STRENGTH TEST CORRELATIONS AND ANISOTROPY OF THE MAIN SYDNEY REGION ROCK UNITS

Peter Waddell and Marco Rafanelli
AECOM

https://doi.org/10.56295/AGJ6035

ABSTRACT

The typical strength descriptor and parameter used for rock is Uniaxial Compressive Strength (UCS). In many small to medium size projects laboratory tests to determine UCS are only conducted on a few rock core samples, if at all. Point Load Strength Index (PLI) testing is commonly conducted at regular intervals on rock core. Correlations between PLI and UCS are used to assess rock strength and as input to rock mass classification systems. PLI tests are usually made parallel (Axial) and perpendicular (Diametral) to the core axis. The Axial results are commonly used to estimate rock strength. The ratio of Axial to Diametral PLI results can be used to assess the degree of anisotropy.

It is common to compare UCS with PLI test results that are close together to establish site specific correlations but limitations in datasets often do not result in clear cut correlations. This paper presents a methodology for assessing UCS and PLI datasets and comparing these to the relationship between UCS and PLI assumed in AS1726 Geotechnical Site Investigation.

There are three main bedrock units encountered in the Sydney Region: Hawkesbury Sandstone, Ashfield Shale, and Bringelly Shale. This paper presents assessments of the relationship between UCS and PLI for these bedrock units. The degree of anisotropy of each of the main Sydney bedrock units is also assessed and compared with published values.

1 INTRODUCTION

Bedrock is often assessed for foundations, open excavations and tunnels using rock mass classification systems that consider criteria such as rock strength, defect spacing and nature of defects. Rock strength is commonly assessed using Uniaxial Compressive Strength (UCS) tests and/or Point Load Index (PLI) tests. Studies in the literature compare UCS with PLI test results to establish site or geological unit specific correlations between the two tests.

The three main bedrock units encountered in the Sydney Region are sedimentary units called Hawkesbury Sandstone, Ashfield Shale, and Bringelly Shale. The literature presents relationships between UCS and PLI, and anisotropy for the three main Sydney Region bedrock units based on limited datasets. In this paper larger datasets of the three main rock units are analysed to:

- Assess whether the ratio of PLI to UCS of 20 assumed for strength classification in AS1726 Geotechnical Site Investigation provides a reasonable basis for classifying the rock strength category
- Recommend alternative multipliers to that of AS1726 for the three main rock units, if supported by the datasets
- Assess the anisotropy of the sedimentary rock units.

2 SYDNEY GEOLOGY

The Sydney Region is an area extending from the Hawkesbury River in the north, up into the Blue Mountains to the west, the Picton area in the south, and with a coastline of sandstone cliffs forming the eastern boundary. Branagan 1985 described the rocks of the Sydney Region as predominantly of sedimentary origin, having been deposited within a broad zone of subsidence known as the Sydney Basin.

The main bedrock units are Triassic Age and are identified as:

- Wianamatta Group – Up to 300 m thick, but generally about 100 m thick and comprising:
  - Bringelly Shale (Twib) – Shale, Carbonaceous Claystone, Laminite, fine to medium grained lithic Sandstone, rare Coal. Maximum thickness about 260 m. Deposited in lagoons, marches levees and backswamps.
  - Ashfield Shale (Twia) – Black to dark grey Shale and Laminite. Ranges in thickness from about 45 m to 60 m. Deposited in an estuarine environment.

- Hawkesbury Sandstone (Tuth) – Medium to coarse grained quartz Sandstone, very minor Shale and Laminite lenses. Maximum thickness is about 290 m. Sandstones deposited in braided channels, with Shale and Laminite beds within the Sandstones deposited in abandoned channels.

Figure 1 is an extract of the NSW seamless geology (Minview) showing the distribution of the three units across the Sydney Region.

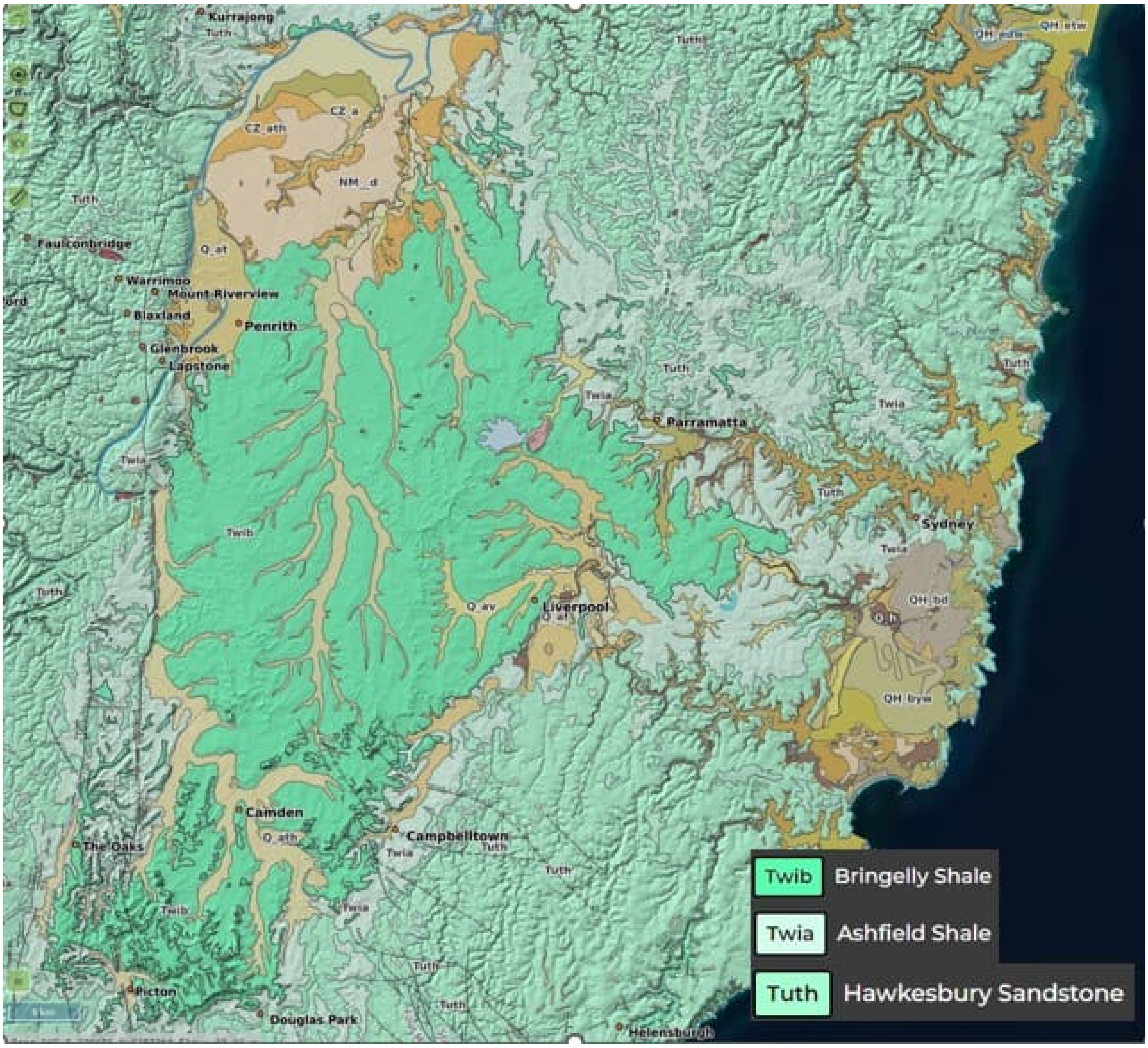


Figure 1: Sydney Region Geology from NSW seamless geology dataset Minview

3 ROCK STRENGTH TESTS

Uniaxial Compressive Strength tests to AS4133.4.2.2-2013 or AS4133.4.3.1-2009 are conducted on rock cores cut into test cylinders of intact rock with the ends ground smooth. A compression pressure is applied to the ends of the test cylinders via flat platens as shown in Figure 2.

PLI tests to AS4133.4.1-2007 consist of applying a compression load to a rock sample via conical shaped platens. Testing can be conducted:

- Across the diameter of a rock core, termed a Diametral test
- Perpendicular to the core axis, termed an Axial test
- To an irregular shaped rock sample, termed an Irregular Lump test.

Figure 3 shows a PLI test setup with a sample in the axial test orientation.

