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Estimation of Shear Strength Parameters of Rock Masses Based on Hoek–Brown Failure Criterion- a Case Study

[1]Ali Salajegheh, [2]Mehdi Ghaffari, [3]Gholamreza Kamali

[1]*M.Sc. Graduate, Department of Civil Engineering, Estahban branch, Islamic Azad University, Estahban, Iran*
[2]*M.Sc. Graduate, Department of Civil Engineering, Estahban branch, Islamic Azad University, Estahban, Iran*
[3]*Assist. Prof., Department of Mining Engineering, Bahonar University of Kerman, Iran*

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ABSTRACT

The Hoek–Brown failure criterion is used in rock mechanics to predict the failure of rock. The criterion was first developed by Evert Hoek and E. T. Brown in 1980, and in 1988 the criterion was extended for use in slope stability evaluation and surface excavation problems. The latest update of this criterion which was presented in 2002 has been used in this research to evaluate the shear strength parameters of rock masses of a dam that is being built in Kerman province of Iran for providing drinkable water by Kerman Regional Water Company. Rock masses on this dam site are made of sedimentary rocks that composed of alternative layers of marl, mudstone, silty marl and sandstone. For estimation of shear strength parameters of these rock masses, Hoek-Brown failure criterion curves were calculated and graphed (with saturated uniaxial compressive strengths of 1 MPa for mudstone and marl, 5 MPa for silty marl and siltstone and 18.3 MPa for sandstone, and the value of (m) of 7, 7&17 and also Geological Strength Index (GSI) of 30, 35 and 45 for these rock masses respectively). The result shows that rock masses in the study area are weak and soft and even the strongest of them, which is sandstone, is not categorized as hard rock.

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INTRODUCTION

"The Hoek–Brown failure criterion is an empirical stress surface that is used in rock mechanics to predict the failure of rock[1,2]. The original version of the Hoek–Brown criterion was developed by Evert Hoek and E. T. Brown in 1980 for the design of underground excavations.[3] In 1988, the criterion was extended for applicability to slope stability and surface excavation problems.[4] An update of the criterion was presented in 2002 that included improvements in the correlation between the model parameters and the geological strength index (GSI).[5]

The basic idea of the Hoek–Brown criterion was to start with the properties intact rock and to add factors to reduce those properties because of the existence of joints in the rock.[4] Although a similar criterion for concrete had been developed in 1936, the significant tool that the Hoek–Brown criterion gave design engineers was a quantification of the relation between the stress state and Bieniawski's rock mass rating (RMR).[6] The Hoek–Brown failure criterion is used widely in mining engineering design."[7].

In this research, Hoek-Brown failure criterion is applied to evaluate the shear strength parameters of rock mass of Safa Dam, and whole analyses were based on this failure criterion.

The Safa Dam site is situated in Rabor town of Kerman Province of Iran. The dam site has been chosen at the cross point of two rivers namely Rabor and Roodbar by HalilAb consultant engineers, that carried out the phase I of study of this dam. This dam is an earth fill dam with vertical clay core and has the capacity of 67 MCM (million cubic meters) of water on the normal elevation of 2160 masl (meters above mean sea level). The dam crest height is 78 meters from the bedrock and has 880 meters length.

Although "earth fill and rock fill dams exert less strain and minor transformation against rock foundation tectonically, but the whole body of the dam may prone to constraints originated in settlement within smashed

Corresponding Author: Ali Salajegheh, M.Sc. Graduate, Department of Civil Engineering, Estahban branch, Islamic Azad University, Estahban, Iran.

components or at karstic zone and develops slippage in rock mass at the dam foundation or abutments due to settlement forces or structural loading" [8], so the strength of rock should be evaluated carefully in these dams.

In the term of dam foundation stability, strength of rock and its discontinuities against shear force is known as the most important characteristics of the rock. Factors that influence the shear strength of the rock include weathering, cutting surface roughness, moisture, type and amount of filling, normal pressure and water pressure at the cutting surface [9]. Formation of joints in the rock mass, influences transformability and shear strength of the rock mass. In hard rocks that bear joints with close distance (e.g. typically in the range of one meter), the rock mechanical behavior is function of joints instead of intact rock behavior [10]. Rock mass on the Safa dam site is made of sedimentary rocks that composed of alternative layers of marl, mudstone, silty marl and sandstone. In addition to stratification, the concerning rock mass is affected by discontinuities, which classified in 5 categories according to the surveys carried out over the dam foundation and because of them, the rock mass assumed homogeneous and isotropic. Due to the joint disruption and blocky structure of rock masses, and the governing role of joints and discontinuities in control of rock mass behaviors at the dam site, the latest update of Hoek-Brown failure criterion [5] is used to estimate the shear strength parameters of rock masses.

