GEOTECHNICAL CHARACTERIZATION AND MODELING OF A SHALLOW KARST BEDROCK SITE

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ABSTRACT

A site with shallow karst bedrock is characterized for engineering purposes by examination and testing of rock samples and by classification of the rock mass according to the RMR system. On the basis of six measurable parameters (intact rock strength, rock quality, joint spacings, joint conditions, groundwater conditions and joint orientations), RMR values were assigned to the rock mass. For analysis purposes, cave roof conditions were considered separately, as well as, incorporated with samples from other site areas. For all of the rock samples, an RMR of 65 was assigned. For the cave roof conditions, an RMR of 50 was assigned. On the basis of the RMR values, a failure criterion (or model) was established using the Hoek-Brown failure criterion. The authors believe that this is the first published application of this approach for evaluation of naturally occurring openings in rock (i.e., caves).

INTRODUCTION

The site of a proposed landfill is located within Valley and Ridge Physiographic Province of Tennessee, and is underlain by hard limestone and dolostone of the Knox Group and the Middle Ordovician Lenior Limestone. The site is rare in that the ground surface is mainly comprised of rock outcrops and, in some areas, a relatively thin soil layer underlain by rock. Naturally occurring caves and sinkholes are present. From the initial review of the site conditions, it was apparent that stability of the rock surface was critical to the permitting and design of the proposed landfill. To allow cave stability analysis, it was necessary to characterize the condition of the rock mass in engineering terms. Extensive examinations and tests were performed on rock core samples to classify the rock conditions according to the Rock Mass Rating (RMR) system (Bieniawski, 1973 and 1989). Failure criterion was developed for the site based on an empirical relationship between rock mass condition and rock mass strength proposed by Hoek and Brown (1980a; 1980b; 1988; and 1997).

SITE GEOLOGY AND HYDROLOGY

Structural elements of the site reflect the typical patterns of deformation found throughout the Valley and Ridge Province of East Tennessee. Bedrock strikes and the trends of fault traces and fold axes are northeast-southwest. Bedrock strike at the site varies between N 30° E and N 70° E. At least six joint sets were recognized by field survey. Neither faults nor joints are considered active, showing no obvious signs of recent crustal movements. They are primarily products of deformation associated with Paleozoic tectonic events hundreds of millions of years ago. Folds within the bedrock are integrally related to the faults, with fold axes oriented northeast-southwest. However, the style of folding varies across the site with northwest fold limbs tending to be steeper (almost vertical in places).

Cave orientations are consistent with bedrock rock strike (i.e., N 30° E and N 70° E), with beds dipping northwest and southeast depending on the location of the bedrock with respect to the folding. Cave orientations are also consistent with the six dominant joint sets measured in rock outcrops and cores.

The site exhibits karst development characterized by (1) numerous coalescing sinkholes, (2) closed depressions, (3) cave development, (4) sinking streams, (5) carbonate rock outcrops, and (6) conduit-fed spring discharges. Geologic structure imposes significant control on groundwater flow at the site, with solution channels (i.e., conduits) developed mostly in the direction of the bedding strike and rock mass permeability significantly higher in the northeast-southwest direction, as opposed to perpendicular to bedding. The larger dissolution features and caves occur within the vadose zone closer to the ground surface, and the intensity and frequency of the larger dissolutional features decreases with depth.

ENGINEERING CLASSIFICATION OF ROCK

Classifications systems allow site-specific rock conditions to be compared to a database of observed rock behavior (e.g., strength, stability). Early in the development of geotechnical engineering, Terzaghi (1946) recommended steel support for tunnel excavations based on empirical data by means of visual classification using terms such as "intact", "blocky", and "seamy". Since then, more sophisticated classification systems have been developed to characterize rock-masses for engineering purposes including Rock Mass Rating (RMR) system (Bieniawski, 1973 and 1989), the Q-system (Barton, et al., 1974), and the recently introduced Geologic Strength Index (GSI) (Hoek, 1998).

For the subject site, the near-surface rock was classified according to the RMR system based on examinations and testing performed on rock samples collected from 13 test borings broadly distributed over the site, including one test boring (designated PAC-7) drilled through the roof of an existing cave. The size designation of the rock cores were NQ with the exception of boring PAC-7 that was HQ size. The following six parameters are used to classify the rock mass according to the RMR system: (1) intact rock strength, (2) rock quality, (3) joint spacings, (4) joint conditions, (5) groundwater conditions, and (6) joint orientations.

