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REINFORCEMENT OPTIMIZATION IN UNSTABLE ROCK SLOPES USING GEOMECHANICAL RATING OF REINFORCEMENT

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Abstract. Discussion of optimization of reinforcement elements in stabilizing rock slopes due to high cost of such operations and problems caused by landslides and slope instabilities because of inadequate reinforcement, have always been a subject of research in the field of geo-mechanic and geotechnique. In this study, optimal distribution of reinforcement elements on the unstable rock slopes, especially in critical zones, has been considered and a new method of Geo-mechanical Rating of Reinforcement (GRR) is used. In this method, rock slope is divided to different zones according to geometrical properties and for each zone the coefficients and finally the influence coefficients' matrix is obtained. Moreover, according to the finite element method and numerical modeling of displacement of each zone, the displacement ratio matrix is calculated. Eventually, within a matrix operation, GRR values for each zone are obtained and distributions of reinforcement elements are determined. As a practical example in order to better assessment, distribution of optimized reinforcement elements in the second and fourth walls in rock slopes of Siah Bisheh Dam, located in Chalus, Mazandaran Province, IRAN have been evaluated. The results show that the GRR method has the advantage of dividing the rock slope into different zones and calculating influence coefficients for each zone, than the other methods of determining reinforcement elements. In the GRR method, geological and geomechanical properties of rock slope are also considered.

Key words: influence coefficient (IC), stabilization, rock Bolt (RB), reinforcement rating.

1. INTRODUCTION

Rock slopes in week and discontinuous rock masses are constantly prone to general or local landslides. The existence of joints and discontinuities in heterogeneous rock slopes is one of the main causes of slippage and instability of rock slopes [8]. In order to prevent sliding and failure of rock slopes, the zones that are likely to have instability, marked through studying and evaluating the geological conditions, were stabilized by engineering methods such as using rock bolts or shotcrete. So, as a prerequisite, it is needed to study and evaluate the conditions of slope stability with local researches, engineering interpretations and also field experiments on the existing samples. Then, by considering the geometric conditions and geotechnical slope parameters, a numerical model of slope stability should be developed and assessed. One of the methods to prevent instability of the rock slopes is using the RB system. The RB system prevents the sliding of unstable stone block by an internal force. For example, reinforcing the rock slope with the height of 165m using the RB system in a power plant in China was carried out [13]. In addition, other methods such as theoretical analysis [11], experimental techniques [12], and method of comprehensive regulatory can be applied for this process. An example of reinforcing the rock slope is located in the Siah Bisheh Dam, at Chalus city, Mazandaran Province, Iran, which is evaluated in this paper.

1.1. Literature review

Since this study proposes a new method in stabilization of the unstable rock slopes, similar advanced researches have not been done in the past. However, some related results to stabilizing the rock slopes with the RB were mentioned in the following paragraphs. For the first time, Weugel [10] presented the RB system for reinforcing rock slopes. He stated that using RB for stabilizing the rock slope is economical and recommended it. Cancelli and Crosta [1] studied and evaluated the risks of failure in unstable rock slopes and concluded that the locations which are not suitable geologically got the highest risk to slide. Hoek et al. [4] studied all kinds of systematic reinforcing in tunnels and eventually chose Rock Mass Rating (RMR) method as a successful method in reinforcing rock slopes. Peckover [7] reported that 70% of instability in rock slopes is related to the existence of water in rock fractures and pores. Based on the results of this research, existence of cracks and their diverse discontinuous directions caused 17% of sliding in the rock slope. Madani [6] discussed all kinds of systematic methods in reinforcing rock slopes. In his results, he presented rating parameters and illustrated the results as design tables for each of the systematic methods like Barton, RMR and RSR. Zhang *et al.* [15] considered the application of rock engineering to evaluate the sliding risk of rock slopes in highways of China and presented influential methods and techniques for studying the interaction of effective factors in stability of rock systems. The first study about optimizing the reinforcement of rock slope was carried out by Yang *et al.* [13] in China. They studied rock slopes as high as165 m during a project implementation. In this study, during excavation and reinforcing the rock slope, some changes happened in slope geometry, rock masses and its properties. These changes caused instability in some rock slope zones. Therefore, more unstable places were required greater reinforcement. The critical zone of sand displacements in each zone was identified and reinforced by high density. Finally, the density of reinforcing components in unstable zones increased. Also, Dehestani and Haddad [2] evaluated the stabilization of first and third wall in rock slopes of Siah Bisheh Dam, located in Chalus, Mazandaran Province, Iran.