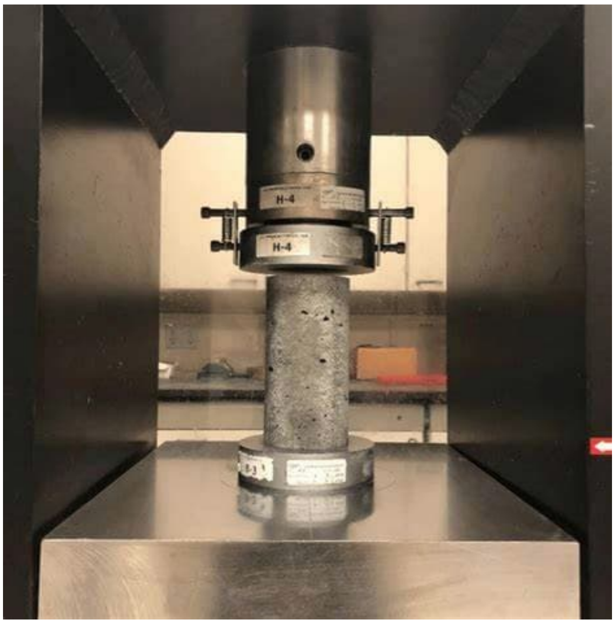


Figure 2 UCS test setup

Figure 3 Point Load Index test setup

PLI tests are commonly conducted at regular intervals on rock core samples. It is common practice to do a diametral test to produce a sample that is then subject to an axial test. In that way, pairs of test results immediately adjacent to each other are produced. Tests can be conducted on samples of different diameter and the results are corrected to a reference diameter of 50 mm and reported as Is_{50} values. In this paper the terms PLI and Is_{50} are used interchangeably.

Bewick et al (2015) indicate that the UCS test result is an index rather than a unique engineering parameter. The accuracy of the UCS test depends on many factors including: the loading rate, specimen homogeneity, size, geometry and moisture content. However, UCS is the measure typically used to characterise rock strength, despite the inherent test limitations and resulting variability.

In practice UCS tests may only conducted on a few rock core samples from each borehole, if at all. PLI tests are a quick and cost-effective test that is commonly used to supplement or substitute for UCS tests. Akbay and Altindag (2020) analyse the impacts of testing methodology on PLI accuracy. They identify that testing methodology shift rocks into another strength category, particularly in weak rocks.

4 THE RELATIONSHIP BETWEEN UCS AND PLI

It is common to compare UCS with PLI test results that are close together to establish site specific correlations. However, limitations in datasets may not provide clear correlations. Laboratory tests to determine UCS are often only conducted on a few rock core samples from investigation boreholes, if at all. Where UCS tests are limited or non-existent, PLI results alone are used to assess rock strength class, as input to rock mass classification systems and to estimate UCS for engineering assessments.

AS1726-2017 Geotechnical Site Investigations the Australian standard adopts a ratio of UCS = 20 x Is_{50} for rock strength classification as shown in Table 1, but recommends site specific correlations. The PLI standard, AS4133.4.1-2007 also recommends that the relationship be established by testing.

Table 1: Rock Material Strength Classification (Table 19 of AS1726-2017)

Term	Abbreviation	Uniaxial compressive strength (see Note 1 and Note 2) MPa	Guide to strength	
			Point load strength index $I_{s(50)}$ (see Note 3) MPa	Field assessment
Very Low Strength	VL	0.6 to 2	0.03 to 0.1	Material crumbles under firm blows with sharp end of pick; can be peeled with knife; too hard to cut a triaxial sample by hand. Pieces up to 30 mm thick can be broken by finger pressure.
Low Strength	L	2 to 6	0.1 to 0.3	Easily scored with a knife; indentations 1 mm to 3 mm show in the specimen with firm blows of the pick point; has dull sound under hammer. A piece of core 150 mm long by 50 mm diameter may be broken by hand. Sharp edges of core may be friable and break during handling.
Medium Strength	M	6 to 20	0.3 to 1	Readily scored with a knife; a piece of core 150 mm long by 50 mm diameter can be broken by hand with difficulty.
High Strength	H	20 to 60	1 to 3	A piece of core 150 mm long by 50 mm diameter cannot be broken by hand but can be broken by a pick with a single firm blow; rock rings under hammer.
Very High Strength	VH	60 to 200	3 to 10	Hand specimen breaks with pick after more than one blow; rock rings under hammer.
Extremely High Strength	EH	more than 200	more than 10	Specimen requires many blows with geological pick to break through intact material; rock rings under hammer.

NOTES:

1 Material with strength less than 'Very Low' shall be described using soil characteristics. The presence of an original rock structure, fabric or texture should be noted, if relevant.

2 The method for measuring the uniaxial compressive strength shall be in accordance with AS 4133.4.2.1.

3 The method for measuring the point load strength index shall be in accordance with AS 4133.4.1.

Axial PLI results are commonly used to estimate rock strength. PLI are most often conducted on cores from vertical boreholes; hence they are strength measures in the vertical axis. Strength anisotropy is assessed from the ratio of axial to diametral PLI results, which is termed the Anisotropy Index (AI) as described by Broch and Franklin (1972).

5 DESKTOP VALUES OF UCS/PLI RELATIONSHIP AND ANISOTROPY

Based on a literature review the relationships between PLI and UCS, and anisotropy of the three main Sydney Region geological units are summarised in Table 2.

Table 2: UCS and PLI relationships for the three Sydney geological units

Geological Unit	UCS/Axial Is_{50}	UCS/Diametral Is_{50}	Anisotropy Index	Dataset Size	Source
Hawkesbury Sandstone	15 to 29 best fit of 20	14 to 35 best fit of 24	1.13 (saturated) 1.3 (oven dried)	<100	Pells 2004
Ashfield Shale	24 14 to 20	- 22 to 35	2 2.4 to 3.7	~50	William & Airey 2004 Won 1985
Bringelly Shale	21	-	3	<10	William & Airey 2004

6 DATASETS

Datasets, each comprising UCS, Axial and Diametral PLI results (Is_{50} values) have been assembled for the three main geological units from several projects across the Sydney Region. The UCS and PLI test results were carried out by several laboratories, using different equipment. The UCS tests were mainly reported as being carried out at 'as received' moisture contents. The PLI tests were mainly carried out in the laboratory based on comparing drilled dates to test certificate dates. Some PLI tests may have been carried out in the field. Testing after variable periods of handling and storage will have resulted in changes in moisture content relative to the rock in the ground.

In both UCS and PLI tests the nature of the failure influences the accuracy of the measured strength. Where failures are not clean and through the intact rock both UCS and PLI will be lower than where the test samples exhibit this failure mode. Hoek 1977 recommended that such results be treated with suspicion and the results should normally be rejected. However, it is not common practice to remove such results. To assess the potential impact of including results that were not clean tensile fractures a dataset of over 2,300 Axial PLI results on Bringelly Shale from a Sydney Metro project was analysed. This included a range of rock types identified as Sandstone, Siltstone and Laminite. The proportion of results recorded as not having clean tensile fractures was about 10%. The average Axial PLI result was only about 3% different when the 10% of 'suspicious' results were removed. This indicates that in typical Sydney rock types this is not a major source of error.

Some of the datasets were assembled from digital data without reference to laboratory test certificates that often provide additional data on the mode of failure. Hence, the datasets used to compare UCS and PLI results have not been filtered to remove results that were not clean breaks.

Axial PLI results have been used for comparison with UCS. Axial and Diametral PLI results have been used to assess anisotropy of the intact rock. Some statistics on the datasets are presented in Table **3**.

Table 3: Summary of Datasets for the three main Sydney Region Rock Units

Geological Unit	Dataset Size(Note 1)	Average UCS (MPa)	Std. Dev. UCS (MPa)	Mean Axial Is_{50} (MPa)	Std. Dev. Axial Is_{50} (MPa)	Mean Diametral Is_{50} (MPa)	Std. Dev. Diametral Is_{50} (MPa)
Hawkesbury Sandstone	425 425 (pairs of Axial and Diametral Is_{50})	25.6	10.2	1.32	0.67	1.18	0.63
Ashfield Shale	111 111 (pairs of Axial and Diametral Is_{50})	22.8	12.8	1.28	0.95	0.74	0.54
Bringelly Shale	187 84 (pairs of Axial and Diametral Is_{50})	13.8	12.3	0.86	0.85	0.32	0.29

Note (1) Refers to the number of compared 'pairs' of UCS and Axial Is_{50} unless stated otherwise

7 HAWKESBURY SANDSTONE

7.1 Traditional Analysis

A common approach to the analysis of UCS versus PLI is to plot UCS versus PLI on linear axes as a single dataset of pairs as shown in Figure 4 for a dataset of 425 paired UCS and PLI test results on Hawkesbury Sandstone. The PLI results were within 0.5 m of a UCS result from the same borehole. Trend lines representing a ratio of UCS = 20 x Is50 as assumed in AS1726-2017 and the linear trendline ratio of UCS = 17.16 x Is50 are shown.

