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RESEARCH PAPER

A technique for estimating permeability of a randomly fractured rock mass

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Abstract Extensive field and laboratory testing programs were performed to develop a relationship between the permeability of a fractured limestone and the core recovery values. The studied limestone does not encompass any jointing system but is consistently and randomly fractured. Nineteen in situ falling head permeability tests were carried out to measure permeability of the fractured rock mass at a representative study area. Analysis of test results has led to the formulation of an empirical equation that estimates the permeability of the rock mass in terms of its solid core recovery value and the permeability of the fractures filling material. Unlike the existing equations for estimating the permeability of rock masses, the proposed equation is simple and utilizes parameters that can be easily determined in regular geotechnical field and laboratory investigations. A technique is also presented to estimate the permeability of a rock layer, the quality of which significantly changes with depth, using the proposed equation that utilizes a single value of core recovery. Analysis of well-documented pumping test results supported the validity of the proposed equation and technique.

Keywords Core recovery · Dewatering · Fractured rock · Limestone · Permeability · Random fractures · Rock masses

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1 Introduction

The coefficient of permeability of rock masses is a crucial parameter in several civil engineering activities such as the construction of dams and the design of rock dewatering systems. Most rocks have a facility for water transmission along discontinuities such as fissures and joints. These discontinuities are usually filled with materials whose properties differ from those of the rock to either side. The filling materials may consist of soils, products of calcareous rock leaching deposited by ground water flow, loose rock fragments created from tectonic activities, or rock flour formed in-place due to weathering of the discontinuity surfaces. Because most of the water flows along open and filled discontinuities rather than through the rock pores, the permeability of rock mass is mainly controlled by the number and orientation of joint sets, the degree and connectivity of fracturing, aperture of fractures, and type of fractures filling material. As a result, in situ permeability tests usually give much higher and more realistic permeability values than laboratory tests on small rock specimens. However, in situ permeability tests are relatively expensive and time consuming. As a result, permeability estimation using numerically derived expressions or empirical relations is frequently proposed.

Louis [6] presented the following expression to estimate the coefficient of permeability of rock in the direction of a set of continuous joints (k_d):

$$k_{\mathrm{d}} = \left(\frac{a}{b}\right) k_j + k_p \tag{1}$$

where a is the mean aperture, b is the mean spacing, k_j is the coefficient of permeability of the joint and k_p is the primary permeability of the rock matrix, often negligible.

Expressions and charts for estimating directional permeability of rock masses as a function of the mean aperture and spacing of joints were proposed by other researchers such as Snow [11], Hoek and Bray [5], and Attewell and Farmer [1]. Based on numerical modeling, Oda [8], Oda et al. [9], Zhang et al. [14] and Price and Indraratna [10] suggested estimating the permeability of fractured rock through formulating a permeability tensor in terms of length, aperture, orientation and connectivity of cracks. Modeling was also used in estimating the permeability of fractured rock mass at different stress levels [3, 7]. However, the use of these equations and charts is limited in practice because of being restricted to estimating the directional permeability through one set of continuous joints and/or the need for complicated mathematical modeling and advanced geological survey in describing the features of discontinuities.

Estimating the permeability of the rock mass has become a major task in constructing hundreds of towers that have been built along the coast of the Arabian Gulf states that are witnessing one of the fastest economical and consequently construction growth rates. As shown in the subsequent section, dewatering for construction along the coast line involves pumping water out of a fractured limestone top layer. Inspection of open pits, construction excavations and boreholes showed that this limestone layer does not encompass any jointing system but is consistently and randomly fractured. The fractures are usually filled with coarse grained soil. The major goal of this study is to develop a simple technique for preliminary estimation of permeability of this rock mass to accelerate the construction process by reducing the number of relatively time consuming and expensive pumping tests usually carried out for this purpose. Because of the structural nature of the studied limestone, the technique involves estimating its mass coefficient of permeability (k_m) in terms of fractures filling material coefficient of permeability (k_f) and an index property that is usually available through rock boring. An extensive field and laboratory testing program was performed on rock and soils of a representative study area to develop this technique and check its validity.

