Optimization of UCS testing of limestone rock

Jørgen S. Steenfelt
COWI, Kongens Lyngby, Denmark

ABSTRACT: Assessment of strength and stiffness of rock is difficult due to the huge variability in these parameters. This is due to the often very heterogeneous nature of the rock. As large-scale testing is often prohibitively expensive or difficult to achieve in practice, the assessment relies on testing smaller specimens, typically from boreholes. The current paper provides guidelines for evaluation and interpretation of rock strength and stiffness based on UCS, Point Load and Brazil tests as a function of size, height/diameter ratio of specimen and rock strength. Based on currently available standards and literature the empirical conversion equations for tests with non-standard *D* and *H/D* values are referenced and evaluated.

Keywords: Limestone strength, UCS, height/diameter ratio, non-standard specimens.

1 INTRODUCTION AND RATIONALE FOR "NON-STANDARD" UCS TESTING

The strength of rock deposits is primarily found for "intact samples" retrieved from boreholes as opposed to the rock mass. There are several empirical correlations to bridge the gap between "intact" and "rock-mass" properties using GSI (Geological Strength Index), RMR (Rock Mass Rating), Q-system and RQD (Rock Quality Designation). However, these are outside the scope of the present paper, which addresses the "intact" rock properties.

Due to the nature of the rocks and the inherent difficulties associated with sampling, not least for weaker types of rock, e.g. limestone, it is costly and often difficult to obtain sound specimens of the size required by the Standards. This has led to the advance of indirect testing of the compressive strength by point load testing, where the Point Load Index, $Is_{(50)}$, is a fraction of the strength value from UCS testing. However, the scatter of the results from the indirect determination of strength advocates more direct testing, i.e. UCS testing. This is "codified" but most of the data, to support the code work, predate more advanced coring methods. Thus, the cores were typically NX (54 mm) or NQ (47.6 mm). With the advent of more sophisticated drilling techniques, larger core sizes are now common, e.g. Mazier and GeoBor S, typically 102 mm. This introduces additional uncertainty as the re-coring may introduce fractures or open existing, closed fissures in the specimen.

Another obvious difficulty is that no unique and universally accepted standard exists for UCS testing specifying the required diameter and height/diameter ratio and often the level of rock strength is not taken into consideration.

2 UCS TESTING FEATURES

2.1 Correlations accounting for H/D ratios

For ground investigations in rock, it is a recurrent problem, that rock core specimens are short either because of inherent properties or because of drilling induced fractures or fissures. Even for RQD =1 individual core specimen need only be 100 mm long. In case of recommended and preferred large dia-meter bore size of say 102 mm (e.g. GeoBor S) this means that it is often impossible to carry out UCS tests according to standards without re-coring to achieve a specified *H/D*-ratio, typically ≥ 2.

Re-coring induces additional uncertainties (and renewed risk of drilling induced fissures/fractures) and the smaller the diameter the larger the scatter in test results. To be able to carry out UCS tests on a higher number of large diameter cores (*D* > 100 mm), even for boreholes with high RQD values, it will be of high importance to allow testing with *H/D* = 1 ratio. To be able to compare UCS test results from *H/D* = 1 tests with UCS tests from previous tests (e.g. data base on Limestone UCS values) with *H/D* > 1 and typically *D* <100 mm, correlations need to be established.

Some of the Standards and scientific papers provide such correlations. However, the majority of these predates the advent of large diameter cores, and there is currently no internationally agreed framework for the correlation of UCS with diameter *D* and height/diameter ratio *H/D*.

2.2 Accuracy requirements on rock specimen tested

The Standards for rock specimens have strict requirements to specimen accuracy (e.g. ends flat to within 0.02 mm and less than 0.001 radian deviation from perpendicularity to the axis of specimen; smooth sides free of abrupt irregularities and straight to within 0.3 mm over the full length).

For igneous rock, this may not present a challenge, but for weaker or heterogeneous limestone rocks of H2-H3 hardness this may be difficult. The demand on straightness is increasingly difficult to comply with for increasing height, H, of the specimen. This also provides a rationale for testing specimens with lower *H/D* ratios, i.e. *H/D* = 1. The demands to the equipment in terms of pressure heads, load capacity and rate of loading are assumed to be as specified in the Standards.

3 UCS STANDARDS FOR ROCK CORES

The ASTM (1986) and ISRM (1978, 1981) standards have a strict demand on height/diameter ratio, *H/D* but only guidance regarding the specimen diameter: “(a) The specimens shall be right circular cylinders having a height to diameter ratio of 2.5 - 3.0 and a diameter preferably of not less than NX core size, approximately 54 mm.” The Standard (and the updated version from 2007) does not give any directions in case of deviations from the stipulated values of *H/D* or *D*.

