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A probabilistic systems methodology to analyze the importance of factors affecting the stability of rock slopes

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ABSTRACT

A probabilistic expert semi-quantitative (PESQ) coding methodology is employed to assess the importance of factors that affect the stability of rock slopes within the rock engineering systems (RES) framework. With this newly proposed PESQ coding framework, uncertainties in the assignments of codes are expressed using probabilities that are assigned to each particular coding value. Rock slopes in the Khosh-Yeylagh region in Iran have been employed as an example case to illustrate the utilization of this method in rock slope engineering, and nine parameters are considered as the main factors modeling the stability of the slope system. In addition to the probabilistic coding, other typical RES procedures can also be performed non-deterministically, therefore allowing consideration of uncertainties in the RES analysis. The existence of "previous instabilities" has been found to be the most important parameter, therefore suggesting the importance of performing a site survey of similar slopes in the area; and "geology and lithology" and "mechanical properties of discontinuities" have also been found to be quite significant parameters. The degree of dominance or subordinance of parameters with respect to the slope system has also been interpreted probabilistically. The newly proposed approach could be a simple but efficient tool in evaluation of the parameters affecting the stability of rock slopes and hence be useful in decision making under uncertainties.

1. Introduction

Rock slope stability analyses are routinely conducted to allow the design of safe and functional excavated slopes (e.g. open-pit mining and road cuts) and/or to assess the equilibrium conditions of natural slopes. In many cases, slope failures can be extremely hazardous and result in significant negative consequences, including loss of human life and extensive property damage (Eberhardt, 2003; Schuster, 1996; Cancelli and Crosta, 1994). Therefore, it is of great importance to identify the most significant parameters (and interactions among parameters) that have an influence on the stability of specific slopes under consideration, and also to identify which parameters (or interactions) are beneficial for the engineering performance (and hence should be enhanced) and, conversely, which ones are detrimental for engineering (and hence should be minimized).

The "systems engineering" approach can be employed to examine this problem from a holistic point of view. To that end, one of the most powerful approaches in rock slope engineering is the Rock Engineering Systems (RES) approach, which was first introduced by Hudson (1992) to deal with complex engineering problems, as it combines adaptability, comprehensiveness, repeatability, efficiency and effectiveness (Hudson and Harrison 1992) (See also Jiao and Hudson, 1995, 1998).

The RES approach has been widely applied to various engineering problems, including environmental studies regarding the disposal of spent fuel (Skagius et al. 1997), river catchment pollution (Matthews and Lloyd 1998), forest ecosystems (Avila and Moberg 1999; Velasco et al. 2006), radioactive waste management (Van Dorp et al. 1999; Agüero et al., 2008), traffic-induced air pollution (Mavroulidou et al. 2004 and 2007), risk of reservoir pollution (Condor and Asghari, 2009), etc. It has also been widely used in other rock mechanics applications such as the general problem of stability of slopes (Smith 1994; Mazzoccola and Hudson 1996; Castaldini et al. 1998; Zhang et al. 2004; Shang et al., 2005; Ceryan and Ceryan 2008; Rozos et al. 2008; Budetta et al. 2008), in stability analysis of tunnels and other underground spaces (Shang et al., 2000; Benardos and Kaliampakos, 2004; Shin et al., 2009), as well as in the analysis of rock blasting (Latham and Lu, 1999; Anderiux and Hadjigeorgiou, 2008), etc.

In the RES approach (see e.g. Hudson, 1992) the interactions between the various parameters of the system are presented in matrix form using a clockwise convention, where the (i,j)-th element of the "interaction matrix" represents the influence of parameter i on parameter j (the matrix is not necessarily symmetric). Of course, the numerical values of the interactions (i.e. the elements of the matrix)

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need to be quantified; assigning numerical values to the interaction boxes is usually referred to as "coding the matrix".

Several coding methods have been developed for this purpose, with the most common being the "expert semi-quantitative" (ESQ) coding method. (ESQ coding has been used in nearly all the previous works cited above). In the ESQ coding method, only one value is deterministically assigned to each interaction. Therefore, it is implicitly considered that there are no uncertainties when the influence of one parameter on the others is expressed in the matrix. Typically, coding values between 0 and 4 are employed with ESQ coding schemes, with 0 indicating no interaction and 4 indicating the higher level of interaction — i.e. "a critical interaction".

However, such coding values are not always constant and/or certain, and they also depend on the type of problem; that is, it is always possible that the coding value needs to be updated and/or modified under the specific conditions of a project, and, in many cases, it is also possible that an exact (and unique) digit-code cannot express the correct particular interaction. This could be due, for instance, to uncertainties in the assignments of values or even due to uncertainties on the physics of the problem. For that reason, in this paper we propose a novel "Probabilistic ESQ" (PESQ) coding approach to be used within the RES systems framework. Within the PESQ coding approach, uncertainties in the assignments of codes are dealt with the aid of probabilities that are assigned for each possible coding value (e.g., between 0 and 4, following the typical coding scheme mentioned above).

Rock slopes in the Khosh-Yeylagh region in Iran are employed to illustrate the utilization of this method in rock slope problems, and nine important parameters are considered as the main factors of the rock engineering system modeling their instability. Finally, we show how the whole RES technique can be employed in a probabilistic way so that the most important modes of interaction of components, as well as their degree of dominance or subordinance, can be compiled and interpreted using the typical procedures of the RES framework.

2. Methodology

With the increasing sophistication of site-investigation and rock characterization techniques, as well as of methods for numerical analysis, it is becoming more important to base rock engineering designs (including site investigation, construction methods, and monitoring procedures) on a coherent and general understanding of the complete rock engineering problem that includes not only the primary mechanisms and parameters, but also the interactions between them (Hudson and Harrison 1992). The rock engineering systems (RES) approach (Hudson, 1992) aims to provide such coherent and general understanding of complex rock engineering projects. More importantly, it also provides a framework from which the complete design procedure can be evaluated, leading to "optimal results" in rock engineering projects.

In the RES approach, the *interaction matrix* is both the basic analytical tool and also the main presentation technique for characterizing the most important parameters, and their interaction mechanisms, in a rock engineering project (Hudson 1992). In the systems analysis of a RES (e.g. a rock slope), all factors (or parameters) influencing the system are arranged along the leading diagonal of the interaction matrix. The influence of each individual factor on any other factor is included at the corresponding off-diagonal position (these are hence named the off-diagonal terms). That is, the off-diagonal terms are assigned values which quantify the degree of the influence of one factor on the other factors. For instance, the (i,j)-th element of the interaction matrix represents the influence of the i-th factor on the j-th factor, whereas the (j,i)-th element of the matrix represents the influence of the j-th parameter on the i-th; note that, therefore, the interaction matrix is not necessarily symmetric. Assigning these values is usually referred to as "coding the matrix".

