

Assessment of Ultimate Bearing Capacity based on the Hoek-Brown Failure Criterion

(Penilaian Keupayaan Galas Muktamad berdasarkan Kriteria Kegagalan Hoek-Brown)

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ABSTRACT

The ultimate bearing capacity is an essential requirement in design quantification for shallow foundations especially for structures built on large rock masses. In many engineering projects, structures built on foundation of heavily jointed rock masses may face issues such as instability and sudden catastrophic rock slope failure. Determination of the ultimate bearing capacity (Q_{ult}) of foundations resting on rock mass has traditionally been determined by employing several strength criteria. One of the accepted and widely implemented methods is to use the Hoek-Brown failure criterion 2002, where the required parameters are determined from a rock mass classification system, Geological Strength Index (GSI). This paper defines an assessment for ultimate bearing capacity (Q_{ult}) based on the Hoek-Brown failure criterion 2002 for a granitic rock slope beneath a 20 m diameter concrete water tank at Bandar Mahkota Cheras, Kajang, Selangor. Based on the Hoek-Brown failure criterion 2002, the ultimate bearing capacity (Q_{ult}) of rock mass was 7.91 MPa. The actual stress acting on the rock mass was 0.32 MPa. The assessment showed that the rock mass is safe since the ultimate bearing capacity (Q_{ult}) is 24.7 times higher than the actual stress acting on the rock mass.

Keywords: Geological Strength Index; Hoek-Brown failure criterion 2002; rock mass; ultimate bearing capacity

ABSTRAK

Keupayaan galas muktamad merupakan keperluan penting dalam reka bentuk pengkuantitian bagi asas cetek terutama bagi struktur yang dibina di atas jasad batuan yang besar. Dalam banyak projek kejuruteraan, struktur yang dibina di atas asas jasad batuan berkekar banyak yang besar mungkin menghadapi isu seperti ketidakstabilan dan bencana kegagalan cerun batu secara tiba-tiba. Penentuan keupayaan galas muktamad (Q_{ult}) pada asas yang berada di atas jasad batuan secara tradisi telah ditentukan dengan menggunakan beberapa kriteria kekuatan. Salah satu kaedah yang diterima dan diguna pakai secara meluas adalah menggunakan kriteria kegagalan Hoek-Brown 2002 dan parameter yang dikehendaki ditentukan daripada pengelasan sistem jasad batuan, Indeks Kekuatan Geologi (GSI). Kertas ini mentakrifkan penilaian bagi keupayaan galas muktamad (Q_{ult}) berdasarkan kriteria kegagalan Hoek-Brown 2002 untuk satu cerun batu granit di bawah tangki air konkrit berdiameter 20 m di Bandar Mahkota Cheras, Kajang, Selangor. Berdasarkan kriteria kegagalan Hoek-Brown 2002, keupayaan galas muktamad (Q_{ult}) jasad batuan adalah 7.91 MPa. Tegasan sebenar yang bertindak atas jasad batuan ialah 0.32 MPa. Penilaian menunjukkan bahawa jasad batuan adalah selamat kerana keupayaan galas muktamad (Q_{ult}) adalah 24.7 kali lebih tinggi daripada tegasan sebenar yang bertindak di atas jasad batuan.

Kata kunci: Indeks Kekuatan Geologi; jasad batuan; keupayaan galas muktamad; kriteria kegagalan Hoek-Brown 2002

INTRODUCTION

Determination of the ultimate bearing capacity (Q_{ult}) is among the basic engineering parameters required for design, construction and execution of any engineering structures especially when the foundation comprises of a large rock mass. Existence of discontinuities such as faults, joints and bedding planes are one of the factors for rock mass failure when subjected to high stresses and strong deformations. However, local researchers only focus on rock mass characterization (Goh et al. 2011a, 2011b, 2011d), shear characteristic of discontinuities surface (Ghani Rafek & Goh 2012; Goh et al. 2011c), rock mass classification (Norbert et al. 2016) and characterization of

rock materials (Goh et al. 2015a, 2015b, 2015c, 2015d, 2014). Consequently, there is a need to accurately assess the ultimate bearing capacity (Q_{ult}) of a rock mass for the construction of roads, tunnels, bridges and structures with high foundation loads such as dams and high-rise buildings. Proper evaluation is essential since the success and safety of such structures depends primarily on the accuracy and sound judgment of the ultimate bearing capacity (Q_{ult}) of the rock mass.

