Rock Engineering Properties of Jurong Formation

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Abstract - The design of underground excavations in rock demands engineers to be able to predict the behavior of the rock mass under certain imposed actions. Two key properties that control this behavior are rock's strength and stiffness. The prediction of these properties and the procedure to establish site specific empirical relationships between different index properties is discussed, using as an example the development of correlations for the rocks of the Jurong Formation in Singapore. A strong empirical correlation between tangent Young's modulus and the uniaxial compression strength for intact rock specimens is derived.

Index Terms – Jurong Formation, rock, anisotropy, tangent Young's modulus uniaxial compression strength, point load strength index, weathering, dry bulk density, empirical relationship.

INTRODUCTION

The design of underground excavations in rock demands engineers to be able to predict the behavior of the rock mass under certain imposed actions. Two key properties that control this behavior are rock mass' strength and stiffness.

Although, laboratory testing on intact rock specimens do not provide direct measurement of the in-situ rock mass properties, it can be considered a good starting point when in-situ tests are not an option. Bieniawski [3] pointed out uniaxial compression strength and triaxial strength of rock as two suitable tests for characterisation of rock mass strength and stiffness. However, these are both relatively expensive tests, which require specimen preparation and therefore might be considered time-consuming, and since ground investigation programmes are typically under time and budget constraints, engineers tend to sacrifice accuracy on results in behalf of cheaper, quicker and simpler testing methods.

The objective of the present paper, with a particular focus on the rocks of the Jurong Formation, is to demonstrate that properties such as the rock's strength, stiffness and anisotropy can be empirically correlated to laboratory test classification and/or strength indices.

The most widely used alternative estimate of the rock's strength is the point load strength index (I_S) [10], which is obtained through an indirect tensile strength test on unprepared rock specimens. Considering that the compressive and tensile strength of rock are closely correlated, Broch E. et al [4] research showed that uniaxial compressive strength of rock could be predicted from point load strength index with a reasonable level of accuracy [18].

The intact rock modulus of deformation can be obtained from unconfined compressive strength test (UCS) with either strain gauge or LVDT measurements.

METHODOLOGY

The approach taken to establish suitable relationships and to normalize the values of different tests for comparison are briefly detailed below.

I - Normalization

The rock specimen shape, dimensions and weathering grade have a considerable effect on the test results. Thus, normalizing the test results becomes even more critical for comparison and development of relationships between different strength indexes. These factors influencing the rock strength indices and the approach taken to normalize them is detailed below.

Shape Effects – Numerous studies ([1], [9], [11], [20]) have been undertaken on the effect on measured UCS and PLT strength of factors such as shape and size.

Uniaxial compression strength values have been found to decrease with increase of specimen's diameter.

Broch E. et al [4] highlighted how for diametral point load test on isotropic to slightly anisotropic rock the failure load is independent of the specimen's length provided that the length is equal or greater than the specimen's diameter. While, for axial point load tests there is a shape effect, in addition to the size effect, with specimen's length and diameter influencing the results obtained with the test. In order for both diametral and axial tests to yield identical results specimens length/diameter ratio on axial tests must be restricted to approximately 1.1, with any differences between axial and diametral point load strength tests being related to strength anisotropy or failure occurring on defects instead of trough the intact rock.

All the above justify the restrictions imposed by ISRM and ASTM procedures on the shape and the size of specimens, so that specimen's geometry has little influence on the strength test results. As an example, it is part of the point load test standard procedure to normalize the strength index obtained for any specimen's diameter to a value $I_{S(50)}$ at a reference diameter of 50mm, using a size correction factor (1.1).

$$F = (\frac{De}{50})^{0.45} \quad (1.1)$$

where :

F: size correction factor

De: specimen's diameter

It is recommended to apply a similar size correction on uniaxial compression strength values, for which Hoek E. et al [9] proposed the use of equation (1.2).

$$\left(\frac{\sigma_c}{\sigma_{c50}}\right) = (\frac{50}{De})^{0.18} \quad (1.2)$$

where :

σ_{c50}: equivalent unconfined compression strength of a 50mm-dia specimen

Weathering Related Effects – Rock's strength is dependent on rock's lithology, as it is dependent on the weathering grade ([5], [8], [15], [21]). Typical classification indices such as moisture content, porosity and dry density provide a useful prediction tool of the engineering properties of the intact rock [2]. These indices evolve and vary throughout the weathering process responsible of a reduction on the geo-mechanical properties of rocks, such as the rock strength.

The sensitivity of the rock strength to variations on these three classification indices has allowed the derivation of site-specific empirical relationships between strength index and classification index.

II - Relationships

The following relationships have been studied:

Unconfined compression strength and dry bulk density –
The measured moisture content was determined non-representative due to uncertainty with regards to the precaution taken, during storage and transport of the cores, to maintain the original moisture content. Due to this, the author decided to bet on certainty and rely on dry bulk density as benchmark classification index instead.

Rock anisotropy and point load strength index – To assess the anisotropy, adjacent pairs of axial and diametral point load strength index of specimens with random orientations have to be cross-checked and grouped as maximum and minimum values. The mean ratio of maximum and minimum strengths is then taken as a representative index of strength anisotropy.

Unconfined compression strength and point load strength index – The test results of pairs of point load strength tests (axial and diametral) undertaken on relatively close specimens of the same lithology and weathering grade are compared against uniaxial compression strength. In order to achieve meaningful comparison, point load test (PLT) specimens right above and below the UCS specimen are to be undertaken, where possible.
Any anomalous values and point load index values lower than 1MPa have to be filtered, due to a loss on reliability of the point load strength test on weaker rock.

