possible way (in a given time, for existing economic and budget constraints) the needs of the different intervening agents (clients, users and non-users, share-holders, employees, etc.)" [2]. (Further considerations of quality as defined in this way are given in [2].)

To be able to make decisions, it is usually necessary to define different types of costs (not always monetary) in terms of monetary costs (e.g., dollar or euro value). The notion of "global cost" (introduced in Spain by E. Torroja) appears as a convenient measure of cost, since it includes the all the costs associated to the facility during its life; that is, the global cost includes the cost of the initial inversion; the cost of financing, maintenance and operation; the cost due to unsatisfactory performance; and the cost of demolition, if applicable. Within that context, we believe that risk management should be associated to construction quality control, so that the quality of a constructed facility should be defined in terms of its risks.

2 Quality and technical design codes

Current legal practice in Spain imposes strict regulations for the construction sector, with the goal of providing satisfaction and protection to customers and users. Several regulations are of application at present, including some European design codes (see e.g., [3, 4, 5]) as well as Spanish codes (see e.g., [6, 7]).

Despite the availability of design codes, we need to emphasize that security cannot be totally assured, even if guidelines proposed in design codes are strictly followed. Therefore, we need to include risk considerations into standard procedures for design in the construction industry: society should know that risks are inherent to the construction process; and engineers should design so that risk exposition is adjusted to acceptable levels. Figure 2 illustrates an example of how the reliability of construction performance relates to construction quality. Based on Figure 2, the goal is to achieve a level of reliability adequate to each aspect of performance; that is, the probability of failure with respect to each aspect of performance should be established having into account (among others):

- The reliability of elements that are susceptible of having high consequences in the event of failure should be increased.
- The influence of bad quality of the materials.
- The likelihood and consequences of human errors during design and construction.
- The likelihood and consequences of errors during operation of the facility.
- The possibility that the code is not properly updated to consider recent research.
- The lack of organization and coordination.

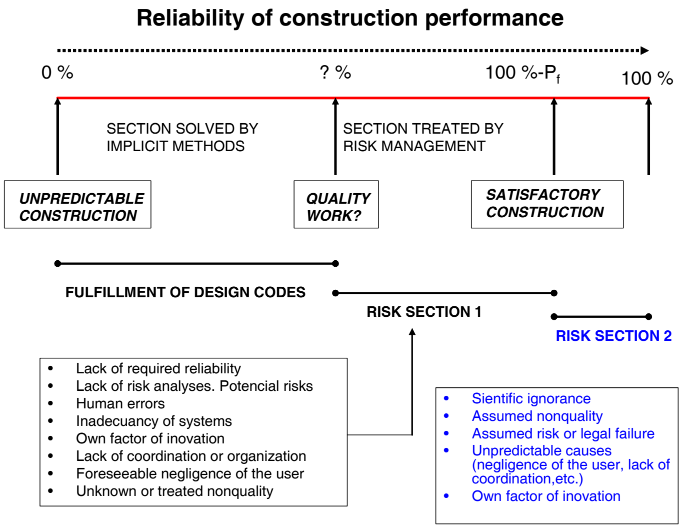

Figure 2: Relation between reliability and quality for constructed facilities (modified from [2]).

3 Quality and the process of risk management

Based on the discussion above, the process of quality control should not be exclusively based on following current design codes. Alternatively, quality control should be associated to risk identification and prevention. This is particularly the case when we have to deal with non-standard designs, when significant uncertainty exists, and when consequences could be very costly in the event of failure. Only in that way we can minimize risk (or exposition to risk) and, in case of failure, we can be confident that failure was either due to some expected factor (hence accepted by the client), or due to some unexpected factor (in which case society as a whole should bear the associated cost—e.g., by means of insurance policies, as it currently happens in Spain). That is, there is a need to finance risk and, in particular, geotechnical risk.

Figure 3 shows the main steps in the process of risk management toward a successful completion of the construction project. In the "Risk definition" step, we should use analysis tools to identify risk situations; it is usually convenient to perform such analysis in a general way (i.e. using a set of similar projects) and then verify which situations are applicable in each specific project. Based on the outcome of the "risk definition" step, we can identify projects in which traditional methods for deterministic analysis are adequate (e.g., common design situations, with well-identified risks and low uncertainty), and projects in which probabilistic methods for risk analysis are needed. In the "Risk analysis" step, we should quantify identified risks so that we can compare them with an acceptance threshold (for instance, as a function of total cost). (In Section 4 we present probabilistic methods for quantification of risk in the context of geotechnical engineering.) Based on the outcome of both steps above, we can implement procedures to make decisions (for instance, related to insurance policies) as a "Response to risks" (see Fig. 1).