Traditional methods based on analytical and numerical methods have been established by previous researchers in computing the possible ways with regard to the assessment of ultimate bearing capacity (Q_{ult}) of foundations on a

rock mass. These methods were introduced and presented aimed at developing an explicit solution to calculate the ultimate bearing capacity (Q_{ult}) of rock mass foundations. The objective of this study was to assess the stability of a rock mass slope underlying a 20 m diameter concrete water tank (Figure 1). With that, the assessment of the ultimate bearing capacity (Q_{ult}) of jointed rock mass has been assessed based on the Geological Strength Index (Hoek et al. 1998) and Hoek-Brown failure criterion 2002 (Hoek et al. 2002).

MATERIALS AND METHODS

GEOLOGY

The study area consists primarily of granite from the Main Range granite body with several enclaves of meta-sedimentary rocks. The granite of this region is popularly known as the Kajang Granite and it is also part of the Kuala Lumpur granite. Granites at the study area composed mainly of medium to coarse grained, lightly to moderately porphyritic and light grey to bluish muscovite biotite granite. Majority of the granite are light grey in color, coarse-grained and massive. Bignell and Snelling (1977) studied the geochronology of granite rocks in Malaysia and reported that almost all the igneous rocks in east part of Malaysia are more mafic compared to the western part of Malaysia. They suggested that the age of the granite body is between Jurassic and Late Triassic. Figure 2 shows the location of the study area.

DISCONTINUITY SURVEY

A total of 200 discontinuity survey data were collected by using the scanline method from the slope labeled as BMC-1 beneath a 20 m diameter concrete water tank at Bandar Mahkota Cheras, Kajang, Selangor (Figure 3). The rock slope was selected in such a manner that they represent various joint sets having various degrees of weathering and slope stability conditions. Field data includes rock type, slope angle, joint set number, orientation of discontinuities, spacing of discontinuities, persistence, roughness of

discontinuities, width of aperture, seepage, rock block dimensions and absence/presence of filling along with type of filling. Figure 4 shows an example of exposed discontinuities of the joint set and spacing for data analysis.

ROCK MASS RATING (RMR)

The Rock Mass Rating (RMR) system developed by Bieniawski (1989) combines the most significant geologic parameters of influence and represents them with a thorough index of rock mass quality. The five parameters evaluated in determining the $RMR_{basic89}$ of the slopes were the compressive strength of rock material, Rock Quality Designation (RQD) index, spacing of discontinuities, condition of discontinuities and groundwater conditions.

GEOLOGICAL STRENGTH INDEX (GSI)

The Geological Strength Index (GSI) is a characterization system based on geological observations of rock mass and has been developed for modeling and design of underground excavations (Hoek et al. 1998). The value of GSI was estimated using (1):

$$\text{For } RMR_{basic89} > 23, \\ GSI = RMR_{basic89} - 5 \text{ (at dry condition).} \quad (1)$$

HOEK-BROWN FAILURE CRITERION 2002

The Hoek-Brown failure criterion 2002 proposed by Hoek et al. (2002) is widely used in rock mechanics to evaluate the design of underground excavations. The concept of the Hoek-Brown failure criterion 2002 was to evaluate the properties of intact rock and to add factors to reduce those properties with regard to the discontinuities existing in the rock mass. The Hoek-Brown failure criterion 2002 (Hoek et al. 2002) is favorable and being used widely by engineers because it gives quantification of the relation between the stress state and the rock mass rating ($RMR_{basic89}$) suggested by Bieniawski (1989). From the Hoek-Brown failure criterion 2002 (Hoek et al. 2002), the ultimate bearing capacity (Q_{ult}) is calculated using (2):

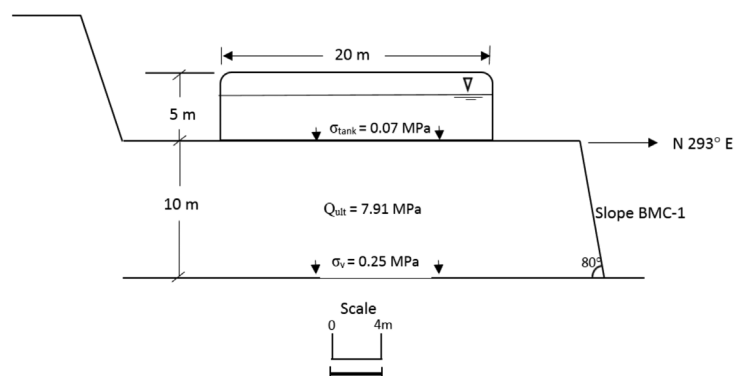


FIGURE 1. Schematic diagram of the rock mass slope (BMC-1) underlying a 20 m diameter concrete water tank