Previous relationships, (1.3) and (1.4), proposed by Broch E. et al [4] and Leung C. F. et al [14], respectively, are compared with the data.

$$\sigma_c = 24 I_{S(54mm)} \quad (1.3)$$
$$\sigma_c = 6.12 I_{s(50)} \quad (1.4)$$

where :

σ_c: unconfined compression strength

$I_{S(XXmm)}$: point load index of a XXmm-dia specimen

To ensure consistency equation (1.3) has been corrected for 50mm-dia specimens (1.5)

$$\sigma_c = 24.85 I_{s(50)} \quad (1.5)$$

Equation (1.4) corresponds to an early assessment on the geotechnical properties of the highly to completely weathered rocks of the Jurong Formation by Leung C. F. et al [14] based on Figure 1.

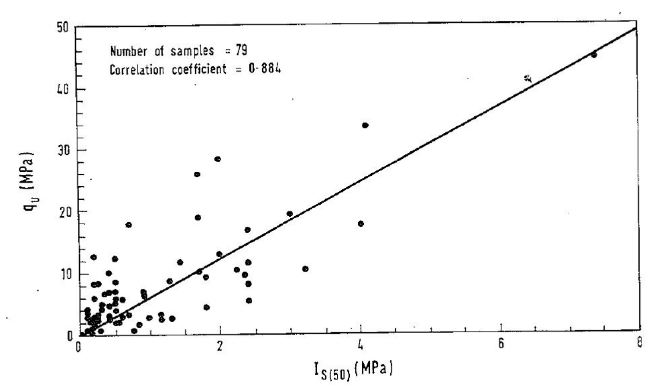

FIGURE 1
LEUNG C. F. ET AL (1990) [4] – UCS VERSUS PLI

Tangent Young Modulus and unconfined compressive strength – As it is well known that elastic Young's modulus increases with increasing uniaxial compression strength; and as the former is a critical parameter to describe the rock's behavior under loading a relationship has to be established between these two properties.

III - Confidence

The confidence on the assessed relationships is measured with the coefficient of determination. This coefficient ranges from 0 to 1, where 0 indicates that the relationship poorly fits the data and 1 indicates it perfectly fits the data.

RESULTS

I - Background

Data – The present work has relied on a total of 2,721 tests, comprising classification and strength index testing, on two major rock units (i.e. sandstones and mudstones of the Ayer Chawan facies) of the Jurong Formation of Singapore. A summary of this information is presented in Table I.

The assessed information was collated from different sites across the Southwest of Singapore, both on the main island and at Jurong Island.

Geology – The sedimentary rocks of the Jurong Formation are present were deposited in a shallow marine continental basin, between the Late Triassic and Early Jurassic, which was formed by the uplift of the Bukit Timah Granite to the northwest and the Malayan Main Range Granite to the southwest [11]. These deposits comprising mostly interbedded sequences of mudstones with sandstones (i.e. greywackes, orthoquartzite, calcarenites and tuffaceous sandstones), as well as localized beds of conglomerates and limestone [21], have undergone uplift, and considerably folding and faulting due to lateral basin compression.

II - Empirical Relationships

UCS versus Dry Bulk Density – Measured uniaxial compression strength values and associated dry bulk densities have been plotted (see Figures 2 to 6) and analysed to confirm if a relationship could be developed.

A correlation has been established for the two rock units as presented in (1.6) and (1.7) with coefficients of determination 0.29 and 0.47, respectively.

$$\sigma_c = 0.0476e^{0.0026\gamma_d} \quad (1.6)$$

$$\sigma_c = 0.0108e^{0.0032\gamma_d} \quad (1.7)$$

TABLE I

ASSESSED JURONG FORMATION GROUND INFORMATION

Property	No. tests	Min. Value	Max. Value	Median	St. Dev.	95% Confidence Intervals		
Sandstone S(IV)								
Et (GPa)	Nil	Nil	Nil	Nil	Nil	Nil		
UCS (MPa)	3	7.33	8.12	7.80	0.42	7.33	to	8.28
PLI (MPa)	6	0.93	3.27	2.17	0.88	1.47	to	2.87
γ_d (kN/m3)	3	1.96	2.30	2.14	0.17	1.95	to	2.34
Sandstone S(III)								
Et (GPa)	37	1.90	41.60	17.72	10.13	14.45	to	20.98
UCS (MPa)	170	5.17	323.74	47.16	35.01	41.89	to	52.42
PLI (MPa)	402	0.50	13.52	4.57	2.53	4.33	to	4.82
γ_d (kN/m3)	171	1.90	2.80	2.54	0.15	2.52	to	2.56
Sandstone S(II)								
Et (GPa)	20	8.10	32.90	19.17	7.47	15.89	to	22.44
UCS (MPa)	85	8.14	159.18	67.86	34.05	60.62	to	75.10
PLI (MPa)	148	1.25	16.76	6.45	2.91	5.99	to	6.92
γ_d (kN/m3)	62	2.18	2.78	2.62	0.12	2.59	to	2.65
Mudstone S(IV)								
Et (GPa)	1	7.80	7.80	7.80	NA	7.80		
UCS (MPa)	1	22.26	22.26	22.26	NA	22.26		
PLI (MPa)	12	0.05	3.01	1.38	0.87	0.89	to	1.87
γ_d (kN/m3)	5	1.85	2.51	2.14	0.25	1.92	to	2.36
Mudstone S(III)								
Et (GPa)	39	2.80	42.00	16.45	10.79	13.06	to	19.84
UCS (MPa)	255	1.42	204.90	41.13	30.60	37.38	to	44.89
PLI (MPa)	599	0.46	14.96	3.81	2.01	3.65	to	3.98
γ_d (kN/m3)	272	1.87	2.82	2.53	0.18	2.51	to	2.55
Mudstone S(II)								
Et (GPa)	19	5.00	49.30	20.59	13.79	14.40	to	26.79
UCS (MPa)	99	13.95	228.80	65.64	38.24	58.10	to	73.17
PLI (MPa)	231	1.23	13.81	5.55	1.91	5.30	to	5.79
γ_d (kN/m3)	81	2.07	2.78	2.64	0.10	2.62	to	2.67

