

The assessment of rock slope instability along the Khosh-Yeylagh Main Road (Iran) using a systems approach

Reza KhaloKakaie · Masoud Zare Naghadehi

Received: 26 July 2009 / Accepted: 16 December 2011 / Published online: 31 December 2011
© Springer-Verlag 2011

Abstract The slope instability is connected to a large diversity of causative and triggering factors, ranging from inherent geological structure to the environmental conditions. Thus, assessment and prediction of slope failure hazard is a difficult and complex multi-parametric problem. In contrast to the analytic approaches, the systems approaches are able to consider infinite number of affecting parameters and assess the interactions of each couple of the parameters in the system. This paper presents a complete application of the rock engineering systems approach in prediction of the instability potential of rock slopes in 15 stations along a 20 km section of the Khosh-Yeylagh Main Road, Iran as the case study of the research. In this research, the main objective has been defining the principal causative and triggering factors responsible for the manifestation of slope instability phenomena, quantify their interactions, obtain their weighted coefficients, and calculate the slope instability index, which refers to the inherent potential instability of each slope of the examined region. The final results have been mapped to highlight the rock slopes susceptible to instability. Finally, as a preliminary validation on the utilization of systems approach in the study region, the stability of investigated rock slopes were analyzed using an empirical method and the results were compared. The comparisons showed a rather good coincidence between the given classes of two methods.

Keywords Rock slope instability · Rock engineering systems · Khosh-Yeylagh Main Road · Iran

Introduction

The stability of slopes is of great importance to civil, geotechnical and mining engineers worldwide. Failure of rock slopes, both man-made and natural, include rock falls, overall slope instability and landslides, as well as slope failures in open pit mines. The consequence of such failures can range from direct costs of removing the failed rock and stabilizing the slope to possibly a wide variety of indirect costs. Examples of indirect costs include damage to vehicles and injury to passengers on highways and railways, traffic delays, business disruptions, loss of tax revenue due to decreased land values, and flooding and disruption to water supplies where rivers are blocked by slides. In the case of mines, slope failures can result in loss of production together with the cost of the failed material, and possible loss of ore reserves if it is not possible to mine the pit to its full depth (Wyllie and Mah 2004). Thus, stability analyses are required for a wide variety of engineering projects and especially for slopes of the highways and railways. Because in these projects, a higher degree of reliability is required since slope failure, or even rock falls, can rarely be tolerated (Ross-Brown 1972).

There are many different techniques for the analysis of slope stability. The most widely used techniques include the various limit equilibrium methods (Hoek and Bray 1981; Nash 1987; Norrish and Wyllie 1996); empirical methods using rock mass classifications, such as RMR¹ (Bieniawski 1976, 1993), SMR² (Romana 1985; Romana et al. 2003) and SSPC³ (Hack 2002; Hack et al. 2003); the numerical methods including continuum and discontinuum models

R. KhaloKakaie · M. Zare Naghadehi (✉)
Faculty of Mining, Petroleum and Geophysics,
Shahrood University of Technology, 361995161 Shahrood, Iran
e-mail: mzare@shahroodut.ac.ir; masoud.zare@hotmail.com

¹ Rock mass rating.

² Slope mass rating.

³ Slope stability probability classification.

(Cundall 1976; Larsson et al. 1992; Stead et al. 2000, 2001) and also by means of a GIS (Irigaray et al. 2003; Kim et al. 2004). These techniques all belong to a category that are generally known as the analytic approaches, and thus are only able to consider a limited number of affecting factors and then solve the problem in details. In contrast, the systems approaches not only can examine the problem in its totality with a complete list of the components, but also can take the interactions between the factors into account. The rock engineering systems (RES) approach has been introduced by Hudson (1992a) to deal with complex engineering problems, as it combines adaptability, objectivity, repeatability, efficiency and effectiveness. In the literature, a few researchers have adopted the RES approach to the general problem of stability of slopes in cases of natural slopes, landslides, etc. (Smith 1994; Mazzoccola and Hudson 1996; Castaldini et al. 1998; Ali and Hasan 2002; Zhang et al. 2004; Ceryan and Ceryan 2008; Rozos et al. 2008; Budetta et al. 2008). Smith (1994) used a similar approach for the engineering geological assessment of shallow mine workings in chalk. Mazzoccola and Hudson (1996) adapted the method for natural slope stability assessment by the construction of a rock mass classification in Cimaganda in the Italian Central Alps. Castaldini et al. (1998) studied the earthquake-induced surface effects on the stability of natural slopes of the Northern Apennines in Italy by using the RES approach. Ali and Hasan (2002) studied the landslides in Bangladesh. This study was based on a field investigation which was followed by geomechanical analyses of the field data. They developed a new method to determine the degree of instability of slopes quantitatively, according to the cause and effect for each parameter in the interaction matrix. Zhang et al. (2004) showed that RES methodology can be used to analyze the interactivity mechanism of numerous parameters sensitive to rockfall hazards, and to evaluate the rockfall intensity, rockfall frequency and rockfall hazard under complex natural environments. Ceryan and Ceryan (2008) utilized the RES approach and interaction matrices (IM) methodology for failure susceptibility zoning in Dogankent area in Turkey. Rozos et al. (2008) used the RES as a tool for ranking the instability potential and hazard of landslides in Karditsa County in Greece. Finally, Budetta et al. (2008) presented a combined approach for landslide hazard zonation using RES and GIS and used the approach on cliffs along the coastline of the Cilento region in Italy.

The RES approach can be considered as a suitable method for assessing the stability of rock slopes in areas with complex environment and multiple affecting parameters. Accordingly, the purpose of the present study is to apply the RES for the rock slope stability assessment of a mountainous area, along the Khosh-Yeylagh Main Road, NE Iran. For this purpose, 15 stations have been selected and a relatively comprehensive database containing the

fieldwork information has been constructed. The procedure which has been followed step by step to develop the tool in question is as follows: the parameters, identified as causative and triggering factors responsible for the slope failure activity, are selected and analyzed. Then, the construction of the interaction matrix is done by using the selected set of the parameters. The interactivity of the parameters is examined by a uniform coding technique and the weighted coefficients for the parameters are obtained. Afterward, the parameters are classified into different categories regarding the field measurements, each one of them representing a specific condition. After that, the data from each of the 15 stations are analyzed and every parameter is assigned with the appropriate rating. Finally, an instability index is established and calculated for each considered station, representing their inherent instability. Eventually, the slope instability zonation map is presented for the Khosh-Yeylagh Main Road.

General characteristics of the study area

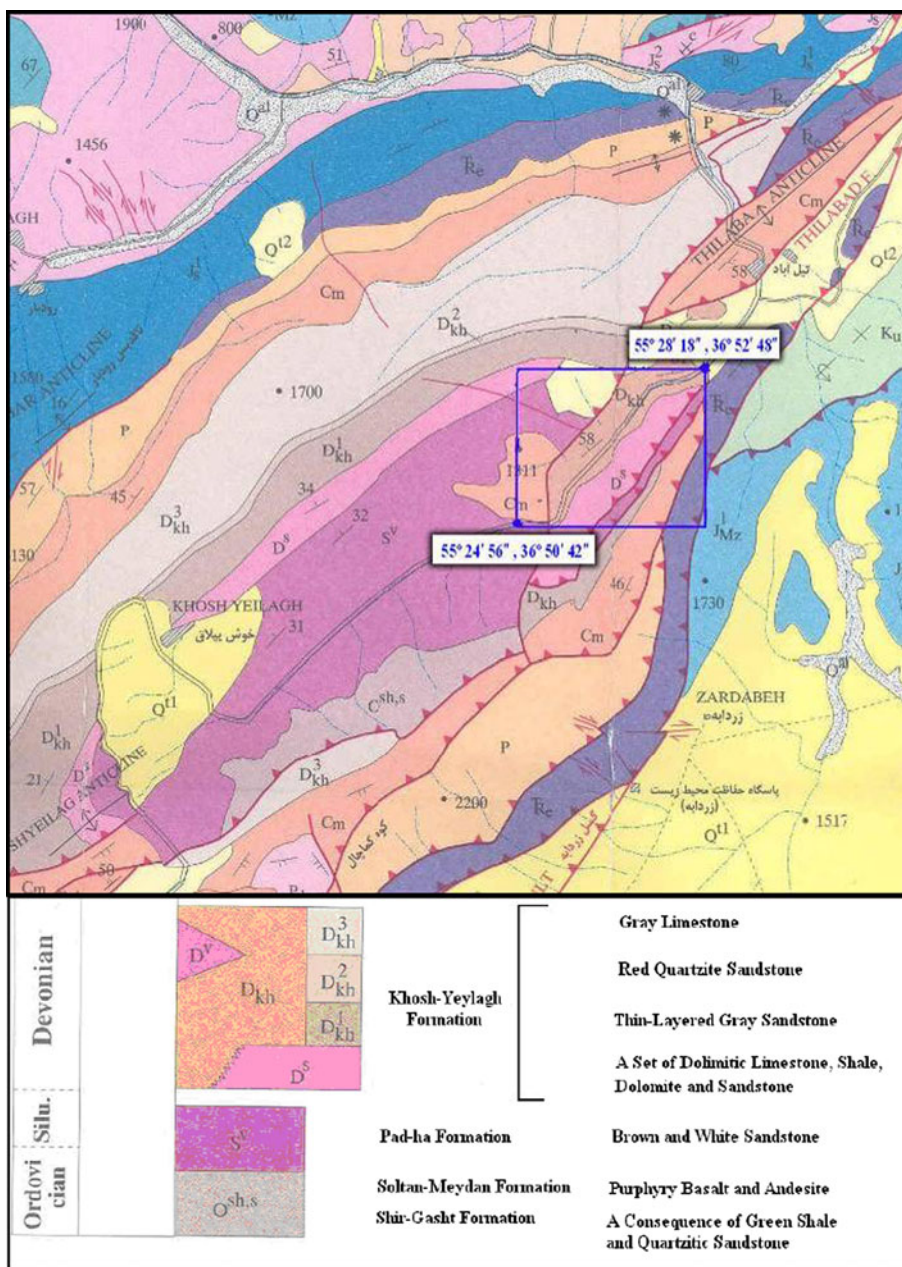
The Khosh-Yeylagh Main Road is situated in a mountainous area, approximately 90 km from northern Shahrood city, north-eastern Iran. This road connects Semnan province to the northern provinces. Figure 1 shows a photograph of the area. Geological map and description of study region in this research can be seen in Fig. 2. In this figure, the main investigated region has been marked by a rectangle with specific coordination of its ending points.