FIGURE 2. Location of study area



FIGURE 3. Discontinuity survey was conducted using the scanline method on slope BMC-1 underlying a 20 m diameter concrete water tank. The orientation of slope face is 293°/080°



FIGURE 4. Exposed discontinuities of the granite slope. The behavior of the discontinuity joints influenced the ultimate bearing capacity of rock slope

$$Q_{ult} = \sigma_i S^{0.5}, \tag{2}$$

where Q_{ult} (MPa) is the ultimate bearing capacity; and σ_i (MPa) is the uniaxial compressive strength of rock material. The parameter S is calculated using (3):

$$S = \text{Exp} \left[\frac{GSI-100}{9-3D} \right], \tag{3}$$

TABLE 1. Property used for the assessment of the water tank and the ultimate bearing capacity of slope

No.	Property	Value
1	RMR _{basic89}	75
2	GSI	70
3	Disturbance factor, D	0.7
4	Uniaxial compressive strength of rock material, σ_1	70 MPa
5	Height of water tank	5 m
6	Diameter of water tank	20 m
7	Capacity of water tank	1500 m ³
8	Density of rock, ρ	2511 kg/m ³
9	Height of slope, h	10 m
10	Acting stress by rock mass load, σ_v	0.25 MPa
11	Acting stress by weight of water tank, σ_{tank}	0.07 MPa
12	Total stress acting on rock mass ($\sigma_v + \sigma_{\text{tank}}$), σ_{total}	0.32 MPa
13	Ultimate bearing capacity, Q_{ult}	7.91 MPa

where D is the disturbance factor. The value of disturbance factor D observed on this site was 0.7.

ASSESSMENT OF THE 20 M DIAMETER CONCRETE WATER TANK

The 20 m diameter concrete water tank is situated at the top of the rock mass slope. Assessment on the water tank were made based upon assumption that the water tank was full at time of the evaluation. The acting stress by the water tank was calculated using (4):

$$\sigma_{\text{tank}} = F/A. \quad (4)$$

where σ_{tank} (MPa) is the acting stress by the weight of water tank; F (kN) is the force acting on the water tank; and A (m²) is the cross-sectional area of the water tank. The acting stress by the rock mass load (σ_v) was calculated using (5):

$$\sigma_v = \rho h, \quad (5)$$

where σ_v (MPa) is the acting stress by the rock mass load; ρ (g/cc) is the density of rock; and h is the height of slope underlying the water tank. The total acting stress on the rock mass is determined using (6):

$$\sigma_{\text{total}} = \sigma_v + \sigma_{\text{tank}} \quad (6)$$

where σ_{total} (MPa) is the total stress acting on the rock mass; σ_v (MPa) is the acting stress by the rock mass load; and σ_{tank} (MPa) is the acting stress by the water tank.

RESULTS AND DISCUSSION

From the results of the discontinuity survey, the value of Geological Strength Index (GSI) of rock mass converted from RMR_{basic89} was 70 with the disturbance factor D of 0.7. The stress acting by weight of the water tank and the rock mass load were calculated by using (4) and (5), respectively and the total stress acting on the rock mass

was 0.32 MPa. The ultimate bearing capacity of the slope was computed by using the Hoek-Brown failure criterion 2002 (Hoek et al. 2002) and was found to be 7.91 MPa. From the assessment, it can be seen that the rock mass is safe since the ultimate bearing capacity is 24.7 times higher than the actual acting stress on the rock mass. Table 1 summarizes the property used for the assessment of the water tank and the rock mass load.

CONCLUSION

The present study deals with analysis of the ultimate bearing capacity of a rock mass slope underlying a 20 m diameter concrete water tank by employing the Hoek-Brown failure criterion 2002 (Hoek et al. 2002). The findings showed that the slope is stable with the safety factor of 24.7. The results have been presented to facilitate the use of the Hoek-Brown failure criterion in solving practical design problems. The assessment showed that the engineering geological parameters need to be justified for the conservative estimate of the ultimate bearing capacity (Q_{ult}) of rock mass load for the development of engineering structures especially on structures with high foundation loads.

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