2 Geotechnical considerations of the study area

A representative area on the coast of Doha, capital of the state of Qatar, was chosen for this study. The entire study area is underlain by fractured limestone of the Eocene age (Fig. 1). The area comprises a reclaimed land built from an original, low lying coastline. A mixture of sand, gravel and limestone fragments tipped from the landward side and dredged from the adjacent sea floor has been used for the reclamation, which spreads some distance inland from the

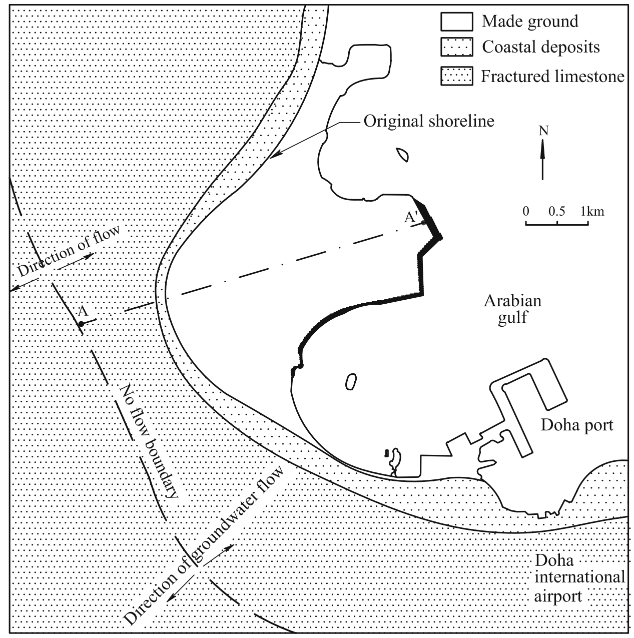

Fig. 1 Outcrop geology and groundwater flow direction for the study area

original coastline (Fig. 1). The fill or made ground overlies and largely conceals the silt and sand coastal deposits that still outcrops inland of the fill. Where the limestone emerges from beneath the cover of fill and coastal deposits, there is a distinct break of slope (Fig. 2). The limestone is frequently interrupted at EL–22.00 m by a layer of Midra shale that varies in thickness from 1.0 to 5.0 m. The shale acts regionally as a confining layer, preventing large scale vertical movement into and out of the overlying limestone. There is free regional connection between the fractured limestone and the overlying coastal deposits and fill.

As shown in Figs. 1 and 2, the groundwater flow pattern indicates the occurrence of a groundwater mound lying under the south-west part of the study area. The water passes laterally from the fractured limestone into the overlying materials approximately along the original shoreline developing high groundwater levels that need to be lowered for several construction activities in this area. This lowering usually involves dewatering the top layer of

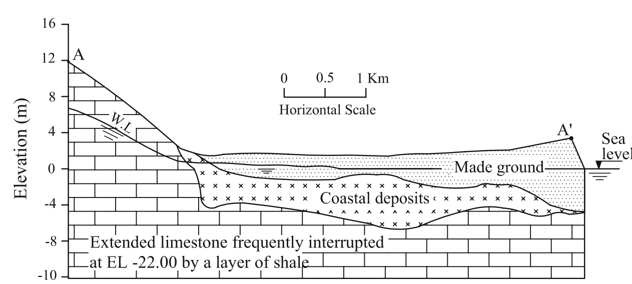

Fig. 2 A simplified geological cross section A–A′

the fractured limestone. Due to the absence of any joint set, and the existence of randomly fully filled fractures, permeability of such layer mainly depends on its degree of fracturing and the type of fractures filling material. As a result, this study aimed to present a simple technique for estimating the permeability of the rock mass as a function of parameters that reflect the effect of these two features.

To include the effect of degree of rock fracturing, three indices that are commonly determined during rock coring were considered. These indices are rock quality designation (RQD), total core recovery (TCR) and solid core recovery (SCR). They are defined in BS 5930 [2] as the sum length of all core pieces that are 10 cm or longer, the length of the total amount of core sample recovered and the length of core recovered as solid cylinders, respectively, expressed as a percentage of the length of core run. The applicability of utilizing each of these indices in estimating the permeability of rock mass is checked as shown in the subsequent section.

The permeability of the fractures filling materials of rock in the study area was estimated based on their grain-sizes. Figure 3 shows the range of grain-size distribution of 12 filling material samples taken from the walls of four different open construction excavations in the study area. It is seen that the materials exhibit a relatively narrow range of grain-size distribution representing sand and gravel-size particles with traces of fines with an average effective diameter (D_{10}) of 0.014 mm. Accordingly, the average coefficient of permeability of these materials estimated using Hazen's formula was 0.02 cm/s. This value was utilized in analyzing the results of the in situ permeability tests described below.