ASTM D2398-86 (1986) must be used in conjunction with ASTM D4543 (2001). The latter requires cylinders with length/diameter ratios *L/D* (=*H/D*) of 2 to 2.5 and specimen diameter *D* ≥ 47 mm. For deviations from the *L/D* = 2 ratio, a correlation is indicated in Eq. (1), where (using the symbols defined in the Code): *C* = computed equivalent strength for *L/D* = 2; *b* = actual core diameter; *h* = actual test core height. A minimum of 10 specimens tested are preferred. Notably, the conversion correlation is omitted from the most recent version ASTM D 7012-14 (2014) and none of the versions indicates correction for diameter. The 1986 version, Eq. (1) suggests a conversion factor 0.89 to be applied on H/D = 1 specimen results.

$$C = C_a/(0.88 + 0.24\, b/h) \quad (1)$$

DS/EN 14227-1:2013 (2013) is not directly applicable to rock cores but appears as a reference Standard. From the numbers indicated in the Standard, a general conversion factor of 0.75 may be inferred to correct *H/D* = 1 results to equivalent *H/D* = 2 results. For lower values of compressive strength (0.4 to 8 MPa) the conversion factor varies between 0.75 and 0.83. The Standard does not indicate any correction for the diameter per se.

ASTM C170 (1989) addresses rectangular cuboid specimens, *h* by *l* by *w*. A conversion factor like ASTM D2938-86 (1986) is indicated in Eq. (2) (using the symbols as indicated in the Code: C=computed equivalent strength for *l/h* = 1; *Ca* = measured compressive strength of the specimen tested; *l* = *w*= core dimensions in plan; *h* = test core height. Thus, the conversion factor, Eq. (2) for *h/l* = 2 to *h/l* = 1 is 0.89/1.00 = 0.89.

$$C = C_a(0.778 + 0.222\ l/h);\ w=l \quad (2)$$

4 UCS CONVERSIONS FACTORS FROM LITERATURE

Many researchers have examined the scale effect in rock strength properties. This involves both core diameter *D*, height diameter ratio *H/D* and the shape (cylindrical versus rectangular cuboid).

Thuro et al. (2001) examined the influence of shape and size for high strength granite and limestone specimens. The correction for shape (54 mm specimen diameter) varied from 0.96 to 1.03 for *H/D* = 1 to 3 of where Eq. (1) gives 0.89 to 1.04. For their specimens they found no discernible size effect (diameters from 45 mm to 112 mm) considering the general scatter of test results of the order ±10%.

Hoek & Brown (1980) reported a size effect, relative to a baseline diameter of 50 mm, for rock specimens which is roughly the same as reported by Hawkins (1998), $\sigma_c/\sigma_{50}=(50/d)^{0.18}$. For 102 mm specimens this indicates a factor 0.88, i.e., the 102 mm specimen underestimates the results compared to a 50 mm specimen with a factor 0.88. For rectangular cuboid specimens on limestone specimens (compressive strength of the order 11 to 18 MPa), Al-Rkaby & Alafandi (2015) found a shape effect comparable to Eq. (1) with a factor 0.93 for *h/l* = 2 to *h/l* = 1.

5 CORRELATION FACTORS BETWEEN UCS AND $I_{S(50)}$

The Point Load Strength test is attractive due to the limited size requirements of the test specimens in ASTM D2938 (1986): “Rock specimens in the form of either core (the diametral and axial tests), cut blocks (the block test), or irregular lumps (the irregular lump test)”.

The ASTM D5731 (1995) and ISRM Standards (1981, 2007) are almost identical, but the test is an index test only. The Standards indicate only a size correction factor, *F*, for deviations from the standard equivalent core diameter D_e = 50 mm. The correction factor is applied on the measured $I_{s(50)}$ value (For GeoBor S cores of 102 mm this corresponds to a correction factor *F* = 1.38.).