In the present study, the effect of geological conditions, geo-mechanical properties, importance and necessity of stabilization and reinforcing the unstable rock slopes were considered. A new cost- effective material, was presented for optimizing the reinforcement of rock slopes, and its comparison with systematic reinforcing forms another part of the present study. For evaluation of the results, this method was carried out in Siah Bisheh Dam, located near the city of Chalus, northern Iran.

Sliding and instability of rock slopes always threaten the safety of main structures such as highways, railroads and power lines in mountainous areas. Instability of rock slopes could have negative effects on these structures. Therefore, stabilization of rock slopes is an important subject to discuss and research. Although there are some reinforcing techniques for reinforcing of the rock slopes, but so far there is no appropriate suggestion for optimization of this problem.

1.2. Purpose of this study

In recent decades, stabilization of rock slopes due to problems caused by land slides and slope instability have been considered by many researchers. In general, one of the methods for preventing land slides and instability in rock slopes is stabilization of rock slope with reinforcing elements (such as RB). The distribution of the RB in rock slopes is usually based on systematic methods such as RMR. Whereas, while the distribution of reinforcing elements on rock slopes surfaces has been considered uniformly, some layers may need more reinforcement elements locally, due to some geometrical and geo-technical properties. Unfortunately, the systematic reinforcement methods could not solve this problem. Recently, in order to improve the disadvantage of this type of reinforcement, the method of the GRR has been recommended. The purpose of this paper is to provide a logical process for optimum distribution of the required reinforcement elements in unstable rock slopes, especially in critical zones.

2. METHODOLOGYOF RESEARCH

In order to use the GRR method for rock slopes, the followings should be taken into consideration. Topography, geological conditions and mechanical properties of the rock masses should vary in different parts of the rock slope. This enables us to divide the surface of the rock slope into different zones (j = 1, 2,…, m) according to the geological features and mechanical properties.

In this method, the IC was defined for any rock slope zone and then the matrix of ICs [A] was written for each zone whose order is $m \times n$. Then, displacement of different zones of the rock slope will be calculated through numerical method or by field measurements. The displacement ratio (DR) of different zones and consequently the matrix of DRs [E] will be available whose order is $n\times m$. Finally, in a matrix operation and multiplication of IC and DRs matrices, the GRR matrix will be obtained whose order is $m\times m$. The diameter values of this matrix are the GRR values for each divided zone, which are stated as r_{jj}. At last, according to these GRR values, the reinforcement optimization of each zone would be performed.

3. FACTORS AFFECTING THE Ics

The factors were evaluated in this study are Hardness of the rock mass (R_c), Faults in the rock slope (A_F), Structure of the rock mass (A_S), Weathering of rock mass (A_w), Angle of rock slopes (A_α), height ratio of rock slope (A_E) and Cracks in rock slope (A_C) [2].

Based on the abovementioned influential features, the matrix of IC is prepared for the rock slope.

4. MATRIX OF GOVERNING EQUATIONS

In this study, matrices were used for combination of coefficients and expediting the operations. For this purpose, after determining the IC for each zone of rock slope, the coefficients were presented in matrix form. Also, after determining the displacement of each zone, the results are presented in the matrix of DRs. The final values of the GRR are diagonal values of GRR matrix that are obtained during a matrix operation.