Fig. 1(a) shows a general example of the mutual influences that occur in a typical system, and how they are described by the system's interaction matrix. (In principle, there is no limitation to the number of factors that may be included in an interaction matrix, as long as the number of factors needed to solve a practical engineering problem is finite.) As a more specific example, Fig. 1(b) shows a 2×2 interaction matrix with only two rock engineering parameters – i.e. rock discontinuity and rock stress – that represents the simplest example case of an interaction matrix containing only two factors. A more general illustration of the coding of a higher-dimensional interaction matrix is shown in Fig. 2. (A problem which includes *N* factors will have an interaction matrix with *N* rows and *N* columns.) The row passing through P_i represents the influence of P_i on all the other factors in the system, while the column through P_i represents the influence of the other factors, or the rest of the system, on parameter P_i.

In order to be of practical value, the matrix needs to be coded, i.e., the interactions between the various parameters need to be quantified, assigning numerical values to the off-diagonal interaction boxes at positions (i,j) and (j,i) in the interaction matrix. There are five matrix coding methods (Hudson and Harrison 1992):

1. The "binary approach" (i.e. switches with on/off positions), whereby the values can be either 0 (no interaction) or 1 (interaction);
2. The "expert semi-quantitative" (ESQ) method, whereby the interaction between the parameters is ranked based on a numerical scale. Typically a scale from 0 to 4 is employed, where 0 represents "no interaction"; 1 represents a "weak" interaction; 2 represents a "medium" interaction; 3 represents a "strong" interaction and, finally, 4 represents a "critical" interaction (this is the type of coding more commonly employed in the literature);
3. Based on the relationship between the two parameters (P_i and P_j) examined, according to the slope of the P_i vs. P_j scatter-plot;
4. Numerically, derived from the computed solutions to a system of partial differential equations (PDE); and
5. Explicitly, through a complete numerical analysis of the interaction mechanism.

After coding the matrix by inserting the appropriate values for each off-diagonal cell of the matrix, the sum of each row and of each column can be calculated. For each parameter (e.g. for the i-th parameter, P_i), the sum of its row values is termed the "cause" (C_i) value, whereas the sum of its column values is called the "effect" (E_i) value. Such information can be summarized as coordinates (C_i, E_i) on a cause–effect plot, where each point in the graph represents a particular factor P_i (see Figure 3). In other words, C_i represents the way in which P_i affects the rest of the system and E_i represents the effect that the rest of the system has on P_i, which is related to the parameter being "dominant" (lower right region of the (C,E) plot) or to the system being "dominant" (upper left region).

Besides, knowledge of C_i and E_i can be employed to compute the "level of interactivity" of each parameter P_i (computed as the sum of C_i+E_i). As shown in Fig. 4, when the (C_i, E_i) coordinate values for each factor are plotted in cause and effect space (forming a so-called (C,E) plot; see Figure 3), it allows us to discriminate between "less interactive" and "more interactive" parameters ("more interactive" parameters are plotted in the upper right region; whereas "less interactive" parameters are plotted in the lower left region) (Hudson 1992). The level of interactivity of parameters can be used to identify parameters to be kept under control, as their variation is likely to induce significant changes in the system (Mazzoccola and Hudson, 1996).

As shown above, the cause–effect plot is helpful to understand the role of each factor within the project. Such understanding is important in conjunction with information about which interactions are beneficial for engineering (and hence should be enhanced) and,

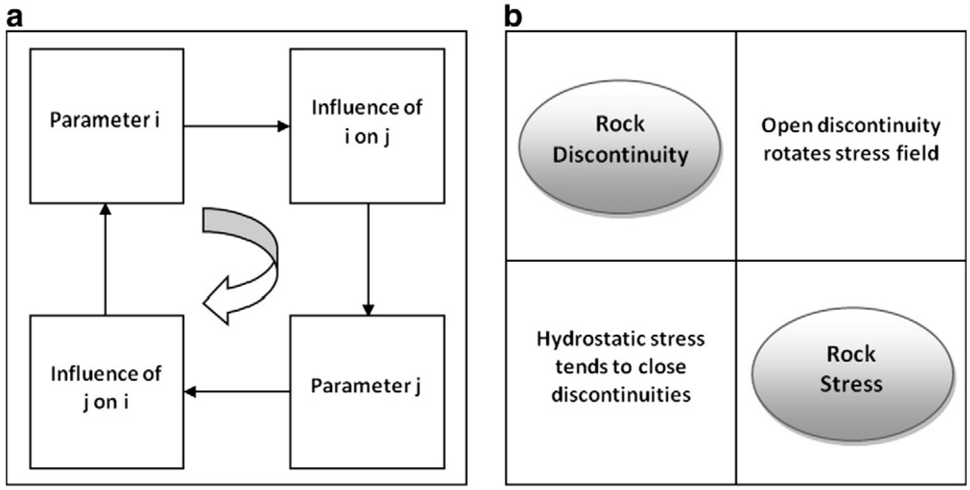

Fig. 1. Interaction matrix in RES (based on Hudson 1992); (a) general illustration of interaction matrix with two factors, (b) A 2×2 interaction matrix with leading diagonal terms, rock discontinuity and rock stress.

conversely, which interactions are detrimental for engineering (and hence should be inhibited) (This is, of course, project dependant). As an example to show how the interactions could be detrimental or beneficial in a specific rock engineering problem, we can consider two parameters such as the "state of stress" and the "water flow along the discontinuities" in an underground excavation project. Generally, high normal stresses reduce discontinuity permeability, which can be considered a beneficial effect if we are concerned with water flow or leakage of contaminants; conversely, water pressure reduces the effective normal stress within the discontinuity, hence producing (in general) a detrimental influence due to reduction of its shear strength.

Representing the results as a (C,E) plot is also helpful (see Figure 4) because it allows to graphically compute the parameter interaction intensity and the parameter dominance. The parameter interaction intensity can be measured along the C = E line, whereas the parameter dominance depends on the perpendicular distance from the parameter's point representation (its (C,E) coordinates) to this line (Hudson, 1992). The two sets of 45° lines in the (C,E) plot in Fig. 4 indicate contours of equal value for parameter interaction intensity

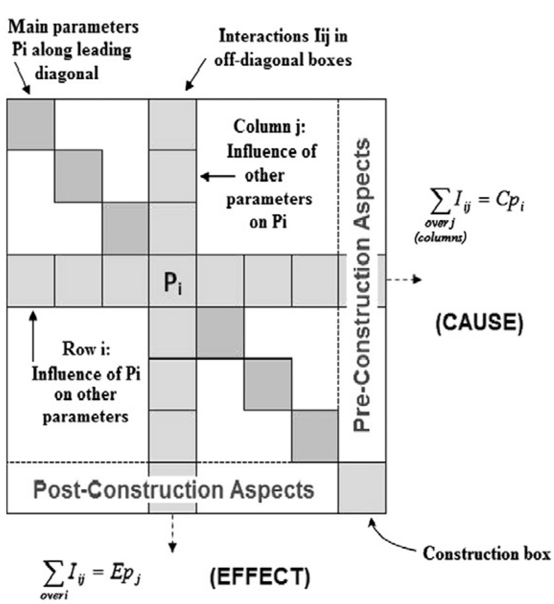

Fig. 2. Summation of coding values in the row and column through each parameter to establish the cause and effect co-ordinates (based on Hudson 1992).

and dominance: The specific numerical values of the two sets of lines are $(C+E)/\sqrt{2}$ for the parameter interaction intensity and $(C-E)/\sqrt{2}$ for the parameter dominance (see Figure 4, Hudson, 1992).