3 Permeability tests and estimation proposed technique

Nineteen in situ falling head permeability tests were carried out at selected boreholes drilled at different locations of the study area to measure the permeability of the fractured rock mass. The tests were performed according to the procedure described in BS 5930 [2]. Figure 4 shows a typical test set up and the associated determined permeability and rock core recovery values. In all tests, the borehole casing was socketed at least 2.0 m in the rock layer. An open hole of a depth of 0.5 m was left for water dissipation during tests. The averages for RQD, TCR, and SCR values measured in a rock depth of 2.0 m below the top of this hole were considered in the permeability correlation analysis.

The measured coefficients of permeability of rock mass were plotted against the associated RQD and TCR values in Fig. 5. It is seen that the large data scatter revokes the possibility of correlating any of these two rock indices to the permeability of rock mass. On the contrary, plotting these permeability coefficients against the associated SCR values showed a clear trend of decreasing permeability

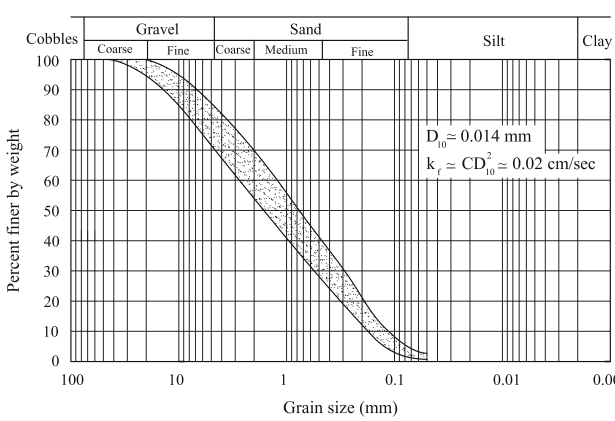

Fig. 3 Range of grain-size distribution for the filling materials of rock fractures

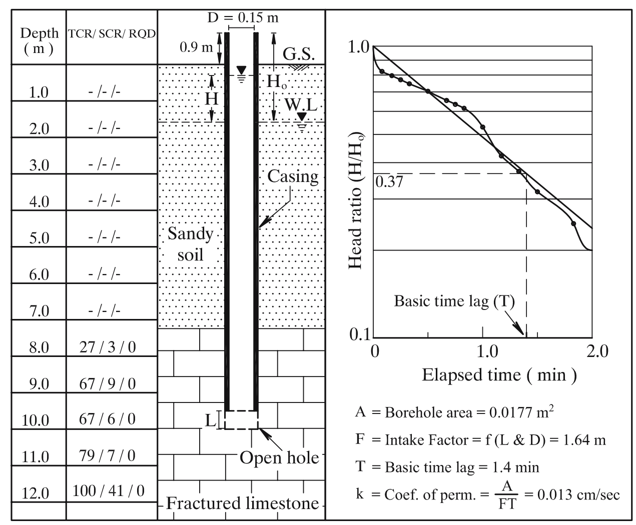

Fig. 4 Typical in situ falling head permeability test set up and results used in the analysis

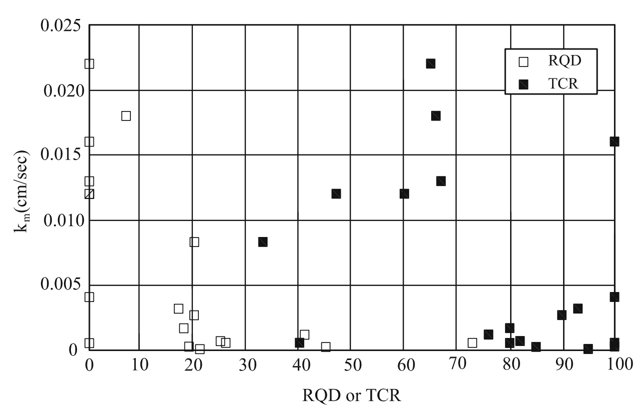

Fig. 5 Measured coefficients of permeability of rock mass (k_m) plotted against the associated values of rock quality designation (RQD) and total core recovery (TCR)

