The Point Load Test in the Persian Gulf Carbonate Rocks

L'essai du charge ponctuelle pour le golfe Persique roche calcaire

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ABSTRACT

The Point Load test is an index test used to provide an economical and quick estimate of the Uniaxial Compressive Strength (UCS) especially for highly fractured rock cores that with geometry not suitable for UCS testing. This is usually done using an empirical conversion factor (K) between the Point Load Index of 50-mm diameter rock cores (Is_{50}) and the UCS. A value of the K factor equal to 24 has been traditionally used in the rock mechanics literature based on the work of Broch and Franklin (1972). Several studies have disputed the applicability of this universal value, especially for weak rocks, and hence developed alternative values for the K factor. An attempt was made in this study to evaluate the applicability of the existing Is_{50}-UCS correlations to carbonate rocks in the Persian Gulf area. This was based on extensive data sets collected from various locations in several countries in that area. The values of K factor were determined using linear regression analyses and were generally in the ranges of 5.4 to 8.6, which is considerably smaller than the universal value of 24. Statistical/probabilistic techniques were used to quantify the uncertainty in the K values and to develop risk based correlations for these rocks. Conglomerate showed the greatest uncertainty in the K value while sandstone and siltstone showed the least uncertainty. Risk-based values of K associated with 2% probability of unsatisfactory performance were found to range from 3.1 to 6.5.

RÉSUMÉ

L'essai du charge ponctuelle est un index de test utilisé pour fournir une estimation rapide et économique de la Résistance à la compression uniaxiale (UCS) spécialement pour les noyaux très fracturée rock que la géométrie ne conviennent pas pour la NGC essais. Cela se fait habituellement en utilisant un facteur de conversion empiriques (K) entre le point d'indice de charge de 50 mm de diamètre, des carottes de roche (Is50) et de l'UCS. La valeur du facteur K égal à 24 a été traditionnellement utilisé dans la mécanique des roches de littérature basée sur les travaux de Broch et de Franklin (1972). Plusieurs études ont contesté l'applicabilité de cette valeur universelle, en particulier la faiblesse des roches, et donc développé d'autres valeurs pour le facteur K. Une tentative a été faite dans cette étude pour évaluer l'applicabilité de l'actuel Is50-UCS corrélations de roches carbonatées dans la région du golfe Persique. Elle était fondée sur des ensembles de données collectées à partir de plusieurs endroits dans plusieurs pays dans ce domaine. Les valeurs du facteur K ont été déterminés en utilisant des analyses de régression linéaire et ont été généralement dans la fourchette de 5,4 à 8,6, ce qui est considérablement plus petit que 24 valeurs de l'universel. Statistiques / techniques probabilistes ont été utilisés pour quantifier l'incertitude dans les valeurs de K et de mettre au point des corrélations basée sur le risque pour ces roches. Conglomerate a montré la plus grande incertitude dans la valeur de K, tout en grès et argiles a montré le moins d'incertitude. Des risques fondée sur des valeurs de K associée à 2% de probabilité de non satisfaisants ont été trouvés à la gamme de 3,1 à 6,5.

Keywords : *rock mechanics, carbonate rocks, point load test, uniaxial compressive strength, probabilistic techniques*

1 INTRODUCTION

The Uniaxial Compressive Strength (UCS) of rock is a key design parameter for various geotechnical applications in rocks. Since its introduction in the 1970s, the Point Load test has been regarded as an alternative to the UCS test that can provide indirect estimates of the UCS at a lower cost and with less sample preparation. The Point Load test has shown particular merits in highly fractured rocks where it is difficult to obtain high quality rock cores with geometry suitable for UCS testing.

In the modern rock mechanics practice, the UCS is estimated from the Point Load Index (Is) using a universal conversion factor (K) equal to 24, following the recommendations of Broch and Franklin (1972). Several subsequent studies have shown that the value of the conversion factor can be substantially smaller than the universal value (24), especially for weak sedimentary rocks, which might result in an engineering design on the unsafe side. Therefore, there is a need to develop more reliable correlation between the UCS and Is especially for the carbonate rocks commonly found in the Persian Gulf countries. These rocks have been the subject of limited studies to evaluate the applicability of the universal conversion factor (K). This has become more critical with the construction boom in the area and the launch of several mega-scale projects that invariably involve design and/or construction in carbonate rocks.