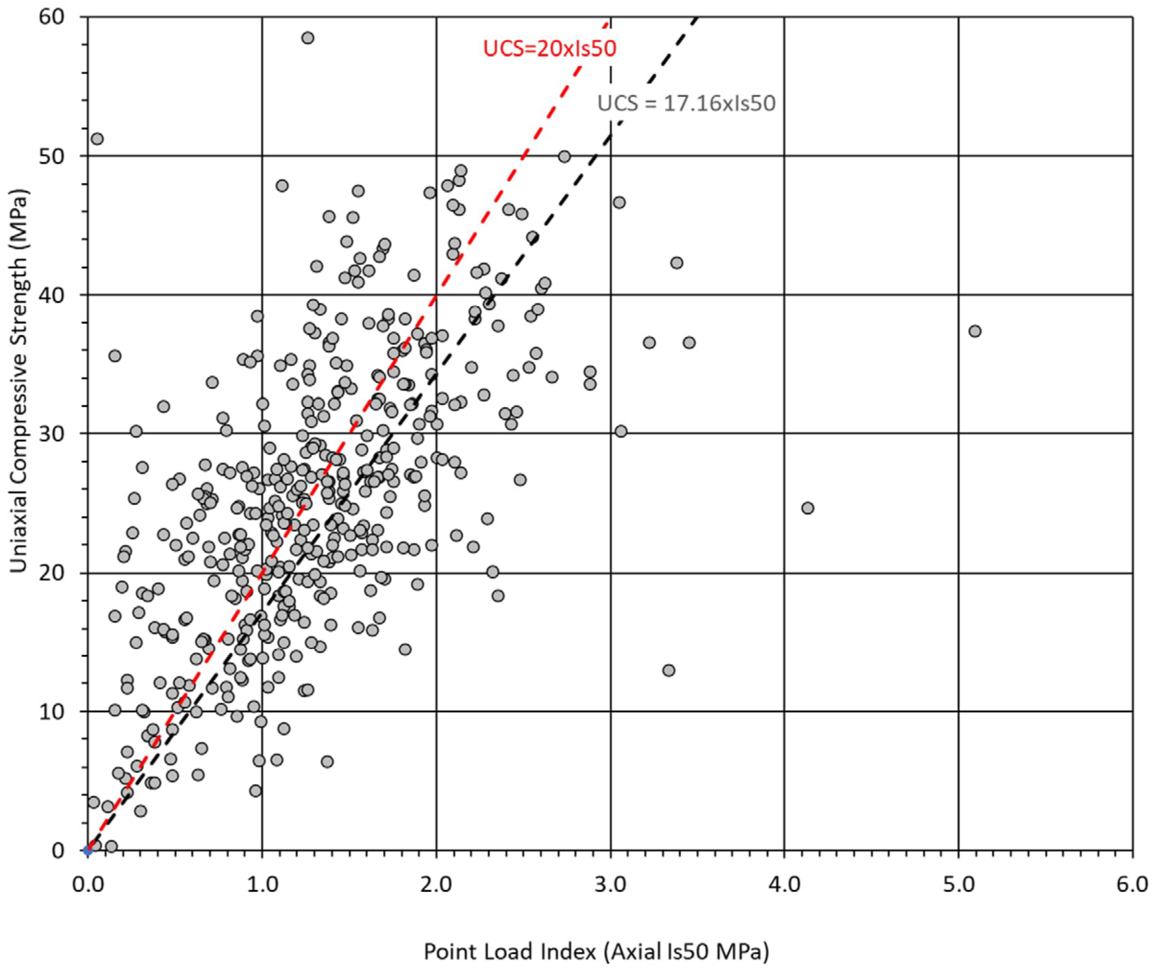


Figure 4: Hawkesbury Sandstone – UCS versus Point Load Index

The traditional analysis provides little insight into the how well the data characterises the rock strength and an alternative approach is used in the following sections for the Hawkesbury Sandstone, Ashfield Shale and Bringelly Shale.

7.2 Rock Strength Categorisation Analysis

To assess the accuracy of rock strength categorisation based on individual test PLI results, the test results are shown on a log scale plot in Figure 5 with shaded areas representing Low (grey), Medium (purple) and High (green) strength for the same dataset plotted in Figure 4.

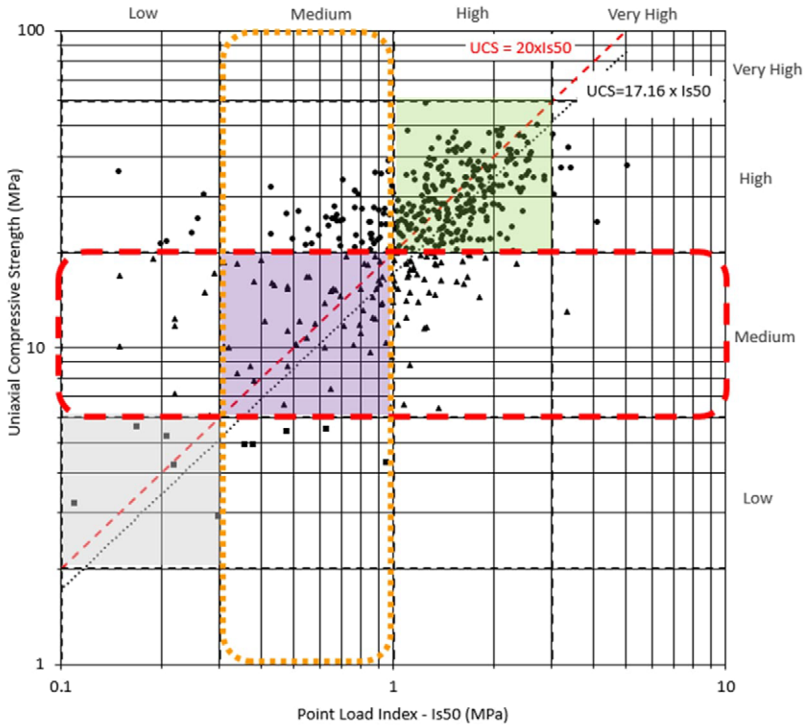


Figure 5: UCS versus PLI plotted on log scales

The statistical distribution of the test results is shown in Figure 6 below. For this dataset the percentage of UCS results within the medium strength category is equal to the one obtained for a ratio of 20 and is about 26%. This should not be considered representative of the accuracy of the UCS-PLI correlation for an individual test. In fact, for a given number of UCS tests within the Medium strength category, only 50% of these instances has a PLI that returns the same classification assuming a ratio of 20.

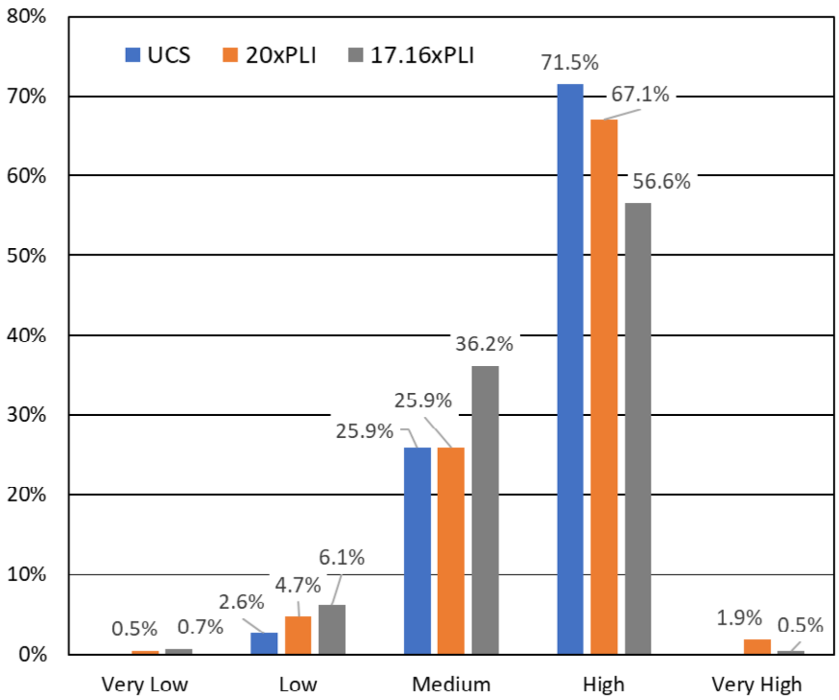
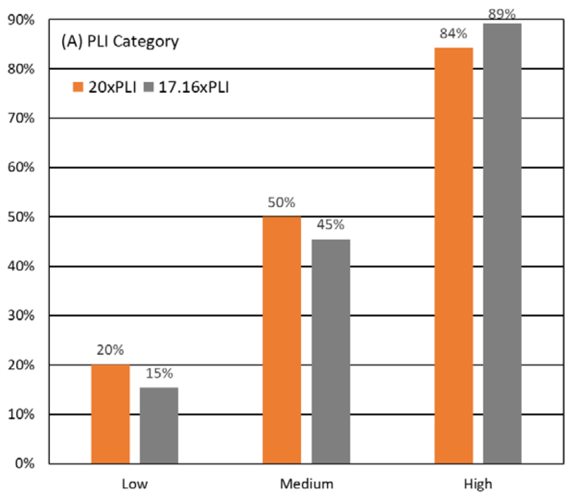