As described above, in the RES method, the selection of influencing factors for the interaction matrix and the coding (quantification) of their interactions are done based on site investigation, engineering expertise, theoretical and numerical analyses, and also by historical documents. Despite all such variety of methods that can be employed to assess interactions, in the conventional ESQ coding approach only one unique code (i.e. numerical value) can be assigned to quantify the influence of a parameter on the other(s) in the matrix. However, in many cases, existing uncertainties on the characterization of parameters, on their relations, or even on the mechanics of the problem, have the consequence that an exact and unique code cannot be selected so that it can fully express the correct particular interaction.

To tackle the problem of dealing with uncertain codes, we propose to consider a probabilistic expert semi-quantitative (PESQ) coding method, in which probabilities are assigned to the different possible coding values considered for each matrix interaction. In other words, each interaction is assigned probabilities of having each of the possible coding values considered (e.g. from 0 to 4 in this case). This information can be represented as a set of matrices (five matrices would be employed in case that a 0–4 coding is used), where each of such matrices contains, in its i–j-th position, the probability that such particular code represents the influence of P_i on P_j. (Of course, the sum of probabilities corresponding to each off-diagonal position in the five matrices has to be one).

Applying this newly proposed PESQ approach to represent the coding of the interaction matrix, all the other steps of the RES analysis can be considered in such probabilistic ways as well. For example, as shown below, we can compute probabilistic C and E distributions; probabilistic (C,E) plots and histograms; etc. In the next section, application of such probabilistic RES approach will be illustrated with the help of a case study on the main factors affecting the stability of rock slopes.

3. Example of application

To demonstrate the application of the probabilistic systems approach to rock engineering problems, some rock slopes were selected and considered as a case study. The slopes are located in the Khosh-Yeylagh region in Iran, and they have introduced in detail in previous publications (Zare Naghadehi et al., 2010; KhaloKakaie and

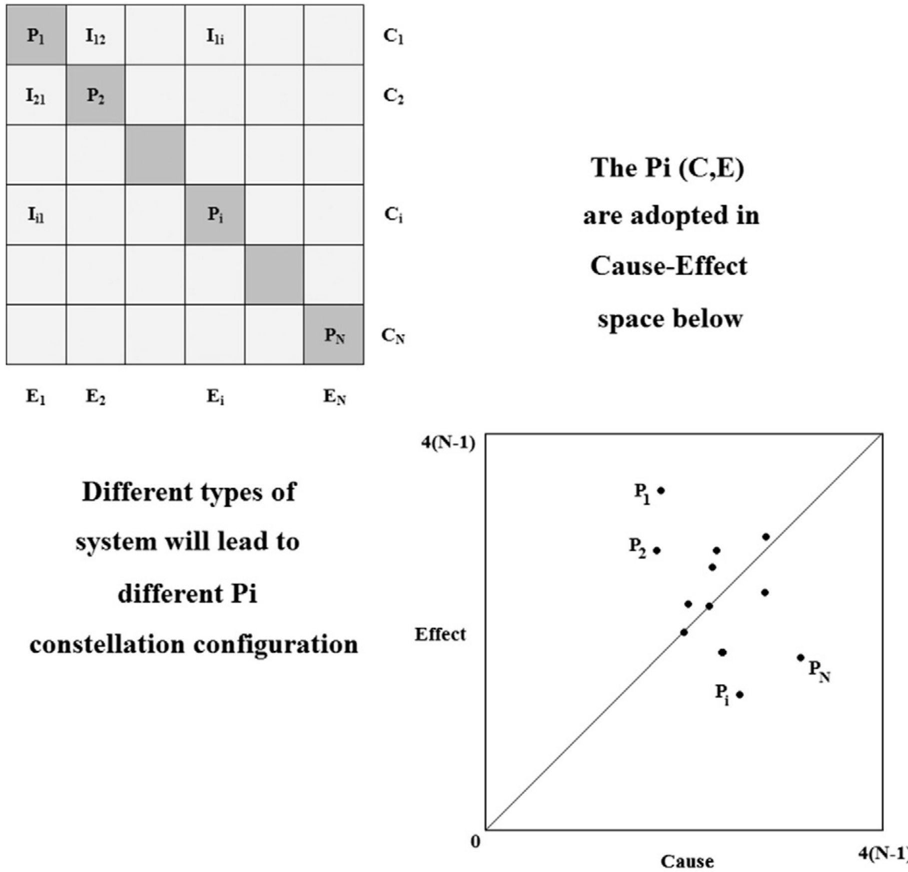

Fig. 3. The (C,E) Plot for the supposed case comprising n influencing factors (based on Hudson 1992).

Zare Naghadehi, 2010). However, for the sake of completeness, we present some explanations of the main characteristics of the area.

The Khosh-Yeylagh Main Road is situated in a mountainous area approximately 90 km north of Shahrood City (north-eastern Iran). Fig. 5 shows a photograph of typical slopes in the area.

The area is principally located on the Khosh-Yeylagh formation with some other formations such as Pad-ha, Soltan-Meydan and Shir-Gasht. The Khosh-Yeylagh formation corresponds to the Devonian period in the Palaeozoic era. Typical rocks within the formation include sequences of gray limestone, red quartzite sandstone, thin-layered gray sandstone and also of green and white sandstones. In addition, dolomitic limestones, shales, dolomites and sandstones can be found in some other parts of the region. The geological structure in the region is quite complex due to multiple folding associated with shear zones and brittle fault zones, but the general attitude of rock units forms a monocline dipping at N130–180E/20–60 (dip direction/dip).

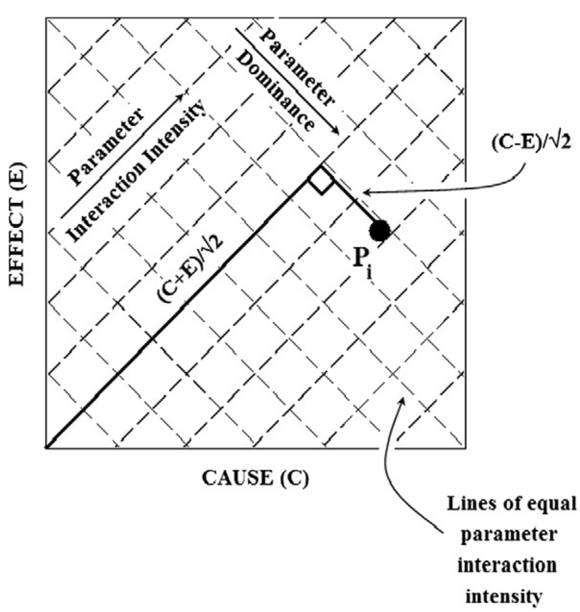

Fig. 4. Expanded view of (C,E) plot to show lines of equal parameter interaction intensity and dominance (Hudson, 1992).