Intact Rock Strength

The strength of intact rock core samples was estimated by uniaxial compressive tests (ASTM D3148). For this test, select samples were cut to a length-to-diameter ratio of approximately two, and their ends were machined to an acceptable flatness. To allow strain measurements during the application of the compressive load, strain gages were epoxied to the rock core samples. Incremental compressive loads were applied along the axis of the rock core sample until failure (i.e., fracture). The average uniaxial compressive strength (q_u) from the uniaxial compressive tests is 82 MPa (11,900 psi). The results of the uniaxial compressive tests on intact rock core samples are summarized in Table 1.

Table 1: Results of Uniaxial Compressive Tests

Boring	Depth (ft)	γ (pcf)	q_u (ksi)	$E/10^3$ (ksi)	ν
GB-3	20	169	16.7	7.5	.30
GB-4	5	174	16.3	12	.32
GB-4	10	174	-	7.3	.33
GB-6	5	168	9.7	10	.30
GB-9	20	169	9.7	-	-
GB-10	40	168	8.7	2.9	.32
EB-3	56	173	10.6	12.8	.30

γ – unit weight, E – elastic modulus, ν – Poisson's ratio

Rock Quality Designation (RQD)

Rock Quality Designation (RQD) is defined as the total length of pieces of sound rock core with length greater than 10 cm (4 inches) divided by the length of the core run (Deere, 1968). The average RQD for all of the rock core samples, weighted by the run length, is 83%. If the upper most core run is not considered (since the upper rock is typically irregular), the average RQD becomes 92%. According to Deere and Deere (1989), an RQD above 90% classifies the bedrock as "excellent" with respect to the stability of underground openings. Although the average RQD is representative of the general rock conditions, cave roof conditions may be better represented by the conditions at PAC-7. Test boring PAC-7 was drilled through the longest spanning cave roof and the resulting average RQD is approximately 36%. Space limitations preclude a complete presentation of the RQD measurements in this paper.

Joint Spacings

Joint spacings were quantified by measuring the distance between similar joint types (e.g., near-vertical joints, along-bedding joints, and cross-bedding joints) in the rock core samples supplemented by observations of rock outcrops. The majority of the joint spacings were relatively evenly distributed from 0.01 m to 1 m (0.2 ft to 6.6 ft). In comparison to the joint spacings from all of the borings, the joint spacings observed in the rock samples from PAC-7 are generally consistent with the rest of the site. Table 2 summarizes the results of the joint spacing measurements performed on rock core samples.

Table 2: Summary of Joint Spacings

	Joint Spacing Categories (Bienawski, 1989)				
Location	< 60mm	60-200mm	200-600mm	0.6-2m	>2m
PAC-7	14%	19%	28%	34%	5%
Site	13%	23%	30%	27%	7%

Joint Conditions

The condition of joints includes roughness, filling, weathering and separation. Examination of rock core samples indicates that slightly more than one-half of the joints (approximately 53%) were healed with calcite filling. The remaining joints exhibited a range of roughness, degree of weathering and separation. An indication of the high strength of the healed joints was that, in many cases, laboratory testing indicated that mechanical breaks in the core occurred through continuous rock rather than along nearby healed fractures.

Table 3: Summary of Joint Roughness and Weathering

	Joint Condition Designation						
Location	Healed	S,U	S,M	S,H	R,U	R,M	R,H
PAC-7	27%	1%	8%	4%	-	2%	56%
Site	53%	5%	7%	<1%	1.4%	13%	20%

Healed – A bonded joint with filling (e.g., calcite)

S,U – smooth, unweathered
S,M – smooth, moderately weathered
S,H – smooth, highly weathered
R,U – rough, unweathered
R,M – rough, moderately weathered
R,H – rough, highly weathered

Comparison between PAC-7 and the results of all of the borings indicates that PAC-7 has a significantly higher percentage of weathered discontinuities. The joint conditions based on examination of the rock samples are summarized in Table 3 and Table 4.