Note : Et - Tangent Young's Modulus (GPa)
UCS - Uniaxial Compressive Strength (Mpa)
PLI - Point Load Index (MPa)
γ_d - Dry Density (kN/m3)
Nil - Not available
NA - Not applicable

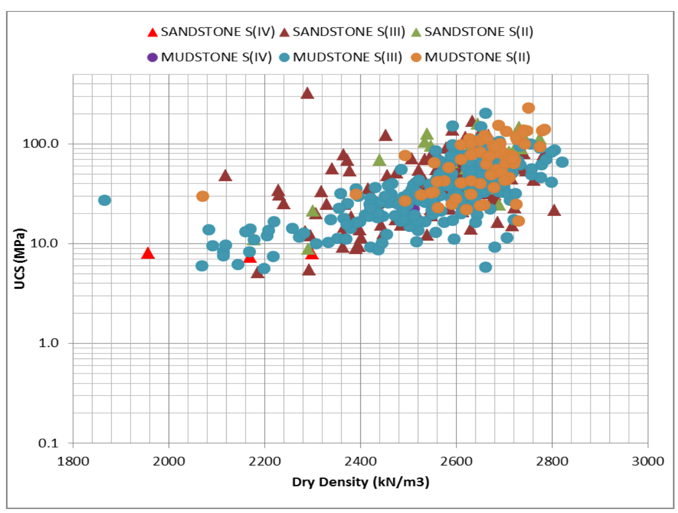

FIGURE 2

GENERAL – UNIAXIAL COMPRESSION STRENGTH VERSUS DRY DENSITY

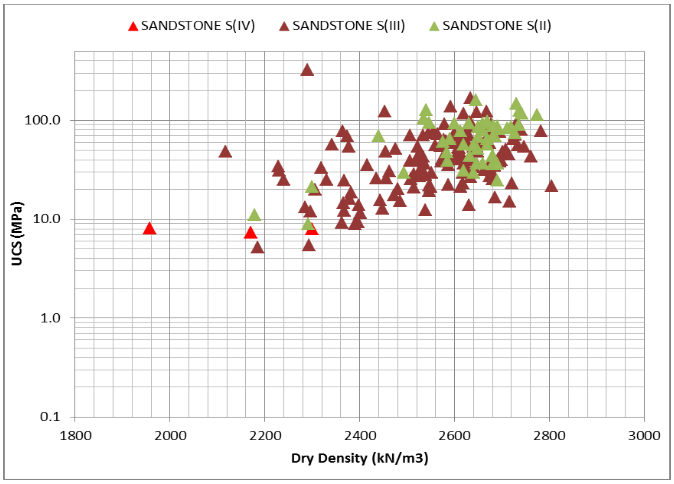

FIGURE 3
SANDSTONE – UNIAXIAL COMPRESSION STRENGTH VERSUS DRY DENSITY

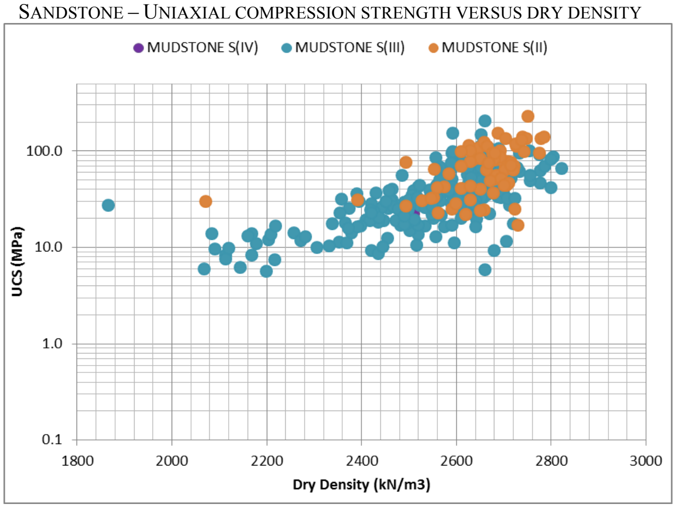

FIGURE 4
MUDSTONE – UNIAXIAL COMPRESSION STRENGTH VERSUS DRY DENSITY

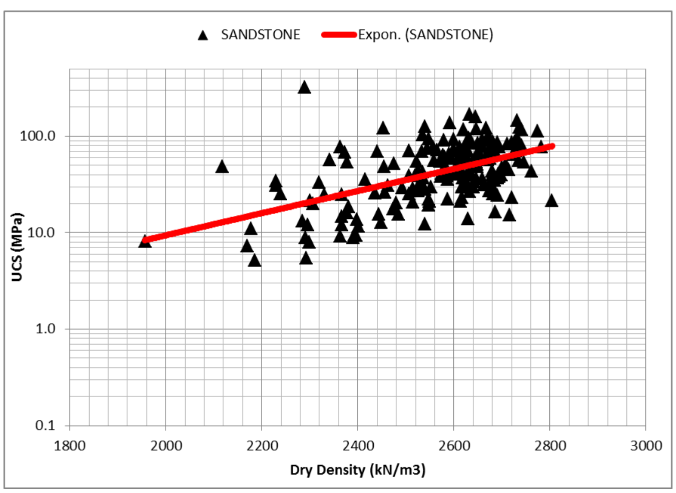

FIGURE 5
SANDSTONE – UCS VERSUS DRY DENSITY BEST FIT

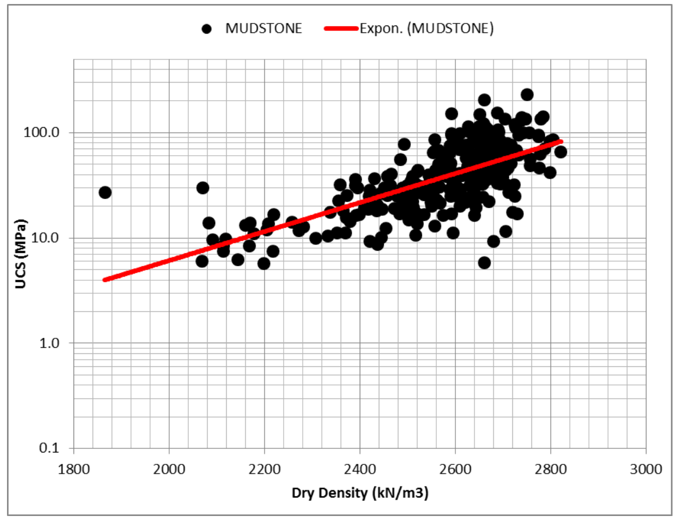

FIGURE 6
MUDSTONE – UCS VERSUS DRY DENSITY BEST FIT

Rock Anisotropy and PLI – To assess the anisotropy of the sandstone and mudstone units, the maximum and minimum values of pairs of adjacent axial and diametral point load strength indices have been plotted in Figures 7 and 8.