The meteorological records for the period 1975–2007 show that the highest mean temperatures are usually experienced in July and August (11 °C to 35 °C) and the lowest in January and February (−10 °C to 7 °C), while the highest rainfall is typically recorded in March and April (300–400 mm) and the lowest in July (70–100 mm) (IGOSIT, 2007).

Rock slopes excavated along the main road in the mentioned area have been selected for analysis in this paper. The main aim of this study is to analyze and identify the most important parameters influencing the stability of rock slopes in the area. Therefore, we start by considering nine parameters that control the stability of the rock slopes under study, as follows:

1– *Geology and lithology:* Lithology or rock type is one of the most decisive parameters (causative factor) regarding slope failure in the study area. There are two dominant rock types in the area: gray sandstones and limestones, plus a range of combinations of the two. The sandstones have fine grain size with a relatively homogenous texture, and they are commonly referred to as the "Khosh-Yeylagh Sandstone" in the geological literature (Zare Naghadehi et al. 2010). Below the sandstone formation there is a (older) limestone formation, which is mainly comprised of limestones with subordinate dolomitic limestones which generally present

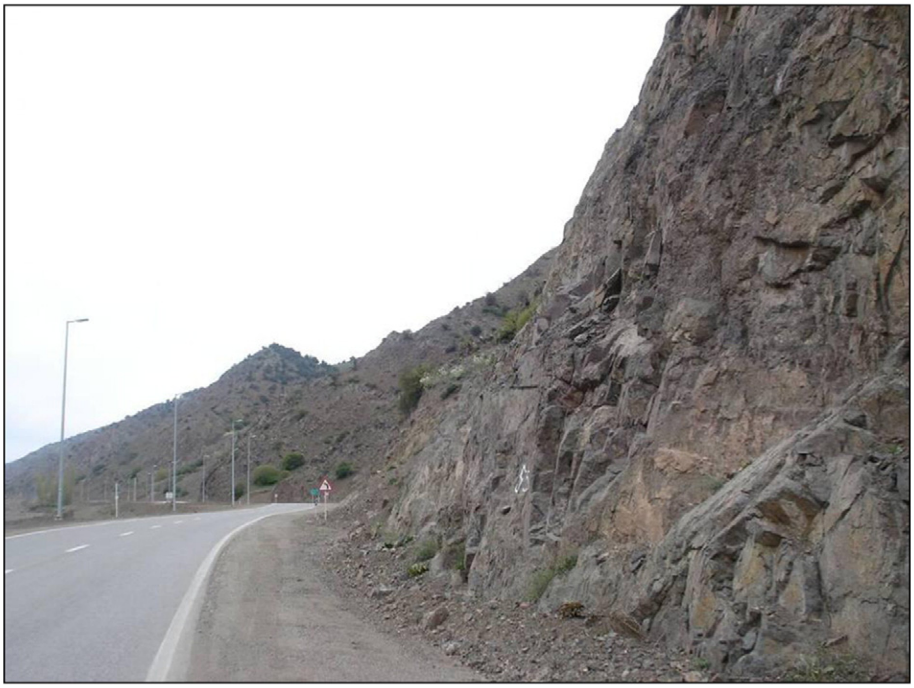

Fig. 5. A typical landscape of the Khosh-Yeylagh Main Road.

higher grades of weathering. From field observations, it was found that more failures (instabilities) occurred in limestone slopes than in sandstone slopes.

2– *Faults and folds:* Faults and folds are commonly the critical features which have a greater effect on rock engineering and rock mass behavior. Faults are particularly important because they tend to induce the formation of major joint sets in their orientation. Also, in their vicinity, the fracture frequency generally increases and, at times, a layer of crushed rock is present (Hattori and Yamamoto, 1999). Moreover, complex jointing, foliation planes and additional joint sets are usually associated to formed folds and found in their vicinity. In the Khosh-Yeylagh region, the major faults are generally oriented parallel to the main faulting direction of the area, which in addition controls the region's morphology.

3– *Previous instabilities:* The presence of previous instabilities demonstrates that a critical combination of factors leading to instability is possible at the site. From the observation of failures, it is usually possible to deduce how these factors (in some combination) led to instability, and also to anticipate how they might combine again in other locations to produce more instabilities. Moreover, even small-scale instabilities may serve as indications of likely failures at larger scales, so that their analysis is always useful to better understand the process (Mazzoccola and Hudson, 1996).

4– *Intact rock strength:* The intact rock strength should be considered, since it is an important parameter to characterize rock mass strength and rock mass quality (e.g. RMR rating heavily depends on intact rock strength; see Bieniawski, 1989). The rock types in the region can be classified as having medium strength, and it is therefore unusual to have failures through the intact rock given the low stress levels associated to common slope heights in the area. However, field studies conducted at the site concluded that some rock types presented high strength anisotropy, which could lead to local failures along weaker directions at depth in high slopes.

5– *Weathering:* Field studies have often shown that both physical and chemical weathering increase the instability of slopes (Giani, 1992; Calcaterra and Parise, 2010). In addition, weathering is known to be a very active factor for the given climatic conditions and rock types at the site, which should therefore be considered. Some alterations along open joints have been further identified at the site, and that may slightly decrease mechanical properties along discontinuity surfaces, hence increasing the instability potential of the slope (see point 6 below).

6– *Mechanical properties of discontinuities:* Slope failures usually occur along a surface or plane of weakness that acts as a discontinuity in the rock. Thus, the stability of rock slopes is strongly related to the geometry and mechanical properties of existing discontinuities. Discontinuity strength and orientation are the most important properties for rock slope stability analyses. Shear strength along the joint surfaces can be considered using Mohr–Coulomb parameters of cohesion and friction angle, although non-linear failure criteria such as Barton–Bandis (Barton and Bandis, 1990) or Hoek and Brown (Hoek and Brown, 1980; Hoek et al., 2002) can be employed as well. Methods for characterization of discontinuities orientation have been summarized by Priest (1993), and Jimenez and Sitar (2006) (see also Jimenez, 2008) have presented methods for automatic identification of discontinuities sets in rock slopes.

7– *Hydraulic conditions:* This parameter includes both the presence of water and the rock mass characteristics which control water flow, such as permeability, interconnectivity and disposition of fractures, drainage paths, etc. The primary effect of groundwater in a rock slope is to reduce the stability as a consequence of the resulting reduction in effective stress within discontinuities, which also reduces shear strength along discontinuities.

8– *Slope height:* The natural height of a slope is a combined result of the tectonic activity and the erosion–weathering processes, and it is also related to climatic conditions throughout an interactive influence. In excavated slopes, however, the height is not completely a result of natural processes, and it also depends on human input as well as on other factors. Rock blocks in higher slopes have more potential energy than rocks in lower slopes; thus they present a greater hazard and are more failure prone (Kliche, 1999).

9– *Slope inclination:* The orientation and the inclination of the slope play a very important role as a cause of slope failure. Slope orientation affects the number of removable blocks that can be formed in a slope (see e.g. Goodman and Shi, 1985). In addition, as the angle of a slope increases, the driving force on blocks also increases, therefore making removable blocks prone to failure. Thus, everything being equal, slope failure would be more frequent on steep slopes.