Figure 6: Hawkesbury Sandstone – Statistical distribution of the tests in each rock strength category

The accuracy of PLI to predict rock strength category can be assessed by moving the category boundaries along the PLI axis based on different multipliers and calculating the effect on the proportions of results falling inside or outside the shaded areas. A summary of the results is shown in Figure 7(A) and (B). Both figures are useful to assess the accuracy of PLI when it is used to classify the rock strength.

Figure 7(A) shows that only 45% of PLI results give a correct strength classification of Medium if used in conjunction with a ratio of 17.16. On the other hand, Figure 7(B) shows that for a given volume of Medium strength rock based on UCS, the PLI results lead to a correct strength classification in 64% of the cases assuming a ratio of 17.16. If a ratio of 20 is assumed a correct classification in produced in only 50% of instances.



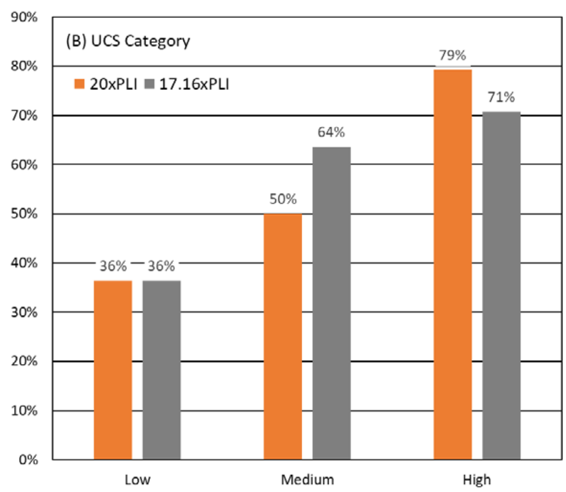


Figure 7: Hawkesbury Sandstone – Prediction accuracy compared to (A) PLI Category, (B) UCS Category

Figure 7(A) shows that where the population within each PLI based strength category is considered, only about 20 % of the Low strength and 50% of the Medium strength predictions are correct for a ratio of 20 (orange). Over 80% of the High strength predictions are correct. Adopting a ratio of 17.16 (grey) based on the trend line does not significantly improve the accuracy.

Figure 7(B) shows that where the population within each UCS based strength category is considered, only about 36% of the Low strength and 50% of Medium strength rock is identified by PLI based on a ratio of 20 (orange). The accuracy for Medium strength improves from 50% to 64% based on a ratio of 17.16. About 80% of High strength rock is identified by PLI based on a ratio of 20 but becomes less accurate at about 70% based on a ratio of 17.16.

Based on the aspects of accuracy above, PLI does not accurately estimate the rock strength category of individual rock samples where the AS1726 ratio of 20 is adopted. Whilst the overall proportions of Low, Medium, and High strength are similar, the accuracy of PLI in correctly categorising rock as Low or Medium strength is poor. Furthermore, the adoption of a ratio based on the trend line derived value of 17.16 does not significantly or uniformly improve accuracy.

7.3 Strength Prediction – Average over Depth Intervals

Based on the analysis in Section 7.2, individual PLI results are an unreliable indicator of strength category for Hawkesbury Sandstone. For many rock mass classification applications, the strength criteria of UCS over a zone of influence is used along with the nature and spacing of defects. In this section an alternative approach of plotting the vertical spatial distribution of PLI and UCS test results is used to predict the mean UCS over a given depth interval.

Figure 8 shows a plot of UCS versus depth based on UCS tests results and estimated based on Axial Is50 values within 0.5 m of the UCS result. At 5 m intervals the median values of actual and estimated UCS values are plotted.

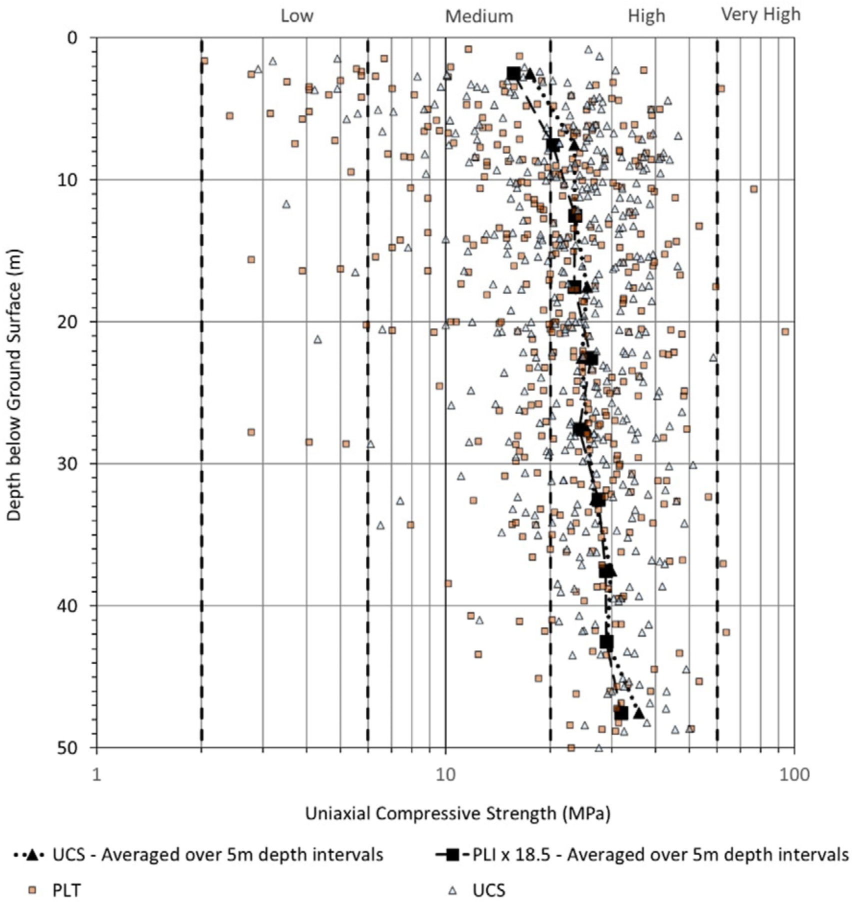


Figure 8: Hawkesbury Sandstone – UCS versus Depth (PLI within 0.5 m of UCS)

Figure 8 shows several features of the Hawkesbury Sandstone:

- Considerable UCS variability in the upper 10 m, with strength ranging from Low to High. This corresponds to the more weathered Hawkesbury Sandstone.
- Less variability below 10 m depth, with most of the rock being Medium or High Strength. This likely corresponds to fresh Hawkesbury Sandstone.
- A ratio of 18.5 on the median values of Axial Is50 produces a relatively good fit to the medians of UCS at 5 m intervals below first 10 m depth.
- A higher ratio is required to improve the fit above 10 m depth. However, if the maximum distance between the UCS and PLI results is reduced to 0.2 m instead of 0.5 m, the ratio of 18.5 produces a reasonable fit. This indicates that the rock is not as well spatially correlated in the upper 10 m as the less weathered rock at depth. A single ratio based on the less weathered rock at depth is still relevant to the more weathered rock.

