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Eren Komurlu*

Case studies on Q-slope method use for slope stability analyses

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Abstract: The use of the Q-slope value is a relatively new approach for the stability investigations of rock slopes. In this study, four different slopes in Giresun and Ordu cities of Turkey were investigated to assess whether the Q-slope approach is usable for varying slope heights, or not. A back analysis was carried out for a landslide in a case study quarry located in Kovanlik municipality of Giresun city. Carrying out detailed investigations on the geotechnical drill cores and the field studies, the Q-slope value of the rock mass of the Kovanlik quarry was determined as 0.58. According to the Q-slope approach, the slope which had a landslide under the case of 49° general slope angle and 225 m height should have been stable at a general slope angle of 59°. It has been found that the Q-slope approach is not favorable for a high slope with the height of 225 m. Two roadway excavations with steep slope angles and low heights smaller than 25 m were also investigated within this study. According to the Q-slope value, the roadway slopes which are stable for more than 3 years are estimated to be unstable. Therefore, the Q-slope approach was found also misleading for slopes with low heights like those under 25 m. On the other hand, the Q-slope method usability is confirmed obtaining parallel results with the observations from another case study slope with a height of 78 m. Although it has become a popular empirical method in the recent years, it is recommended to revise the Q-slope approach or limit its use depending on the slope height parameter.

Keywords: Slope stability; Rock mass stability; Empirical methods in rock engineering; Q-slope.

***Corresponding author: Eren Komurlu,** Giresun University Department of Civil Engineering, Giresun, Turkey, E-mail: ekomurlu@giresun.edu.tr; ORCID: 0000-0002-2123-7678

1 Introduction

Empirical analyses are preferred due to their practical use in the engineering applications, such as tunnels, slopes, foundations, and mines. Although empirical methods are not all sufficient for a rock engineering design, their use together with different methods such as numerical and analytical analyses is beneficial. The Q-slope is a relatively new empirical approach suggested by Bar and Barton to use in the rock mass quality evaluations for the slope stability investigations [1]. Since the first rock mass classification system suggested by Karl von Terzaghi [2], researchers have focused on the empirical methods to assess the necessity of some revisions to improve the methodological details by elimination of doubts and some disadvantages. Various researchers have performed different studies to investigate the use of the new Q-slope approach as well [3-6].

In the Q-slope approach, limit slope angles are varied depending on the rock mass quality parameters without concerning a direct height parameter of slopes. In site studies carried out by Bar and Barton [1], slopes with different heights under 200 m are mostly focused on to suggest the Q-slope approach. It is a well-known information from numerous references that the height has a notable role on the slope stability property [7-13]. The lack of proper number of studies in the high slopes has been found to be a doubt as a motivation for performing this site study to investigate the use of Q-slope approach for slopes with various heights.

Q-slope calculations are derived and suggested for its use in the geotechnical engineering in accordance with the data obtained from different parts of the world. This situation has supplied exhaustive works for the Q-slope method. On the other hand, the height parameter is not directly used in the calculations of the Q-slope value as seen in Eq. (1). According to the Q-slope approach, safe slope angle can vary independently from the height parameter. For instance, a same slope angle can be preferred for two different slopes with 250 m and 25 m heights despite of having the same rock mass quality.

$$Q_{slope}: (RQD/J_n)(J_r/J_a)(J_{wice}/SRF_{slope}) \quad (1)$$

where RQD is Deere's rock quality designation (RQD), J_n is the number of joint sets, J_r is the joint set roughness parameter value, J_a is joint set alteration value, J_{wice} is environmental and geological condition number, and SRF_{slope} is strength reduction factor from SRF_a (physical condition number), SRF_b (stress and strength number), and SRF_c (major discontinuity number) factors. The only parameter for a possible consideration of the height is SRF_b, which can be determined as the ratio of unconfined compressive strength (UCS) to maximum principal stress which may not be proportional with the height parameter depending on its direction and the geological conditions. The SRF_b factor can reduce the Q-slope value as the slope height is increased. However, it should be reminded herein that the SRF_{slope} factor is taken as the maximum value among the SRF_a, SRF_b, and SRF_c. Therefore, the Q-slope value can be determined independently from the slope height and safe slope angle can be estimated without a concern of the height parameter according to the method. Although the Q-slope method has been suggested after worldwide rock engineering works, 95% of its reference works were for slopes with lower heights than 120 m [1]. This situation makes a necessity for further analyses to check the usability of the method for relatively higher slopes. As a contribution from that point of view, a high slope in Turkey was investigated in accordance with the Q-slope method within this study.