The main objective of the current study is to evaluate the applicability of the universal conversion factor to the Persian Gulf carbonate rocks, such as limestone, siltstone, sandstone, and conglomerates. This was carried out through collecting rock testing data from several projects in Bahrain, Qatar, and the United Arab Emirates (UAE), where the geological conditions are relatively similar. An attempt is also made to develop region-specific K values for these rocks and to evaluate the uncertainty in these values using probabilistic techniques. This was accomplished by the introduction of risk-based estimates of K based on 2% probability of unsatisfactory performance.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-372

2 GELOGY OF THE PERSIAN GULF COUNTRIES

The UAE, Qatar, and Bahrain are part of the Persian Gulf countries and occupy the east part of the Arabian Platform, a body of continental rock that has remained tectonically stable since the Cambrian Period more than 500 million years ago. The geologic history of these countries has been primarily a history of the advance and retreat of the sea with sediments accumulated with time on the coast and on the continental shelf. Limited pre-Permian exposures in the area reveal fine-grained, shallow water terrigenous sediments (silt and shale). Later, in the tropical Mesozoic seas, thick sequences of carbonate rocks, such as calcareous sandstones and conglomerates, limestone and dolomites. Most of the surface of the present day in the area is a sand desert, a geologically recent feature usually the result of prolonged sub-aerial erosion and deposition in an arid environment. In addition, some parts of these countries are covered with sabkha crusts and sand dunes with patterns and alignments that vary considerably from one part to another.

3 BACKGROUND ON THE UCS-IS CORRELATIONS

The first attempt to estimate rock strength from the results of the Point Load test was carried out by Broch and Franklin (1972) where the Uniaxial Compressive Strength (UCS) of rock was correlated to the Point Load Index (Is_{50}). The Is_{50} was defined as the point load index corrected to a standard equivalent diameter of 50 mm. The correlation between the UCS and Is_{50} was in the form:

$$UCS = K \cdot Is_{50} \qquad (2)$$

The conversion factor K was determined using linear regression analysis of data collected for 15 different rock types; and was found to be about 24. Since then, this value has been regarded as a universal value applicable to all rock types in most rock mechanics text books. It should be noted, however, that significant uncertainty is usually associated with the application of the universal factor (K), especially for soft rocks. This can be attributed to the following factors:

- The correlation was based on the median value of the UCS and $(Is)_{50}$ for each rock type and hence overlooked the effect of extreme value statistics;
- The correlation was mainly developed for strong and very strong rocks with UCS values of 20 MPa or more; and
- No information was provided on the rock types used to develop the factor K.

Several subsequent studies have investigated the reliability of the universal conversion factor (K) and its applicability to different rock types. Bieniawski (1975) showed that the error in the universal conversion factor (K) can be up to 20% for several rock types. Hassani (1980) proposed a K value of 29 based on rock testing results of different rock types in the UK. Chau and Wong (1996) showed that the K value is about 12.5 for Hong Kong rocks. The considerable variation in the K value from one location to another across the world questioned the applicability of a universal conversion factor and suggested that the value of the conversion factor may depend on rock type and origin.

Recent studies have, therefore, focused on examining the variation of the conversion factor (K) from one rock type to another. Read et al. (1980) and Forster (1983) indicated that the K values in sedimentary rocks were typically smaller than igneous rocks; and generally ranged from 14.5 to 16. More rock type-specific studies have shown that the K value for different sedimentary rocks can be as follows:

- Sandstone: 17.3 to 27 (Brautigam et al. 1998), 17.4 (Vallejo et al. 1989), 18 (Das 1995), and 20.2 to 20.6 (Rusnak and Mark 2000);
- Siltstone: 14.7 (Das 1995) and 19.6 to 20.8 (Rusnak and Mark 2000);
- Claystone: 11.1 (Akram and Bakar 2007), 12.6 (Das 1995), 12.6 (Vallejo et al. 1989), and 20.2 – 22.4 (Rusnak and Mark 2000); and
- Limestone: 11.1 (Akram and Bakar 2007), 17.7 to 27.1 ((Brautigam et al. 1998), and 21.9 (Rusnak and Mark 2000)

Limited studies have been carried out to determine the value of the conversion factor (K) for the carbonate rocks in the Persian Gulf area. These rocks are typically characterized by high calcium carbonate contents and high void ratio and hence relatively low dry density compared to other rock types. These special characteristics, therefore, have made the need to examine the UCS-Is_{50} correlation more compelling, especially with the numerous engineering applications in the area that deal with carbonate rocks.

