International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Application of Q-slope classification in seismic-prone regions

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Abstract

The paper presents an idea for modifying the Q-slope system for designing rock slopes in seismic-prone regions. The idea is developed based on Barton's earlier works, where he suggests introducing Q-static and Q-seismic values for tunnels constructed in seismic-prone regions. In known rock mass classification systems, seismic influences are incorporated in some way in the Slope Stability Rating (SSR) method earlier developed by Taheri.

The analyses are prepared on 58 cut slopes on the highway from Kichevo to Ohrid in Macedonia and other infrastructural projects. The basics of the methodology are related to the parallel use of data sets for Q-slope with results from stability analyses with known limit equilibrium methods. In analyses, besides other input parameters, two sets of values were used for the seismic coefficients in the horizontal direction, k_h=0.1 and k_h=0.2, while the seismic coefficient in the vertical direction is $k_v=\pm0.5k_h$. Based on a finding from analyses, an additional border zone is suggested on the graph recommended by Barton and Bar 2015, 2017. The minimum required angle to ensure the long-term stability named β-seismic for the analysed cases, without the application of additional stabilization measures, should be lower by 8º compared to the usual procedure of the Q-slope method.

A correlation between SSR and Q-slope, as well as safety factor and horizontal seismic coefficient are presented.

The presented methodology can be an example for further development of the Q-slope method for some other regions in the world with specific geological development and seismic conditions.

Keywords

Limit equilibrium method, Q-slope, seismicity coefficient, slope angle, slope stability

1 Introduction

The importance of choosing an appropriate method in the definition of rock slope stability is related to the fact that millions of cubic meters of rock masses with different origins and parameters are excavated yearly in different rock engineering projects. Many direct and indirect associated risks are also related to this problem. In rock engineering practice, numerous methods of kinematics, limit equilibrium or numerical methods are developed and applied to solve complex problems, but still, there are a lot of open questions that can be a subject for further practical and scientific efforts.

In the article, the emphasis is put on empirical methods and the possibilities to use them comparatively with limit equilibrium methods for stability analyses. At the present state of the art, several empirical methods exist, and they are based on several factors influencing the strength and deformability of the rock masses, such as joint orientation and density, intact strength, geological structure, groundwater etc. For example, the Slope Mass Rating (SMR) developed by Romana (1985, 1995) and the Global Slope Performance Index developed by Sullivan (2013) can be used to evaluate the competence and performance of a particular excavated rock slope and to predict measures for stabilization. Slope stability rating (SSR) is a classification system for slope stability estimation, which consists of five parameters developed by Taheri (2012). Interestingly, the SSR method incorporates seismic influences in some way, and it shall be mentioned as a rare example because of that fact.

In the last 10 years, the Q-slope method developed by Barton and Bar (2015, 2017) has been widely used all over the world. The main idea of the Q-slope was to modify the original Q-system and apply it in rock slope engineering. It is considered a very helpful method in the definition of stable slope angles of reinforcement-free slopes in civil engineering and mining projects. A well-known fact is that the Q-system has been extensively used for 50 years and it has become widely recognised as a very useful empirical method in numerous projects, while the Q-slope is used in over 600 case studies in 36 rock types across 5 continents. The method is applied for slopes ranging from less than 5 m to more than 250 m in height (Bar and Barton, 2024). Summarising the findings from the Q-slope application, it is clear that it is applied in different rock mass media, where different modes of failure can occur, such as global failure, plane failure, wedging, local toppling etc.

Here, we are presenting some experiences for the application of the Q-slope method in several large infrastructural projects in Macedonia. They are mostly related to the highway section between the towns Kichevo and Ohrid, but also to the access road to dam Sveta Petka, the expressway from town Stip to town Kochani and others. More than 80 deep cuts are constructed in different rock mass media, such as highly weathered anisotropic rocks at highway Kichevo-Ohrid, marbles for access road to arch dam Sveta Petka, Eocene flysch deposits from Stip to Kochani etc. With the analyses, extensive databases are established and the results are summarised by Janevski (2024).