The geological structure is complicated in the region by 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). The area is principally located on the Khosh-Yeylagh formation with some other formations such as Pad-ha,



Fig. 1 A landscape of the Khosh-Yeylagh Main Road

Fig. 2 Part of geological map for the Khosh-Yeylagh region in scale of 1:100,000 as the sampling area (IGMEO 2001)



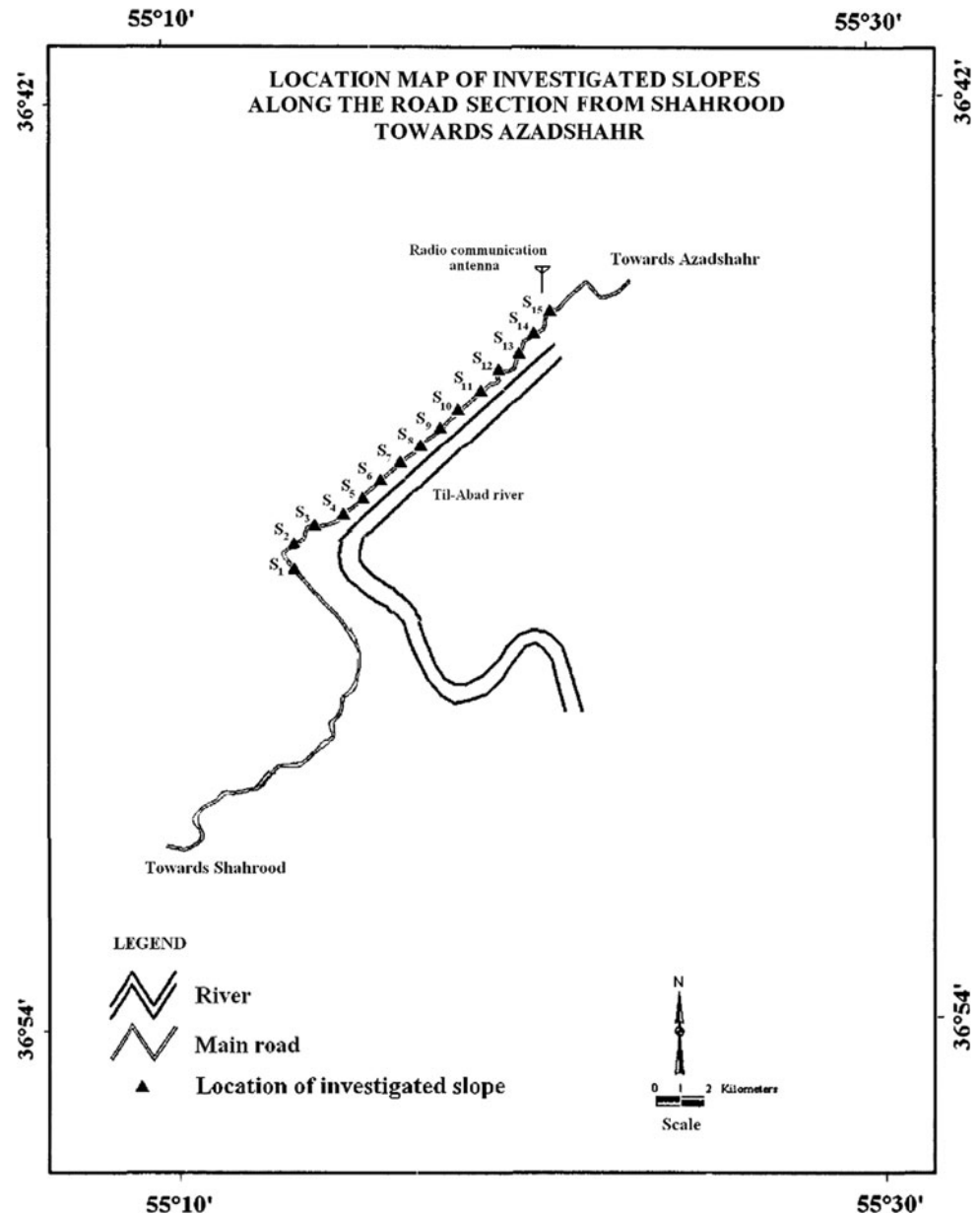
Soltan-Meydan and Shir-Gasht. The Khosh-Yeylagh formation pertains to the Devonian period in the Paleozoic era. The formations comprise the consequences of gray limestone, red quartzite sandstone, thin-layered gray sandstone and also green and white sandstones. Moreover, a set of dolomitic limestone, shale, dolomite and sandstone can be found in some parts of the region. The major parts of these rocks belong to a spectrum of weathered rocks found in the region. Based on the type and macrostructure of the rock block, the integrity and mechanical properties of the rock mass, and the hydrologic properties, four different grades of weathering in the rocks are identified as

follows: completely weathered rock (I); heavily weathered (II); moderately weathered (III); and slightly weathered and fresh (IV).

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

Along 20 km of the road, 15 stations were selected as rock slopes to be investigated in this research. Figure 3 shows the location of considered slopes along the road.

Fig. 3 The location of considered slopes along the road



Rock engineering systems

With the increasing sophistication of our interpretive techniques, numerical analysis and rock characterization schemes, it is becoming more important to base rock engineering design and the associated site investigation, construction and monitoring procedures on a coherent structural understanding of the complete rock engineering problem. This includes not only the primary mechanisms and parameters, but also the interactions between them (Hudson and Harrison 1992). The RES as a systems approach introduced by Hudson (1992a) aims to provide a useful checklist for a rock engineering project. More importantly, it also aims to provide a framework from

which the complete design procedure can be evaluated, leading a rock engineering project to an optimal result. The RES approach contains a very useful procedure for devising a rock mass classification scheme for any rock engineering project. In a rock mass classification scheme, a single parameter is required to comprehensively characterize the quality of any rock mass for a given engineering project that is to take place within the rock mass (Latham and Lu 1999). According to the RES approach, all possible rock mass classification schemes can be represented by a function of the leading diagonal parameter values of an interaction matrix. The selection of the parameters and the definition of the weighting of each parameter in a classification system can be made through the coding of the

Fig. 4 Interaction matrix in RES (after Hudson 1992a); **a** a general illustration of interaction matrix with two factors, **b** a 2 × 2 interaction matrix with leading diagonal terms, rock discontinuity and rock stress