The selection of parameters listed above agrees well with other similar works on the application of RES to the analysis of rock slopes (see e.g. Mazzoccola and Hudson, 1996). However, several parameters (e.g., rainfall, freeze thaw cycles, in-situ stresses, and other parameters of discontinuities—besides mechanical properties) have not been considered in this study either because they do not generally change much within the study area or because they have found to have a relatively small importance on previous (deterministic) RES studies (for details, see, KhaloKakaie and Zare Naghadehi, 2010).

The implementation of the RES method with the newly proposed PESQ coding has been achieved through five interaction matrices (one for each code value of 0 to 4). For each code-value matrix (we will call them M_0 to M_4), the 9 principal parameters are placed in its leading diagonal positions, together with the "potential instability" of the slope (i.e. the subject to be studied), which is considered as the 10th parameter of the analysis. Therefore, based on the typical RES methodology, the column of interactions through this last bottom-right box in the matrix represents how the rock mass system affects potential instability; while the row through this box represents the influence of potential instability on the rock mass (which is not considered herein because we are interested in cases in which instability is "potential" and has not yet occurred).

As described in the previous section, probabilities are considered for each interaction coding value in the PESQ coding method. That is, instead of assigning a unique (and deterministic) coding value to each interaction, probabilities are assigned (for each interaction) to represent the likelihood of each possible coding value considered (from 0 to 4 in this case). This can be expressed by five matrices (M_0 to M_4, one for each code value from 0 to 4), where the off-diagonal elements of each matrix contain the probabilities for occurrence of that particular code for that particular interaction (see Tables 1–5).

As an example of this coding procedure, next we discuss the probability values assigned to the five possible codings considered to represent the influence of weathering (P_5) on mechanical properties of rock mass (P_6) (i.e. element (5,6) in matrices M_0 to M_4; see Tables 1 to 5). This interaction is considered to be relatively strong, and therefore probability assignments have been 5% for occurrence of code 0 (no interaction), 10% for occurrence of code 1 (weak interaction), 50% for occurrence of code 2 (medium interaction), 25% for occurrence of code 3 (strong interaction), and 10% for occurrence of code 4 (critical interaction) (Of course, PESQ is still somewhat subjective, but it has the advantage that it allows us to incorporate our best estimates of uncertainties into the analysis).

Table 1
Interaction matrix M_0 for probabilities of code 0 for rock slope instability in the Khosh-Yeylagh region.

P_1	5	5	5	5	5	5	10	5	5
5	P_2	5	90	20	0	0	5	5	5
100	100	P_3	95	20	5	15	0	5	5
100	100	5	P_4	0	0	90	0	0	5
100	100	5	0	P_5	5	100	95	95	5
100	100	0	100	100	P_6	95	90	5	0
100	100	5	95	0	0	P_7	55	80	5
100	100	5	100	100	100	5	P_8	0	5
100	100	0	100	100	100	95	90	P_9	0
100	100	100	100	100	100	100	100	100	P_{10}

P_1: Geology and lithology; P_2: Faults and folds; P_3: Previous instabilities; P_4: Intact rock strength; P_5: Weathering; P_6: Mechanical properties of discontinuities; P_7: Hydraulic conditions; P_8: Slope height; P_9: Slope inclination; P_{10}: Potential instability.

Table 2
Interaction matrix M_1 for probabilities of code 1 for rock slope instability in the Khosh-Yeylagh region.

P_1	25	15	5	15	20	15	15	10	5
15	P_2	5	10	55	10	10	25	20	5
0	0	P_3	5	55	25	45	5	10	15
0	0	10	P_4	5	20	10	15	15	10
0	0	5	10	P_5	10	0	5	5	5
0	0	20	0	0	P_6	5	10	20	0
0	0	5	5	5	5	P_7	30	15	5
0	0	5	0	0	0	15	P_8	15	5
0	0	0	0	0	0	5	10	P_9	0
0	0	0	0	0	0	0	0	0	P_{10}

P_1: Geology and lithology; P_2: Faults and folds; P_3: Previous instabilities; P_4: Intact rock strength; P_5: Weathering; P_6: Mechanical properties of discontinuities; P_7: Hydraulic conditions; P_8: Slope height; P_9: Slope inclination; P_{10}: Potential instability.

Table 3
Interaction matrix M_2 for probabilities of code 2 for rock slope instability in the Khosh-Yeylagh region.

P_1	40	15	15	20	40	40	45	25	15
60	P_2	15	0	15	10	15	40	45	15
0	0	P_3	0	20	40	25	20	25	55
0	0	50	P_4	15	50	0	55	50	40
0	0	15	60	P_5	50	0	0	0	15
0	0	50	0	0	P_6	0	0	65	0
0	0	15	0	15	10	P_7	15	5	15
0	0	15	0	0	0	65	P_8	50	15
0	0	0	0	0	0	0	0	P_9	0
0	0	0	0	0	0	0	0	0	P_{10}

P_1: Geology and lithology; P_2: Faults and folds; P_3: Previous instabilities; P_4: Intact rock strength; P_5: Weathering; P_6: Mechanical properties of discontinuities; P_7: Hydraulic conditions; P_8: Slope height; P_9: Slope inclination; P_{10}: Potential instability.

4. Results

As described before, when the matrix is coded in deterministically with the typical ESQ coding method, the influence of each parameter on the system, as well as the influence of the system on each parameter, can be computed (respectively) as the sum of codes in the parameter's row and column within the interaction matrix. In the PESQ coding method, however, we have probabilities for each code in each off-diagonal element of the matrix, which means that (instead of unique deterministic C_i and E_i values) we can compute the probability distributions of C_i and E_i. Given such distributions, we can also compute expected C_i and E_i values for each parameter P_i by simply using basic probability rules. As an example, Fig. 6 shows the probability (mass) distributions for cause and effect of the "intact rock strength" parameter (P_4). (Note that, as we have 9 off-diagonal boxes in each row and column with interaction values between 0 and 4, C and E are therefore distributed between 0 and 36.) As it can

Table 4
Interaction matrix M_3 for probabilities of code 3 for rock slope instability in the Khosh-Yeylagh region.

P_1	25	45	50	40	30	25	20	40	55
15	P_2	55	0	10	55	55	20	20	55
0	0	P_3	0	5	25	10	50	45	20
0	0	30	P_4	55	25	0	20	25	30
0	0	55	20	P_5	25	0	0	0	55
0	0	25	0	0	P_6	0	0	10	10
0	0	55	0	60	70	P_7	0	0	55
0	0	55	0	0	0	10	P_8	25	55
0	0	10	0	0	0	0	0	P_9	10
0	0	0	0	0	0	0	0	0	P_{10}

P_1: Geology and lithology; P_2: Faults and folds; P_3: Previous instabilities; P_4: Intact rock strength; P_5: Weathering; P_6: Mechanical properties of discontinuities; P_7: Hydraulic conditions; P_8: Slope height; P_9: Slope inclination; P_{10}: Potential instability.