Nevertheless, it is still not possible to establish some “universal” methodology that can solve all problems in rock slope engineering. On the other side, it is possible to suggest the integration of findings from several approaches and some modifications and accommodation of known methods to certain specifics for some regions. This can lead to successful solutions even in complex rock mass conditions, complicated lithological structures, degree of alteration, tectonic disturbances, relaxation phenomena, short-term seismic blasting influences possible earthquake seismic force, etc. Knowing this, the authors present an idea to use Q-slope application in seismic-prone regions, to estimate possible time-dependent behaviour of rock slopes exposed to stronger earthquakes. This is related to the fact, that the selected case histories in the country are located in seismic-prone areas, where the earthquakes can exceed up to 9 degrees according to European Macroseismic Scale EMS-98. As a result of extensive analyses, an idea for modification of Q-slope diagrams is presented.

2 Applied methodology

The applied methodology of work is based on the following well-known facts:

- Empirical rock-engineering methods can be very helpful in slope design procedures,
- Kinematic and limit equilibrium methods are widely used in rock slope analyses,
- Every method can be applied with success if it is based on a realistic physical model and reliable input parameters
- Every method has limitations, and it must be used with careful engineering judgment.

In the frame of this article, only the basics for Q-slope and SSR methods are briefly explained, because they serve as a basis for the presented idea here. Even though empirical methods do not give a clear indication of the long-term stable slope angles in seismic-prone regions, the idea is to suggest a way to incorporate the seismic effects in the Q-slope method. It is important to note, that a similar approach has already been introduced using the Q-seismic method in the case of the Mingtan Pumped Storage machine hall at Sun Moon Lake in Taiwan. In that case, the reinforcement in the arch was designed with a capacity increased by 25% due to the use of a dynamic design rule-of-thumb of 2·SRF or Q-dynamic = 0.5·Q-static. The cavern complex was tested severely years later during the 30-second duration M7.7 Chi-Chi earthquake (Barton, 2022).

The development of the idea is based on a concept presented in Slope Stability Rating (SSR), where the magnitude earthquake accelerations is used as one of the classification parameters an input from seismic influences. The basics of the SSR method are presented in Table 1.

Table 1 Slope Stability Rating Method developed by Taheri, 2012 (from Botjing et al., 2019)

Parameter	**Rating range**					
Modified GSI	Note: The Quantitative GSI chart, proposed by Sonmez and Ulusay (2002) is recommended					
Value	0 ÷ 100					
UCS [MPa]	0 ÷ 10	10 ÷ 25	25 ÷ 50	50 ÷ 100	100 ÷ 150	150 ÷ 200
Rating	0	7	18	28	37	43
Rock Type	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Rating	0	4	9	17	20	25
Slope Excavation method	Waste dump	Poor Blasting	Normal Blasting	Smooth blasting	Presplitting	Natural slope
Rating	-11	-4	0	6	10	24
Groundwater (Groundwater surface from under slope/slope)	Dry	0 ÷ 20%	20 ÷ 40%	40 ÷ 60%	60 ÷ 80%	80 ÷ 100%
Rating	0	-1	-3	-6	-14	-18
Magnitude Earthquake (Horizontal acceleration as a percentage of ground accelerations g)	0	0.15g	0.20g	0.25g	0.30g	0.35g
Rating	0	-11	-15	-19	-22	-26

In addition, it can be mentioned, that the main parameters in the SSR method are the Geological Strength Index value (GSI), Uniaxial Compressive Strength (UCS), Rock Type, Slope Excavation Method, Groundwater and Earthquake influences. Seismic influences are expressed as a percentage of ground accelerations (Taheri, 2012).

The basics of the Q-slope method are presented in Eq. 1.

$$Q_{slope} = \frac{RQD}{J_n}\left(\frac{J_r}{J_a}\right)_O \frac{J_{wice}}{SRF_{slope}} \tag{1}$$

Where RQD Rock quality designation index
J_n Joint set number
J_r Joint roughness number
J_a Joint alteration number
O Discontinuity orientation factor
J_{wice} Environmental and geological condition number
SRF_{slope} Strength reduction factor

This is a modification of the original Q-system, where the first four parameters (RQD, J_n, J_a, and J^r) in the equation remain unchanged from the original Q-system (Barton et al., 1974). Important changes to the original Q-system are the introduction of the discontinuity orientation factor (O) shown in Table 2. Set A refers to the most unfavourable discontinuity set, while Set B refers to the secondary discontinuity set. Set B is applied only in case of forming potentially unstable wedges. Important modifications are also related to environmental and geological condition number (J_{wice}) and the strength reduction factor SRF_{slope}. Details are presented by Bar and Barton (2015, 2017).