4 DEVELOPMENT OF UCS-IS CORRELATIONS FOR THE PERSIAN GULF COUNTRIES

Rock testing data on carbonate rocks, such as conglomerate, sandstone, siltstone, and limestone, was collected from various projects in the UAE, Qatar, and Bahrain in the Persian Gulf area. The conglomerate, sandstone, and siltstone were mainly calcareous with calcium carbonate contents ranging from 35 to 62%. The collected data included UCS testing on high quality rock cores, obtained using double or treble core barrels. The Point Load test was carried out on either the remnants of the UCS cores or rock samples immediately below/above the UCS samples. Outliers were identified as test data that fall outside the range of the mean plus/minus double the standard deviation ($m \pm 2\sigma$); and were excluded from the data set used in the analyses.

Cross plots between the UCS and Is_{50} were developed for the four rock types, as shown in Figure 1 for the limestone. Linear regression analyses were used to estimate the values of the conversion factor (K) that best fits the collectd data. The estimated K values were about 5.4, 6.2, 8.6, and 6.5 for the conglomerate, sandstone, siltstone, and limestone, respectively, as shown in Table 1. These values are significantly smaller than the universal value (24) proposed by Broch and Franklin (1972) and also smaller than other typical values cited in the geotechnical engineering literature for similar rocks. This could be attributed to the high calcium carbonate contents in these rocks which results in stronger cementation and hence higher tensile strength. This will, in turn, results in smaller ratio between the UCS and Is_{50} since the point load test usually causes rock samples to fail in tension (Hoek 1977). The smallest K factor (5.4) was that for conglomerate due to the presence of gravel/boulder in the rock matrix, which might result in an over-estimated point load index. The coefficients of determination (R^2), as a measure of the scatter in the collected data, associated with the estimated K values generally ranged from 0.53 to 0.75.

Table 1. Summary of conversion factors for different rock types.

Rock Type	Conglomerate	Sandstone	Siltstone	Limestone
K	5.4	6.2	8.6	6.5
K_2	3.1	5.1	6.5	5.3
K_2/K	0.57	0.82	0.76	0.82

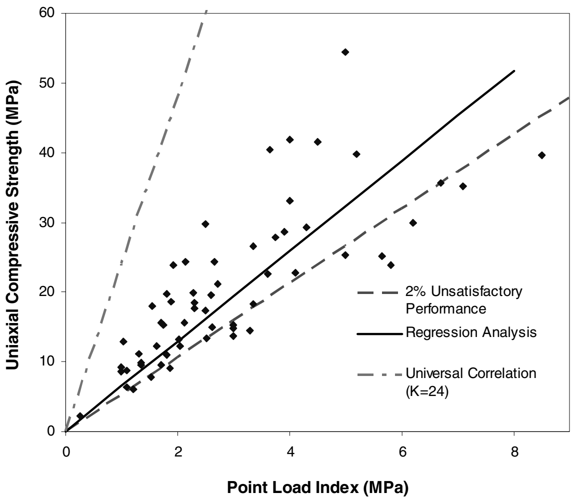

Figure 1. UCS-$(Is)_{50}$ correlation for limestone.

5 UNCERTAINTY IN THE UCS-IS CORRELAIONS

An attempt was made in this study to quantify the uncertainty in the developed UCS-Is_{50} correlation. This was carried out through the treatment of the conversion factor (K) as a random variable. The statistical characteristics of the random variable (K) were determined for each rock type and are shown in Table 2. The mean values of K were 7.2, 9.5, 10.3, and 7.5 for the conglomerate, sandstone, siltstone, and limestone, respectively. The coefficients of variation were 0.54, 0.44, 0.37, and 0.31 for the conglomerate, sandstone, siltstone, and limestone, respectively. The lognormal distribution was found to best-fit the probability distribution function (PDF) of the random variable (K) for the four rock types with 0.05 level of significance, as determined from the Chi Square test.

Table 2. Statistical characteristics of the random variable (K).

Rock Type	Conglomerate	Sandstone	Siltstone	Limestone
Mean	7.2	9.5	10.3	7.5
Standard Deviation	3.9	4.2	3.8	2.3
COV	0.54	0.44	0.37	0.31
PDF Type	Lognormal Distribution			