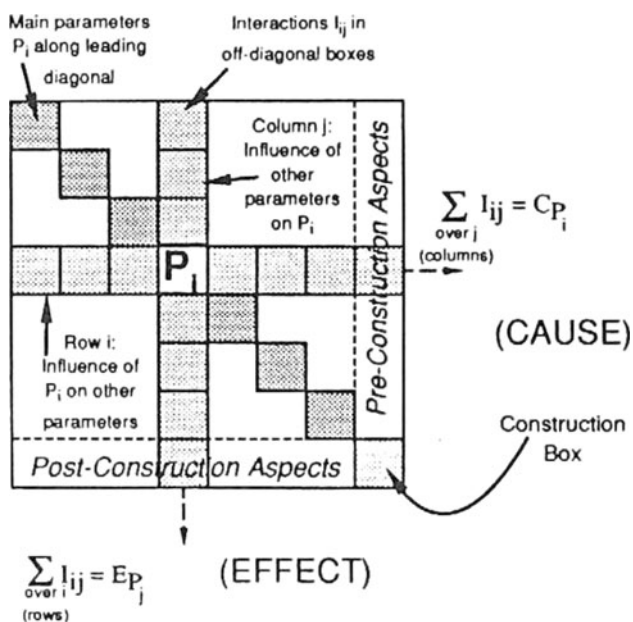
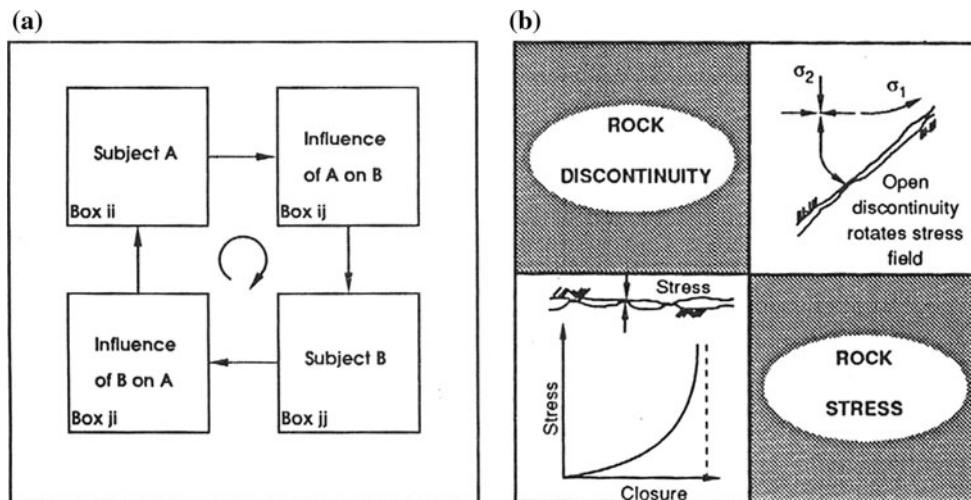


Fig. 5 Summation of coding values in the row and column through each parameter to establish the cause and effect co-ordinates (Hudson 1992a)

interaction matrix following a rational procedure. This coding is crucial to the applicability of the equation in the classification scheme.

In the RES approach to rock engineering, the interaction matrix device (Hudson 1992a) is both the basic analytical tool and a presentational technique for characterizing the important parameters and the interaction mechanisms in RES. In the interaction matrix for a RES (e.g., a rock slope system), all factors (or parameters) influencing the system are arranged along the leading diagonal of the matrix, called the diagonal terms. The influence of each individual factor on any other factor is accounted for at the corresponding off-diagonal position, and these are named the off-diagonal terms. The off-diagonal terms are the assigned values which

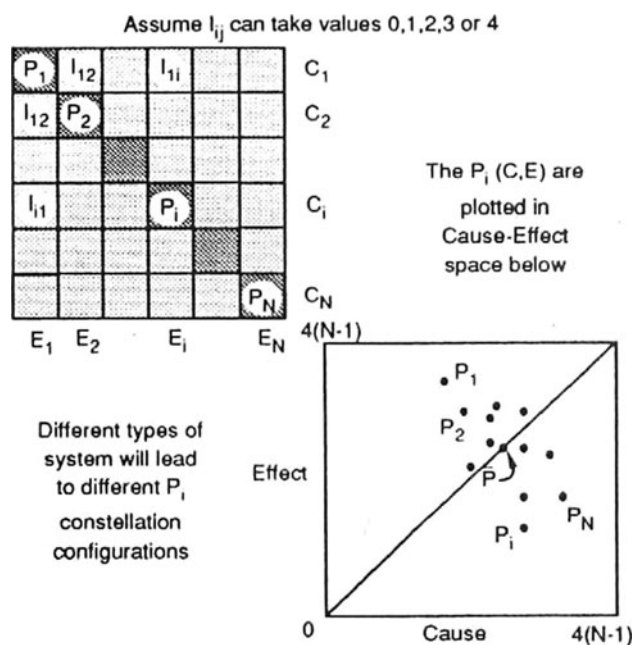


Fig. 6 The (C, E) plot for the supposed case comprising *n* influencing factors (Hudson 1992a)

describe the degree of the influence of one factor on the other factor. Assigning these values is called coding the matrix. The general concept of the influences in a system is described by the interaction matrix, which is shown in Fig. 4a. Also, a problem containing only two factors is the simplest example of the interaction matrix, as shown in Fig. 4b. A general illustration of the coding of interaction matrix is shown in Fig. 5. 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 the P_i . Several procedures have been proposed for numerically coding this matrix, for example, the 0–1 binary and the expert semi-quantitative (ESQ) method (Hudson 1992a).

After coding the matrix by inserting the appropriate values for each cell of the matrix, the sum of each row and of each column can be calculated. The sum of a row is termed the “cause” value and the sum of a column is the “effect” value, designated as coordinates (C , E) for a particular factor. C represents the way in which P_i affects the rest of the system and E represents the effect that the rest of the system has on P_i . The coordinate values for each factor can be plotted in cause and effect space, forming a so-called $C \pm E$ plot allowing the discrimination between “less interactive” and “more interactive” parameters (Hudson 1992a). After obtaining the $C \pm E$ plot for a system, an equation defining a classification index that takes into account key contribution factors can be developed. These stages would be followed and shown in the next sections. In principal, there is no limit to the number of factors that may be included in an interaction matrix, although the number of factors needed to solve a practical engineering problem is finite. A problem which includes n factors (or parameters) will have an interaction matrix with n rows and n columns, as shown in Fig. 5. Also, Fig. 6 shows the resulted (C , E) diagram for this case comprising n influencing factors.

The application

Selection of the parameters affecting the system

In consecutive steps for selection of the key parameters in the system, one has to firstly define the project and the environment. The task ends with a detailed list of parameters related to the rock and site characteristics (which are determined by site investigation, expertise, theoretical analyses and historical documents), with their quantitative or qualitative descriptions. Hudson (1992b) has proposed a set of general parameters affecting the stability of rock slopes which has been followed in the selection of the key parameters in this research.

In this paper, dealing with the general setting, the overall geological, climatic and previous instability conditions were outlined for the studied site, and all these factors were found to be relevant for the study of potential instability. The final list of 17 parameters can be grouped into 5 main headings:

- Setting:
 - 1, Geology and lithology; 2, faults and folds; 3, intact rock strength; 4, previous instability; 5, weathering; 6, rainfall; 7, freeze and thaw cycles;
- Discontinuities:
 - 8, Number of sets; 9, orientation; 10, aperture; 11, persistence; 12, spacing; 13, mechanical properties;

- Rock mass:
 - 14, Hydraulic conditions;
- Slopes:
 - 15, Slope height, 16, slope inclination;
- Others:
 - 17, Potential instability.

The choice of parameters does not include items that are considered insignificant; for example, seismic activity would be taken into account if we moved to Central Iran. On the other hand, there were not any reliable data for in situ stress status in the study area. Thus, in spite of its significance, we could not add it to the list. A brief description on the importance of each parameter and also some field observations are given below.

Geology and lithology

Lithology or rock type is one of the most decisive parameters (causative factor) regarding the slope failure manifestation. There are two dominant rock types in the study area: gray sandstones and limestones, plus a range of combinations of the two. The found sandstones have relatively more homogenous texture with fine grain size that is called “Khosh-Yeylagh Sandstone” (Zare Naghadehi et al. 2010). As evident from the stratigraphic position of the area, the older rocks mainly comprised limestones with subordinate dolomitic limestones which are classified into higher grades of weathering. From field observations, it was found that more failures (instabilities) occurred in limestone slopes.

Faults and folds

Faults and folds are the critical features which have great effect on some other important parameters in rock engineering activities. Faults are particularly important because they induce the formation of major joint sets in their orientation. Also in their vicinity, the fracture frequency increases and at times a layer of crushed rock is present. Moreover, the complex jointing, foliation planes and additional joint sets are usually formed by the folds and found in their vicinity. In the Khosh-Yeylagh region, the major faults are generally along the main faulting direction of the area and control the region’s morphology.

Previous instability

The presence of previous instability demonstrates that a critical combination of factors leading to instability is possible and, from the observation of failures, it is possible

to deduce how these factors in some combination led to instability and anticipate how they might combine again. Moreover, even small-scale phenomena may be repeated at larger scales and their analysis is always useful to understand the process (Mazzoccola and Hudson 1996).

Intact rock strength

The intact rock strength has to be taken into consideration since it is included in rock mass strength. The rock types in the region can be classified as medium rocks from strength point of view and this is unusual to have failure through the intact rock in these stress levels. But field studies concluded that the high anisotropy of the intact rock could lead to local failures along weaker directions at depth in high slopes.

Weathering

Field studies indicated that both physical and chemical weathering increase the instability of slopes in many ways. This is a very active factor for the given climatic conditions and rock types. Some alterations along open joints are present and may slightly decrease mechanical properties along discontinuity surfaces.

Discontinuity properties

It is obvious that the discontinuity properties are so important in slope stability problem. These properties include the *number of discontinuity sets* and their *spacing*, the *orientation* of discontinuities with respect to the slope orientation, the *aperture* of discontinuities, and the *persistency of discontinuities*.

Mechanical properties of discontinuities

Slope failures usually occur along a surface, plane, or weakness that is a discontinuity in the rock. Thus, the stability of rock slopes is strongly related to the mechanical properties of existing discontinuities. This term is basically intended to include the shear strength along the joint surfaces, which incorporates cohesion and friction angle.

