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Characterisation of Small Strain Rock Modulus from Ultrasonic Pulse Velocity Testing

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ABSTRACT: Small strain rock shear modulus is increasingly being used in routine design by applying a reduction factor applicable to foundations under normal serviceability conditions. While, the velocity measurement provides a reliable means of determining the small strain modulus, this represents only an upper bound, and an appropriate modulus degradation factor is required. A database of various rock types in South East Queensland, tested with the intact rock modulus derived from both a non - destructive pulse velocity and traditional UCS testing to failure are compared. Ultrasonic pulse velocity (UPV) testing was used to establish if this would be a reliable test method on Brisbane rock cores and provided the modulus at low strain. The UCS – modulus ratios at low strain levels and at failure are also compared. The results suggest that a strong relationship exists between the pulse velocity and mechanical properties of rock in the Brisbane.

1 INTRODUCTION

The International Society for Rock Mechanics and the American Society for Testing and Materials have standardized the procedure for measuring uniaxial compressive rock strength (UCS) and Young's modulus (E), but this method is time-consuming and expensive (Bakar, 2007). The UCS is often derived using the point load index (PLI) test, but rock specific correlations need to be established for soft rocks. For example, Look and Griffiths (2001) found the UCS/PLI ratio of 11 for soft rocks (R^2 = 0.4) in Brisbane, whereas a ratio of 23 is the most common ratio quoted in the international literature. A UCS to Young's modulus conversion factor in the range of 200 to 500 (Deere & Miller, 1966) is typically applied to approximate the Young's modulus from UCS.

The UCS and E of rocks can also be estimated by non-destructive methods, such as ultrasonic pulse velocity (UPV) testing (Hudson & Harrison, 2007).

The Pundit (Portable Ultrasonic Non-destructive Digital Indicating Tester) is relatively new to the Queensland industry. This equipment measures the velocity, which can then be converted to a modulus value. The objective was to first independently assess its reliability (with the default correlations), and then to establish correlations between the PUNDIT measured velocities and other laboratory-tested properties of Brisbane rock cores. This would add credence as an acceptable measuring device.

2 ULTRASONIC PULSE VELOCITY TESTING

Non-destructive testing such as ultrasonic pulse velocity testing can be used for rock characterization. The modulus is directly related to the pulse velocity (Equations 1 - 3) of the rock (Yasar & Erdogan, 2004), who found strong correlations ($R^2 \geq 0.8$) for carbonate rocks. A.S. 1170.4 (2007) uses shear wave velocity (V_s) directly for rock definitions with the lowest rock classification of V_s = 300m/s and a UCS > 0.8 MPa. Strong rocks would have an average shear velocity of 1500 m/s.

Proceq produces a portable UPV testing instrument for the non-destructive testing of the material properties of metal, concrete, rock, paper and composites. The "Pundit PL-200" provides a wide range of measurements, including UCS and E (Proceq, 2014). The uniaxial compressive strength is estimated by a pre-determined correlation between measured velocity and known UCS values. However, this "universal" correlation needed to be validated for Brisbane rocks.

The shear modulus obtained from the Pundit is an idealized value and is referred to as G_{max} or G_0, i.e. the modulus under very small strain (Schneider, Hoyos, Mayne, Macari, & Rix, 1999). In practice, as the strain increases the shear modulus will decrease, as shown in Figure 1. The secant modulus may be 20% to 40% of G_{max} for a practical range of factor of safety (Poulos, 2015).

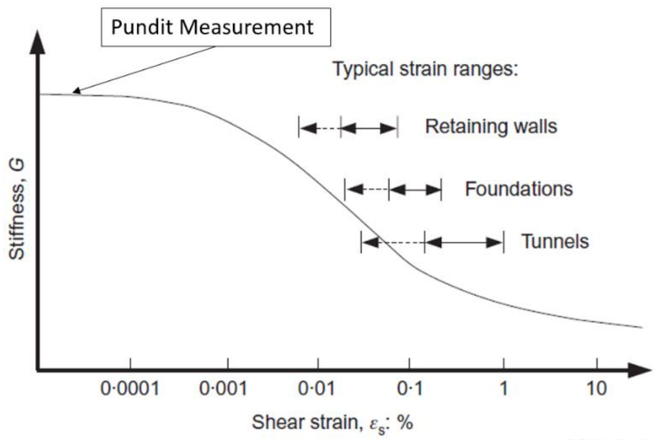

Figure 1. Stiffness variation and strain ranges (Clayton, 2011).