The mean ratio of strengths taken as a representative index of strength anisotropy, is as follows: 1.31 for sandstones and 1.33 for mudstones, with coefficients of determination 0.69 and 0.71, respectively.

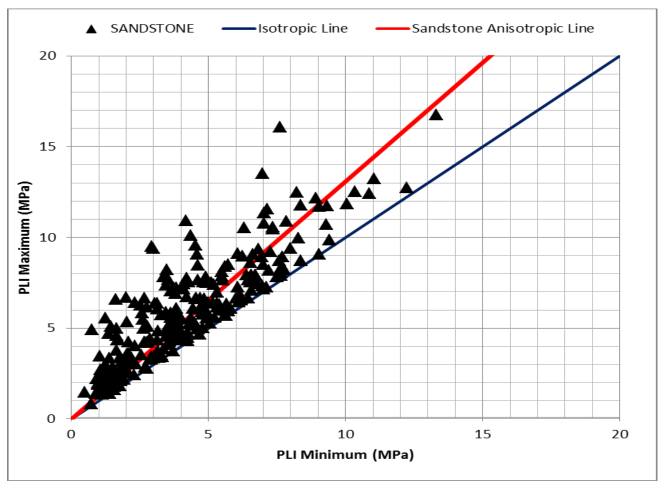

FIGURE 7
SANDSTONE – ANISOTROPY BASED ON POINT LOAD STRENGTH INDEX

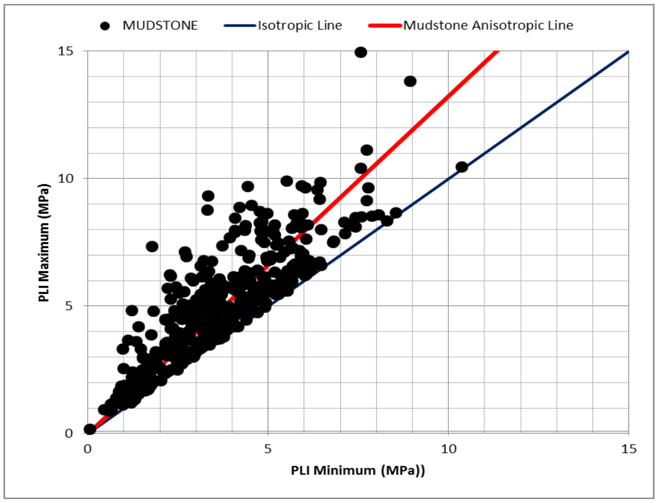

FIGURE 8
MUDSTONE – ANISOTROPY BASED ON POINT LOAD STRENGTH INDEX

UCS versus PLI – A comparison is presented in Figures 9 to 15. The relationships (1.4) and (1.5) are compared against the best fit on Figures 12 to 15.

For moderately to slightly weathered sandstones and mudstones, linear relationships are given in (1.8) and (1.9) with coefficients of determination 0.33 and 0.32, respectively.

$$\sigma_c = 10.11 I_{s(50)} \tag{1.8}$$

$$\sigma_c = 11.21 I_{s(50)} \tag{1.9}$$

These can also be expressed as a exponential relationship as presented in (1.10) and (1.11) with coefficients of determination 0.45 and 0.40, respectively.