Table 5
Interaction matrix M_4 for probabilities of code 4 for rock slope instability in the Khosh-Yeylagh region.

P_1	5	20	25	20	10	15	10	20	20
5	P_2	20	0	0	25	20	10	10	20
0	0	P_3	0	0	5	5	25	15	5
0	0	15	P_4	25	5	0	10	10	15
0	0	20	10	P_5	10	0	0	0	20
0	0	5	0	0	P_6	0	0	0	90
0	0	20	0	20	15	P_7	0	0	20
0	0	20	0	0	0	5	P_8	10	20
0	0	90	0	0	0	0	0	P_9	90
0	0	0	0	0	0	0	0	0	P_{10}

P_1: Geology and lithology; P_2: Faults and folds; P_3: Previous instabilities; P_4: Intact rock strength; P_5: Weathering; P_6: Mechanical properties of discontinuities; P_7: Hydraulic conditions; P_8: Slope height; P_9: Slope inclination; P_{10}: Potential instability.

be seen in Fig. 6, the value of C_4 would be between 14 and 17 with a probability of more than 50% and, similarly, the value of E_4 would be between 6 and 7 with more than 50% probability (similar graphs can be plotted for all the parameters).

In addition, by combination of the probability distributions of C_i and E_i for each parameter P_i, probabilistic (C,E) plots can be developed as well. Fig. 7 shows these plots for all the parameters considered in this slope stability problem.

The probabilistic (C,E) plots presented in Fig. 7 can be analyzed in a similar fashion as with the (deterministic) (C,E) plot presented in Fig. 4. In the deterministic case, as we described in the previous section, the (deterministic) interaction intensity and dominance of each parameter in the system can be analyzed based on its location in the (C,E) plot. Similarly, as an extension of this idea, we can compute probabilities of interaction intensity and dominance using the probabilistic (C,E) plots of Fig. 7. (Instead of having unique C,E combinations for each parameter, in this case we have several possible C,E combinations, and each of such combinations has a probability of occurrence.) That is, in Fig. 7, we can observe that for some parameters the probability content in the probabilistic (C,E) plot tends to assume positions further away from the diagonal line with equation $C=E$, therefore indicating that they have high dominance on the system (when the probability content is on the lower right region; see e.g. plots for P_1, P_2, and P_4); that the system has a dominance on them (when the probability content is on the

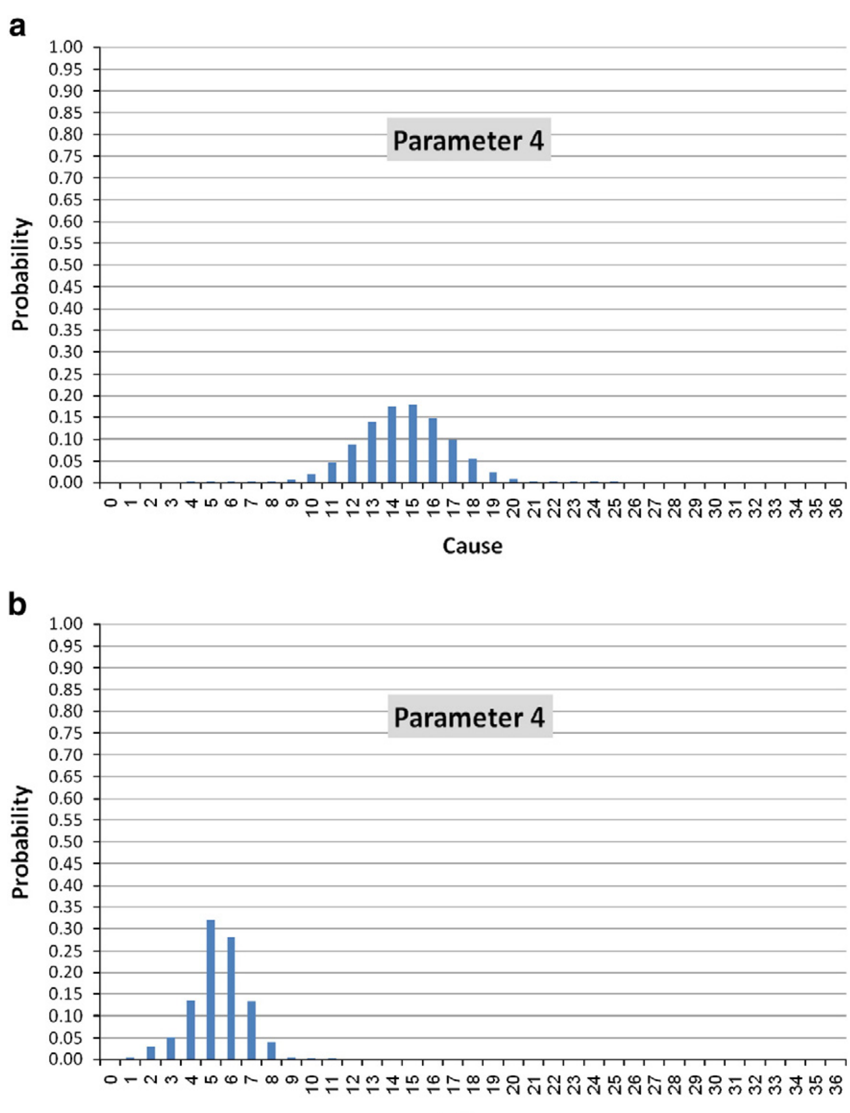

Fig 6. Probability mass distributions for cause and effect of P_4 (intact rock strength); (a) cause, (b) effect.