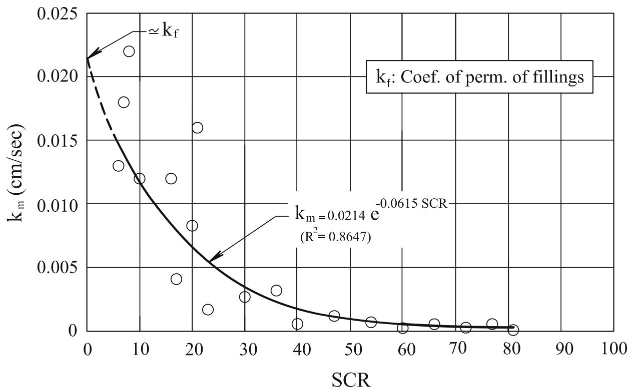

Fig. 6 Relation between the mass permeability (k_m) and the solid core recovery (SCR) for a randomly fractured rock

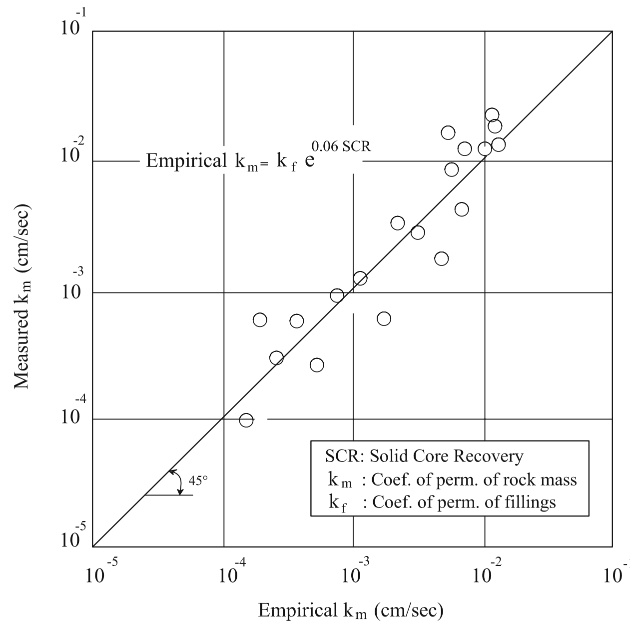

Fig. 7 Relation between measured and estimated coefficients of permeability for randomly fractured rock masses

with the increase of rock SCR (Fig. 6). This may be attributed to the definition and consequently to the method of calculating the SCR that does not include the long recovered pieces only, or all of the recovered materials even those considered as fillings as in the cases of RQD and TCR calculation, respectively, which better reflects the facility of water transmission along the fissured rock.

The best fit for the permeability coefficients and the associated SCR values can be represented mathematically by an exponential function with a regression coefficient (R^2) of 0.8646 (Fig. 6). It should be noticed that extending this function to SCR of zero, which represents a totally fractured rock, logically reads a value of rock mass permeability which is close to that estimated for the filling materials in the previous section, i.e., 0.02 cm/s (Fig. 6). Consequently, it was decided to simplify the correlation function shown in Fig. 6 and estimate the coefficient of permeability of the randomly fractured rock mass using the following equation:

$$k_m = k_f \mathrm{e}^{-0.06\ \mathrm{SCR}} \tag{2}$$

Permeability values estimated using the proposed equation were plotted against those measured in the corresponding in situ falling head permeability tests and shown in Fig. 7. It is seen that the equation yields estimated permeability values that are in reasonable agreement with the measured ones. Unlike the existing equations for estimating the permeability of rock masses, the proposed equation is simple and utilizes parameters that can be easily determined in regular geotechnical field and laboratory investigations. The scatter of data points shown in Figs. 6 and 7 is acceptable considering the significantly wide range of permeability values for different soil and rock types. In addition, the scatter is less than that of widely recognized correlations of rock properties such as the relation between RQD and the deformation modulus of rock masses first presented by Coon and Merritt [4] and recently expanded to include low RQD values by Zhang and Einstein [13]. It should be noted that Eq. (2) was developed and recommended for estimating the mass permeability of randomly fractured rocks. As a result, utilizing this equation in a case of having a set of continuous joints leads to an underestimation of the rock mass directional permeability that is better estimated using formulas such as Eq. (1).