Depending on the mechanical properties, even soil slopes can be stable in the case of perpendicular slope angles and low heights like some meters as seen from the foundation pit excavations. It is possible to predict that a medium-quality rock mass like those with a Q-slope value about 0.5 should be also stable in the case of steep slope angles (70°–90°) and low slope heights which soil slopes remain stable. However, the medium-quality rock masses excavated with a slope angle of 60° are estimated to be unstable even under the case of very few slope heights like 3 m, according to the Q-slope chart (Fig. 1). This situation is not confirmed by observations in engineering sites and the nature. Therefore, lack of the height parameter is thought to be open for focusing on in further studies on the Q-slope empirical method.

2 Methodology of Case Studies

One of the case study areas of this study is a quarry within the borders of Kovanlik municipality of Bulancak district of Giresun city. In the Kovanlik quarry, a landslide occurred when the slope angle is 49° in 2021. It is aimed to make a back analysis from the instability of the slope which makes an opportunity to investigate the usability of the Q-slope value for a high slope with the height of 225 m. Two geotechnical drillings with a total length of 300 m were carried out to determine the rock mass properties of the slope. In order to reflect the original field conditions, core samples were taken from the rock mass that did not have landslides by drilling in the vertical direction from the upside of the slope (Figs. 2 and 3). Additionally, rock mass properties were carefully investigated in the site. It should be noted that the residual rock mass is not used to correctly determine the in situ properties. The rock mass faces which show the in situ properties were carefully investigated to accurately evaluate the Q-slope value. The slope height and slope angle values were determined within regular measurements by mining company topographers who reported that the major slide has occurred when the slope angle is 49°. Some views of the Kovanlik quarry are given in Figs. 3 and 4.

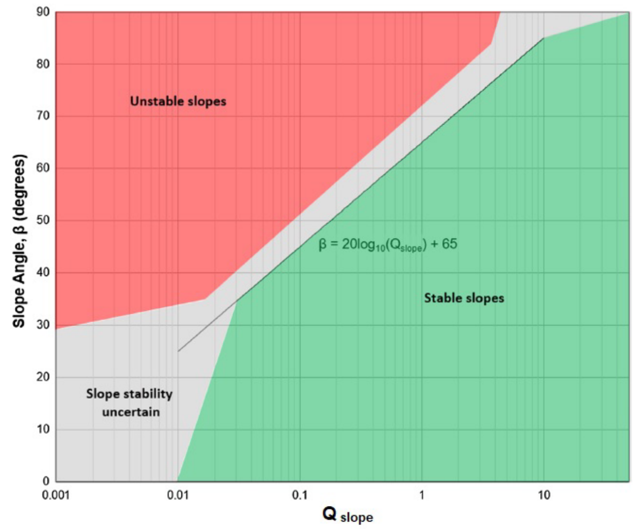

Figure 1: The Q-slope chart [1].

The RQD value which is an important parameter for Q-slope determination was calculated with length measurements on the cores bored (Fig. 5). Discontinuity properties (roughness, spacing, weathering, infilling, aperture, water condition, etc.) were carefully investigated to be rated. To determine the rock material strength values, specimens from the core boxes of the geotechnical drills were cut and used in the uniaxial compressive strength (UCS) tests. One specimen was used per each 5 m lengths of the drill cores. Loading rate was chosen 0.5 MPa/sec in the UCS tests (Fig. 6). As parallel to the Q-slope determination

Figure 2: Drilling at the Kovanlik quarry site.

Figure 3: Shown of drilling locations (D1, D2) on the failed Kovanlik quarry.

methodology, the UCS test results are used as the SRF_b determination parameter of σ_c. The Q-slope determination procedure is briefly given in Tables 1–7. The maximum principal stress (σ_1) is considered to be the gravitational one in the vertical direction. To estimate the σ_1 in Table 6, unit volume weight and the slope height parameters were used as stated in the Q-slope methodology. The density of rock mass was approximately evaluated weighing the UCS test specimens.