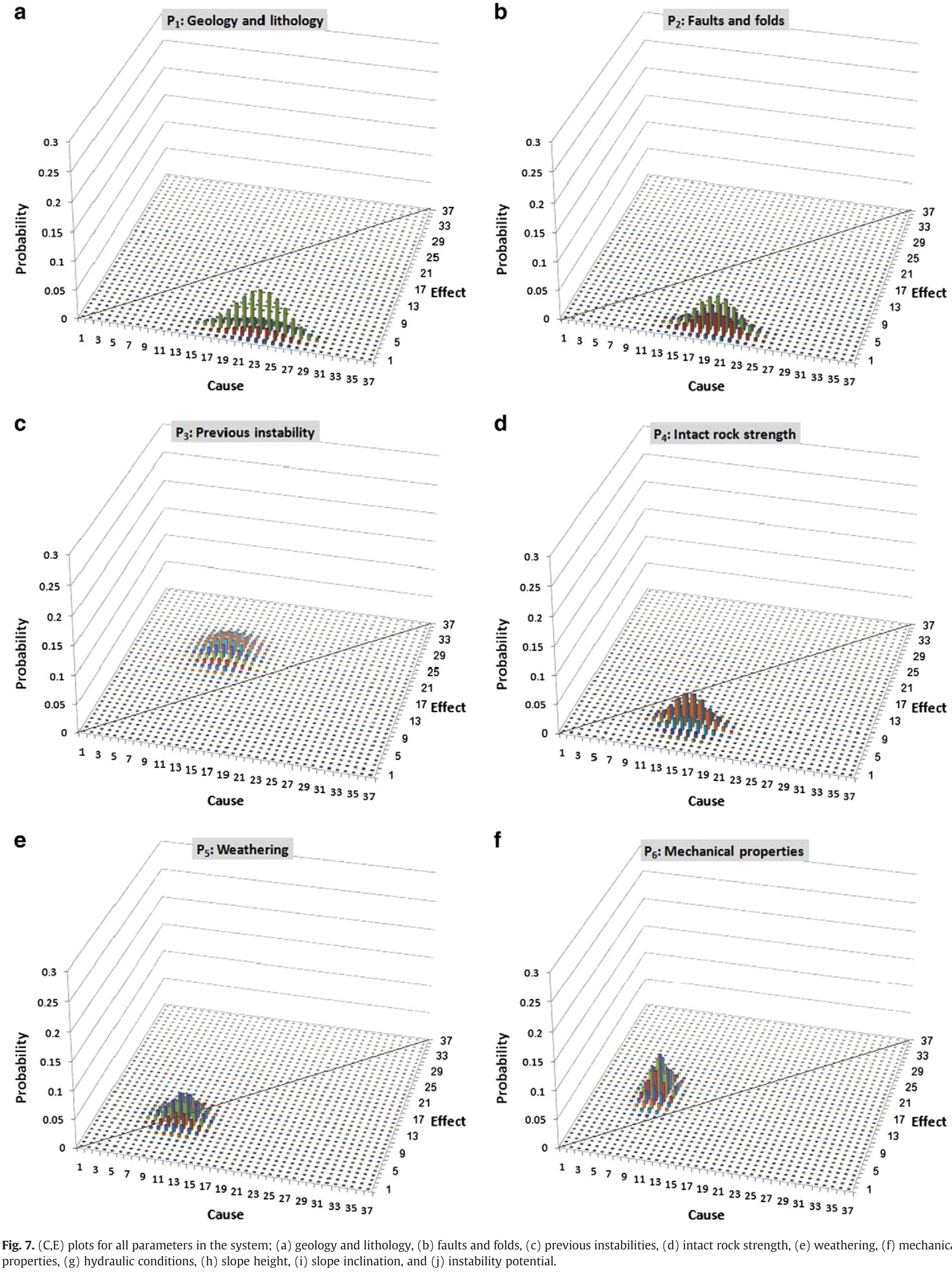

Fig. 7. (C,E) plots for all parameters in the system; (a) geology and lithology, (b) faults and folds, (c) previous instabilities, (d) intact rock strength, (e) weathering, (f) mechanical properties, (g) hydraulic conditions, (h) slope height, (i) slope inclination, and (j) instability potential.

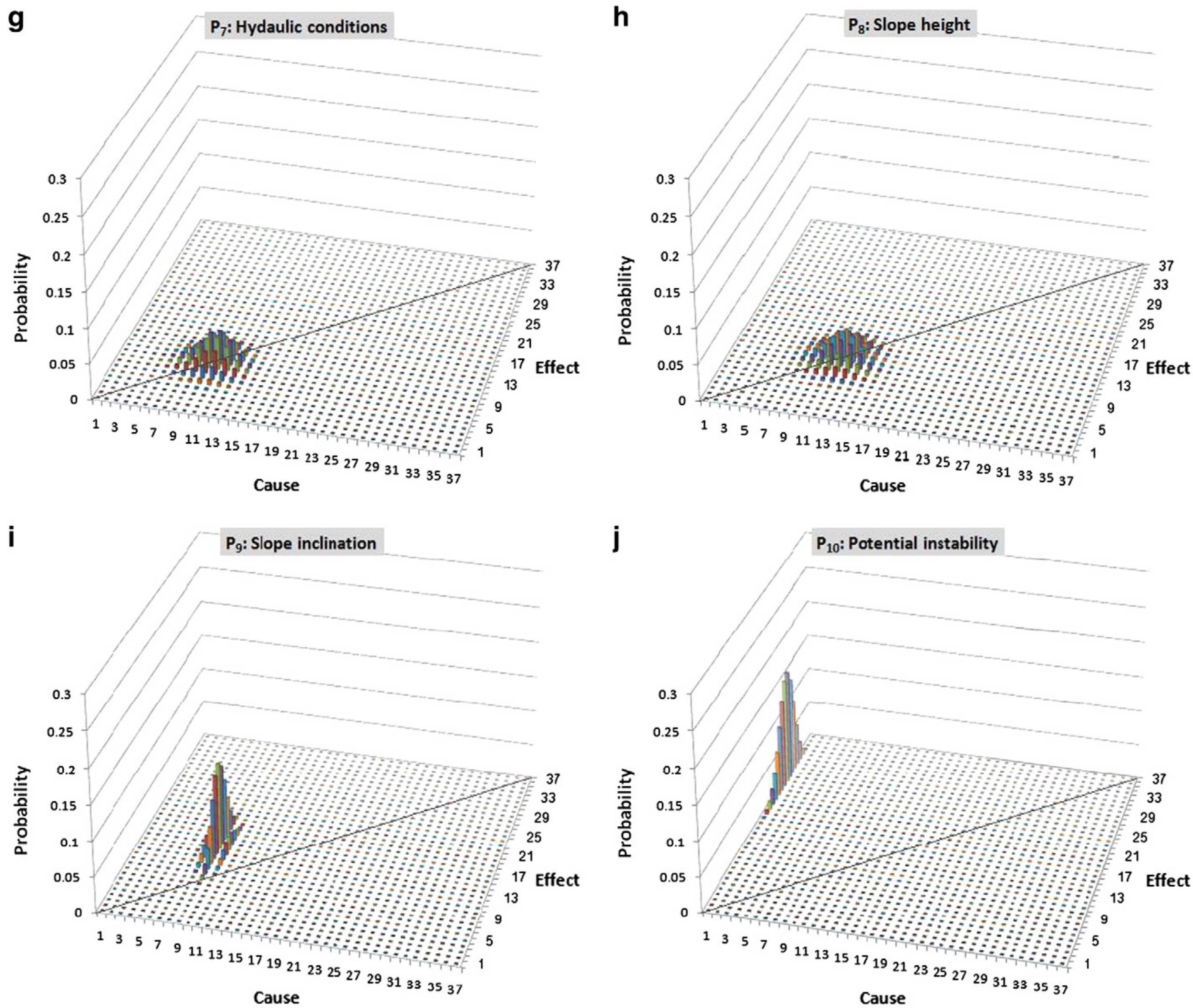

Fig. 7 (*continued*).

upper left region; see e.g. plots for P_3, P_6, and P_9); or that they are "neutral" with respect to the system (when the probability content is mainly on the C = E line; see e.g. plots for P_5, P_7, and P_8).

In addition, the probabilistic (C,E) plots allow us to identify whether all parameters are important for the definition of the system or whether there is any (or some) parameters that do not have any influence. To that end, we can plot the expected values of the interaction intensities (C + E values) for each parameter considered (Figure 8), and we can also plot error bars to indicate uncertainties in such estimations as measured by their standard deviations. (To obtain such values, all C + E probability distributions, as well as their means and standard deviations, have been computed.)