4.1. Structure of the matrix of Ics

In the matrix of ICs, [A], the order is $m\times n$, where m is the number of rows and representative of zones of the rock slope, and n is the number of columns and representative of number of ICs. In this paper, eight Ics were considered and this number can change according to the geological conditions of the rock slope.

4.2. Matrix of the DRs

After calculating the matrix of IC, the matrix of DR of rock slope should be determined. After dividing the rock slope in to j sections, the highest displacement should be measured in the field or be estimated by numerical modelling. Then the DR will be computed for each zone by the following equation [2]:

$$e_j = \frac{\delta_j}{\sum_{j=1}^{m}\delta_j}, \qquad (1)$$

where j is the DR for each zone and δ_j is maximum measured displacement for each zone of the rock slope.

This ratio is dimensionless and summation of e_j equals to 1. Now, the matrix of DR was formed. The order of this matrix is $n \times m$, where n is number of rows and representative of ICs of the rock slope, and m is number of columns and representative of zones of rock slope.

4.3. The calculation model of GRR matrix

Hudson [5] applied Rock Engineering System (RES) approach and matrix computations and found the interaction between ICs. On this basis, the GRR matrix determined as shown in equations (2) and (3):

$$[\boldsymbol{R}]_{m\times m} = [\boldsymbol{A}]_{m\times n} \times [\boldsymbol{E}]_{n\times m} \qquad (2)$$

$$[\boldsymbol{R}] = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m-1} & r_{1m} \\ r_{21} & r_{22} & & \vdots & \vdots \\ \vdots & \vdots & \ddots & & \\ r_{m-11} & \cdots & & r_{m-1m-1} & \\ r_{m1} & \cdots & & & r_{mm} \end{bmatrix} \qquad (3)$$

This matrix is diagonal and its order is $m \times m$. The main diameter values (r_{11}, r_{22},..., r_{mm}) are the desired values of the GRR for each zone. The higher the GRR values, the more unstable the rock slope. Therefore, it needs denser reinforcement component.

4.4. Flowchart and scheme for GRR method

Flowchart of the GRR method was prepared for better application and use of this approach in analysing unstable rock slopes was shown in Figure 1 [2]. Step by step, application of this method for unstable rock slopes was described in this flowchart. Usually, the first step is to analyse the rock slope by using finite-element software such as Plaxis. If it is stable, it doesn't need to be reinforced. But if the rock slope isn't quite stable, it is possible to use the GRR method to reach the optimum reinforcement of the slope. For facilitating and expediting the process of algorithm calculation, a program was written using MATLAB software. The GRR values were obtained for each zone of the rock slope. Based on these values, the density of reinforcement elements for unstable parts were decided. The rock slope characteristics were reformed after implementing the decision and the above steps and stages were repeated until the rock slope reinforcement was optimized. However, a comparison between the GRR and other methods of reinforcement the rock slope, for instance, here is the RMR method performed the important results of this comparison were presented in the following part:

In the GRR method rock slope with respected to geometric feature and geo mechanical was divided into different zones and one of the requirements of this method is the slope zoning, while in RMR method special emphasis in dividing tunnels and rock slope to different zone was not mentioned. So the GRR method results is more accurate and relevant to each region will increase safety in reinforcing the rock slope. One of the advantages of the GRR method, especially respect to RMR, is the number of influence coefficients used in the GRR technique was than other methods for investing stability. These ICs due to geographical location of the project could increase while in RMR methods important factors such as height and angles of the slope, structure and mass of rock layers and faults have not been fully considered and clearly. Therefore, the GRR method according to the most influential factors in mind, it can produce results with higher safety [2]. The GRR method could be useful as a guideline for the optimal distribution of reinforcing elements in the rock slopes uniform intervals have the precise distribution grid and so that in zone of instability requires more density in reinforced elements and these distances of grid have been reduced and where appropriate in terms of stability, the space of grid is increased. As a result of using this method in the unstable rock slope stabilization and optimization will increase the slope safety.