The recommended “generalized” factor applied for estimation of the uniaxial compressive strength is *C* (which according to the Standards should be site specific) as indicated in Eq. (3).

$$I_{s(50)} = FI_s \quad \text{where } F = \left(\frac{D_e}{50}\right)^{0.45};\ \sigma_c = C \times I_{s(50)} = 24 \times I_{s(50)} \quad (3)$$

Akram & Bakar (2007) clearly demonstrates that the correction factor, *C,* is both rock type and strength dependent. For limestone they suggest *C* = 11 (and the limestone samples are at the same time showing lower UCS values compared to the other types of rock examined). The data from Altindag et al. (2010), for many tests from literature on sedimentary, igneous, and metamorphic rocks, illustrate the scatter and that the *C*-value of Eq. (3) is likely much too high. Although it is tempting to use the point load index this is strongly discouraged as: (i) it is only an index test, and (ii) it requires site and rock specific correlation with many UCS, and particularly point load tests.

6 MODULUS OF ELASTICITY FROM UCS TESTING

The Standards ISRM (1978, 1981, 2007) and ASTM (2014) are not very specific regarding determination of the elastic modulus of the rock specimens. The modulus, *E*, is assessed as tangent or secant values (typically based on the value at 50% failure stress, but other pre-defined values may also be used). The strain is the relative shortening between the end platens or more directly measured by strain gauges attached to the rock specimen at the central part of the specimen. The latter method allows for measurement at low strains comparable to assessing the small to very small strain modulus. However, the strain gauges typically malfunction for larger strains.

To facilitate determination of the modulus of elasticity, *E*, a number of researchers have tried to correlate *E* with bulk density, ρ, or the compressive strength, σ_c. Exponential relationships with ρ and a linear relationship between log *E* and logσ_c seems to be predominant (e.g. DGI, 1994; Ocak, 2008). There is consensus that *E* increases slightly with increasing core size, whereas the shape has a bigger impact. The *E* value for *H/D* = 1 may be of the order 20% higher than for *H/D* = 2, i.e. the opposite trend of the influence on σ_c. It is apparent that the modulus of elasticity is very much dependent on the rock type in question and thus depends on both ρ and σ_c. Considering the uncertainty attached to the determination of the modulus of elasticity (secant/tangent value and not least strain level), testing of specimens with *H/D* = 1 is deemed as reliable as testing using *H/D* > 2.

7 TENSILE STRENGTH BY BRAZIL TEST

The ASTM (1995, 2001) and the ISRM standard (1978, 1981) are similar. In both cases, the test specimen is a circular disk. However, ASTM allows a thickness/diameter ratio, *t/D*, between 0.2 and 0.75 with a diameter > 50 mm, whereas ISRM requires a height/diameter ratio *H/D* = 2.5/3 (~ 0.8) and a diameter preferably not less than NX core size, approximately 54 mm.

None of the Standards indicates corrections for larger diameter disks.

8 CURRENT PRACTICE FOR LIMESTONE TESTING IN DENMARK

Unfortunately, there are few literature references available for weak limestone specimens to indicate the size and shape effect compared to the recommended values in the current Standards.

For testing on limestone in Denmark, a height diameter ratio *H/D* ≤ 2 is routinely used to safeguard against tilting of samples. This is particularly important for H2 specimens with σ_c in the range 1 to 5 MPa. To achieve *H/D* = 2 re-coring has been applied down to *D* = 38 mm and *H* = 76 mm, e.g., on the metro-project Cityringen (SGI, 2012) and on HOFOR projects for storage tunnels used as protection from torrential rainstorms (GEO, 2013), (both in Copenhagen, Denmark).

In SGI (2012) the rationale for re-coring specimens was stated as: "The recommended height to diameter ratio by the ISRM standard is 2.5 – 3.0, when performing UCS tests. UCS tests performed in this project have a height to diameter ratio of 2.0 due to the quality of the available core material and the risk of bending effects. All UCS tests were carried out on samples cored to a diameter of 38 mm and a height of 76 mm”. The need for re-coring appears from the photo of a GeoBor-S core-run from Cityringen (SGI, 2012) shown in Figure 1.

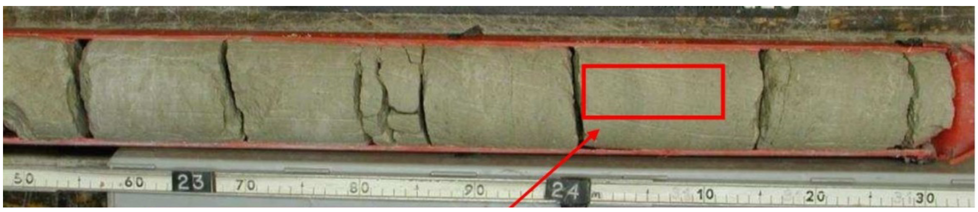

Figure 1. Core photo of Copenhagen limestone from Cityringen project (SGI, 2012).