Construction of several engineering projects requires the estimation of permeability for randomly fractured rock layers, the quality of which significantly changes with depth, i.e., SCR values have wide range within the considered depth. For such cases, utilizing Eq. (2) in estimating the rock mass permeability requires dividing the layer into horizontal sub-layers where the SCR values of each are in the same range. The coefficient of permeability for each sub-layer can then be calculated using Eq. (2). Therefore, the rock mass permeability can be determined by either taking the weighted mean or taking the weighted harmonic mean of the sub-layers permeability values, in case of having horizontal or vertical flow condition, respectively [12].

4 Verification of the study results

The validity of the proposed technique for estimating the permeability of the randomly fractured rock layers is checked using well-documented pumping test results. This is done through comparing the rock mass coefficient of permeability that is calculated from the pumping test to that estimated utilizing the technique described earlier.

Figure 8 shows the subsurface profile and pumping test set up used in this analysis. A pumping well having a diameter of 0.25 m was installed to a depth of 22 m, i.e., down to shale surface, below the ground surface. Twelve piezometers were installed at 5 m distances from the pumping well in four directions set at 90° to the well to a depth of 20 m. Water levels recorded in the piezometers were plotted in Fig. 9 forming the cone of depression during a steady state flow resulting from a pumping rate of 50 m^3/h.

As a typical stratification in the study area, the fractured rock layer at the test location is overlain by a 1.1 m deep layer of coastal deposits and a 2.2 m surface layer of fill or made ground. Water level is encountered at a depth of 2 m. As a result, the pumping developed a water flow through three layers, the permeability values of which were estimated for the purpose of this study. Permeability of the top layers, i.e., the fill and coastal deposits, were estimated from grain-size distributions of 63 and 48 samples, respectively. Figure 10 shows the frequency of those estimated coefficients for both soils. Based on these frequency distributions, geometric means of 0.05 and 0.03 cm/s were

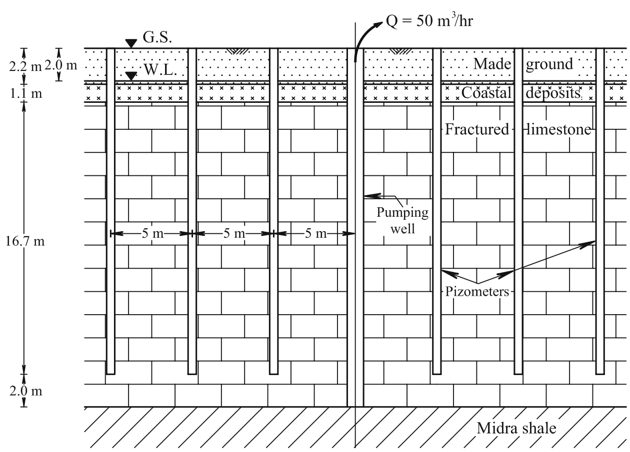

Fig. 8 Geological profile and pumping test set up

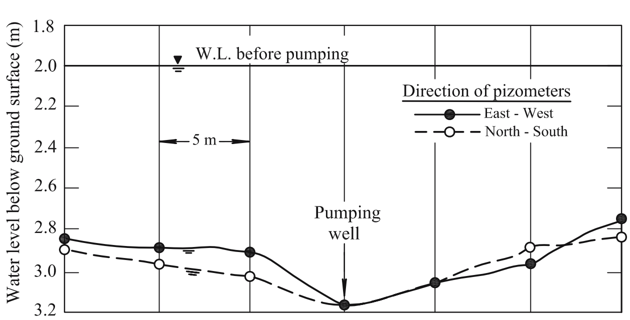

Fig. 9 Cone of depression for the pumping test

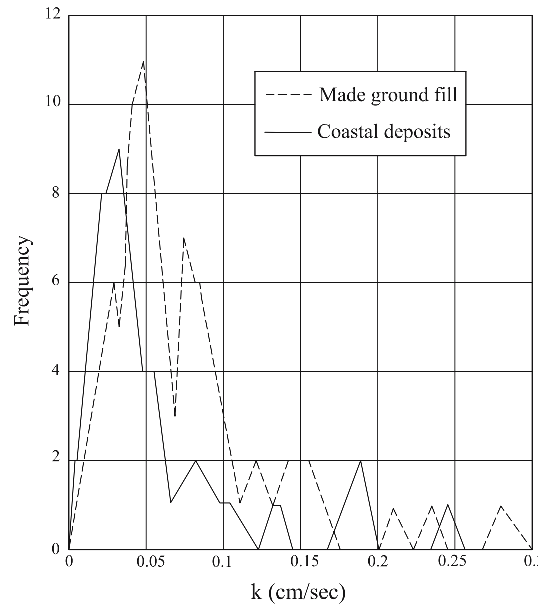

Fig. 10 Frequency of the estimated coefficient of permeability for the made ground fill and coastal deposits