Table 2 Discontinuity orientation factor (O-factor)

Description	**Set A**	**Set B**
Very favourably oriented	2.0	1.5
Quite favourable	1.0	1.0
Unfavourable	0.75	0.9
Very unfavourable	0.50	0.8
Causing failure if unsupported	0.25	0.5

After evaluation of the Q-slope value, we can estimate the steepest long-term stable slopes, which are reinforcement-free. Namely, the authors derived a simple formula for the steepest slope angle (β) not requiring reinforcement or support:

$$\beta = 20 \log_{10} Q_{slope} + 65° \quad (2)$$

It should be noted, that although Eq. 2 does not estimate a specific factor of safety, it represents a long-term stable slope angle without reinforcement measures. The equation represents the average data for stable slope angles greater than 35° and less than 85°.

3 Presentation of results and discussion

The idea for modifying the Q-slope method is connected with known arguments about the importance of seismic factors in stability analyses. From Eq.2, it can be noted, that in Q-slope, almost all influential factors on slope stability are incorporated, and only some elements of seismicity are still not introduced. On the other side, in analytical procedures for slope stability calculations, it is known that seismic influences affect a lot the results.

One illustration is presented for a “simple” model of planar failure analyses presented in Fig. 1, for a slope at access road to Sveta Petka Dam.

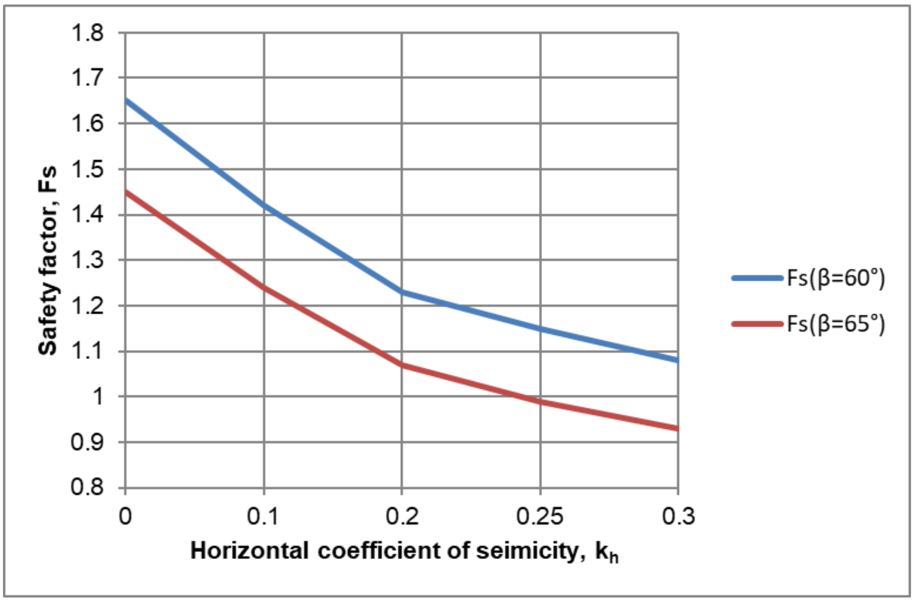

Fig. 1 Reduction of the Safety Factor (Fs) with increasing of horizontal coefficient kh for a slope at the access road to Sveta Petka dam, for a case of slope angles of 60° and 65°.

The case presented in Fig. 1 is related to a planar failure of a 14 m high slope, excavated with a slope angle of 65° in foliated marbles with uniaxial compressive strength of UCS= 60–80 MPa. An outward dipping joint set (~ 40°) caused the planar failure. Variation of the slope angle and the horizontal coefficient of seismicity presents their influence on the safety factor value.

This "simple" case of planar failure, is analysed using limit state design approach 1, combination 2 according to Eurocode 7, where the general geometrical and mechanical properties are presented in Table 3.