8 ASHFIELD SHALE

8.1 Rock Strength Categorisation

The Ashfield Shale is lower strength compared to the Hawkesbury Sandstone. About 55% of the Ashfield Shale is High strength, about 36% Medium strength and 8% Low strength based on the UCS results. This is reflected in Figure **9** where, plotted to log scales and with shaded areas delineating Low (grey), Medium (purple) and High (green) strength category as per AS1726. Figure 9 also shows the relationship between UCS and Is50 proposed by AS1726, (UCS=20 x Is50); a linear trendline (UCS=13.38 x Is50); and the one given by the coefficient that provides best fit in the averaged strength vs depth diagram (UCS=15 x Is50).

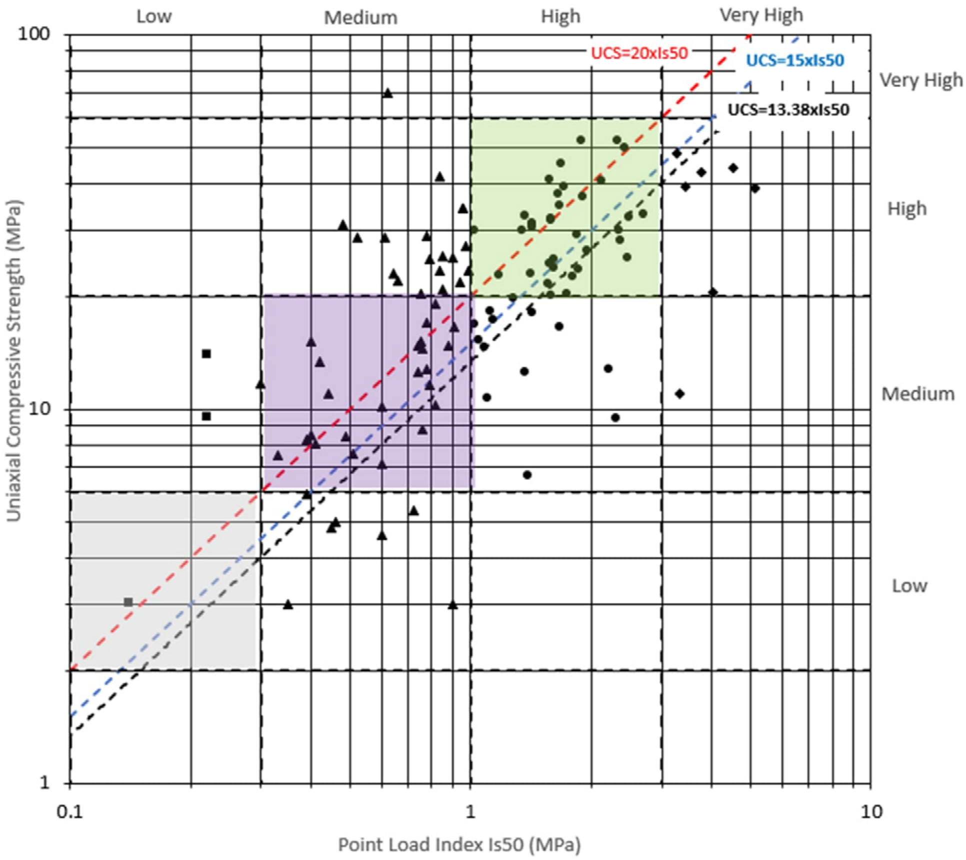


Figure 9: Ashfield Shale – UCS versus PLI

Figure 10(A) and (B) show the accuracy of the predictions of rock strength category based on Is50 for each of these coefficients produced with the same methodology discussed above for Hawkesbury Sandstone.

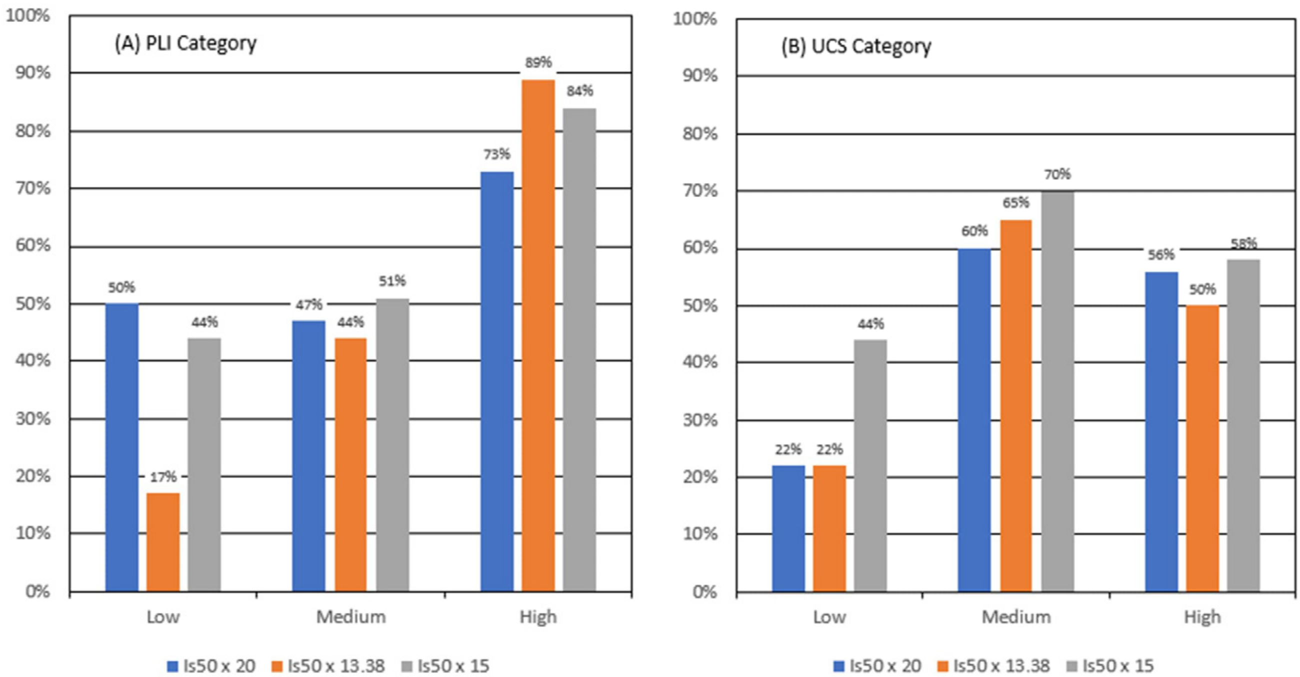


Figure 10: Ashfield Shale - Accuracy of Predictions relative to (A) PLI Category, (B) UCS Category

Figure 10 shows that, irrespective of the value of the adopted correlation factor, assigning rock strength category for Ashfield Shale based on individual PLI tests can lead to incorrect classifications. However, adopting a ratio of 15 produces at least a 10% increase in the correct classifications for Low and Medium strength categories.

8.2 Strength Prediction – Average over Depth Intervals

Like the Hawkesbury Sandstone analysis, the Ashfield Shale test results are plotted relative to depth in Figure 11. This shows available UCS test results and values estimated based on Axial Is50 within 0.5 m of the UCS test. At 5 m intervals the median values of actual and estimated UCS values are plotted.