The Q-slope value of another case study area of a roadway slope in Gure district of the Giresun city has been also determined (Fig. 7). Instead of using geotechnical drill cores, rock blocks from the Gure slope site were brought to the laboratory, cored, and cut by the sawing machine to have the length to diameter ratio of 2 to prepare specimens for the uniaxial compressive strength (UCS) test. Discontinuity properties were carefully investigated to be rated within the site study. The height of the Gure slope is 20 m, and it has

Figure 4: The Kovanlik quarry after the slope instability.

been mechanically excavated 3 years before. It is currently stable at a slope angle (β) of 75° and has an altered rock mass with relatively smooth and random joints. The third case study area, a basalt quarry in Gulyali district of Ordu city, has also a steep (β: 70°) and stable slope with a height of 78 m (Fig. 8). The fourth case study area is another roadway slope in Piraziz district of Giresun city, which is a quite steep one (β: 80°) and has a low height of 11 m (Fig. 9). The Q-slope values of Gulyali and Piraziz slopes were also carefully determined by carrying out intensive and detailed site and laboratory investigations.

3 Results

For the Kovanlik quarry, Q-slope parameters were determined as follows: RQD: 70, Jn: 12 (three-joint sets plus random joints), Jr: 2 (undulating and smooth), Ja: 2 (slightly altered joint walls, nonsoftening mineral coatings, clay-free), J_{wice}: 0.6 (wet environment, incompetent rock), and SRF_{slope}: 6 (SRF_a: 0, SRF_b: 6 (σ_c/σ_1: 9), SRF_c: 2). The Q-slope value is calculated as 0.58 for the Kovanlik quarry which is

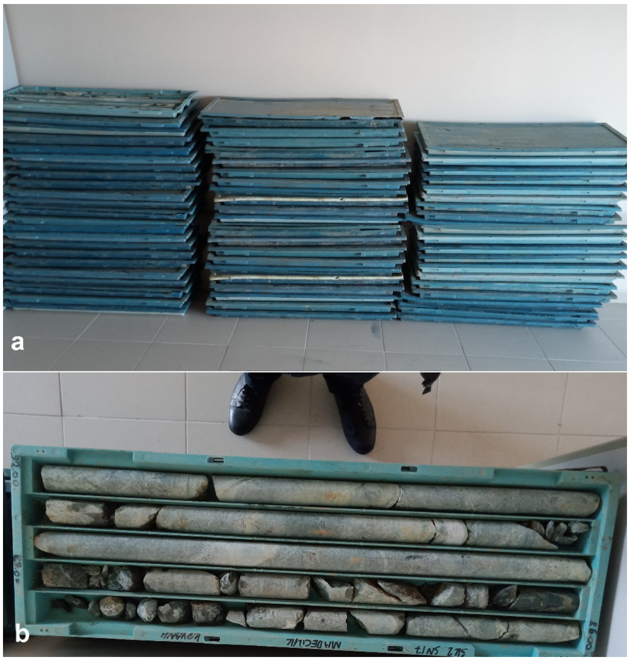

Figure 5: a) Drill cores taken from the Kovanlik quarry and b) investigations of the core samples.

Figure 6: Uniaxial compressive strength testing.

Table 1: J_n values [1].

Joint set number description	J_n
Massive, no or few joints	0.5–1
One joint set	2
One joint set plus random joints	3
Two joint sets	4
Two joint sets plus random joints	6
Three joint sets	9
Three joint sets plus random joints	12
Four or more joint sets, random, heavily jointed	15
Crushed rock, earthlike	20

Table 2: J_r values [1].

Description	J_r
Discontinuous joints	4
Rough or irregular, undulating	3
Smooth, undulating	2
Slickensided, undulating	1.5
Rough or irregular, planar	1.5
Smooth, planar	1.0
Slickensided, planar	0.5
Zone containing clay thick enough to prevent rock-wall contact	1.0
Sandy, gravely, or crushed zone to prevent rock-wall contact	1.0

Table 3: J_a values [1].