$$\sigma_c = 13.54 {I_{s(50)}}^{0.80} \tag{1.10}$$

$$\sigma_c = 10.79 {I_{s(50)}}^{0.94} \tag{1.11}$$

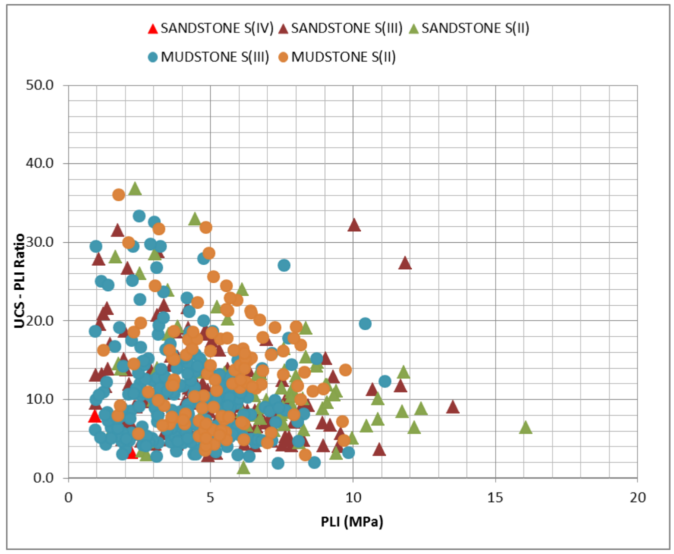

FIGURE 9
GENERAL – UCS/PLI RATIO VERSUS POINT LOAD STRENGTH INDEX

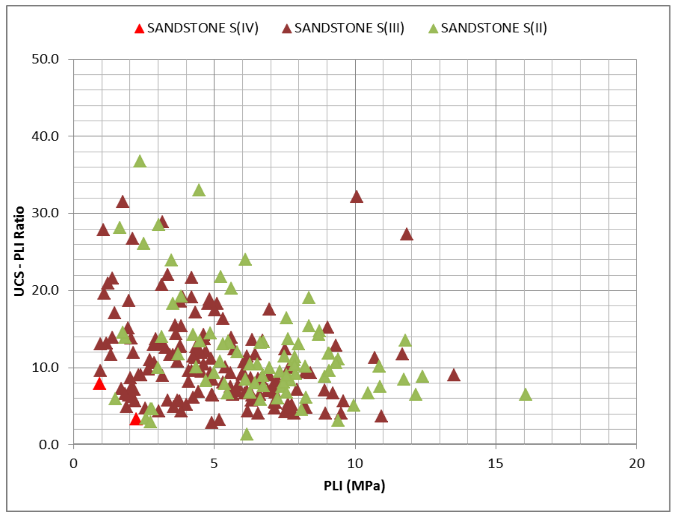

FIGURE 10
SANDSTONE – UCS/PLI RATIO VERSUS POINT LOAD STRENGTH INDEX

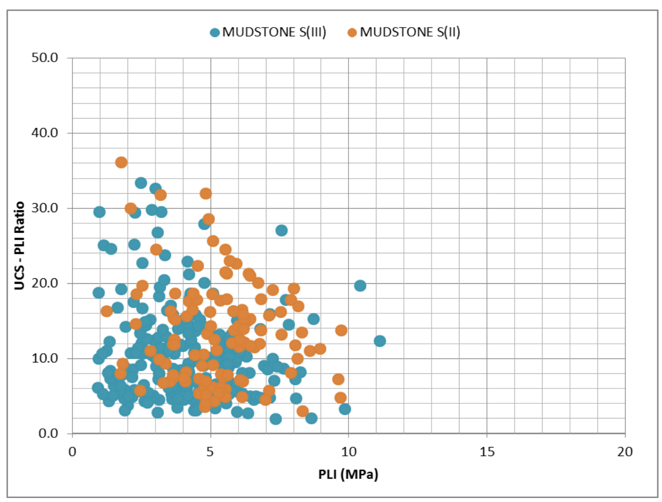

FIGURE 11
MUDSTONE – UCS/PLI RATIO VERSUS POINT LOAD STRENGTH INDEX

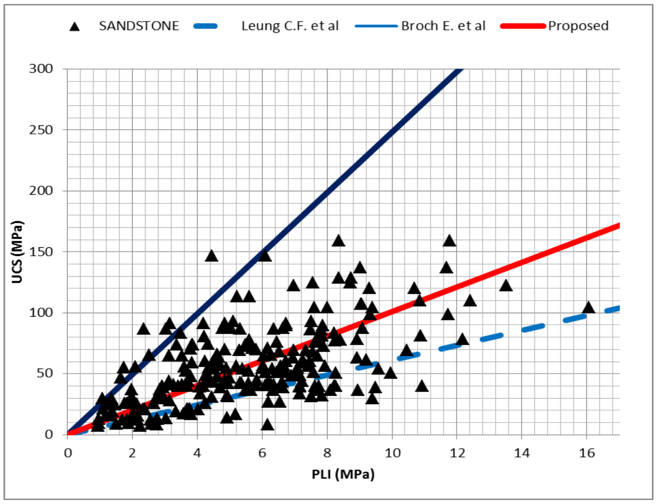

FIGURE 12
SANDSTONE – UNIAXIAL COMPRESSION STRENGTH VERSUS POINT LOAD STRENGTH INDEX

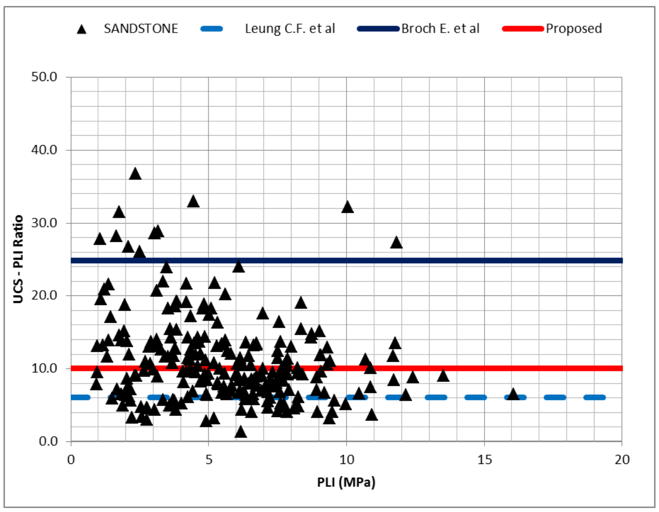

FIGURE 13
SANDSTONE – UCS/PLI RATIO VERSUS PLI BEST FIT

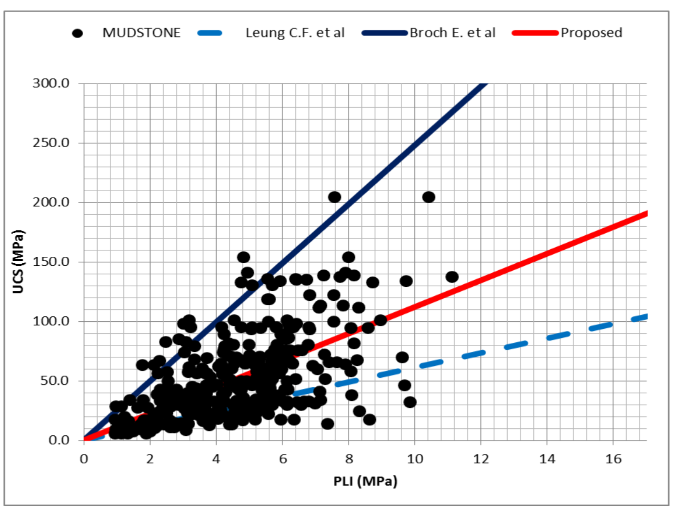

FIGURE 14
MUDSTONE – UNIAXIAL COMPRESSION STRENGTH VERSUS POINT LOAD STRENGTH INDEX

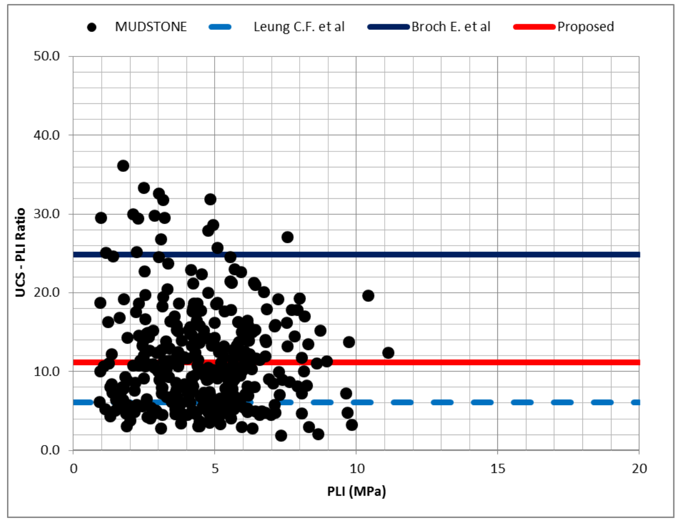

FIGURE 15
MUDSTONE – UCS/PLI RATIO VERSUS PLI BEST FIT

E_t versus UCS – The tangent Young's modulus/uniaxial compression strength ratio is plotted against the uniaxial compression strength on Figures 16 to 18. As there is considerable overlap between weathering grades and there is not an obvious trend, the tangent Young's modulus is plotted against the uniaxial compression strength (the weathering not being considered) in Figures 19 and 21 yielding much clearer results.

The data might be fitted by a straight line defined by equations (1.12) and (1.13) with strong coefficients of determination 0.86 and 0.82, for sandstone and mudstone respectively.

$$E_t = 300.3\sigma_c \tag{1.12}$$

$$E_t = 304.6\sigma_c \tag{1.13}$$

These approximately match Deere D. U. et al ([6], [7]) average 300:1 modulus ratio line, upper and lower bound of which have been plotted on Figures 19 and 21.

An improved relationship can be obtained using a power relationship presented in (1.14) and (1.15) with coefficients of determination 0.91 and 0.90, respectively.