Similarly, Fig. 9 presents the expected values of the parameters dominance (or subordinance) (C–E values) for each parameter considered. (Error bars, as measured by the standard deviations of the C–E distributions have been presented as well.)

In this case, from the results shown in Fig. 7 and 8, it can be concluded that all the 9 "input" parameters are rather interactive and have a significant influence on the "outcome" parameter (i.e. potential instability) so that, therefore, they should be taken into account in the engineering decisions. Similarly, Fig. 9 presents the expected values (and their uncertainties, as measured by their standard deviations) for the "dominance measure" of each parameter considered (i.e. its C–E values).

In addition, based on the cause–effect probabilistic diagrams of the 10 parameters considered in the presented rock slope stability analysis (Figures 7 to 9), the following remarks can be made:

- All the parameters considered are rather interactive, as their probability contents are located away from the origin as measured along the diagonal of the C,E diagram.
- The factor with higher probability for being interactive is "previous instabilities" (P_3), whereas the factors with the lowest probability for being interactive in this case are the weathering (P_5) and the hydraulic conditions (P_7).
- The geology and lithology (P_1) and the faults and folds (P_2) are the parameters that have the highest probability to dominate the system, while the previous instabilities (P_3) and the potential instability (P_{10}) parameters have the highest probability of being dominated by the system. (Note that these results agree well with the outcomes of previous applications of RES to slope stability problems; see e.g. Mazzoccola and Hudson, 1996).

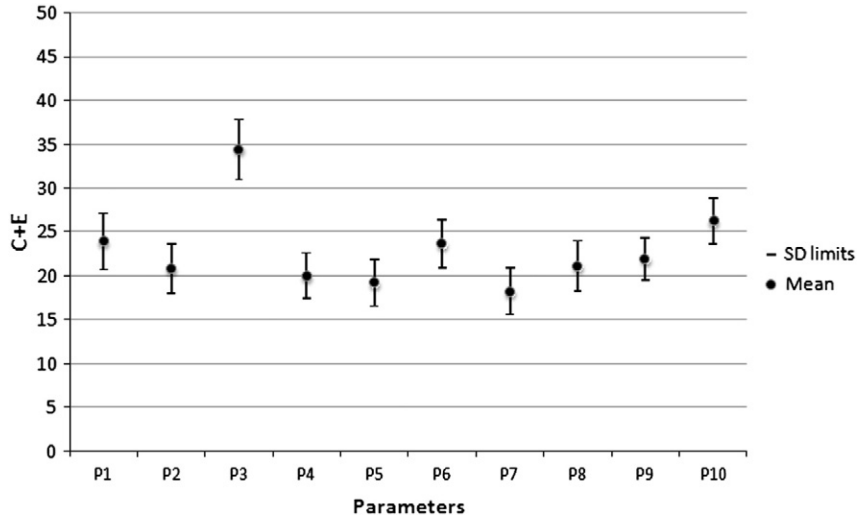

Fig. 8. Mean values and standard deviation limits for interactivity of 10 parameters affecting the stability of rock slopes in Khosh-Yeylagh region.

5. Concluding remarks

Our example case illustrates the utilization of the newly proposed PESQ coding method to rock slopes in the Khosh-Yeylagh region in Iran. Nine parameters were considered as possible factors influencing the potential instability of slopes in the region, and the whole rock engineering systems approach was formulated in a probabilistic way.

However, in this work, and as a new idea, it has been shown that uncertainties in the codings can be considered using the Probabilistic Expert Semi-Quantitative (PESQ) method.

We have also shown that the consideration of probabilistic codes within the PESQ coding framework can be associated to a full probabilistic RES approach, causing the rest of the methodology to become non-deterministic. For example, and as an extension to traditional (deterministic) RES analyses, the newly proposed probabilistic approach allows to identify the parameters with the highest probability of being dominant or subordinant, and also the parameters with the highest probability of being interactive. That is, variability and/or uncertainties can be explicitly included in the analysis, and the effects of such uncertainties can be quantified.

Such information has important practical use and, for instance, has implications on site characterization since it allows the designer to identify parameters that should be characterized in more detail in any particular case. For example, results show that the parameter related to existence of “previous instabilities” (P_3) has the highest expected interaction with the system (in other words, the most important parameter), therefore suggesting the importance of performing a site survey of similar slopes in the area. Similarly, “geology and lithology” and “mechanical properties of discontinuities” have also been found to be quite significant parameters. This agrees well with observations in the area, as failures have been mainly found associated to specific types of geological materials (failures occur in limestone slopes mainly); and, similarly, mechanical properties of discontinuities are also known to significantly affect instability potential in rock slopes.

In addition, the newly proposed probabilistic RES methodology allows to compute uncertainties (or variabilities) of computed results. For instance, the “previous instabilities” parameter also has the greatest standard deviation (and, hence, the greater uncertainty) among all the parameters. Similar comments could be made about the dominance/subordinance of the system and, for instance, it is found that computed subordinance of the “previous instabilities” factor has the highest uncertainty. Such information could have not been obtained by only using a deterministic approach and/or mean values only.

Therefore, this work illustrates the value of the new probabilistic coding method (and the subsequent probabilistic analysis that follows) to incorporate uncertainties and variabilities into the analysis

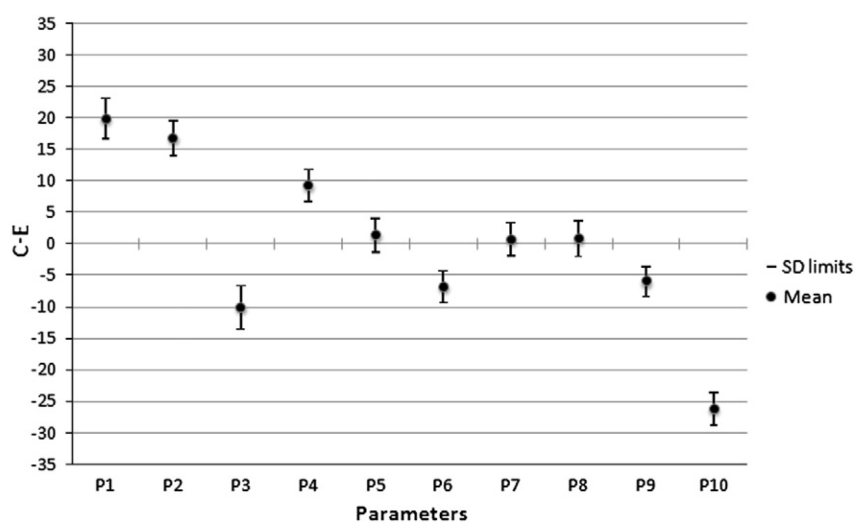

Fig. 9. Mean values and standard deviation limits for subordinance of 10 parameters affecting the stability of rock slopes in Khosh-Yeylagh region.

of the main factors influencing the stability of rock slopes. In addition, it illustrates how the inclusion of probabilities in the coding of the matrices can help reduce problems associated to the subjectivity in the coding of interaction matrices for RES analysis.

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