Description	J_a
(a) Rock-wall contact (no clay fillings, only coatings)	
Tightly healed, hard nonsoftening, impermeable filling, i.e., quartz or epidote	0.75
Unaltered joint walls, surface staining only	1
Slightly altered joint walls. Nonsoftening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2
Silty- or sandy-clay coatings, small clay disintegrated rock, etc.	3
Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays	4
(b) Rock-wall contact after some shearing (thin clay fillings, probable thickness & 1–5 mm)	
Sandy particles, clay-free disintegrated rock, etc.	4
Strongly over-consolidated nonsoftening clay mineral fillings	6
Medium or low over-consolidation, softening, clay mineral fillings	8
Swelling-clay fillings, i.e., montmorillonite. Value of Ja depends on percent of swelling clay-size particles and access to water	8–12
(c) No rock-wall contact when sheared (thick clay/crushed rock fillings)	
Zones or bands of disintegrated or crushed rock and clay	6–12
Zones or bands of silty or sandy clay, small clay fraction (nonsoftening)	5
Thick, continuous zones or bands of clay	13–20

Table 4: J_{wice} values [1].

Description	Desert environment	Wet environment	Tropical storms	Ice wedging
Stable structure; competent rock	1.0	0.7	0.5	0.9
Stable structure; incompetent rock	0.7	0.6	0.3	0.5
Unstable structure; competent rock	0.8	0.5	0.1	0.3
Unstable structure; incompetent rock	0.5	0.3	0.05	0.2

Table 5: SRF_a values [1].

Description	SRFa
Slight loosening due to surface location, disturbance from blasting or excavation	2.5
*Loose blocks, tension cracks, joint shearing, weathering susceptibility, severe blasting disturbance	5
As above (*), but strong susceptibility to weathering	10
Slope is in advanced stage of erosion and loosening due to erosions by water and/or ice-wedging effects	15
Residual slope with significant transport of material downslope	20

Table 6: SRF_b values [1].

Description	σ_c/σ_1	SRF_b
Moderate stress-strength range	50–200	2.5–1
High stress-strength range	10–50	5–2.5
Localized intact rock failure	5–10	5–10
Crushing or plastic yield	2.5–5	15–10
Plastic flow of strain softened material	1–2.5	20–15

Table 7: SRF_c values (RQD_{100}: 1 m perpendicular sample of discontinuity, RQD_{300}: 3 m perpendicular sample of discontinuity) [1].

Description	Favorable	Unfavorable	Very unfavorable	Causing failure if unsupported
Major discontinuity with little or no clay	1	2	4	8
Major discontinuity with RQD100 ≈ 0 due to clay and crushed rock	2	4	8	16
Major discontinuity with RQD300 ≈ 0 due to clay and crushed rock	4	8	12	24

the first case study area. Q-slope values of the case study slopes are given in Table 8.

For the slope in the Gure, Q-slope parameters were determined as follows: RQD: 65, J_n: 15 (random joints), J_r: 1 (smooth, planar), J_a: 3 (silty- or sandy-clay coatings, small clay disintegrated rock, etc.), J_{wice}: 0.6 (wet environment, incompetent rock), and SRF_{slope}: 4.6 (SRF_a: 0, SRF_b: 4.6 (σ_c/σ_1: 17), SRF_c: 3). The Q-slope value is calculated as 0.19 for the Gure slope which is the second case study area.

For the Gulyali quarry, Q-slope parameters were determined as follows: RQD: 90, J_n: 6 (two-joint sets plus random joints), J_r: 3.5 (favorable joint contacts), J_a: 1 (unaltered joint walls), J_{wice}: 0.7 (wet environment, competent rock), and SRF_{slope}: 3 (SRF_a: N/A, SRF_b: 3 (σ_c/σ_1: 42), SRF_c: N/A). The Q-slope value is calculated as 12.25 for the Gulyali slope which is the third case study area.

For the Piraziz slope, Q-slope parameters were determined as follows: RQD: 64, J_n: 12 (three-joint sets plus random joints), J_r: 1.25 (smooth, about planar), J_a: 1.5 (indistinct surface staining and slightly altered joint walls), J_{wice}: 0.6 (wet environment, not a competent rock), and SRF_{slope}: 1.25 (SRF_a: N/A, SRF_b: 1.25 (σ_c/σ_1: 174), SRF_c: N/A). The Q-slope value is calculated as 2.1 for the Piraziz slope which is the fourth case study area.

4 Discussions

According to the Q-slope approach, the Kovanlik quarry slope should be stable at a slope angle (β) of 59° (Fig. 1). However, the slope with the height of 225 m has slid when it is only 49°. In consideration of the results, the use of the Q-slope approach was not found reliable for high heights

Figure 7: The Gure slope in Giresun city.