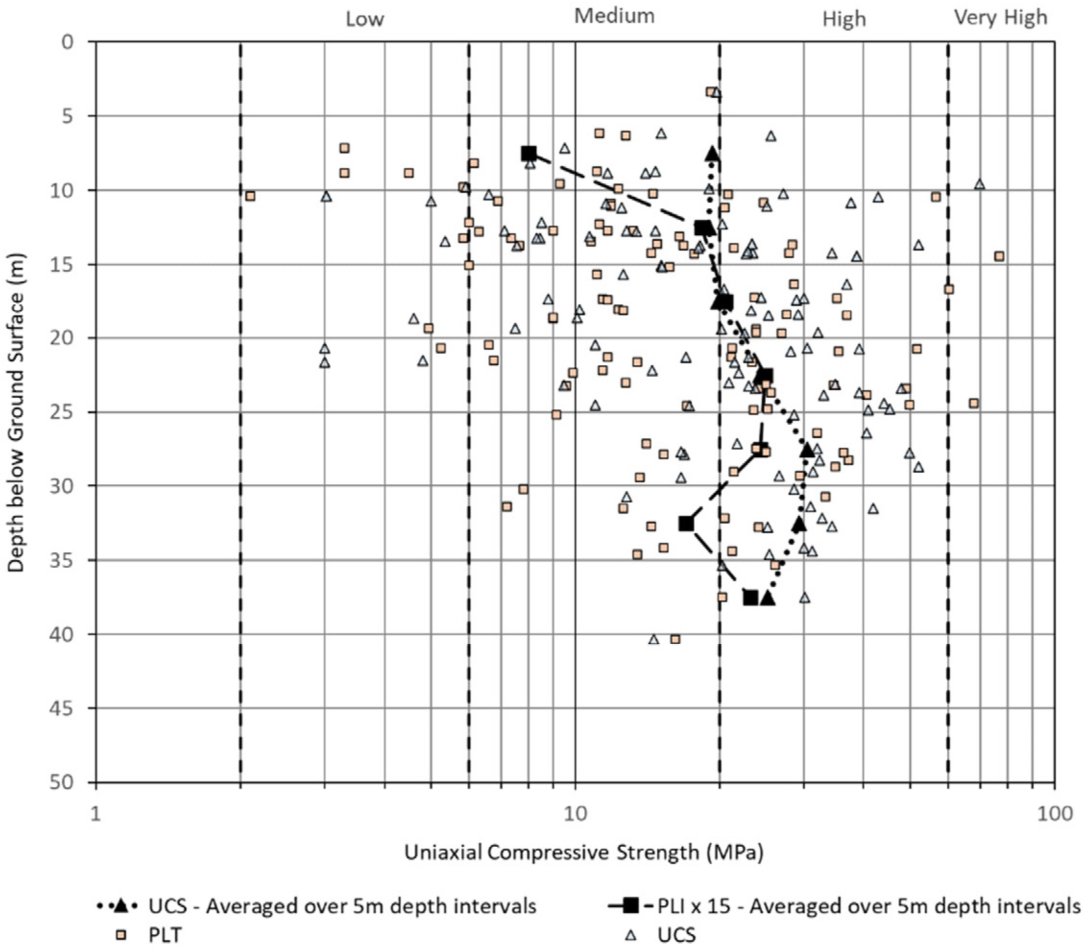


Figure 11: Ashfield Shale – UCS versus Depth

Figure 11 shows several features of the Ashfield Shale:

- Rock strength is Low and Medium in the upper 5m to 10 m. This likely corresponds to the more weathered Ashfield Shale.
- Most of the rock is Medium and High Strength below 10 m depth.
- A ratio of 15 on the median values of Axial Is50 produces a relatively good fit to the medians of UCS at 5 m intervals between 10 m and 40 m depth. The fit in the upper 10 m is not clear but there is little data, and it may be poorly spatial correlated.

9 BRINGELLY SHALE

9.3 Rock Strength Categorisation

The Bringelly Shale dataset of 188 UCS and PLI results is plotted in Figure 12. The Bringelly Shale is lower strength compared to the Hawkesbury Sandstone. About 22% of the Bringelly Shale is High strength, about 45% Medium strength and 28% Low strength. Figure 12 shows the relationship between UCS and Is50 proposed by AS1726 (UCS=20 x Is50); a linear trendline (UCS=10.63 x Is50); and the one given by the coefficient that provides best fit in the averaged strength vs depth diagram (UCS=15 x Is50).

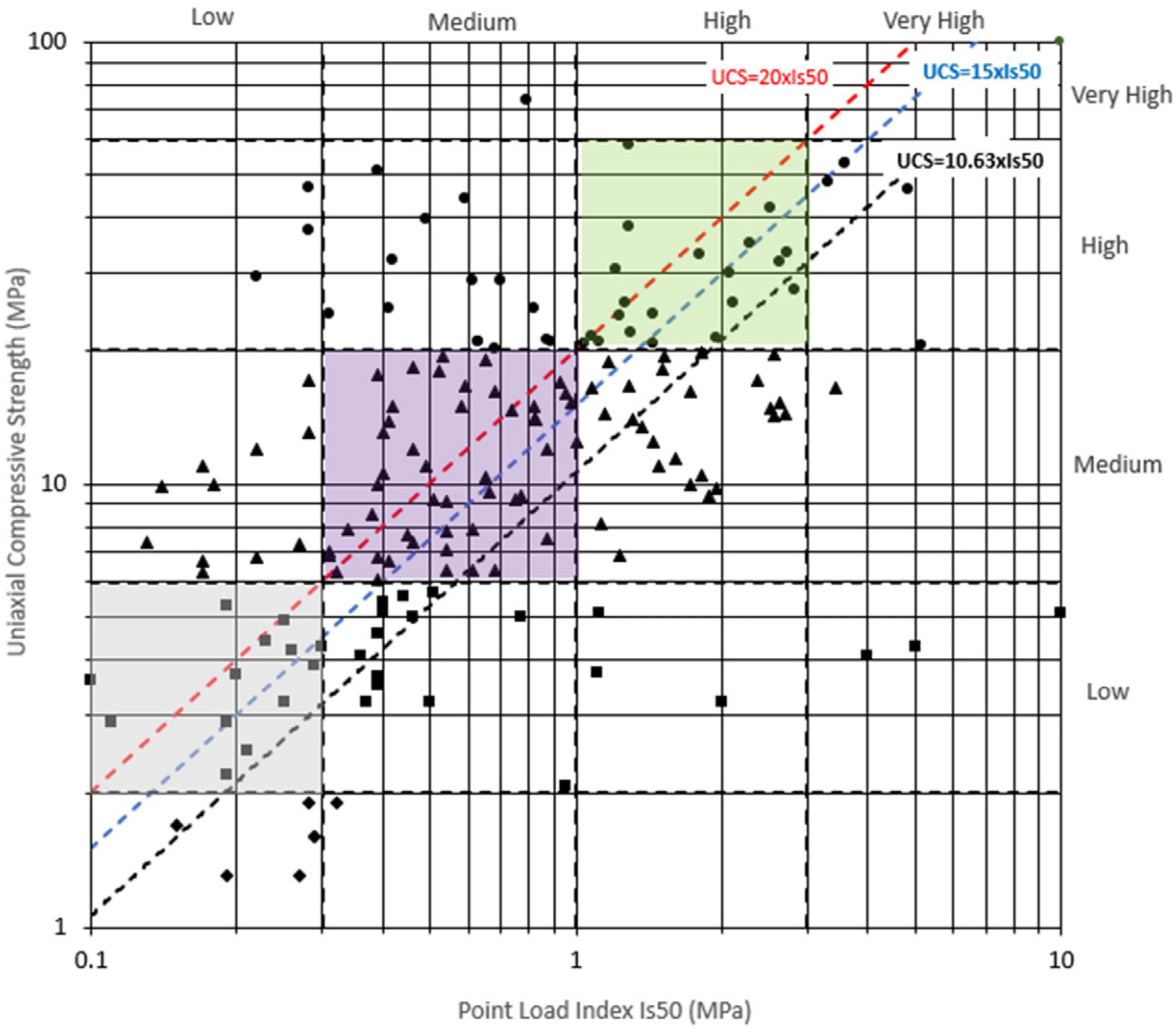


Figure 12: Bringelly Shale - UCS versus PLI

Figure 13(A) and (B) show the accuracy of the predictions of rock strength category based on Is50 for each of these coefficients. The accuracy plots have been produced with the same methodology discussed above for Hawkesbury Sandstone.

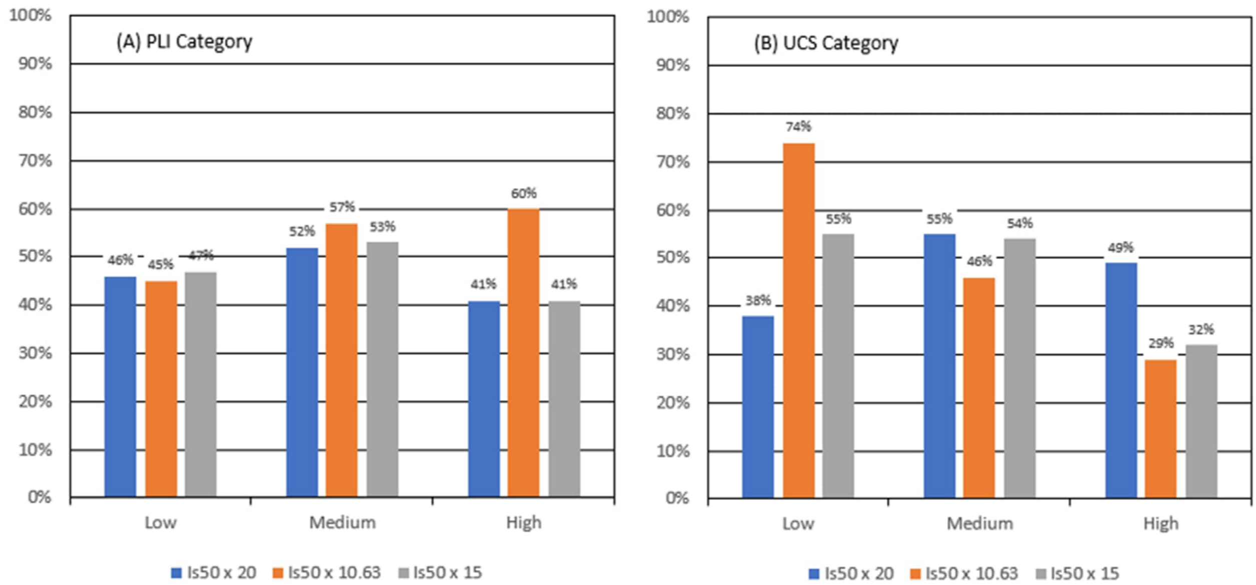


Figure 13: Bringelly Shale - Accuracy of Predictions (A) PLI Category, (B) UCS Category

Figure 13 shows that, irrespective of the value of the adopted correlation factor, assigning rock strength category for Bringelly Shale based on an individual PLI test leads to significant risk of incorrect classification.