Table 3 Input parameters for the analysed case from Fig. 1

Slope height [m]	**H**	**14.0**
Slope face angle [°]	ψ_f	65.0
Upper surface angle [°]	ψ_s	5.0
Sliding plane angle [°]	ψ_p	40.0
Tension crack inclination [°]	ψ_c	90.0
Tension crack distance [m]	b	19.2
Cohesion [MPa]	c	0.06
Friction angle [°]	φ	38.0
Unit weight [kN/m³]	γ	26.5

The evaluated parameters of the Q-slope method for the particular slope are shown below:

- RQD = 75–90; $J_n = 9$
- $J_r = 1.5$; $J_a = 2$; O-factor = 0.5
- $J_{wice} = 0.7$; $SRF_{slope} = SRF_a = 2.5$

Using these values, the Q-slope is estimated in the following manner, using also the O-factor:

$$Q_{slope} = \frac{82}{9}\left(\frac{1.5}{2}0.5\right)\frac{0.7}{2.5} = 0.951 \tag{3}$$

It can be concluded, that this (or other) calculated Q-slope value doesn't account for possible different design scenarios including different seismic coefficients, and that stability conditions are implicitly assumed. On the other side, the SSR method gives a possibility to define SSR value in a term of possible decrease of initial SSR value, when no acceleration is introduced. An example is presented in Table 4 and Fig. 2. There, variations of horizontal accelerations are used in the calculation of SSR for main rock types dominantly present at slopes along the highway from Kichevo to Ohrid.

Table 4 Presentation of Q-slope and SSR range for main lithological units for rock masses along the highway Kichevo–Ohrid

Rock type	**Unit weight [kN/m³]**	**UCS [MPa]**	**GSI [/]**	**Q-slope [/]**	**SSR (Taheri) [/]**
Completely weathered schists (CWS)	22.5 – 24.0	3.0 – 5.0	10 – 20	0.04	SSR = 24 SSR (0.15g) = 13 SSR (0.20g)= 9 SSR (0.3g) = 5
Partially weathered schists (PWS)	25.0 – 26.0	10.0 – 15.0	20 – 30	0.1	SSR = 41 SSR (0.15g) = 30 SSR (0.20g) = 26 SSR (0.3g) = 22
Relatively fresh schists (RFS)	25.5 – 26.5	30.0 – 35.0	35 – 45	0.5	SSR = 67 SSR (0.15g) = 56 SSR (0.20g) = 52 SSR (0.3g) = 48

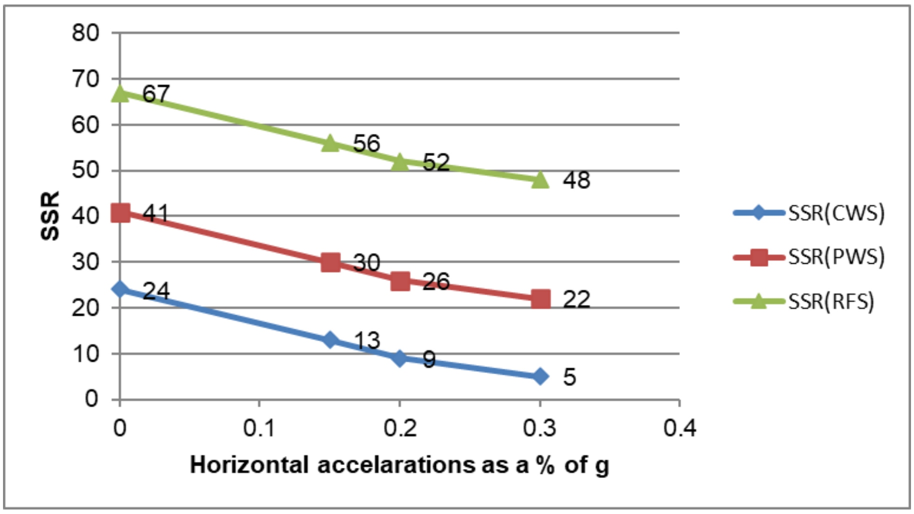

Fig. 2 Reduction of initial Slope Stability Rating without seismic effect (SSR) and for different values of horizontal seismic coefficient (0.15g, 0.2g and 0.3g) for main rock mass types along the highway from Kichevo to Ohrid.

The influence on the selected design value for horizontal accelerations is more than evident. One way to indirectly incorporate the seismic effect is using a correlation between SSR and Q-slope, as shown in Fig. 3.