Hydraulic conditions

This parameter covers all the rock mass characteristics which control water flow, such as permeability, interconnectivity and disposition of fractures, drainage paths, etc., leaving apart the actual presence of water in the rock mass. The primary effect of the groundwater pressure in reducing the stability of rock slopes is the resulting decrease in effective shear strength of discontinuities. This phenomenon is described by the effective stress principal, which is

fundamental to understanding the influence of groundwater on rock slope stability.

Slope height

The height of a slope is the combined result of the tectonic activity and the erosion-weathering processes and is related to climatic conditions throughout an interactive influence. Rock blocks in higher slopes have more potential energy than rocks in lower slopes; thus, they present a greater hazard and are more prone to failure (Kliche 1999).

Slope inclination

The orientation along with the inclination of the slope plays a very important role in the concept of failure manifestation as causative factor. As the angle of a potential slip plane increases, the driving force also increases. Thus, everything being equal, slope failure would be more frequent on steep slopes.

Rainfall

Precipitation is highly connected with slope failure manifestation and usually constitutes their triggering cause. In general, the participation of precipitation (mainly rainfall) in the problem of failure manifestation is multi-folded, and it plays the most important role in triggering mechanisms or reactivation of failure phenomena. In fact, many large and small failures occurred after a period of particularly heavy rainfall, although this period has not been unequivocally defined (Koukis et al. 1997). The triggering effect may be due to the combination of different factors: the increments of erosional capacity of rivers and streams, which can remove material from the toe of the slopes; the increase of the superficial runoff which may erode the slope laterally; the rise of the ground water table, which depends on the rock mass permeability, may lead to the complete saturation of the rock mass and to water pressure build-up into fractures, providing an additional component to the actuating forces. Water saturation also increases the weight of the rock mass.

Freeze and thaw cycles

This process is a peculiarity of the mountain regions at high elevation and is linked to the presence of a number of conditions. The fundamental one is the cyclic temperature oscillation around 0°C. In some ranges of the months, the maximum and minimum daily temperatures are on average below 0°C, and thus are critical for freeze and thaw. Another basic condition is the presence of water due to rainfall or snowfall and of structures able to retain it, such as open vertical fractures. The possibility of ice freezing or

Table 1 Interaction matrix coded for the Khosh-Yeylagh region

P_1	2	3	3	3	2	0	0	2	2	2	2	3	0	0	3	29	Cause
2	P_2	3	0	1	4	4	4	4	4	3	3	2	2	0	0	3	39
0	0	P_3	0	1	0	0	2	0	1	2	1	3	3	0	1	2	16
0	0	2	P_4	3	2	0	0	0	1	2	0	2	2	0	0	2	16
0	0	3	2	P_5	0	0	0	0	0	2	0	0	0	0	0	3	10
0	0	3	0	2	P_6	0	0	0	0	0	3	2	2	0	4	4	20
0	0	3	0	0	0	P_7	2	2	2	1	2	2	3	0	3	4	24
0	0	3	0	3	0	0	P_8	2	2	3	4	0	1	0	0	4	22
0	0	3	0	2	0	0	1	P_9	1	2	3	3	2	0	2	4	23
0	0	3	0	1	0	0	1	1	P_{10}	0	3	1	0	0	0	4	14
0	0	2	0	0	0	0	0	0	0	P_{11}	0	0	2	0	0	4	8
0	0	3	0	3	0	0	2	1	0	3	P_{12}	0	0	0	2	3	17
0	0	3	0	0	0	0	0	1	1	0	2	P_{13}	2	0	0	3	12
0	0	4	0	0	0	0	0	0	0	0	0	0	P_{14}	0	0	4	8
0	0	3	0	2	0	0	0	0	0	2	4	0	0	P_{15}	2	3	16
0	0	3	0	3	0	0	3	2	0	1	2	0	0	0	P_{16}	3	17
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	P_{17}	0
2	2	44	5	24	8	4	15	15	14	23	29	17	22	0	14	53	

Effect

P_1 , Geology and lithology; P_2 , faults and folds; P_3 , previous instability; P_4 , intact rock strength; P_5 , weathering; P_6 , number of sets; P_7 , orientation; P_8 , aperture; P_9 , persistence; P_{10} , spacing; P_{11} , mechanical properties; P_{12} , hydraulic conditions; P_{13} , slope height; P_{14} , slope inclination; P_{15} , rainfall; P_{16} , freeze and thaw cycles; P_{17} , potential instability

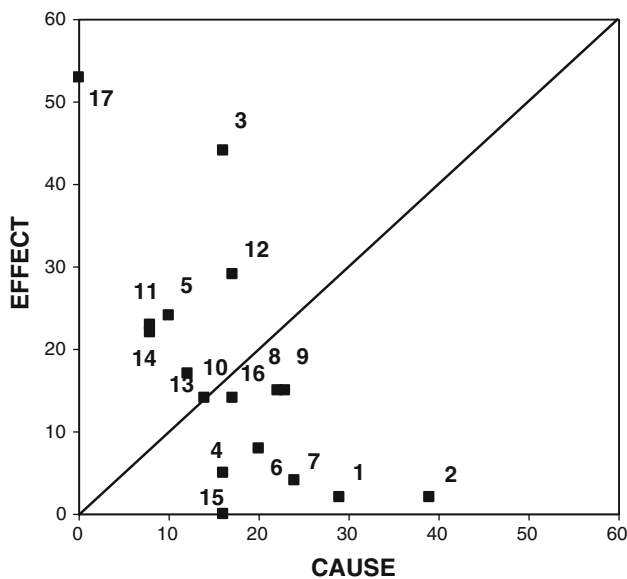


Fig. 7 The cause–effect plot for the Khosh-Yeylagh region

thawing depends on its depth inside the rock mass, as heat transmission through the rock has to be taken into account (Notarpietro 1990).

Interactions

The implementation of the RES method has been achieved through an interaction matrix (Table 1), where the 16

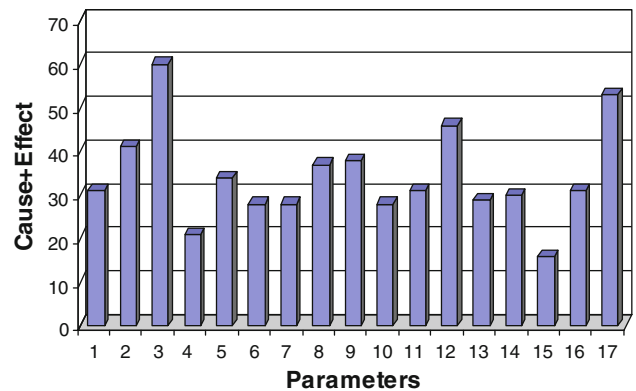


Fig. 8 Histogram of interactive intensity for the considered system

principal parameters are placed in its leading diagonal positions, together with the “potential instability”, i.e., the concept in question (the subject to be studied) as the 17th parameter. The bottom right box is occupied by this parameter. The column of interactions through this last box 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 does not exist in this application because instability is “potential”). The coded expressions of all possible binary interactions between every two parameters are placed in all the off-diagonal positions. To quantify the result of binary interactions, a semi-quantitative coding method (ESQ) has been used with values including 0,

1, 2, 3, and 4 corresponding to no, weak, medium, strong, and critical interaction, respectively (Hudson 1992a; Mazzoccola and Hudson 1996).

As described in “Rock engineering systems”, from this matrix, the influence of each parameter on the system (named cause, *C*) and the influence of the system on each parameter (named effect, *E*) are presented in an external row and a column, respectively. Cause and effect are considered to be the sums from coding the considered level of interaction, in both ways (i.e., P_1 on P_2 parameter and P_2 on P_1 parameter), between all possible parameter couples. The influential role of each parameter on slope failure (weighted of coefficient influence) is revealed from a cause versus effect diagram (Fig. 7), while the role of system’s interactivity is expressed from the histogram of the interactive intensity (cause, *C* + effect, *E*) versus the parameters (Fig. 8).

The cause–effect plot is helpful in understanding the role of each factor within the project and may be used to decide which interactions are beneficial for engineering, and hence could be enhanced and, conversely which ones are detrimental for engineering, and hence should be minimized. In this case, the computation of the level of interactivity via the *C* + *E* value may be an indication of identifying parameters to be kept under control, as their variation is likely to induce significant changes in the system (Mazzoccola and Hudson 1996).

The choice of considering the summation *C* + *E* as a discriminating factor among the parameters is made to emphasize the role of the system interactivity. On average, the more a system is interactive, the more it is potentially unstable because there is more chance of a small variation in one parameter significantly affecting the system behavior.

Plotting the cause–effect diagram of the 17 parameters engaged in the presented method (Fig. 7), the following remarks can be made: (a) all the parameters used are rather well interactive, as their cloud in the diagram is elongated perpendicularly to the center of the *C* = *E* locus (the diagonal of the diagram). This means that the parameters do not have a great scatter in their level of interactivity, i.e., in their *C* + *E* values. This is different to other systems in which the parameters points are in a cloud along the main diagonal, with some parameters having a very low activity and others being highly interactive; (b) the more interactive is the previous instability (3rd), the less interactive is the rainfall (15th); and (c) the lithology (1st) and faults and folds (2nd) are the ones that dominate the system, while the potential instability (17th) is the one, which is dominated by the system. These are confirmed from the histogram of the interactive intensity (Fig. 8) versus the parameters, as this intensity for the majority of the parameters is slightly above the mean value.