9.2 Strength Prediction – Average over Depth Intervals

Like to the Hawkesbury Sandstone analysis, the Bringelly Shale test results are plotted in Figure 14 relative to depth. This shows available UCS test results and values estimated based on Axial Is50 within 0.5 m of the UCS test. At 5 m intervals the median values of actual and estimated UCS values are plotted.

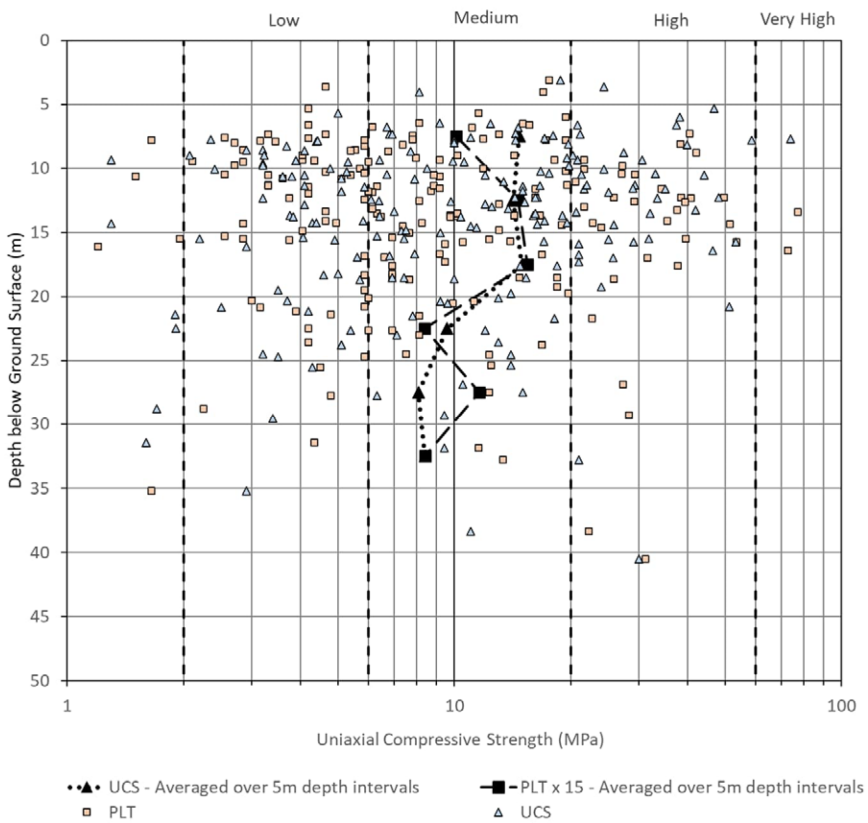


Figure 14: Bringelly Shale – UCS versus Depth

Figure 14 shows several features of the Bringelly Shale:

- Considerable UCS variability in the upper 20 m, with strength ranging from Low to Very High.
- Most of the rock is Low and Medium Strength below 20 m depth.
- A ratio of 15 on the median values of Axial Is50 produces a relatively good fit to the medians of UCS at 5 m intervals between 10 m and 35 m depth.

10 ANISOTROPY

AS4133.4.1 (2007) defines the Strength Anisotropy Index Ia_{50} as the ratio of Is_{50} values for tests perpendicular and parallel to planes of weakness. Planes of weakness in the main Sydney sedimentary rocks are generally related to sub-horizontal bedding partings. Hence, Axial and Diametral Is_{50} values from vertical cored boreholes provides data to evaluate anisotropy. Plots of Axial versus Diametral Is_{50} are shown in:

- Figure 15 for Hawkesbury Sandstone – the linear trend of 1.04 indicating the Sandstone is isotropic.
- Figure 16 for Ashfield Shale – the linear trend line of 1.53 indicating the Shale is anisotropic.
- Figure 17 for Bringelly Shale – the linear trend line of 1.38 indicating the Shale is anisotropic.