The risk level (uncertainty) in the K values estimated using regression analysis, as presented in Table 1, was determined by calculating the probability of unsatisfactory performance when using these values in the Limit State Design method. This was carried out by assuming that the K values presented in Table 1 represent the characteristic (design) values and hence were divided by a partial safety factor equal to 1.4, as per the recommendations of Eurocode 7: Part 1 (1997). This resulted in factored K values (K_r) equal to 3.9, 4.4, 6.1, and 4.6 for the conglomerate, sandstone, siltstone, and limestone, respectively. The probability of unsatisfactory performance (P_F) was defined as the probability that the value of the random variable K will be smaller than the factored K values (K_r), as shown in Figure 2 for the sandstone. This resulted in probability of unsatisfactory performance (P_F) equal to 16.5, 5.4, 10.2, and 7.6% for the conglomerate, sandstone, siltstone, and limestone, respectively. These values are relatively high/unsatisfactory when compared with typical admissible probabilities of unsatisfactory performance used in the geotechnical literature, as outlined below. This implies that using K estimates based on (best-fit) regression analysis may be on the unsafe (non-conservative) side. It can be, therefore, concluded that there is a need to develop theoretically sound risk-based estimates of the K factor that take the uncertainty/scatter of field data into consideration and would result in more acceptable probabilities of unsatisfactory performance.

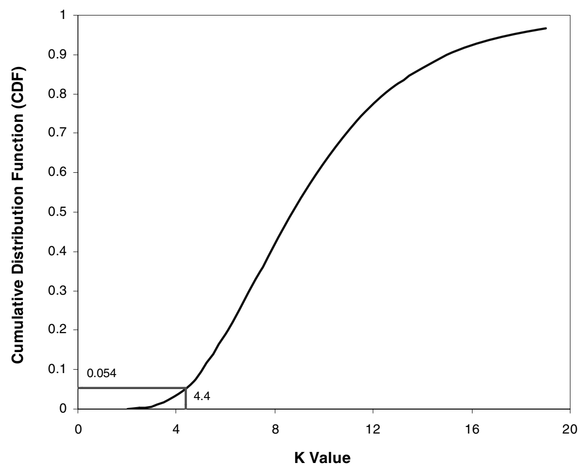

Figure 2. Determination of the probability of unsatisfactory performance for the best-fit estimate of the K factor for sandstone.

The cumulative distribution function (CDF) of the K factor for each rock type was used to develop a correlation between the value of K and the associated probability of unsatisfactory performance, as shown in Figure 3. The K value increased in a linear fashion with higher probability of unsatisfactory performance (P_F) on a log-log scale, which can be expressed in the following form:

$$\text{Log}(K) = A\,\text{Log}(P_F) + B \qquad (3)$$

Where A and B are empirical factors obtained from regression analysis. The values of A and B for the four rock types considered in this study are presented in Table 3.

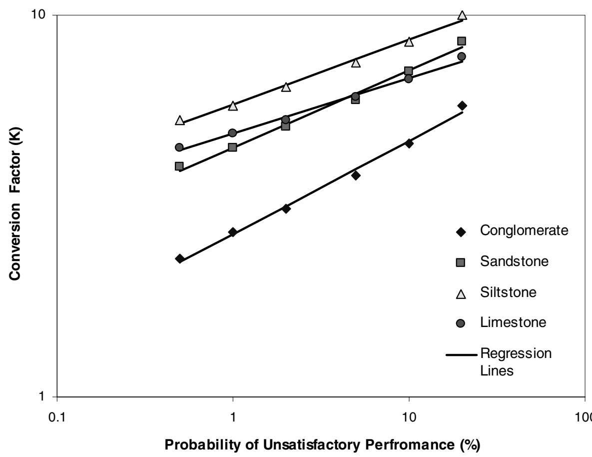

Figure 3. Variation of the conversion factor (K) with the probability of unsatisfactory performance for different rocks.

Table 3. The factors A and B for different rock types.

Rock Type	Conglomerate	Sandstone	Siltstone	Limestone
A	0.24	0.20	0.17	0.15
B	0.43	0.65	0.77	0.70

Several studies have been carried out in the last two decades to determine the value of the probability of unsatisfactory performance that can be used in engineering design. Details of these studies are beyond the scope of this paper and can be found elsewhere, e.g. Elkateb et al. (2003). In this study, the admissible probability of unsatisfactory performance was taken equal to 2%. This is based on a study carried out by El-Ramly (2001), where critical failure (unsatisfactory performance) probability of 2% was regarded as an upper bound for the satisfactory performance of earth slopes based on several case histories in North America and Hong Kong. To satisfy the above-noted critical threshold, a new risk-based estimate (K_2) of the conversion factor K was introduced in the current study. K_2 was defined as the value of K that, when divided by a partial safety factor equal to 1.4, will result in a 2% probability of unsatisfactory performance. The value of K_2 was determined for each rock type and was found equal to 3.1, 5.1, 6.5, and 5.3 for the conglomerate, sandstone, siltstone, and limestone, respectively, as shown in Table 1. The ratio between K_2 and K, determined from regression analysis, ranged from 0.57 to 0.82 and decreased with higher COV of K, i.e. with greater scatter in the rock testing data.