Rating assignments of the selected parameters

It was observed from the histogram of interactive intensity (Fig. 8) that the interactive intensities of the majority of the parameters were around the mean value. Consequently, it is not possible to say that only a few parameters are important for the definition of the system interactivity, nor that others do not have any influence. From these observations, it can be concluded that all the 16 parameters combine to influence the 17th “potential instability” and have to be taken into account in ratings and then in the calculation of an “index of instability”.

Table 2 Rating assignments of the parameters for the Khosh-Yeylagh region

Parameters	Rating		
	0	1	2
Geology and lithology	Gray sandstone	Sandstone and limestone	Limestone
Faults and folds	Not present	Minor	Major
Previous instability	Inactive	Quiescent	Active
Intact rock strength ^a (MPa)	>50	30–50	<30
Weathering	Unweathered	Discolored	Infilling material
Number of joints sets	1	1–3	>3
Orientation ^b	<2	2–5	>5
Aperture (mm)	<1	1–5	>5
Persistence (m)	<5	5–10	>10
Spacing (m)	>0.4	0.15–0.4	<0.15
Mechanical properties ^c (MPa)	>1	0.5–1	<0.5
Hydraulic conditions	Dry	Wet	Flow
Slope height (m)	<5	5–15	>15
Slope inclination (°)	<45	45–75	>75
Rainfall ^d (mm)	<300	300–500	>500
Freeze and thaw ^d (cycles)	<80	80–120	>120

^a Uniaxial compressive strength (UCS)

^b Number of major directions of instability

^c Peak shear strength under normal load = 1 MPa

^d Per annum

Table 3 Dominant field conditions for the study area

Slope no.	Lithology	Faults and folds	Previous instability	Hydraulic conditions	Slope height (m)	Slope angle (°)
S1	Sandstone	Minor	Quiescent	Dry	5.5	82
S2	Sandstone and limestone	Minor	Active	Dry	4.3	78
S3	Sandstone and limestone	Minor	Active	Dry	4.2	85
S4	Sandstone and limestone	Major	Quiescent	Dry	3.5	84
S5	Sandstone	No	Inactive	Dry	6.1	79
S6	Sandstone and limestone	No	Quiescent	Dry	14.2	73
S7	Sandstone	Minor	Active	Dry	19.5	79
S8	Sandstone and limestone	Minor	Active	Dry	4.8	76
S9	Sandstone and limestone	Major	Active	Dry	5.1	85
S10	Sandstone and limestone	Major	Active	Dry	12.5	81
S11	Limestone	Major	Active	Dry	17.4	78
S12	Sandstone and limestone	Minor	Quiescent	Dry	7.3	81
S13	Limestone	No	Inactive	Dry	5.4	73
S14	Sandstone and limestone	Minor	Inactive	Dry	11.5	67
S15	Sandstone and limestone	Minor	Quiescent	Dry	13.2	77

At this stage, having defined the relative interactive intensity as a measure of the significance of the parameters, the actual parameter values must come into play and a more detailed data input is needed from the field. The parameter values are chosen from a table formerly called “pull-down menu” by Mazzoccola and Hudson (1996). The list of the 16 relevant parameters was used on the field to collect data on 15 slopes, located in the Khosh-Yeylagh Main Road. Note that the parameter “potential instability” is of course not used and so the number of indicator parameters is 16. Some parameters were described qualitatively; others were described quantitatively. For this reason, it was not possible to utilize the actual parameter values directly to compute an instability index, but a rating was assigned to different classes of parameter descriptions and values. Three classes of parameter values were set, with ratings of 0 for “low contribution”, 1 for “contributory” and 2 for “strongly contributing”. Thus, higher ratings are always assigned to classes of parameter values associated with higher instability (Table 2). Some brief descriptions about the assignments to the parameters are presented in subsections.

Geology and lithology

The rock types for the studied slopes can be seen in second column of Table 3. Some strength characteristics were considered for the major rock types found in the region. As a result, a qualitative description of the lithology which constitutes all of the investigated slopes is given as gray sandstone (rating 0), complex of sandstone and limestone (rating 1) and limestone (rating 2).

Faults and folds

The presence of faults and folds has been described as: not present, presence of minor structures, presence of major structures (Table 3) with associated ratings of 0, 1, and 2. Minor faults are those discontinuities which present signs of relative movements of blocks, such as slickensided surfaces. Major faults are those which are parallel to regional trends, usually accompanied by increase of fracture frequency and locally crushed rock. On the other hand, large scale or minor folds influence the whole slope face, while small scale or minor folds are developed on the limbs of adjacent major folds and usually only affect part of the slope face.

Previous instability

The presence of previous instability has been classified as inactive, quiescent or active (Table 3) with associated ratings of 0, 1, and 2, according to the definitions given by Varnes (1978): inactive slopes are those for which factors for movement have been removed naturally or by human activity; quiescent slopes are those for which there is no evidence that the movement is taking place in the present conditions, but the movement may be renewed; active slopes are those that are currently moving.

Intact rock strength

Average values of the uniaxial compressive strength (UCS) have been computed for each slope by laboratory experiments. Table 4 shows the results of these experiments. Higher ratings are given to lower UCS values. In this

Table 4 The results of uniaxial compressive strength (UCS) tests for rock specimens of 15 rock slopes

Slope no.	Specimen no.	Dry specific weight (kN/m ³)	UCS (Mpa)
S1	A-1-1	26.5	37.5
	A-1-2	26.5	42.7
S2	A-2-1	26.8	28.2
	A-2-2	26.8	33.5
S3	A-3-1	27.4	25.9
	A-3-2	27.4	23.2
S4	A-4-1	26.1	34.1
	A-4-2	26.1	31.6
S5	A-5-1	26.7	48.5
	A-5-2	26.7	38.3
S6	A-6-1	26.9	38.9
	A-6-2	26.9	35.1
S7	A-7-1	26.7	56.2
	A-7-2	26.7	47.5
S8	A-8-1	27.1	52.9
	A-8-2	27.1	44.7
S9	A-9-1	27.6	41.3
	A-9-2	27.6	38.2
S10	A-10-1	26.4	29.5
	A-10-2	26.4	31.1
S11	A-11-1	27.4	18.8
	A-11-2	27.4	15.5
S12	A-12-1	26.9	29.5
	A-12-2	26.9	27.5
S13	A-13-1	27.3	22.7
	A-13-2	27.3	19.1
S14	A-14-1	27.3	24.4
	A-14-2	27.3	15.6
S15	A-15-1	26.1	23.8
	A-15-2	26.1	35.2

manner, the UCS values >50 MPa have rating of 0; the values between 30 and 50 MPa have rating of 1; and finally the values lower than 30 MPa have rating of 2.

Weathering

A qualitative description of the average weathering conditions of discontinuity surfaces, according to the ISRM suggested methods (1981) is presented for each slope, assigning higher ratings to classes of highly weathered discontinuity surfaces. The field observations of the weathering conditions of the investigated slopes can be seen in the second column of Table 5. The ratings of this parameter considered as 0 for unweathered discontinuities, 1 for discolored ones and 2 for the discontinuities having infill material between their planes.

Number of joint sets and orientation

A more detailed survey of the discontinuity orientations has been made. The data collected for each slope have been plotted on hemispherical projections as pole plots and contour plots. In this way, the major directions of instability (which involve discontinuity surfaces parallel to fault directions) and minor directions of instability (which involve any other discontinuity set) were recognized. In this case, the criterion of grouping the slopes with a similar number of major sets and direction of instability was used, with higher ratings being given to classes with a greater number of critical sets or directions of instability. The measurements of discontinuity properties are presented in Table 5.

Aperture, persistence, and spacing

Systematic measurements of the aperture and persistence have been done. The final results for these parameters are seen in Table 5. These factors plus the spacing are presented in the rating assignments according to the field conditions and the gathered data from scanlining.

Mechanical properties

For this parameter, the mean peak shear strength value of the major discontinuities of the rock slope under normal load of 1 MPa has been considered as the representative factor in ratings. The results of laboratorial tests on the rock discontinuities from all of the studied slopes are presented in Table 6. Higher ratings are given to lower peak shear strength values ranging from lower than 0.5 MPa to greater than 1 MPa.

Hydraulic conditions

As a water table is not present at the site, the discontinuity conditions can be used as an indication of preferential water pathways. Hence, a qualitative description of the hydraulic characteristics, according to the ISRM suggested methods (1981), exhibited by the discontinuities is provided (Table 3, column 5), with assigned ratings of 0 for dry discontinuities, 1 for wet discontinuities, and 2 for discontinuities with considerable flow of water.

Slope height

In the present study, the height of the slopes ranges from 3 to 25 m from the adjacent road (Table 3, column 6). Higher ratings are given to the higher slopes ranging from lower than 5 m to greater than 15 m.