Table 4: Summary of Joint Separation

Location	No Separation	< 1mm Separation	>1mm Separation
PAC-7	24%	20%	56%
Site	52%	24%	24%

Groundwater Conditions

Considering the extensive groundwater and geo-chemistry studies performed at this site, a thorough discussion of the groundwater flow at this site will be published at a later date. In summary, groundwater flow within the karst aquifer occurs below the depth pertinent to this evaluation (i.e., the depth of the caves). Furthermore, stormwater control measures will be implemented during construction of the proposed landfill, and, once in place, the landfill bottom liner will preclude the downward flow of surface water. For these reasons, the cave conditions are expected to be moist, but not inundated.

Joint Orientations

The RMR classification includes an adjustment for the orientation of joints. This adjustment considers steeper dip angles as less favorable. It also considers an orientation of the underground opening parallel to strike as less favorable. The latter adjustment is more applicable to man-made openings (e.g., tunnels) in which the orientation of the opening is less variable than naturally occurring caves. For purposes of determining a failure criterion, a rating of “fair” was conservatively assigned for the orientation of the joints.

Table 5: Site-Specific Rock Mass Rating

RMR Parameter	PAC-7	Site
Strength of Intact Rock	8 (assumed)	8
RQD	7	18
Joint Spacings	9	9
Joint Conditions	16	20
Groundwater	15	15
Joint Orientation	-5	-5
RMR	50	65

Rock Mass Rating

On the basis of the six parameters (i.e., intact rock strength, rock quality, joint spacings, joint conditions, groundwater conditions, and joint orientations), the RMR values shown in Table 5 were assigned to the rock mass at the subject site. It is useful to consider the results for PAC-7 separately (as a conservative estimate of rock mass strength) as well as incorporated with the other rock samples. For all rock samples, an RMR of 65 was assigned. For PAC-7, an RMR of 50 was assigned.

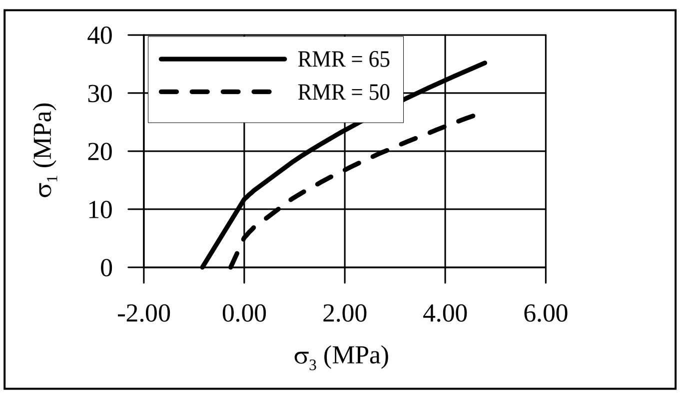

Figure 1: Site-Specific Hoek-Brown Failure Criterion

HOEK-BROWN FAILURE CRITERION

Using the RMR values determined for the subject site, the failure criterion shown in Figure 1 was established for use in cave stability evaluations. The Hoek-Brown failure criterion is an empirical approximation of the strength of jointed rock masses, and is defined, in terms of the major and minor principal stresses, by the following equation:

$$\sigma_1 = \sigma_3 + (m q_u \sigma_3 + s q_u^2)^{1/2}$$

where σ_1 and σ_3 are the major and minor principal stresses at failure, respectively, q_u is the uniaxial compressive strength of the intact rock, and m and s are empirical constants which depend on rock type and condition of the rock mass. As suggested by Hoek and Brown (1980), the dimensionless empirical strength constants m and s were estimated using the following correlations with the RMR:

$$s = \exp\left(\frac{\text{RMR} - 100}{9}\right) \qquad m = m_i \exp\left(\frac{\text{RMR} - 100}{28}\right)$$

where the dimensionless constant m_i is determined by triaxial testing. From statistical analysis of published triaxial strength data, Brady and Brown (1993) presented the values of m_i as a function of rock type. For the carbonate rock types present at this site, a value of 7 was assigned to m_i.

CONCLUSIONS

A site with shallow karst bedrock is characterized by examination and testing of rock samples, and by classification of the rock mass according to the RMR system. Using the RMR, a failure model was established using the Hoek-Brown failure criterion. The authors believe that this is the first publish application of this approach for the evaluation of naturally occurring caves.

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