$$E_t = 304.6{\sigma_c}^{0.99} \tag{1.14}$$

$$E_t = 338.7{\sigma_c}^{0.99} \tag{1.15}$$

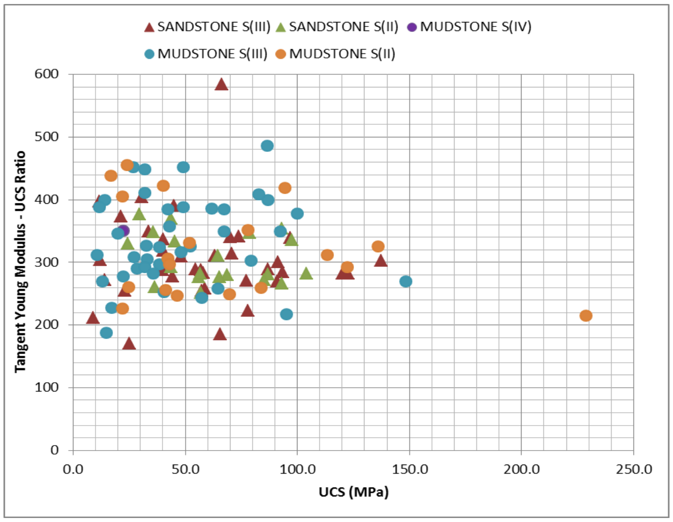

FIGURE 16

GENERAL – E_T/UCS RATIO VERSUS UNIAXIAL COMPRESSIVE STRENGTH

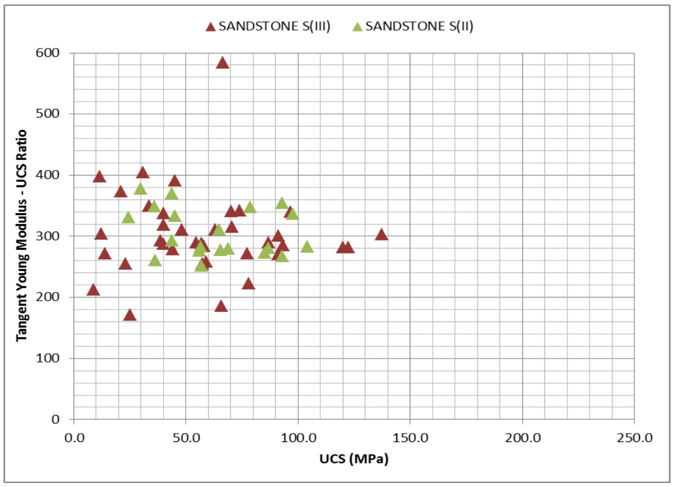

FIGURE 17

SANDSTONE – E_T/UCS RATIO VERSUS UNIAXIAL COMPRESSIVE STRENGTH

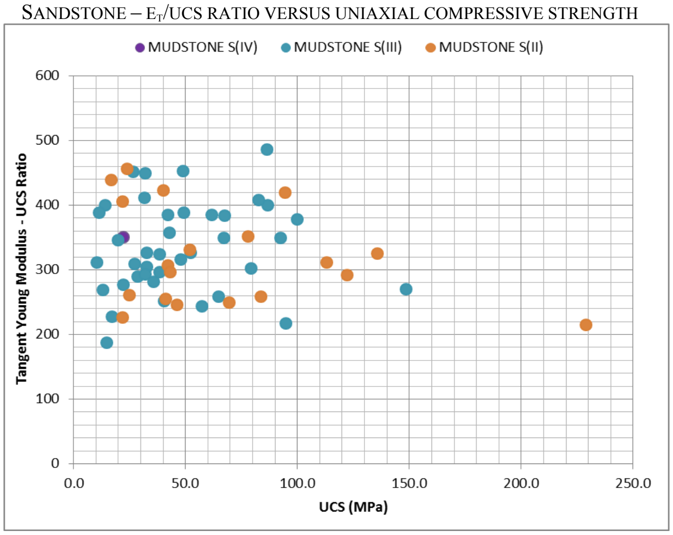

FIGURE 18

MUDSTONE – E_T/UCS RATIO VERSUS UNIAXIAL COMPRESSIVE STRENGTH

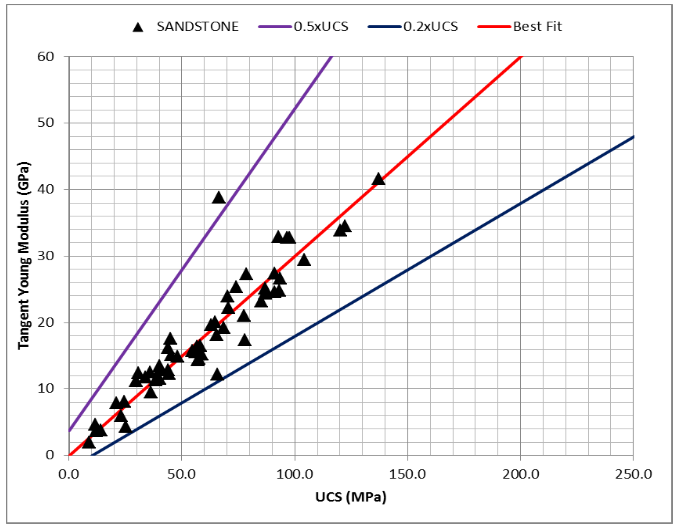

FIGURE 19

SANDSTONE – TANGENT YOUNG'S MODULUS VERSUS UNIAXIAL COMPRESSIVE STRENGTH

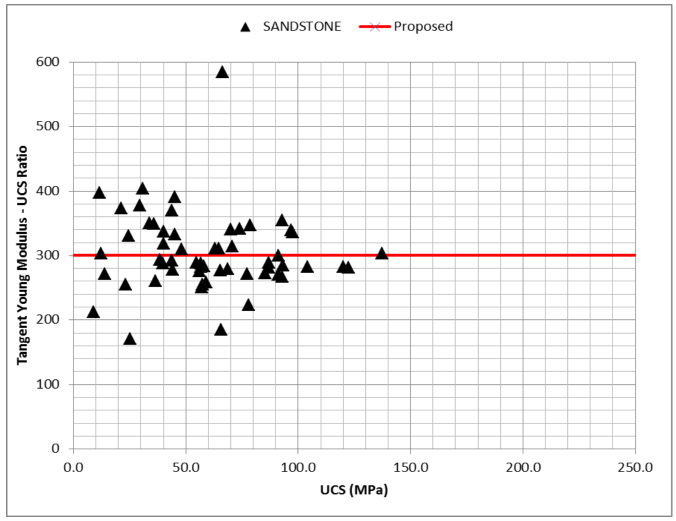

FIGURE 20

SANDSTONE – E_T/UCS RATIO VERSUS UCS BEST FIT

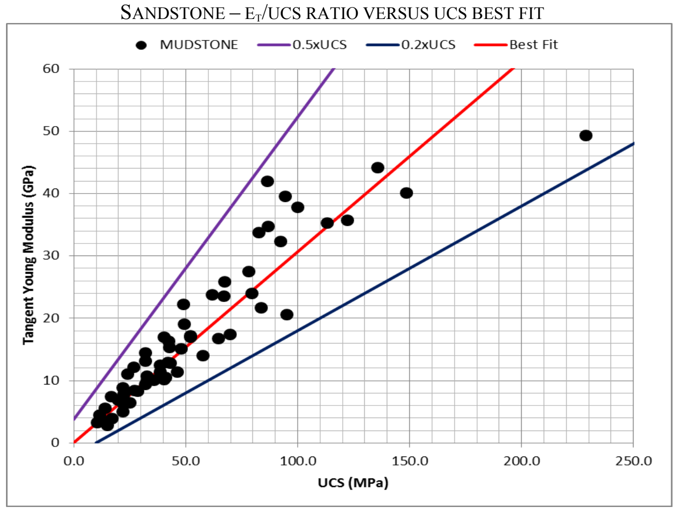

FIGURE 21

MUDSTONE – TANGENT YOUNG'S MODULUS VERSUS UNIAXIAL COMPRESSIVE STRENGTH

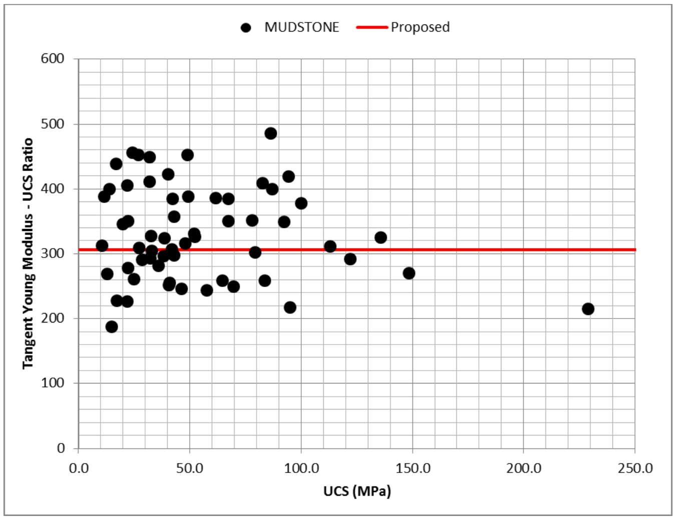

FIGURE 22
MUDSTONE – E_T/UCS RATIO VERSUS UCS BEST FIT

DISCUSSION

UCS versus Dry Bulk Density – As shown in Figures 2 to 6, there is a trend where lower values dry bulk density yield lower values of uniaxial compression strength for both sandstones and mudstones. However, the confidence levels are poor to moderate, with coefficients of determination 0.29 and 0.47, respectively.