Table 5 Gathered field data from scanlining on the discontinuities

Slope no.	Weathering	Joint sets number	Joints orientation	Joints aperture (mm)	Joints persistence (m)	Joints spacing (m)
S1	Severe	2	1	2	6.5	0.12
S2	Severe	3	2	<1	8.2	0.08
S3	Severe	4	3	3.5	12.1	0.14
S4	Severe	3	2	2	13.5	0.28
S5	Change in color	3	2	<1	4.3	0.23
S6	Change in color	2	1	<1	2.7	0.20
S7	Change in color	5	3	1.5	4.5	0.05
S8	Change in color	2	1	2	12.1	0.12
S9	Severe	4	3	1.5	5.6	0.05
S10	Severe	4	2	<1	16.7	0.03
S11	Severe	3	1	<1	11.4	0.18
S12	Change in color	3	2	<1	7.9	0.15
S13	Change in color	2	2	1	11.2	0.30
S14	Change in color	4	3	1	8.5	0.27
S15	Severe	4	2	<1	7	0.13

Table 6 The results of laboratorial tests on the rock discontinuities

Slope no.	Specimen no.	C (kPa)	ϕ (°)	Max. shear strength (MPa) under normal load = 1 MPa
S1	A-1	600	32	1.22
S2	A-2	750	29	1.3
S3	A-3	620	31	1.22
S4	A-4	950	33	1.59
S5	A-5	670	25	1.14
S6	A-6	470	27	0.98
S7	A-7	380	29	0.93
S8	A-8	620	30	1.19
S9	A-9	510	27	1.02
S10	A-10	670	26	1.16
S11	A-11	520	23	0.94
S12	A-12	410	27	0.92
S13	A-13	560	30	1.14
S14	A-14	420	24	0.86
S15	A-15	470	26	0.96

Slope inclination

Within the unstable slopes of the investigated area, the angle of the slope ranges from 50 to 85°. Thus, the safe angle may be considered as <45° (no one of the parameters is a controlling factor solely). The measurements for the slopes in the study area can be seen in last column of Table 3. As a result, the higher ratings are assigned to the

higher slope angles ranging from lower than 45° to greater than 75° (ranging from 0 to 2).

Rainfall and freeze and thaw

Because all the slopes have the same climatic conditions, they are here given the same rating (the intermediate rating of 1) for those two factors. The ratings were similarly assigned for these parameters to take into account eventual changes in climatic conditions toward situations of greater or lower instability potential.

Calculation of slopes instability and mapping

The rating of the slopes is presented in Table 3. In this table, the $C + E$ values (interactive intensity) have been transformed into a percentage form acting as weighting coefficients, which express the proportional share of each parameter (as a failure causing factor) in slope failure, and normalized by dividing with the maximum rating (i.e., 2), giving the $a_i\%$. The maximum possible slope instability index (SII) value is 100. As it can be deduced from the process presented above, a careful compilation and running of the interaction matrix optimize the expert's subjective judgment, and eventually, the resulting weighting coefficients are expressing the maximum possible objectivity, which can be revealed from a given experience.

Having established both the value scaled from the $C + E$ histogram for each parameter and the rating for each parameter for each slope, the SII can be computed according to the formulae (Hudson 1992a):

Table 7 Computation of the slope instability index

Slopes	Parameters rating																SII _j
	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈	P ₉	P ₁₀	P ₁₁	P ₁₂	P ₁₃	P ₁₄	P ₁₅	P ₁₆	
1	0	1	1	1	2	1	0	1	1	2	0	0	1	2	1	1	45.841
2	1	1	2	1	2	1	1	0	1	2	0	0	0	2	1	1	50.851
3	1	1	2	2	2	2	1	1	2	2	0	0	0	2	1	1	62.571
4	1	2	1	1	2	1	1	1	2	1	0	0	0	2	1	1	53.497
5	0	0	0	1	1	1	1	0	0	1	0	0	1	2	1	1	25.992
6	1	0	1	1	1	1	0	0	0	1	1	0	1	1	1	1	32.042
7	0	1	2	0	1	2	1	1	0	2	1	0	2	2	1	1	53.686
8	1	1	2	1	1	1	0	1	2	2	0	0	0	2	1	1	52.079
9	1	2	2	1	2	2	1	1	1	2	0	0	1	2	1	1	63.611
10	1	2	2	1	2	2	1	0	2	2	0	0	1	2	1	1	63.705
11	2	2	2	2	2	1	0	0	2	1	1	0	2	2	1	1	66.352
12	1	1	1	2	1	1	1	0	1	1	1	0	1	2	1	1	46.975
13	2	0	0	2	1	1	1	1	2	1	0	0	1	1	1	1	41.682
14	1	1	0	2	1	2	1	1	1	1	1	0	1	1	1	1	44.612
15	1	1	1	2	2	2	1	0	1	2	1	0	1	2	1	1	55.482
Max P _{ij}	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
$\frac{(C+E)}{\sum_i(C+E)}\%$	5.86	7.75	11.342	3.969	6.427	5.293	5.293	6.994	7.183	5.293	5.86	8.696	5.482	5.671	3.024	5.86	100
a _i	2.93	3.875	5.671	1.985	3.214	2.646	2.646	3.497	3.592	2.646	2.93	4.348	2.741	2.836	1.512	2.93	

Table 8 The classification of stability status

Index range	Class	Stability status
SII < 30	Very good	Completely stable
30 < SII < 40	Good	Stable
40 < SII < 50	Fair	Partially unstable
50 < SII < 60	Bad	Unstable
SII > 60	Very bad	Completely unstable

$$a_i = \frac{1}{MP_{ij}} \times \frac{(C + E)}{\sum_i(C + E)}\% \tag{1}$$

$$SII_j = \sum_{i=1}^{16} a_i \times P_{ij} \tag{2}$$

where *i* refers to parameters (from 1 to 16), *j* refers to slopes (from 1 to 15), *a_i* is the value scaled from the *C + E* histogram for each parameter and *P_{ij}* is the rating assigned to different classes of parameter values and is different for different slopes.

The results of this final computation are shown in Table 7. SII is an indication of the level of potential instability of the slopes in the sense that higher SII values indicate more critical slopes.

Table 8 shows the presented classification of stability status for the slopes according to the SII values according to the field observations. Then, as it can be inferred, among

the 15 investigated rock slopes, 1 slope ranked to be completely stable; 1 ranked stable; 4 ranked partially unstable; 5 ranked unstable; and 4 of them ranked to be completely unstable. Finally, Fig. 9 shows the mapping of the SII classes for the investigated slopes along the Khosh-Yeylagh Main Road on the region’s map.

Validation of the results by using an empirical approach

In this section, the obtained results and classes for the slopes stations using the RES approach are compared with the results of an empirical method. The slope mass rating (SMR) approach is utilized for this task for its special use in rock slopes stability analysis. The SMR is obtained from rock mass rating (RMR) geomechanics classification by adding a factorial adjustment factor depending on the relative orientation of joints and slope and another adjustment factor depending on the method of excavation (Romana 1985; Romana et al. 2003) [SMR = RMR_B + (F₁ × F₂ × F₃) + F₄].

The RMR_B (see Table 9) is computed according to Bieniawski’s1979 proposal, adding rating values for five parameters: (1) strength of intact rock; (2) RQD; (3) spacing of discontinuities; (4) condition of discontinuities; and (5) water inflow through discontinuities and/or pore pressure ratio. The adjustment rating for joints (see Table 10) is the product of three factors as follows:

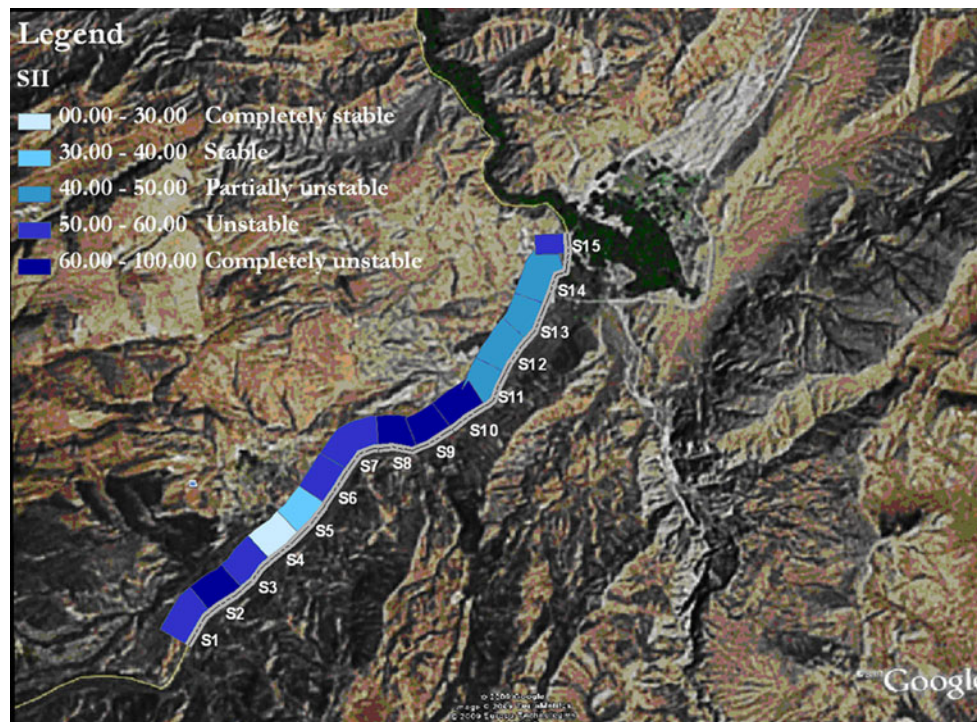


Fig. 9 Mapping of the resulted slope instability index (SII) for the investigated slopes along the Khosh-Yeylugh Main Road