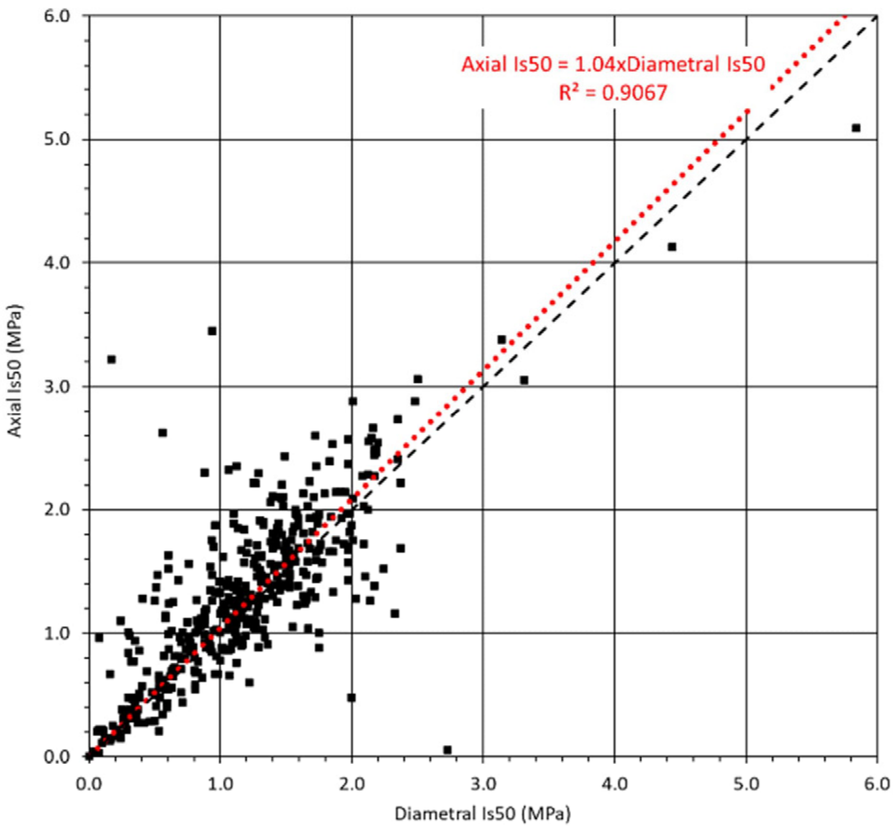


Figure 15: Hawkesbury Sandstone Axial/Diametral Is50

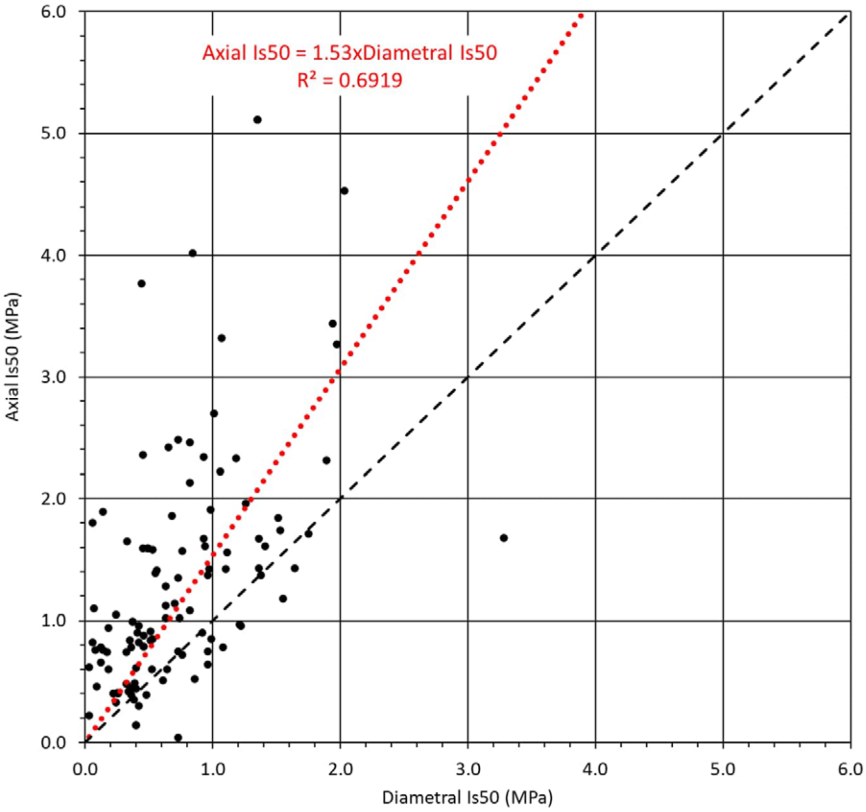


Figure 16: Ashfield Shale Axial/Diametral Is50

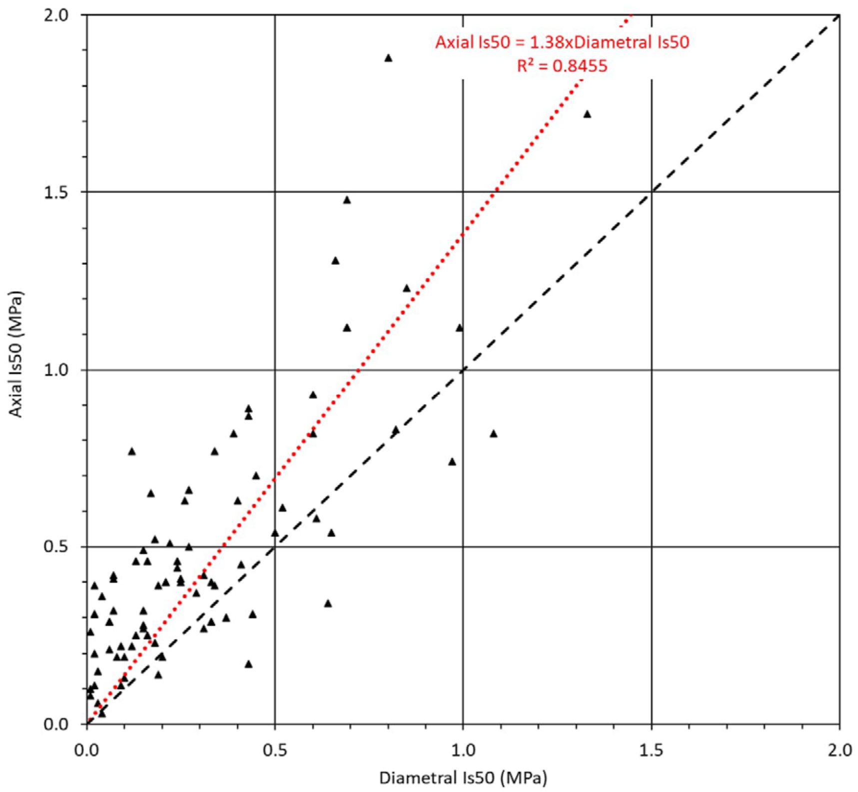


Figure 17: Bringelly Shale Axial versus Diametral Is50

11 CONCLUSIONS

The datasets analysed in this paper show that the Point Load Index test provides poor estimates of UCS if the strength is assessed based on isolated PLI values for all three of the main Sydney Region rock units. Estimates of rock strength category based on PLI are not very accurate even though the category boundaries are on a log scale. The accuracy of the individual tests does not improve significantly when best-fit trend lines are used.

PLI is a measure of tensile strength and therefore only an indirect measure of compressive strength. Furthermore, issues with testing methodology and failure to fully mobilise tensile strength contribute to PLI inaccuracy. This results in PLI not being a reliable predictor of UCS at a particular point in a rock mass. However, these limitations may not matter where estimates of rock strength within a zone of influence are adequate for rock mass classification systems used in foundation or excavation design.

The datasets examined in this paper show a reasonably good assessment of average UCS can be obtained by plotting PLI results with depth and averaging these values over depth intervals (2.5 m to 5m). The best-fit ratios obtained with this method are reported in Table 4.

Table 4: Recommended UCS/PLI ratios and Anisotropy for Sydney Region rock types

Geological Unit	UCS/Axial Is_{50}	Anisotropy Index (AI)	Dataset Size
Hawkesbury Sandstone	18.5	1.04	427
Ashfield Shale	15	1.53	111
Bringelly Shale	15	1.38	187 (84 for anisotropy)

Comparing these values with those from the desktop study in Table 2 results in the following conclusions:

- For the Hawkesbury Sandstone the ratio of UCS/Axial Is50 is consistent with the value reported by Pells (2004).
- For the Ashfield Shale the results are towards the lower end of the range from Won 1985 and much lower than William & Airey (2004).
- For the Bringelly Shale the ratio is much lower than William and Airey (2004).
- The results indicate the Hawkesbury Sandstone is isotropic at the scale of the test samples. The Ashfield and Bringelly Shales are anisotropic, although significantly less anisotropic than reported in earlier studies.

The ratios in Table 4 could be adopted for rock mass classifications of the three main Sydney Region rock units in lieu of the coefficient of 20 implied in Table 19 of AS1726. Those ratios should be applied to average values of PLI over depth intervals rather than individual values.

If a site-specific assessment of the relationships between UCS and PLI is required, rock testing should be planned to reduce the impacts of limitations on the datasets and poor spatial correlation. Well maintained and calibrated test equipment should be used. Sample moisture content should be maintained. UCS and PLI tests should be carried out as close as practicable for comparison, particularly in the more weathered upper part of the rock profile. Tests that fail to produce clean tensile fractures should be removed from datasets.

The discussions above in relation to the low accuracy of individual results of PLI shouldn't discourage practitioners from scheduling PLI tests for ground investigations. In fact, reasonable correlations with UCS can be achieved only if an adequate number of PLI and UCS results can be paired. On their own, PLI tests are a cost-effective way to assess rock strength category and variability in a rock mass.

CRediT authorship contribution statement

Peter Waddell: Conceptualization, Formal Analysis, Writing - review and editing. **Marco Rafanelli:** Data Curation, Formal Analysis, Writing - review and editing

12 REFERENCES

Australian Standard AS 1726:2017 – Geotechnical Site Investigations

Bewick R.P. Amann F. Kaiser P.K. Martin C.D. (2015) Interpretation of UCS Test Results for Engineering Design. *ISRM Congress 2015 Proc. Int'l, Symp. Rock Mechanics* ISBN: 978-1-926872-25-4.

Branagan D.F. (1985). An overview of the Geology of the Sydney Region. *Engineering Geology of the Sydney Region,* pp 3 to 46, edited by P.J.N. Pells, published on behalf of the Australian Geomechanics Society, Balkema.

Brock E. and Franklin J.A. (1972). The point load strength test. Int. J. of *Rock Mechanics and Min. Sc. Volume 9* pp 669-697 Pergamon Press.

Hoek E. (1977) Rock Mechanics Laboratory Testing in the Context of a Consulting Engineering Organization. Int. J. *Rock Mech. Min. Sci. & Geomech. Abstr. Vol 14*, pp91-101 Pergamon Press 1977.

Pells P.J.N. (2004). Substance and Mass Properties of Sandstone. *Australian Geomechanics Journal, Volume 39 No.3* September 2004.

Rusnak J and Mark C. (2004). Using the Point Load Test to Determine the Uniaxial Compressive Strength of Coal Measure Rock. Proc. *19th Int. Conf. on Ground Control in Mining, Morgantown, WV, USA*, pp 363-371

William E. and Airey D. (2004). Properties and Behaviour of Bringelly Shale. *Australian Geomechanics Journal, Volume 39 No.*3 September 2004.

Won G.W. (1985). Engineering properties of Wianamatta Group rock from laboratory and in-situ tests. *Engineering Geology of the Sydney Region*, pp 143 to 155, edited by P.J.N. Pells, published on behalf of the Australian Geomechanics Society, Balkema.