5. CASE STUDYOF APPLYINGTHE GRR METHOD

5.1. Introducing Siah Bisheh Power Plant (SBPP)

The Siah Bisheh Pumped-Storage Power Plants constructed in the Alborz Mountains range near the village of Siah Bisheh, 48 km south of Chalus, Mazandaran Province, IRAN. The power plant generates electricity to full fill partially the peak demands in Tehran City (60 km to the south). When completed, it has an installed generating capacity of 1040 MW and a pumping capacity of 940 MW [9].

5.2. Application of the GRR method

The SBPP rock slope trenches have been studied. There are four trenches in this case study. In this paper, second and fourth walls of these trenches were chosen and investigated. The rock slopes were initially divided to different zones. Based on geometric conditions, the second wall slope was divided into four zones and the fourth wall slope into six zones. Also in the previous study, the stabilization of first and third wall in rock slopes of Siah Bisheh Dam were evaluated [2].

5.3. Calculation of IC for each zone

After dividing the rock slopes into ten zones, the IC values are determined for each zone. Two examples of the tables related to fault coefficient and weathered rocks are presented in Tables 1 and 2.

Table 1

Fault coefficient values (A_F) for the second and fourth walls

Zone	1	2	3	4	5	6	7	8	9	10
Mean width of the fault (cm)	---	40	45	---	60	22	35	180	20	55
A_F coefficient	1	22	22	1	28	22	22	28	22	28

Table 2

Weathering coefficient values (A_w) for the fourth wall

Zone	1	2	3	4	5	6
Number of weathered rock masses	17	7	10	18	11	20
Sum of the weathering coefficients	172	38	64	219	68	182
A_W coefficient	10	5	6	12	6	9