Table 9 Basic rock mass rating (RMR_B) classification (Bieniawski 1976)

Parameter	Intervals				
UCS (MPa) unconfined compressive strength of intact rock material	<250	250–100	100–50	50–25	<25
	15	12	7	4	2 1 0
RQD (%) rock quality designation	100–90	90–75	75–50	50–25	<25
	20	17	13	8	3
Spacing (mm) between discontinuities	>2,000	2,000–600	600–200	200–60	<60
	20	15	10	8	5
Condition of discontinuities roughness, persistence, separation, weathering of walls and gouge	Very rough surfaces, no separation, unweathered wall, rock not continuous	Slightly rough, separation <1 mm, slightly weathered walls, not continuous	Slightly rough, separation <1 mm, highly weathered walls	Slickensided walls or gouge <5 mm or separation 1–5 mm	Soft gouge >5 mm or separation >5 mm continuous
	30	25	20	10	0
Groundwater in joints (pore pressure ratio)	Completely dry (0)	Damp (0–0.1)	Wet (0.1–0.2)	Dripping (0.2–0.5)	Flowing (0.5)
	15	10	7	4	0

1. F_1 depends on parallelism between joints and slope face strike. Its range is from 1.00 to 0.15. These values match the relationship: $F_1 = (1 - \sin A)^2$ where A denotes the angle between the strikes of slope face and joints.
2. F_2 refers to joint dip angle in the planar mode of failure. Its value varies from 1.00 to 0.15, and matches the relationship: $F_2 = \tan^2 B_j$ denotes the joint dip angle. For the toppling mode of failure F_2 remains 1.00.
3. F_3 reflects the relationship between slope and joints dips. Bieniawski's (1976) figures have been kept (all are negative).
4. F_4 adjustment factor for the method of excavation has been fixed empirically.

Table 10 The adjustment rating for joints in SMR method (Romana et al. 2003)

Adjusting factors for joints (F_1, F_2, F_3)	$\alpha_j =$ dip direction of joint $\alpha_s =$ dip direction of slope			$\beta_j =$ dip of joint $\beta_s =$ dip of slope	
	Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
Plane failure: $ \alpha_j - \alpha_s $	$>30^\circ$	$30-20^\circ$	$20-10^\circ$	$10-5^\circ$	$<5^\circ$
Toppling: $ \alpha_j - \alpha_s - 180 $					
F_1 value	0.15	0.40	0.70	0.85	1.00
Relationship	$F_1 = (1 - \sin \alpha_j - \alpha_s)^2$				
$ \beta_j $	$<20^\circ$	$20-30^\circ$	$30-35^\circ$	$35-45^\circ$	$>45^\circ$
F_2 value	Plane failure	0.15	0.40	0.70	0.85
	Toppling	1.00			1.00
Relationship	$F_2 = \tan^2 \beta_j$				
Plane failure: $\beta_j - \beta_s$	$>10^\circ$	$10-0^\circ$	$0^\circ\theta$	$0-(-10^\circ)$	$<(-10^\circ)$
Toppling: $\beta_j + \beta_s$	$<110^\circ$	$110-120^\circ$	$>120^\circ$	–	–
F_3 value	0	–6	–25	–50	–60
Relationship	F_3 (Bieniawski adjustment ratings for joints orientation 1976)				
F_4 adjusting factor for excavation method	$F_4 =$ empirical values for method of excavation				
F_4 value	Natural slope	Presplitting	Smooth blasting	Blasting or mechanical	Deficient blasting
	+15	+10	+8	0	–8

Table 11 Tentative description of SMR classes (Romana 1985)

Class	SMR	Description	Stability	Failures	Support
I	81–100	Very good	Completely stable	None	None
II	61–80	Good	Stable	Some blocks	Occasional
III	41–60	Normal	Partially stable	Some joints or many wedges	Systematic
IV	21–40	Bad	Unstable	Planar or big wedges	Important/corrective
V	0–20	Very bad	Completely unstable	Big planar or soil-like	Re-excavation

Table 11 shows the different stability classes. The empirically found limit values of SMR for the different failure modes are also listed in this table.

The complementary measurements were done on all the considered stations in the study region to calculate the SMR value for them. At first, the measured data were utilized to gain the RMR values for slope faces using Table 9 and then the adjusting factors were calculated (using Table 10) to obtain the final SMR values for each station. Finally, Table 7 was employed to achieve the SMR stability classes of the rock slopes. Table 12 shows the results for the RMR values, adjusting factors and final SMR values for the investigated slopes.

Table 13 reflects a comparison between the given classes by two methods of RES and SMR. A rather good adaption could be seen between the different methods; ten slopes out of 15 have been given coincident classes of stability by 2 methods and 5 numbers of them change in 1 class only.

Discussion and conclusions

A large variety of causative factors have been known to be involved in the slope instabilities. These factors include several types of interactions ranging from geological structure to environmental conditions. Thus, assessment and prediction of slope failure hazard is a difficult and complex multi-parametric problem. Because of this need to incorporate many factors into the analysis, the RES approach was adopted. The RES methodology implemented for the preliminary assessment of slope instability potential of 15 slope sites in the Khosh-Yeylagh Main Road was proved to be successful in fulfilling the requirements of the particular problem. This was found to be so as some examined slopes were known as failure-manifested ones, the calculated instability indices through the RES methodology, have attained relatively high values. The proper implementation of the ranking process using

Table 12 Calculation of SMR values and given stability classes for investigated slopes

Slope no.	RMR _B value	Adjusting factors				SMR value
		F_1	F_2	F_3	F_4	
S1	50	0.70	0.85	-6	0	46.43
S2	40	0.40	1.00	-50	0	20.00
S3	38	0.85	1.00	-25	0	16.75
S4	56	0.85	1.00	-25	0	34.75
S5	66	0.15	0.85	-6	0	65.24
S6	62	0.15	1.00	0	0	62.00
S7	50	0.85	1.00	-25	0	28.75
S8	60	0.40	1.00	-25	0	50.00
S9	37	0.40	1.00	0	0	37.00
S10	37	0.70	1.00	-25	0	19.50
S11	52	0.40	1.00	-50	0	32.00
S12	60	0.40	0.70	0	0	60.00
S13	64	0.70	1.00	-6	0	59.80
S14	60	0.40	1.00	-6	0	57.60
S15	40	0.70	1.00	-6	0	35.80

Table 13 Comparison between the given classes by different methods

Slope no.	RES stability class ^a	SMR stability class	Adaption status between two methods
S1	Partially unstable	Partially stable	Coincident
S2	Unstable	Completely unstable	Change in one class only
S3	Completely unstable	Completely unstable	Coincident
S4	Unstable	Unstable	Coincident
S5	Completely stable	Stable	Change in one class only
S6	Stable	Stable	Coincident
S7	Unstable	Unstable	Coincident
S8	Unstable	Partially stable	Change in one class only
S9	Completely unstable	Unstable	Change in one class only
S10	Completely unstable	Completely unstable	Coincident
S11	Completely unstable	Unstable	Change in one class only
S12	Partially unstable	Partially stable	Coincident
S13	Partially unstable	Partially stable	Coincident
S14	Partially unstable	Partially stable	Coincident
S15	Unstable	Unstable	Coincident

^a The classes “partially unstable” in RES classification and “partially stable” in SMR classification have been considered to be equal in the stability status of the rock slopes

the instability index can facilitate a justified and cost/time-effective compilation of zonation maps regarding the failure hazard in an area.

In this study, an application of the RES approach has been utilized to obtain the inherent potential instability of road rock slopes in 15 stations. This RES application was a case where the distribution of the points representing the interactive intensity of parameters on the cause–effect diagram implied that it was not appropriate to take only a few parameters into account in this kind of system; hence,

all of them were considered. The classes of parameter ratings have to be assigned taking into account both the overall distribution of the parameter values (in order to discriminate among the different slopes) and the mechanical significance of the given parameters values (in order to give the classes a more scientific basis). The implementation of such a method indicates that when the value of instability index increases, that station could be affected encountering progressively more important problems where the need for drastic remedial measures is necessary.