2- Geomorphology and Geology in the Region:

The Safa Dam basin limited in Sahand – Bazman zone (Beneath the Dehaj-Sardoie magmatic arc), and Colored Melange of Turonian - Coniacian. This zone is one of the most disturbed zones in the country, while the area experiences a large number of magmatism phases. Safa Dam basin located in extremely complex formation. The presence of major and minor faults and volcanic outcrop demonstrates the complexity of this formation. There are narrow and lengthened anticlines at the northern zones which interrupted by volcanic and rock masses, the orientation of those anticline axes are east – west, while there are irregular formation faults at the west under radial deviation. The orientation of those faults are parallel to north-south and northeast – southwest.

The bedrock on dam site composes of sequences of marl, mudstone with reddish brown and gray sandstone with silty-marl and greenish silt related from upper red formation (URF), while the abutments covered with old alluvial terrace. The stratification orientation is northwest–southwest. The stratification slope stands 40 degrees at the right abutment while at the left abutment stand 20 degrees with the orientation of the northeast. Fig. 1 depicts the general view of the Safa Dam site and demonstrates stratification in this site.

Fig. 1: General view of the Safa Dam site.

It is notable that sandstone is discernable from other rock masses because it rested in continuum and integrated formation and easily can be found in drilled cores and their width seemed in narrow to fairly medium layers. Due to weathering and erosion of marl and mudstone rocks, they cannot easily be distinguished at the surface. At river bed the bedrock lied 5.5 meters beneath the coarse grains of alluvium while in abutments, it may be found beneath the slope washes of old alluvial terraces, while it is underlying the old alluvial terraces beyond the contour of 2160 masl [11].

3- Analyses and results:

As it mentioned before, Hoek-Brown failure criterion [5] was used to calculate shear strength parameters of rock masses.

To calculate shear strength parameters of rock masses based on this criterion, with the saturated uniaxial compressive strength of the intact rock of samples (σ_{ci}), the value of (m) for the intact rock (mi) and Geological Strength Index (GSI), Hoek-Brown curves in the existing stress range have been calculated and drawn.

Constants and input data used to calculate the failure criterion based on the results of laboratory tests and engineering classification of rock masses have already been calculated, and the summarized data are presented in Table 1.

Table 1: Constants & input parameters of Hoek-Brown failure criterion for rock masses at Safa Dam site.

Rock mass	σ_{ci} (MPa)	mi	GSI index
Marl & Mudstone	1	7	30
Silty marl & siltstone	5	7	35
Sandstone	18.3	17	45

Equation 1 is the main equation of Hoek-Brown failure criterion, and by using equations 2-4 of this failure criterion (which are illustrated below), parameters and constants of this criterion was calculated for each rock mass and are demonstrated in table 2.

$$\sigma_1' = \sigma_3' + \sigma_{ci}(m_b \frac{\sigma_3'}{\sigma_{ci}} + S)^a \quad (1)[5]$$

$$m_b = m_i \exp(\frac{GSI-100}{28-14D})^a \quad (2)[5]$$

$$S = \exp(\frac{GSI-100}{9-3D}) \quad (3)[5]$$

$$S = \frac{1}{2} + \frac{1}{6}(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}}) \quad (4)[5]$$

Table 2: Calculated constants of Hoek-Brown failure criterion for rock masses at *Safa Dam* site.

Rock mass	m_b	s	a
Marl & Mudstone	0.575	0.0004	0.522
Silty marl & siltstone	0.687	0.0007	0.516
Sandstone	0.979	0.0022	0.508

The curves of Hoek-Brown failure criterion including input information and other parameters are presented in figures 2, 3 and 4 for each rock mass kind. The concerning curves with the presented constants will be used to analyze the dam body and conducting other design goals, including designing of tunnels and controlling slope stability.

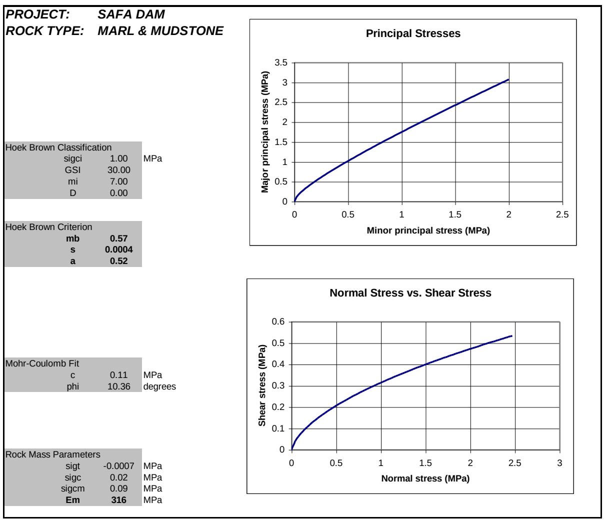

Fig. 2: Hoek-Brown failure criterion curve on mudstone & marl.