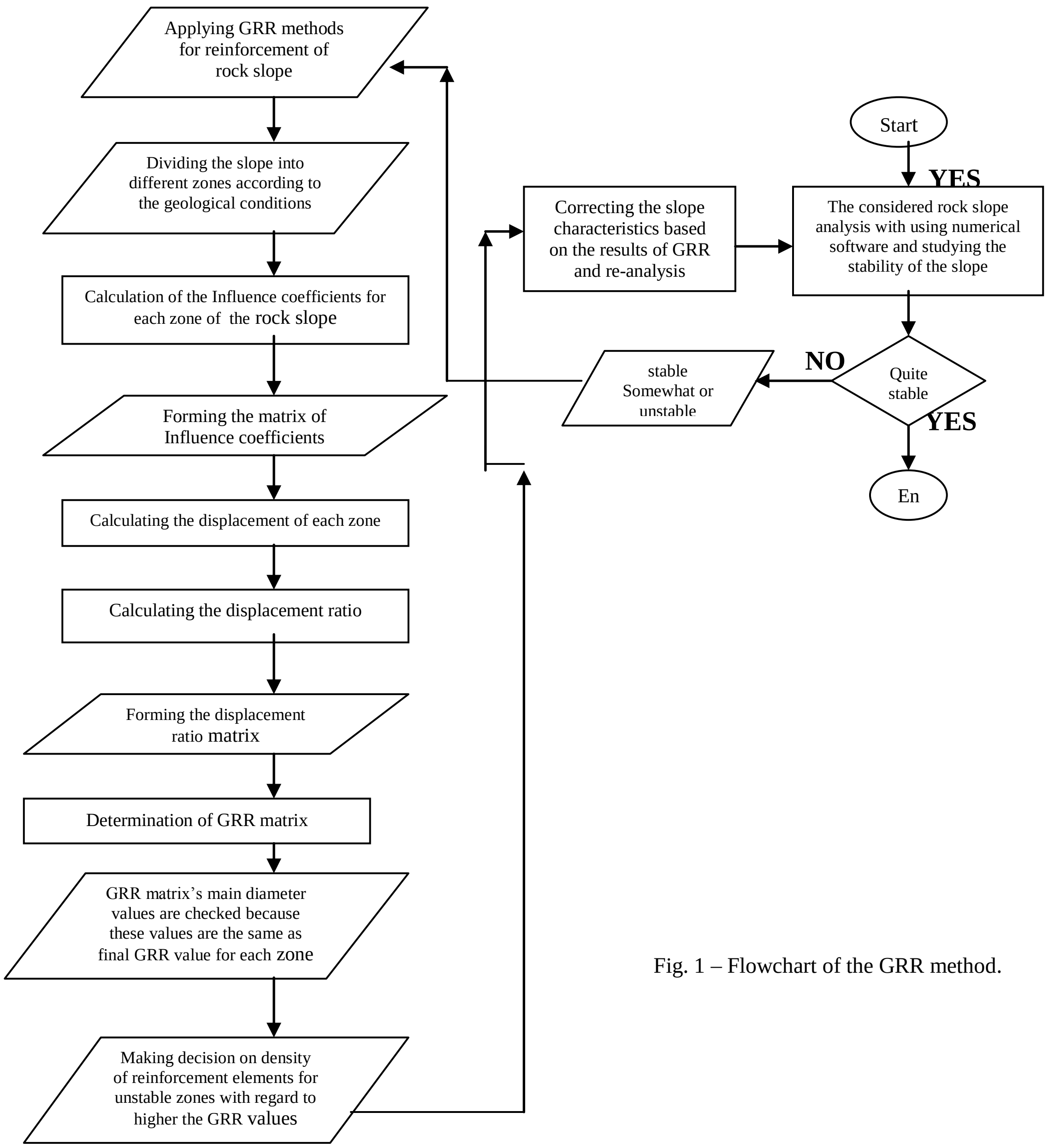


Fig. 1 – Flowchart of the GRR method.

Table 3

Final IC values for different zones of the second and forth walls

Target zone	A_{RC}	A_F	A_S	A_W	A_α	A_E	A_C
Wall 2 Zone 1	4	1	8	8	16	6	3
Wall 2 Zone 2	8	22	18	4	16	6	3
Wall 2 Zone 3	4	22	8	5	16	6	6
Wall 2 Zone 4	4	1	8	1	16	6	3
Wall 4 Zone 1	8	28	18	10	16	12	10
Wall 4 Zone 2	4	22	8	5	16	12	6
Wall 4 Zone 3	4	22	8	6	16	12	3
Wall 4 Zone 4	12	28	18	12	16	12	10
Wall 4 Zone 5	4	22	8	6	16	12	3
Wall 4 Zone 6	8	28	18	9	16	12	6

The final table of ICs for the second and fourth walls of Siah Bisheh rock slope trenches is shown in Table 3. ICs matrix is determined for ten zones of the rock slopes. The rows show ten zones and the columns show seven ICs. Structure of this matrix is as follows:

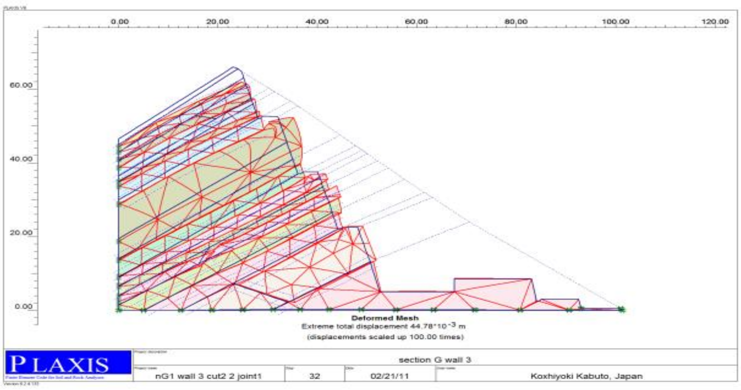
$$[A]_{10\times 7}=\begin{bmatrix} 4 & 1 & 8 & 8 & 16 & 6 & 3 \\ 8 & 22 & 18 & 4 & 16 & 6 & 3 \\ 4 & 22 & 8 & 5 & 16 & 6 & 6 \\ 4 & 1 & 8 & 1 & 16 & 6 & 3 \\ 8 & 28 & 18 & 10 & 16 & 12 & 10 \\ 4 & 22 & 8 & 5 & 16 & 12 & 6 \\ 4 & 22 & 8 & 6 & 16 & 12 & 3 \\ 12 & 28 & 18 & 12 & 16 & 12 & 10 \\ 4 & 22 & 8 & 6 & 16 & 12 & 3 \\ 8 & 28 & 18 & 9 & 16 & 12 & 6 \end{bmatrix}$$