For the Ø102 mm core it would not be possible to adhere to *H/D* > 2. The specimens tested were re-cored to dimension *H* ~ 106 mm, *D* ~ 54 mm. In general, the resulting σ_c values are not corrected for diameter and *H/D* ratio for specimens with *H/D* = 2. In case of larger deviation from *H/D* = 2, it is believed that the ASTM correction, Eq.(1) was likely applied.

An extensive database exists for testing of Copenhagen and Bryozoan limestone primarily from the Øresund Fixed Link Project, DGI (1994), see Figure 2. The paper describes the geology, main physical characteristics, and the mechanical properties of the limestone in detail.

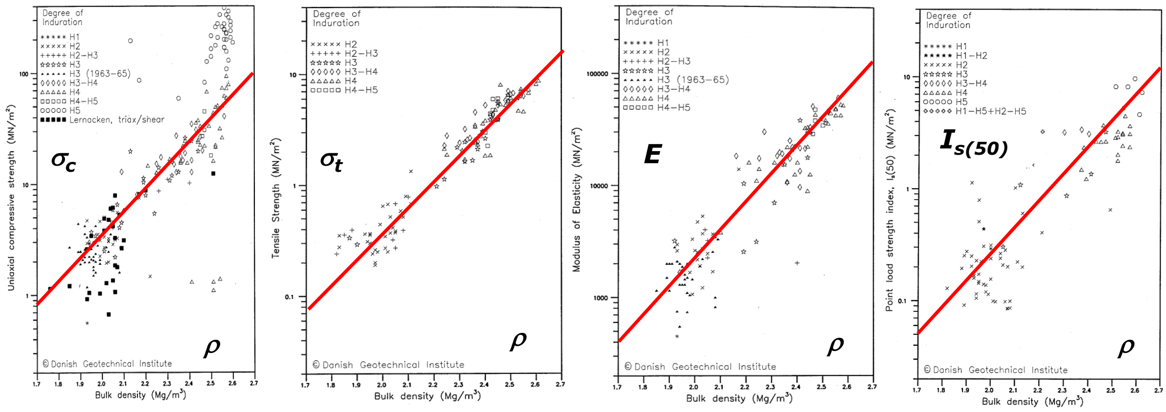

Figure 2. Data from DGI (1994) with COWI interpretation of "representative fit" indicated as a red line; (a) compression σ_c; (b) tension σ_t; *(c) elasticity E and (d) point load index* $I_{s(50)}$ versus bulk density ρ.

The paper indicates testing in accordance with ISRM (1978, 1981). However, *H/D* = 2 was very likely used for the specimens and the diameter was likely close to 50 mm, although not indicated.

DGI (1994) indicates tentative interrelationships between the parameters: σ_c = (6 to 12) σ_t, σ_c = (10 to 24) $I_{s(50)}$, E = (600 to 1200) σ_c. These correlations are valid for "normal limestone", i.e. limestone with an average grain density of 2.71 Mg/m³ (range of 2.68 to 2.74 Mg/m³ and carbonate content > 90%). Using "best-fit" (i.e. "representative fit") lines through the data points presented in DGI (1994) (see Figure 2) the relationship between bulk density, ρ (Mg/m³) and the other parameters (in MPa) may be described by Equations (4). From these it is possible to better describe the interrelations indicated in DGI (1994) taking the influence of the bulk density into consideration.

$$\sigma_c = exp(4.85\rho - 8.48); \quad E = 1000\, exp(6.125\rho - 11.62)$$

$$\sigma_t = exp(5.42\rho - 11.79); I_{s(50)} = exp(5.755\rho - 13.0) \tag{4}$$

9 EVALUATION

To allow testing of intact limestone cores and minimize specimen disturbance UCS testing of *H/D* = 1 specimens on core samples from GeoBor-S or similar, with *D* > 100 mm is recommended.

Compared to literature indications, albeit for compressive strength typically in excess of 10 MPa, the effect on the unconfined compressive strength, σ_c, from shape and size results in:

- An increase in strength of the order 0.8 to 1 for *H/D* specimens compared to *H/D* = 2
- A decrease in strength of the order 0.8 to 1 for increase in diameter from 50 to 102 mm
- A slight increase in the elastic modulus with increasing core diameter
- An increase up to 20% of the elastic modulus for *H/D* = 1 specimens compared to *2*

Compared to the uncertainty of UCS testing, with a standard deviation typically of the order >20%, the corrections for *D* and *H/D* are not significant. The uncertainty imposed by re-coring specimens to achieve *H/D* > 2 is estimated to impose a much higher uncertainty than the uncertainty inherent in the conversion equations proposed by Standards and literature.