6 CONCLUSIONS

The uniaxial compressive strength of rock is often calculated from the point load index using a universal conversion factor (K). The applicability of the universal conversion factor to the carbonate rocks of the Persian Gulf area was investigated in this study. This was carried out through the collection of extensive rock testing data on limestone and other sedimentary rocks, such as conglomerate, sandstone, and siltstone, with high calcium carbonate contents. The rock testing data was used to develop region-specific estimates of the conversion factor (K) using regression analysis. In addition, statistical/probabilistic techniques were used to evaluate the uncertainty in the regression analysis estimates and to develop risk-based estimates of the conversion factor (K) that take the scatter in the testing data into consideration.

The main conclusions of this study can be summarized as follows:

1. The universal conversion factor (24), commonly adopted in the rock mechanics literature, tends to overestimates the uniaxial compressive strength determined from the point load test and could result in engineering design on the unsafe (non-conservative) side.
2. Conversion factors equal to 5.4, 6.2, 8.6, and 6.5 were estimated for the conglomerate, sandstone, siltstone, and limestone, respectively, using linear regression analysis.
3. The probability of unsatisfactory performance associated with the regression analysis estimates was found equal to 16.5, 5.4, 10.2, and 7.6% for the conglomerate, sandstone, siltstone, and limestone, respectively, which are high compared to admissible values commonly used in the geotechnical literature.
4. Risk-based estimates of the conversion factor were considered to be associated with 2% probability of unsatisfactory performance. These estimates were found equal to 3.1, 5.1, 6.5, and 5.3 for the conglomerate, sandstone, siltstone, and limestone, respectively.

ACKNOWLEDGMENT

The author is grateful to Dar Al Handasah Consultants (Shair and partners) and Sogreah Gulf FZCO for their help in collecting the data used in the current study.

REFERENCES

Akram, M. and Bakar M.Z. 2007. Correlation between uniaxial compressive strength and point load index for salt-range rocks. Pakistan Journal of Engineering & Applied Science 1: 1-8.

Bieniawski, Z.T. 1975. Point load test in geotechnical practice. Bulletin on Engineering Geology 9(1):1–11.

Bräutigam, T., Knöchel, A., and Lehne, M. 1998. Prognosis of uni-axial compressive strength and stiffness of rocks based on point load and ultrasonic tests. Otto-Graf Journal 9: 61-79.

Broch, E. and Franklin, J.A. 1972. The Point Load Strength Test. International Journal of Rock Mechanics and Mining Science 9: 669-697.

Chau, K.T. and Wong, R.H.C. 1996. Uniaxial Compressive Strength and Point Load Strength of Rocks. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts 33: 183-188.

Das, B. M. 1985. Evaluation of the point load strength for soft rock classification. Proceeding of the 4th International Conference on Ground Control in Mining. Morgantown, WV, USA, pp. 220-226.

El-Ramly, H. 2001. Probabilistic and quantitative risk analysis for earth slopes. Ph.D. thesis, University of Alberta, Edmonton, Alberta, Canada.

Elkateb, T., Chalaturnyk, R., and Robertson, P.K. 2003. An overview of soil heterogeneity: quantification and implications on geotechnical field problems. Canadian Geotechnical Journal 40 (1): 1-15.

Eurocode 7 (1997): Geotechnical design - Part 1: General rules.

Forster, I.R. 1983. The influence of core sample geometry on the axial point-load test. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts 20: 291–295.

Hoek, E. 1977. Rock mechanics laboratory testing in the context of a consulting engineering organization. International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts 14: pp.93-101.

International Society of Rock Mechanics (ISRM). 1985. Suggested method for determining point-load strength. International Journal of Rock Mechanics and Mining Science 22: 53–60.

Read, J. R.L., Thornton, P.N., and Regan, W.M. 1980. A Regional Approach to the Point Load Test. Proceeding of the Australia-New Zealand Geomechics Conference, pp. 35-39.

Rusnak, J. and Mark, C. 2000. Using the point load test to determine the uniaxial compressive strength of coal measure rock. Proceedings of the 19th International Conference on Ground Control in Mining, Morgantown, WV, USA, pp. 362-371.

Vallejo, L.E., Walsh, R.A., and Robinson, M.K. 1989. Correlation between unconfined compressive and point load strength for appalachian rocks. Proceeding of the 30th U.S. Symposium on Rock Mechanics, Morgantown, WV, USA, pp.461-468.