Notice that, in this matrix, first row to fourth row is related to the second wall and fifth row to tenth row is for the fourth wall.

5.4. Displacement of classified zones with numerical modeling

After obtaining the ICs matrix and following the flowchart steps, displacement of every divided zone (totally ten zones) should be calculated. In each zone, some sections were considered and analyzed with the finite element Plaxis software to obtain the required displacement. In this section, displacement of fourth zone in the fourth wall is calculated as an example. With the use of cross-sectional geometry and geological and geo-mechanical properties of the layers, the finite element mesh of the zone has been presented in Figure 2. Considering the results of displacement, because of the displacement amounts of rock slope, fourth zone in fourth wall is one of the most critical zones. An important reason for this high displacement is the existence of wide faults in geological layers of this wall. Another reason for great displacement can be attributed to its height. However, the existence of faults in geological layers of the wall causes a reduction of resistance and the need for high density of reinforcement.

5.5. Final results of displacements



After completing the calculation of displacement in different points and zones of the second and fourth walls, the final results have been provided in Table 4.

Fig. 2 – Numerical model developed in the fourth zone.

Table 4

Final results of displacement for the second and fourth walls

Zone	Displacement U (mm)
Wall 2 zone 1	1.59
Wall 2 zone 2	6.56
Wall 2 zone 3	10.36
Wall 2 zone 4	4.57
Wall 4 zone 1	31.63
Wall 4 zone 2	11.28
Wall 4 zone 3	16.38
Wall 4 zone 4	45.58
Wall 4 zone 5	18.02
Wall 4 zone 6	26.66

5.6. Matrix of displacement ratio

Now, according to the algorithm presented in subsection 4-4, arrays of ICs and displacement values (shown in Table 4), were used as input data to compute displacement ratio matrix as presented below:

$$[E]_{7\times10}=\begin{bmatrix}0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\\0.009 & 0.038 & 0.06 & 0.026 & 0.182 & 0.065 & 0.095 & 0.264 & 0.104 & 0.154\end{bmatrix}$$

Finally the GRR results for the two walls are presented in Table 5. It is clear that three of the highest GRR values are related to first, fourth and sixth zones in the fourth wall. These amounts seem to be logical regarding wide faults and unfavourable geological conditions and therefore these zones need the highest density of reinforcement.

5.7. Distribution of reinforcement elements on rock slope

The results of the distribution of reinforcement elements on rock slopes by method of GRR were compared with the performed reinforcement in the Siah Bisheh Dam site. According to the table 5 and to achieve higher safety, systematic reinforcement were performed by using 6 m long rock bolts in the form of 2×2 lattices. Although there are faults, geological heterogeneity and joints in some rock slope zones, the rock bolt distances are the same for these rock slopes. But, with the help of the GRR method, the weak zones could be supported locally. Therefore, the optimum RB distribution on rock slopes was achieved by using relative-coefficients (*n*) and the GRR parameters. In this method, spacing of performed net for systematic reinforcement divide to this coefficient to obtain density rate and spacing of bolts in the GRR method. As shown in Table 5, it is clear that the obtained GRR values in different zones are not uniform. Therefore, in zones with the GRR values greater than 2, the bolts could be installed in denser networks. The new distribution of reinforcement elements are showed in Table 5.