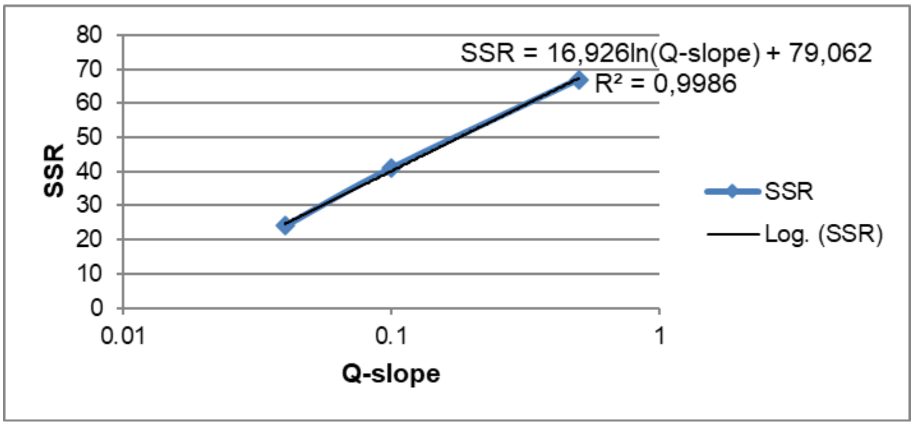

Fig. 3 Correlation between the Q-slope and SSR values for the data in Table 3.

To illustrate additional suggested modifications, in Fig. 4, the Q-slope value and calculated Safety factors with the software package Slide or Swedge are given in parallel. This is the case for some of the slopes on the Kichevo-Ohrid highway. From the chart, it is clear that data for the cuts with observed failures are quite deep in the unstable zone of the Q-slope stability chart, while the slopes with satisfactory values of safety factors are in the stable zone of the chart. In the diagram, it is proposed how to reduce the slope angle for a cut at chainage km 17+900–18+200 as one of the ways to modify Q-slope to Q-slope seismic. The red arrow in Fig. 4 shows the path to decrease the slope angle in cases of stronger seismic events in an analysed region.

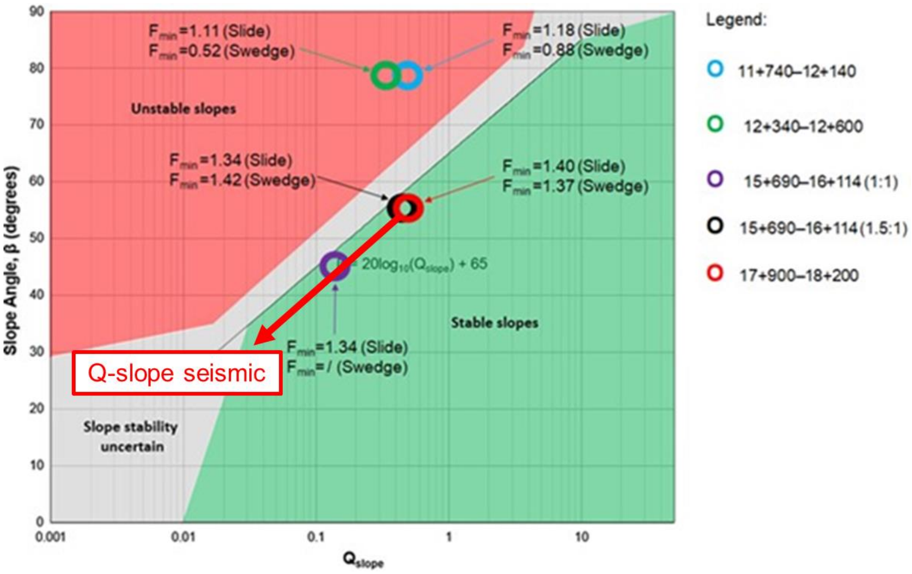

Fig. 4 Q-slope stability chart (Barton and Bar, 2015) for the subject cut slopes and their corresponding safety factors obtained in Slide and Swedge, with dots representing the chainages of several deep cuts along the highway route.

In the following, another correlation of empirical and analytical methodological approaches is presented. According to the results presented in the diagram in Fig. 4, it is seen that the slopes with unsatisfactory values of the factors of safety, where significant instability of the slopes appeared on site, are located deep in the zone that indicates instability. The rest of the slopes are in the safe zone but are very close to the limit itself, which means that the inclination of these slopes as well as the safety factors are at the very limit of satisfactory values.