Slope sites in the Khosh-Yeylagh where the value of SII calculated through the RES method is lower than 40 should be considered as the stable and completely stable slopes. Actually, based on the interpretation of the existing data referring to the 15 failure sites, in Khosh-Yeylagh, areas with values between 40 and 50 may be characterized as partially unstable sites. The slopes with SII values >50 should be classified as the unstable and completely unstable areas (Table 8). Finally, as a preliminary validation on the utilization of systems approach in the study region, the stability of investigated rock slopes were analyzed using an empirical method and the results were compared. The comparisons showed a rather good coincidence between the given classes of two methods. Therefore, the implementation presented could be a simple but efficient tool in ranking the potential instability in rock slopes and be useful in decision making, regarding the physical, natural and environmental conditions in slope failure susceptible sites.

As a recommendation for the future researches, a GIS cross-correlation between the properties and evidences of instability can be considered as a way in selection of the key parameters in such studies and could help showing significant parameters and rejecting those useless for the purposes of identification of instable slopes. This approach has been widely applied to GIS landslide susceptibility mapping (e.g., see Irigaray et al. 1999, 2007; Chacon and Corominas 2003; Chacon et al. 2006; Fernandez et al. 2008).

Acknowledgments This work was financially supported by the research grant from Shahrood University of Technology. The authors wish to thank for helps and supports provided by the university during the research. Also, the comments received from and the enlightening discussions with our anonymous reviewers improved the paper and are appreciated.

References

- Ali KM, Hasan K (2002) Rock mass characterization to indicate slope instability in Bandarban: a rock engineering systems approach. *Environ Eng Geosci* 8(2):105–119
- Bieniawski ZT (1976) Rock mass classification in rock engineering. In: Proceedings of the symposium on exploration for rock engineering, vol 1. Balkema, Rotterdam, pp 97–106
- Bieniawski ZT (1993) Classification of rock masses for engineering—the RMR system and future trends. In: Hudson J (ed) *Comprehensive rock engineering*, vol 3. Pergamon Press, London, pp 553–574
- Budetta P, Santo A, Vivencio F (2008) Landslide hazard mapping along the coastline of the Cilento region (Italy) by means of a GIS-based parameter rating approach. *Geomorphology* 94:340–352
- Castaldini D, Genevois R, Panizza M, Puccinelli A, Berti M, Simoni A (1998) An integrated approach for analyzing earthquake-induced surface effects: a case study from the Northern Apennines, Italy. *J Geodyn* 26(2–4):413–441
- Ceryan N, Ceryan S (2008) An application of the interaction matrices method for slope failure susceptibility zoning: Dogankent settlement area (Giresun, NE Turkey). *Bull Eng Geol Environ* 67(3):375–385
- Chacon J, Corominas J (2003) Landslides and GIS. *Nat Hazards* 30(3):263–512 (special issue)
- Chacon J, El Hamdouni R, Irigaray C, Fernandez T (2006) Engineering geology maps: landslides and GIS. *Bull Eng Geol Environ* 65:341–411
- Cundall PA (1976) Explicit finite difference methods in geomechanics. In: Proceedings of the 2nd international conference on numerical methods in geomechanics, vol 1. Blacksburg, Virginia, pp 132–150
- Fernandez T, Irigaray C, El Hamdouni R, Chacon J (2008) Correlation between natural slope angle and rock mass strength rating, Granada, Spain. *Bull Eng Geol Environ* 67:153–164
- Hack R (2002) An evaluation of slope stability classification. In: Proceedings of the EUROCK 2002, Madeira, Portugal, pp 3–32
- Hack R, Price D, Rengers N (2003) A new approach to rock slope stability—a probability classification (SSPC). *Bull Eng Geol Environ* 62:167–184
- Hoek E, Bray JW (1981) *Rock slope engineering*. Institution of Mining and Metallurgy, London
- Hudson JA (1992a) *Rock engineering systems, theory and practice*. Ellis Horwood Ltd, Chichester
- Hudson JA (1992b) Atlas of rock engineering mechanisms: part 2—slopes. *Int J Rock Mech Min Sci* 29(2):157–159
- Hudson JA, Harrison JP (1992) A new approach to studying complete rock engineering problems. *Q J Eng Geol* 25:93–105
- IGMEO, Iranian Geology and Mining Exploration Organization (2001) Geological map of Khosh-Yeylagh region in scale of 1:100,000. IGMEO, Tehran, Iran
- IGOSIT, Iranian General Office for Statistics and Information Technology (2007) *Annuals of meteorology*. IGOSIT, Tehran, Iran
- Irigaray C, Fernandez T, El Hamdouni R, Chacon J (1999) Verification of landslide susceptibility mapping: a case study. *Earth Surf Process* 24:537–544
- Irigaray C, Fernandez T, Chacon J (2003) Preliminary rock-slope-susceptibility assessment using GIS and the SMR classification. *Nat Hazards* 30:309–324
- Irigaray C, El Hamdouni R, Fernandez T, Chacon J (2007) Evaluation and validation of landslide susceptibility maps obtained by a GIS matrix method: examples from the Betic Cordillera (southern Spain). *Nat Hazards* 41:61–79
- ISRM (1981) International Society for Rock Mechanics (ISRM) Suggested Methods. In: Brown ET (ed) *Rock characterization, testing & monitoring-suggested methods*, part 1: site characterization. Pergamon, Oxford
- Kim KS, Park HJ, Lee S, Woo I (2004) Geographic Information System (GIS) based stability analysis of rock cut slopes. *Geosci J* 8(4):391–400
- Kliche C (1999) *Rock slope stability*. Society for Mining, Metallurgy, and Exploration, Inc (SME), The United States
- Koukis G, Rozos D, Hatzinakos I (1997) Relationship between rainfall and landslides in the formations of Achaia County, Greece. In: Proceedings of international symposium of iaeg in engineering geology and the environment, vol 1. AA Balkema, Rotterdam, pp 793–798
- Larsson R, Runesson K, Axelsson K (1992) Finite element analysis of slope stability accounting for plastic localization. In: Proceedings of the 7th international conference on computer methods and advances in geomechanics, vol 3. A.A. Balkema, Rotterdam, pp 1711–1717
- Latham J-P, Lu P (1999) Development of an assessment system for the blastability of rock masses. *Int J Rock Mech Min Sci* 36:41–55
- Mazzoccola DF, Hudson JA (1996) A comprehensive method of rock mass characterization for indicating natural slope instability. *Q J Eng Geol* 29:37–56

- Nash D (1987) A comparative review of limit equilibrium methods of stability analysis. In: Slope stability. Geotechnical engineering and geomorphology. John Wiley & Sons, Chichester
- Norrish NI, Wyllie DC (1996) Rock slope stability analysis. In: Turner AK, Schuster RL (eds) Landslides Investigation and Mitigation, Transportation Research Board Special Report 247. National Academy Press, Washington, DC, pp 391–425
- Nortarpietro A (1990) Geological structure and landslides in the province of Sondrio. In: Cancelli A (ed) Alps 90, Alpine landslide practical seminar, sixth international conference and field workshop on landslides, Switzerland-Austria-Italy, Milano, Italy
- Romana M (1985) New adjustment ratings for application of Bieniawski classification to slopes. In: Proceedings of the International Symposium on the Role of Rock Mechanics, ISRM, Zacatecas, pp 49–53
- Romana M, Seron JB, Montalar E (2003) SMR Geomechanics classification: application, experience and validation. In: Proceedings of the ISRM 2003—technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy, pp 981–984
- Ross-Brown DM (1972) Design considerations for excavated mine slopes in hard rock. Research Report No 21, Departments of Civil Engineering, Geology and Mining and Mineral Technology, Imperial College of Science and Technology, London
- Rozos D, Pyrgiotis L, Skias S, Tsagaratos P (2008) An implementation of rock engineering system for ranking the instability potential of natural slopes in Greek territory: an application in Karditsa County. *Landslides* 5(3):261–270
- Smith GJ (1994) The engineering geological assessment of shallow mine workings with particular reference to chalk. Dissertation, University of London
- Stead D, Benko B, Eberhardt E, Coggan J (2000) Failure mechanisms of complex landslides: a numerical modeling prospective. In: Bromhead et al (eds) Landslides in research, theory and practice: Proceedings of the 8th international symposium on landslides. Thomas Telford, Cardiff, London, pp 1401–1406
- Stead D, Eberhardt E, Coggan J, Benko B (2001) Advanced numerical techniques in rock slope stability analysis—applications and limitations. In: Kuhne et al (eds) UEF international conference on landslides—causes, impacts and countermeasures. Verlag Gluckauf GmbH, Davos, Essen, pp 615–624
- Varnes DJ (1978) Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) Landslides Analysis and Control. Transportation Research Board Special Report 176. National Academy of Sciences, Washington
- Wyllie DC, Mah CW (2004) Rock slope engineering, civil and mining, 4th edn. Spon Press, Taylor & Francis Group, Great Britain
- Zare Naghadehi M, KhaloKakaie R, Torabi SR (2010) The influence of moisture on sandstone properties in Iran. *PI Civ Eng Geotech Eng* 163(2):91–99
- Zhang LQ, Yang ZF, Liao QL, Chen J (2004) An application of the rock engineering systems (RES) methodology in rockfall hazard assessment on the Chengdu-Lhasa highway, China. *Int J Rock Mech Min Sci* 41(3):833–838