Figure 8: The Gulyali quarry in Ordu city.

Figure 9: The Piraziz slope in Giresun city.

like 225 m. According to the Q-slope approach, the Gure slope should be unstable at a slope angle (β) of 52° (Fig. 1). However, the slope with the height of 20 m is stable under the case of β: 75°. Therefore, it can be inferred that the Q-slope approach should be also revised for the low

Table 8: Q-slope values of the case study slopes.

Slope	Q-slope value
Kovanlik	0.58
Gure	0.19
Gulyali	12.25
Piraziz	2.10

height slopes. As parallel, the Piraziz slope which has the height of 11 m is stable in case of β: 80°, whereas it is estimated as unstable according to the Q-slope chart.

In consideration of the high Q-slope value of 12.25, the slope angle can increase to be nearly perpendicular and stability of the basalt quarry in the Gulyali district is confirmed. The Q-slope method was found to give parallel results with the observations from the Gulyali quarry. According to that result, Q-slope method was found to be usable for the slope height of 78 m.

The Q-slope values can be calculated without the height parameter, whereas it is one of the most important parameters which have effect on the slope stability [14-17]. As the SRF_b decreases with an increase in the σ_c parameter, stability property increases. The ratio of σ_1/σ_c can be quite low and the Q-slope value can notably increase in case of high UCS values of rock materials. However, structural controlled instability problems which mostly depend on the joint properties are not affected by the material strength parameter that much [18-21]. The Q-slope method and that kind of empirical methods are usable for the rock masses which are able to be homogenized. In case of various structural controlled failure mechanisms like toppling or a planar slide at the major weakness plane, rock mass cannot be homogenized and the homogenization approach should not be trusted because of having lacks of details [22-25]. As noted before, the SRF_{slope} value is taken as the biggest one of the strength reduction factors of SRF_a, SRF_b, and SRF_c. It is another doubtful approach to neglect effect of any stress reduction factor on the slope stability. For instance, a very unfavorable major discontinuity (SRF_c: 4) are neglected in determination of the Q-slope value, in case of a higher SRF_b value than 4.

It can be noted herein that an empirical method is not sufficient alone for a safe slope design. The empirical methods should be verified with other methods such as numerical, analytical, and/or different empirical ones to make sure about the designs in the rock engineering works. The Q-slope is a relatively new empirical method which is thought to be not sufficiently verified by works in long years after its suggestion and needs better focusing on to fix its shortages. Because the height parameter is not taken into account sufficiently in the Q-slope approach, it was found to need revisions.

From the early times of the empirical method suggestions to the present, the height parameter is always considered as one of the major parameters in the slope stability analyses [26-31]. While processing the height parameter in many approaches, not taking this parameter into account properly in the Q-slope method is considered as an important deficiency and possible for causing misleading stability estimations as seen from the site studies.

This study is aimed to contribute for improving the Q-slope method in terms of the height parameter effect. If necessary, the empirical methods can be revised in various times. The Q-slope method also seems to need an improvement from the point of the height effect in the slope stability analyses.

The only parameter including the height effect, SRF_b, is not used if it is smaller than SRF_a or SRF_c. In the Q-slope method, SRF_c is a parameter for joints. It is questionable to understand why the height parameter can be eliminated and not considered when the SRF_c value increases due to the unfavorable joint properties. Additionally, it is inexplicable that the height effect can be eliminated by increases in the SRF_a value of the Q-slope method, because of highly weathered rock masses. Moreover, the SRF_b value is not directly varied by the height parameter, since it depends on the σ_c parameter which is also doubtful because of its use for the rock material strength instead of rock masses. As the uniaxial compressive strength value of rock materials (σ_c) is not an effective parameter in some structural controlled failure cases, the SRF_b can become unreasonable because it is a function of the σ_c parameter.

5 Conclusion

In this study, the use of the Q-slope method was investigated for the stability analyses of four different slopes with 225 m, 78 m, 20 m, and 11 m heights. As a conclusion from this study, it can be stated that the Q-slope method can cause misleading estimations of the stability property of rock slopes with high and low heights. According to the results, it is recommended to revise the Q-slope approach or limit its use depending on the slope height parameter. The Q-slope method is believed to be more usable if the height parameter revisions are carried out by the future studies.

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