5.8. Relative-coefficients (n) diagram in GRR method

The aim of this subsection is to prepare a relative-coefficients diagram for the GRR method that applies to every project and rock slope in the SBPP site. The reinforcement rate was obtained for each zone of the rock slopes based on reinforcement quantity needed for systematic reinforcement. For this purpose, relative-coefficients *n* and GRR values presented in Table 5 and finally graph of Fig. 3 is suggested. In this graph the point of the GRR and *n* from Table 5 is displayed and finally embedding graph is produced and suggested for using relative-coefficient to every project and rock slope project. By Comparing of *n* coefficient in the previous and present study, it is readily seen that the results are consistent, in the other words when the value of GRR is increased, the *n* coefficient is also increased.

Table 5

Comparison of distribution of reinforcement elements in the GRR method and the SBPP site

Zone	GRR value	Spacing of bolts in GRR method		Spacing of performed net in SBPP site		Relative-coefficients (*n*)
		S_v (m)	S_h(m)	S_v (m)	S_h (m)	
Wall 2 zone 1	0.414	3	3	2	2	0.67
Wall 2 zone 2	2.926	1.75	1.75	2	2	1.14
Wall 2 zone 3	4.020	1.4	1.4	2	2	1.42
Wall 2 zone 4	1.014	2.5	2.5	2	2	0.8
Wall 4 zone 1	18.564	0.5	0.5	2	2	4
Wall 4 zone 2	4.745	1.35	1.35	2	2	1.48
Wall 4 zone 3	6.745	1.2	1.2	2	2	1.67
Wall 4 zone 4	28.512	0.4	0.4	2	2	5
Wall 4 zone 5	7.384	1	1	2	2	2
Wall 4 zone 6	14.938	0.6	0.6	2	2	3.33

In order to apply and better discussion of the GRR method, in addition to the second and fourth walls, this method was performed similarly for downstream trenches at the SBPP site. Finally, Table 6 represents the proposed relative coefficients and criteria for reinforcement of the rock slopes in the SBPP site.

Table 6

Final GRR range based on stability and requirement of reinforcement of rock slope in the SBPP site

GRR value	Stability conditions	Reinforcement necessity
0–2	Complete stability	No need for dense reinforcement
2–5	Ordinary stability	A little need for dense reinforcement
5–8	Not critical	Not much need for dense reinforcement
8–10	Not critical	A little more need for dense reinforcement
10–15	semi critical	Needs dense reinforcement
15–20	semi critical	Needs more dense reinforcement
20–30	Critical	Needs highly dense reinforcement
30–50	Completely critical	Intense need for dense reinforcement

6. CONCLUSIONS

The results and advantages of the GRR method were summarized as follows:

1 – Generally, the GRR method has the advantage of dividing the rock slope into different zones and calculating the effect of coefficients, over other methods of determining reinforcement elements.

2 – In the GRR method, geological and geo-mechanical properties of rock slope have been considered.

3 – GRR values for rock slope trenches in the SBPP site is between 0.414 and 28.512.

4 – In the optimum distribution of the reinforcement elements at the highest GRR value zone, spacing of the net decreased from 2×2 m^2 to 0.4×0.4 m^2.

5 – In the optimum distribution of the reinforcement elements for the zone that had the minimum amount of the GRR, spacing of the grid increased from 2×2 m^2 to 3×3 m^2.

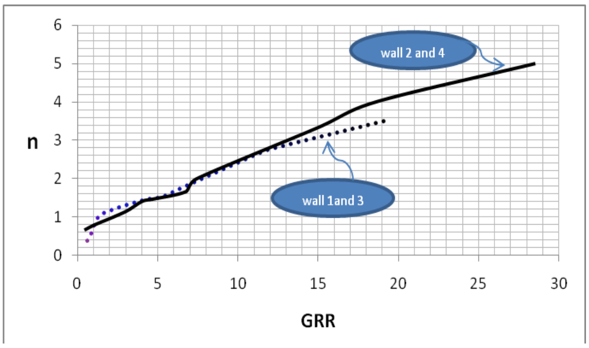


Fig. 3 – The prepared graph for rock slope of trenches in the SBPP site.

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