assigned for the coefficients of permeability of the fill and coastal deposits, respectively. Considering these permeability values, the pumping rate, the monitored cone of depression and an approximately horizontal flow direction during the test, a value of 0.004 cm/s was calculated for the average coefficient of permeability for the fractured rock layer. This value was determined using the formula presented in BS 5930 [2] for pumping test in unconfined aquifer condition.

The technique proposed in this study was also used to estimate the average permeability of the fractured rock layer at the test location. Accordingly, the 20 m-thick rock layer was divided into four sub-layers based on their measured SCR values. The coefficient of permeability for each sub-layer was then estimated using Eq. (2). The thicknesses, average SCR values and estimated permeability values of the sub-layers are shown in Fig. 11. The coefficient of permeability of the rock layer was calculated as the weighted mean of the permeability values of sub-layers using the following equation:

$$k_m = \sum_{i=1}^{n} \frac{H_i}{H} k_i \qquad (3)$$

where k_i, H_i and H, are the sub-layer coefficient of permeability, sub-layer thickness and total thickness of rock layer, respectively. This yielded an estimated coefficient of permeability of the rock layer of 0.003 cm/s. The close agreement between the measured and estimated coefficients of permeability of the rock layer supports the validity of the proposed technique.

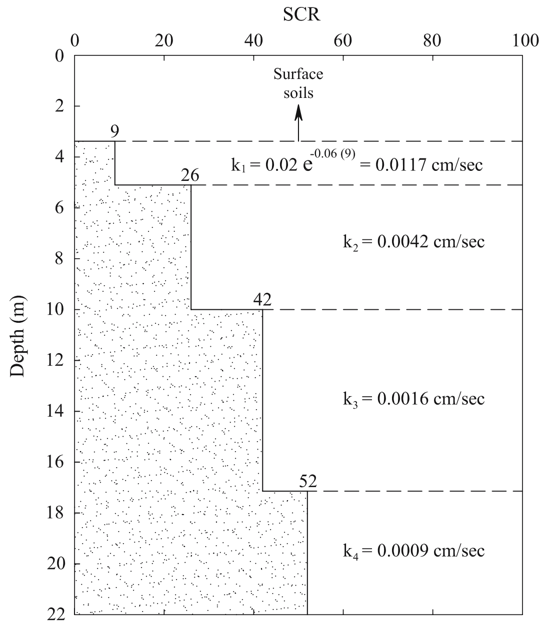

Fig. 11 Thicknesses and the coefficients of permeability of limestone sub-layers determined based on measured SCR values

5 Conclusions

This study was initiated to help in estimating the permeability of a fractured limestone usually dewatered for construction of multistorey basements of towers that have been extensively built along the coast of the state of Qatar. The limestone layer involved in such activity does not encompass any jointing system but is consistently and randomly fractured. Fractures are filled with coarse grained soil. To establish a simple method for the preliminary estimation of the permeability of this rock mass, results of 19 in situ falling head permeability tests were used to develop a relationship between the coefficient of permeability of rock mass and its core recovery values. Plotting the solid core recovery values against the corresponding measured coefficients of permeability of fractured rock mass yielded a simple relationship that is a function of the permeability of the fractures filling material. This analysis has led to proposing an equation for estimating coefficient of permeability of the randomly fractured rock masses in terms of easy-to-measure parameters. The proposed equation utilizes a single value of core recovery which in turn usually changes with depth for the same site. As a result, a technique is presented to estimate the rock mass permeability required for designing dewatering system for construction excavations through a rock layer with different core recovery values. The rock mass permeability measured in a well-documented pumping test was compared to that estimated utilizing the proposed technique. The close agreement between the measured and estimated permeability values supports the validity of the proposed equation and technique. Such a technique could be utilized for the preliminary estimation of permeability of any rock mass, the structure of which is similar to that of the limestone described in this study.

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