Although there is an obvious overlap for dry bulk unit weight greater than 25kN/m^3, the weathering grade and dry bulk density can still be related. It is to be noted that the inferred weathering grade, as a visual classification is subjective and highly dependent upon professional judgement and experience [19].

Rock Anisotropy and PLI – The mean ratio of strengths, taken as a representative index of strength anisotropy, are as follows: 1.31 for sandstones and 1.33 for mudstones, with coefficients of determination 0.69 and 0.71, respectively. The results for both materials are consistent with each other, as expected for materials that share bedding orientations.

UCS versus PLI – Although anomalous values and point load index values lower than 1MPa have been filtered, Figures 9 to 11 show that although there is considerable scatter for point load strength index values lower than 5MPa, these tend to converge towards higher values. The reason for the scatter can be:

- Strength anisotropy – axial and diametral ratio between tensile and compressive strength;
- Failure through defects and discontinuities instead of through the intact rock;
- Point load strength tests and associated uniaxial compression strength tests undertaken on adjacent specimens of different lithology and/or weathering grade, and
- Higher sensitivity of point load strength test on weaker rock, with potential to cause loss of test reliability.

Equation (1.5) while perhaps being appropriate for some strong and isotropic rocks, overestimated the UCS strength on weaker rock such as the ones studied on the present work. The plots presented on Figures 12 to 15 highlight the inadequacy of equation (1.5) on Jurong Formation materials. Meanwhile, equation (1.4) seems reasonable, although it might look like it underestimates the rock strength. It is key to understand that the relationship given by (1.4) was fruit of the combined assessment of strength estimates of sandstones and siltstones along with estimates of shaley mudstones. The fissile nature and usual lower unconfined compressive strength of the latter [13] may have influenced the lower ratio proposed on equation (1.4). Marinos P. et al [16] highlighted that for clayey shales point load strength tests may cause plastic deformation rather than fracture of the specimen, yielding non-reliable results.

Nearly all the results assessed in the present work relate to moderately to slightly weathered rocks of Jurong Formation, and therefore might not be representative of highly weathered rock, for which Leung C. F. et al [14] relationship might be applicable. Some studies indicate that the UCS/PLI ratio increase with the increase of rock strength [8] and therefore Leung C.F. et al [14] equation (1.4) seems reasonable for shaley mudstones of Jurong Formation, and even highly weathered sandstones and mudstones of the Jurong Formation.

The relationships established by the author have moderate confidence levels with coefficients of determination ranges between 0.3 and 0.4. Thus, for moderately to slightly weathered sandstones and mudstones, the author's recommendation is to use the relationships presented in (1.8) to (1.11) with engineering judgment.

E_t versus UCS – While a similar assessment on slightly weathered to fresh rocks of Jurong Formation by Nonaka T. et al [17] concluded the absence of a trend independently of the rock type or weathering grade, the present work shows that the data might be suitably fitted by a straight line defined by equations (1.12) and (1.13) with strong coefficients of determination 0.86 and 0.82, for sandstone and mudstone respectively.

An improved relationship can be obtained using a power relationship presented in (1.14) and (1.15) with excellent coefficients of determination with values of 0.91 and 0.90, respectively.

CONCLUSIONS AND RECOMMENDATIONS

I. Conclusions

UCS versus Dry Bulk Density – The derived relationships provide with a poor to moderate estimation of the UCS strength.

Rock Anisotropy and PLI – The approach taken to derive the anisotropy has given consistent results between sandstones and mudstones.
Considerable scatter on point load strength index values

UCS versus PLI – Moderate relationships have been derived. Equation (1.5) is not applicable to rocks of the Jurong Formation, as it overestimates the strength. Equation (1.4) seems reasonable on general highly weathered rocks of Jurong Formation, while equations (1.8) and (1.9) may be more adequate on moderately to slightly weathered rock units.

E_t versus UCS – The present paper has established that a strong relationship exists between uniaxial compression strength and tangent young modulus, with equations (1.12) to (1.15) defining that relationship.

Generally the strength and stiffness are slightly greater for the mudstones, this might be related to the grain size, for which a decrease in grain size leads to an increase in strength and stiffness. The bonding between particles and the fact that a much larger number of grains have to fail, might be the reason behind that slight difference between sandstones and mudstones.

II. Recommendations

Shape effects must be considered and strength test results normalized (e.g. at a reference diameter of 50mm) according to latest standards or state-of art procedures. This is critical for comparison and assessment between different strength indexes.

To adequately assess the reliability of point load strength data it is recommended to ensure the GI Contractor included photographs, as well as description of the specimen's mode of failure (i.e. failure through joint, lamination, intact rock). At the same tame we recommend to filter any anomalous values and treat point load strength index values lower than 1MPa with suspicion.

Point load strength tests on shaley mudstones might yield unrepresentative results, and hence customized testing must be specified and results carefully reviewed on such fissile materials.

Point load strength index must be used in conjunction with uniaxial compressive strength tests, when possible. This approach allows engineers to verify and confirm the reliability of proposed empirical relationships or even establish site-specific relationships.

III. Future Work

Except for the established empirical correlation between tangent Young's modulus and the uniaxial compression strength, the relationships between UCS and both dry bulk density and point load strength index have given low to medium coefficients of determination for both rock units.

Therefore the next step may be to evaluate these relationships considering multiple-variables, as well as to include in-situ testing results.

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