Results for more detailed analyses are presented in Fig. 5, where an option for adjusting the Q-slope system in seismically active areas is presented with a dashed line. There, the projected line for evaluation of the slope angle is modified and leads to a certain dependence on the seismicity coefficient for a specific seismic region. Namely, 58 slopes were analysed with different coefficients of seismicity in the horizontal and vertical directions. Two sets of values were used for the seismic coefficients in the horizontal direction, k_h=0.1 and k_h=0.2, while the seismic coefficient in the vertical direction is k_v=±0.5k_h. A minimum value of Fs=1.1 is adopted as a reference value.

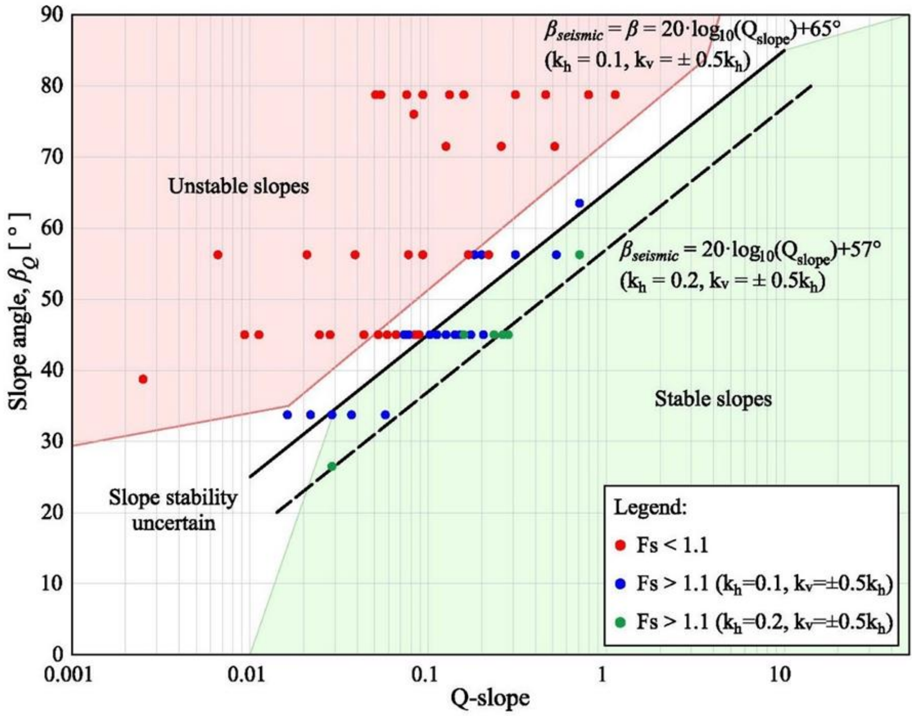

Fig. 5 Q-slope stability chart (Barton and Bar, 2015) with proposed boundary zone for stable slopes, including the seismic influence for a case of seismic coefficient in horizontal direction k_h=0.2.

According to the presented results from Fig. 5, it is interesting to emphasize that for a value of the seismic coefficient in the horizontal direction of k_h=0.1, the results indicate that the proposed boundary zone presented with a solid line from the original Q-slope method satisfies the conditions for stable slope angle. However, for a value of the seismic coefficient in the horizontal direction of k_h=0.2, the values of the safety factors are below the usual suggested range for stable slopes under seismic influences in a country practice. For this case, an additional border zone presented with a dashed line is introduced in the original graph of Barton and Bar (2015, 2017). This shows that the minimum required angle to ensure long-term stability (βseismic), without additional stabilization measures, should be lower by 8º. Therefore, in these conditions, for this case, we recommended using Eq. 4:

$$\beta_{seismic} = 20log_{10}Q_{slope} + 57°, \text{(for } k_h\text{=0.2)} \quad (4)$$

According to these research findings, it is obvious, that in every case of analyses for other seismic zones and different geological conditions, some new boundary lines (zones) can be suggested.

4 Concluding remarks

In the frame of the article, one approach to include seismic influences in the Q-slope method is introduced. The results are mainly related to geological conditions and seismicity expected influences in the area of the highway from Kichevo to Ohrid. A comparative parallel application of the traditional limit equilibrium method and the Q-slope method is presented, also including seismic influences in the analyses.

The presented results indicate that practical experiences can be useful in developing some new ideas, despite the fact that every analysed area is unique in its nature and it has to be considered in terms of the particular set of circumstances.

The main conclusion is that a clever approach is to combine different tools and techniques and to choose which one suits best for the particular case.

The authors believe that the presented results can help in developing of Q-slope seismic method for specific seismic regions.

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