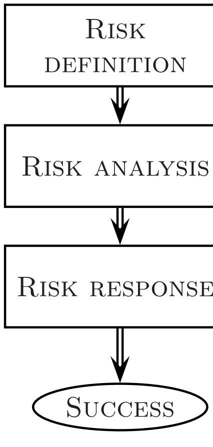

Figure 3: Steps of the risk management process.

4 Quantification of risks

In this section we present examples of the use of state of the art probabilistic methods for quantification of risks in geotechnical engineering. As illustrated in Figure 1, proper quantification of failure probability (i.e. hazard) is a crucial aspect of decision making under uncertainty and, accordingly, there is a need for advanced computational tools to solve that problem.

As an example case, we focus on the problem of block failures in the context of slope stability analyses in rock slopes. To that end, we present computational tools to estimate the distribution of the size of discontinuities in rock masses [8]; furthermore, we discuss how the probability of formation of removable wedges can be updated to consider the probability of failure of wedges of different sizes. (Note that the size of unstable wedges is an indicator of the consequences of failure.) For additional approaches for risk analysis in the context of rock slope stability, see e.g., [9].

4.1 Maximum likelihood estimation of discontinuity sizes

Discontinuities may be considered to be the individual factor with the most significant impact on the behavior of rock masses [10]. Observations of discontinuity traces at rock exposures are commonly used to infer their size, so that the distribution of discontinuity dimensions is inferred from the underlying distribution of trace lengths [11].

The Expectation-Maximization (EM) algorithm [12] has been used to calibrate distributions that mimic the "real" (and unknown) distribution of trace lengths [8]. The EM algorithm is based on the use of an auxiliary function, $\mathcal{L}(\cdot, \Theta)$, which is a lower bound to the (incomplete) log likelihood, $l(\Theta; \mathcal{D}_o)$. The log likelihood is obtained as:

$$l(\Theta; \mathcal{D}_o) = \log p(\mathcal{D}_o|\Theta) = \sum_{i=1}^{N_o} \log p(c, l_o|\Theta), \tag{1}$$

where $\mathcal{D}_o$ is the set of observed traces, Θ is the set of parameters to infer, and l, l_o, and c are the length, observed length, and censoring conditions of discontinuity traces. (For details, see [8]). Figure 4 shows an example of statistical distributions inferred with the EM algorithm, as compared with those originally used for generation; as observed, the inference capabilities of the methodology are good, and distributions very similar to the original distribution are computed.

4.2 Probabilistic prediction of formation of unstable wedges

Next, we discuss a methodology for considering uncertainties in the estimation of block stability. The Poisson disk model is used to characterize the rock mass structure. Removable wedges can be identified using block theory, and four failure modes may be defined for a removable wedge [13]: Sliding along the line of intersection of both planes; sliding along plane 1 only; sliding along plane 2 only; and

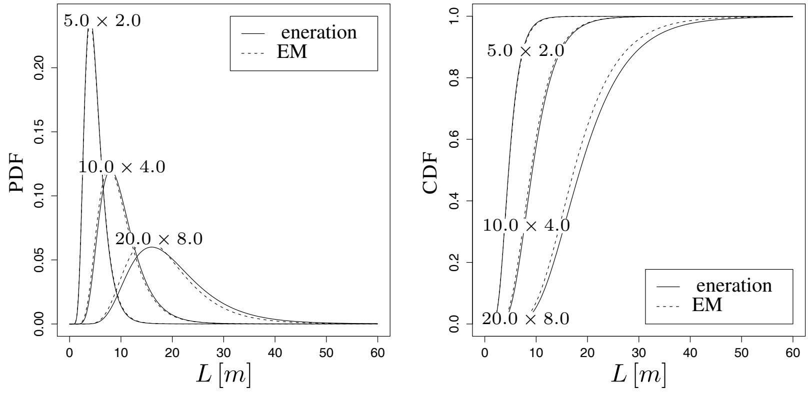

Figure 4: Comparison between generation and inferred distributions (lognormal distribution).