Since most geotechnical software is still written in terms of the Mohr-Coulomb failure criterion, it is necessary to determine equivalent angles of friction and cohesive strengths for each rock mass and stress range [5]. This was also done by using the mentioned method in the 2002 edition of Hoek-Brown failure criterion.

In order to calculate angle of friction and cohesive strength based on Mohr–Coulomb failure criterion, it is necessary to calculate and estimate the concerning parameters for different levels of stresses, because this methodology promote the concise calculation of rock mass strength. Consequently the shear strength parameters of rock masses of dam site based on Mohr–Coulomb failure criterion with possible stress levels (which could be exerted to the dam foundation) were calculated and the results are presented in Table 3.

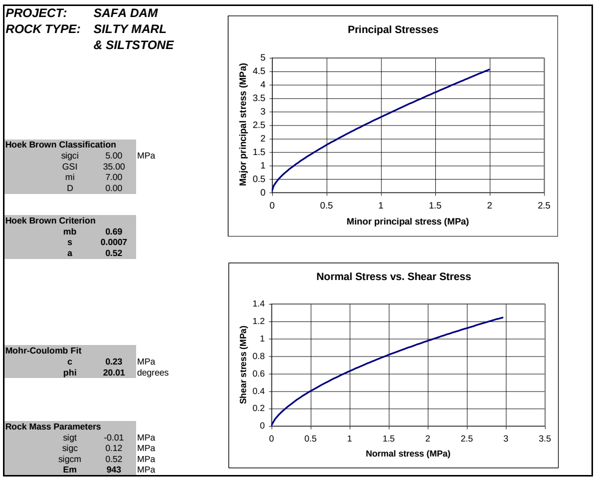

Fig. 3: Hoek-Brown failure criterion curve on silty marl & siltstone.

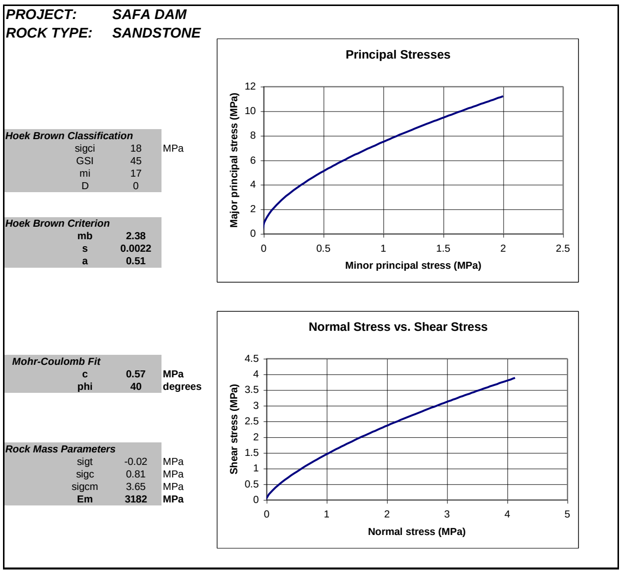

Fig. 4: Hoek-Brown failure criterion curve on sandstone.

Table 3: Shear strength parameters of rock masses of Safa Dam site based on Mohr–Coulomb failure criterion according to minor principal stress.

σ_3	Mudstone& Marl		Silty marl & siltstone		Sandstone	
	C (MPa)	φ(°)	C (MPa)	φ(°)	C (MPa)	φ(°)
0.05	0.02	27	0.05	40	-	-
0.1	0.03	23	0.07	36	-	-
0.25	0.06	16	0.13	28	0.18	32
0.5	0.1	13	0.2	23	0.28	27
0.75	0.13	11	0.26	20	0.37	25
1	0.15	10	0.3	18	0.49	23
1.25	0.17	8	0.36	17	0.51	22
1.5	0.19	8	0.4	16	0.58	20
2	0.23	7	0.48	14	0.69	19

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In Table 4 the results of estimation of modulus of deformation of rock masses of Safa Dam site are presented.

Table 4: Results of estimation of modulus of deformation of rock masses of Safa Dam site.

Rock mass	modulus of deformation (MPa)
Mudstone& Marl	300±50
Silty marl & siltstone	900±100
Sandstone stone	3000±500

Conclusion:

Rock mechanics Studies of Safa Dam site were conducted to find the shear strength parameters of rock masses which underlying the foundation of this dam and related structures. According to the defined requirements, due to blocky nature and existence of many joints in these rock masses, Hoek-Brown failure criterion was applied to estimate these shear strength parameters. It is revealed that rock masses on this site are weak and soft and their shear strength parameters, (which were estimated and presented in this research) show that even the strongest of them, which is sandstone is not categorized as hard rock, but because of the nature of stress exertion of earth fill dams, they have enough strength to provide stability of this dam.

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