10 RECOMMENDATIONS

For large diameter specimens of limestone rock, e.g., from GeoBor S or similar, it is recommended to carry out the UCS testing on specimens of *H/D* =1 without corrections on the measured compressive strength. For smaller diameter cores it is recommended to use H/D = 2 (in Denmark) to allow for comparison with previous experience and data base knowledge from testing on limestone cores. This means in both cases deviations from the ASTM and ISRM Standards. This shall appear explicitly on the testing sheets.

The use of point load tests is discouraged unless proper site-specific correlations are established, considering the strength dependence.

Based on the extensive experience with Danian limestone (Copenhagen and Bryozoan limestone) the correlations Eq. (4) may be helpful as a sanity check on achieved results.

However, the influence from actual mineralogy, bulk density, and level of compressive strength on the parameters determined by the testing should never be underestimated. The correlations and conversion factors described in the paper are believed to be generally applicable for rock cores although the emphasis here has been on (weaker) limestone rock.

REFERENCES

Altindag, R., Demirdag, S, Sengun, N, Guncy, A., Mutluturk, M, Karaguzel, R. 2010. Evaluation of empirical equations for assessing the true UCS of rocks. *Rock Engineering in Difficult Ground Conditions – Soft rocks and Karst*, pp 201-207. Taylor & Francis Group, London, ISBN 978-0-415-80481-3.

Akram, M., Bakar, M.Z.A. 2007. Correlation between Uniaxial Compressive Strength and Point Load Index for Salt.Range Rocks. Pak. J. Engg. & Appl. Sci., Vol 1.

Al-Rkaby, A.H.J., Alafandi, Z.M.S. 2015. Size effect on the Unconfined Compressive Strength and Modulus of Elasticity of Limestone Rock. EJGE, Vol. 20, Bund. 12, pp5143-5149

ASTM D2938-86 1986. *Unconfined Compressive Strength of Intact Rock Core Specimens*, *ASTM*.

ASTM C170 1989. Standard Test method for Compressive Strength of Natural Building Stone, *ASTM*

ASTM D 5731-95 1995. Standard method for determination of the Point Load Strength Index of Rock. *American Society for Testing and Materials, ASTM*.

ASTM D4543-01 2001. Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances. *American Society for Testing and Materials, ASTM*.

ASTM D 3967-95a 1995, 2001. Standard test method for splitting tensile strength of intact rock core specimens. *American Society for Testing and Materials, ASTM*.

ASTM D7012-14 2014. *Standard Test Method for Compressive Strength and Elastic Modulus of Intact Core Specimens under Varying states of Stress and Temperatures*. ASTM.

DGI 1994. Limestone – a geological and rock mechanical description, Report No. 1 submitted to Øresundskonsortiet. DGI and DGU, PA3 GEOI 106, dated 1994-05-24.

DS/EN 14227-1:2013 (E). 2013. Hydraulically bound mixtures - Specifications - Part 1: Cement bound granular mixtures. *DS Danish Standard*.

GEO. 2013. Adaptation to climate change and protection from torrential rainstorms. Geotechnical site investigation, Report 1, issued 2013-07-04 to HOFOR, Copenhagen.

Hawkins, A.B. 1998. Aspects of rock strength. *Bull. Eng. Geol. Rnv.* 57, 17-30.

Hoek, E., Brown, E.T. 1980. *Underground excavations in rock*. Inst. Min. Metall. London, Chapman & Hall.

ISRM. 1978, 1981. Suggested Methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials, Part 1. *International Society for Rock Mechanics*

ISRM. 2007. Suggested Methods for Determining the Uniaxial Compressive Strength and De-formability of Rock Materials, Part 1. *International Society for Rock Mechanics, pp 137-38.*

Ocak, I. 2008. Estimating the modulus of elasticity of the rock material from compressive strength and unit weight. The Journal of the Southern African Institute of Mining and Metallurgy, Vol. 108, pp 621-626.

SGI. 2012. Geomechanical characterization of Copenhagen limestone, Cityringen (Copenhagen Metro). Report submitted 2012-05-29 by Studio Geotechnico Italiano to Tecnimont Civil Construction (Milan).

Thuro, K., Plinninger, S., Zäh, S., Schütz, S. 2001. Scale effect in rock strength properties. *Rock Mechanics – a Challenge for Society, Särkkä & Eloranta (eds.).* Swets & Zeitlinger Lisse, 169-174.