a "floating" type of failure. To simplify the computations, we work with a *disjoint cut-set* formulation, as follows (for details, see [14]):

$$P(E_{general}) = P\left(\bigcup_{k=1}^{N_{CS}} \bigcap_{i \in C_k} E_i\right) = \sum_{k=1}^{N_{CS}} P\left(\bigcap_{i \in C_k} E_i\right). \tag{2}$$

To compute the reliability of each component in the model, we use:

$$P_f = P(g(\mathbf{x}) \leq 0) = \int_{g(\mathbf{x}) \leq 0} f(\mathbf{x}) d\mathbf{x}, \tag{3}$$

where $f(\mathbf{x})$ is the PDF of the input variables $\mathbf{x}$ in the corresponding limit state function, $g(\mathbf{x})$. Then, the probability of failure of each parallel system C_k may be approximated by a first order approximation, where the necessary reliability information is computed after using FORM analysis to estimate the probability in Eq. (3).

The results of the reliability analysis may be used to compute updated estimates of the rate of formation of keyblocks. As illustrated in Figure 5, the rate of formation of keyblocks is computed as the product of the rate of formation of removable blocks times their probability of failure. As shown in [1], the relative probabilities of occurrence of keyblocks of different sizes varies significantly, hence affecting our risk considerations. In this particular example, keyblocks of "medium" to "high" size (i.e. intervals I_4 and I_5) are significantly more likely than keyblocks of other sizes.

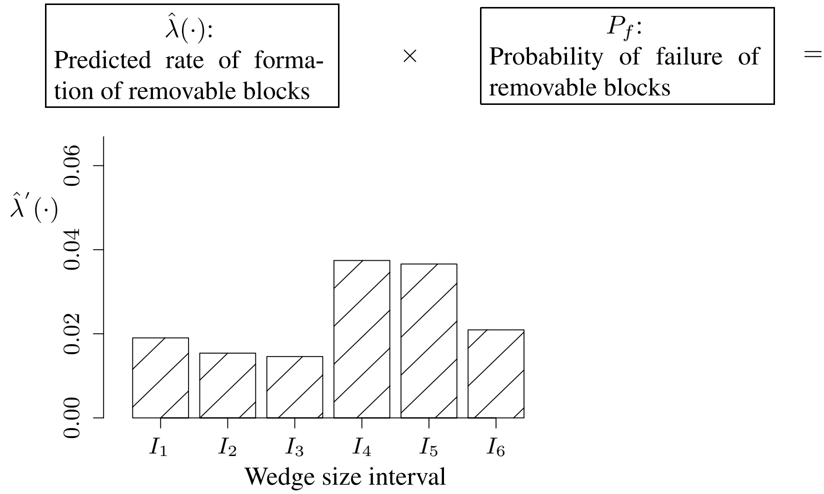

Figure 5: Predicted rates of formation for keyblocks of different sizes after [1]).

5 Conclusions

In recent years, construction industry in Spain has evolved toward a performance-based approach, in which the quality of the construction is defined as a function of the end result, and it is now accepted that existing uncertainties have the consequence that security cannot be totally assured. This fundamental observation has lead to a recent interest in risk management methodologies for quality assurance in the construction industry in Spain; such methodologies of risk management include steps related to risk definition, risk analysis and response to risk.

The need for risk management methodologies is even more important in non-standard situations, or when large consequences can be expected in the event of failure. It is also important to recognize the need to finance construction risks, so that we can account for failures due to some unexpected factor; in that sense, the involvement of the insurance industry, as it currently happens in Spain, has made it possible to finance such risks.

In addition, we suggest that proper quantification of hazards is a crucial aspect of risk management methodologies, and we present some examples of the use of state-of-the-art probabilistic methods that can be used for the quantification of risk, with an emphasis on the problem of formation of keyblocks in rock excavations. We present computational tools to infer the distribution of discontinuity sizes in rock masses (an important factor affecting their performance), and to estimate the probability of formation of keyblocks of different sizes. The results indicate that the relative probabilities of occurrence of keyblocks of different sizes varies significantly, hence affecting risk considerations.

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