The Young's modulus (E) is also proportional to velocity using P-wave (compression) and S-wave (shear) measurements. By measuring P-wave transmission time and S-wave transmission time, the P-wave modulus (M) and the shear modulus (G_{max}) can be determined.

$$M = \rho V_p^2 \quad \text{and} \quad G_{max} = \rho V_s^2 \qquad (1)$$

Where: ρ = density of the material
V_p = pulse velocity of P waves
V_s = pulse velocity of S waves

Poisson's ratio (ν) can then be determined by:

$$\nu = (M - 2G) / (2M - 2G)$$
$$\nu = (V_p^2 - 2V_s^2) / [2(V_p^2 - V_s^2)] \qquad (2)$$

The small-strain Young's modulus can then be calculated using:

$$E_0 = 2G\,(1 + \nu) \qquad (3)$$

3 METHODOLOGY

The rock cores were of different rock types, varying degrees of weathering and were from projects (past and present) around Brisbane, Queensland, Australia. The rock types included Brisbane Tuff, Phyllite, Argillite, Spillite, Coal, Greywacke and Sandstone. The degree of weathering ranged from distinctly weathered (DW) to fresh rock (Fr). A total of 149 samples were tested. The measured pulse velocities were correlated against the UCS and E values. In addition, the measured E-modulus values were compared to the E-modulus obtained from the stress-strain curve in the laboratory testing results.

Goodness of fit tests were used to determine best fit Probability Distribution Functions (PDF) and regression analysis (trend analysis) was used to determine correlations between the data obtained. The data was analyzed as a whole data set, as well as broken down into smaller data sets to analyze effects of rock type, weathering, specimen length and RQD on the correlation results (Schneider, 2015).

Various test lengths were also compared. Test lengths of 200 – 250 mm had a UCS – Velocity (V_p) relationship with R^2 = 0.8 as compared to shorter lengths with R^2 = 0.4. This is opposite of what was expected based on ASTM (2008). The data below does not differentiate lengths as test were carried out on available or standard sample sizes.

4 TEST RESULTS AND DISCUSSION

4.1 *Probability Distribution of UCS and Modulus*

Figure 2 shows the probability distributions for all data. Using all the data (*n*=144), the best fit distribution is the Gamma PDF. The coefficient of variation (CV) is 82% with a mean of 33.4 MPa.

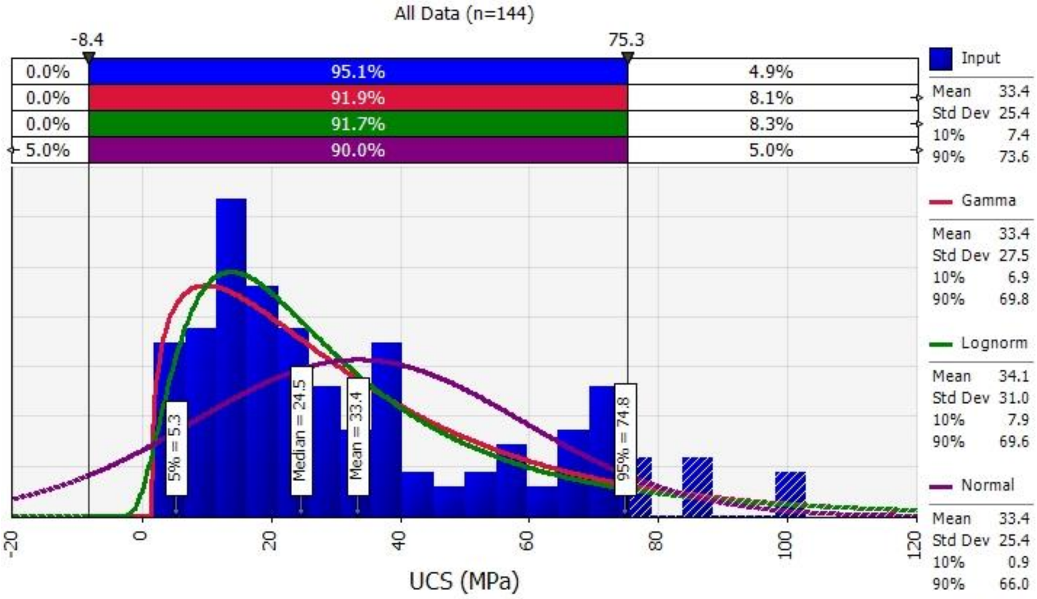

Figure 2. Probability Distribution for UCS (All Data).

Table 1. Summary of UCS (MPa) Fit Comparisons

Rock Type	No. of Samples	Best Fit Distribution	Mean	Standard Deviation	Percentile		Coefficient of Variation (CV, %)
					10^{th}	90^{th}	
All Data	144	Gamma	33.4	27.5	6.9	69.8	82
Argillite	53	Gamma	34.1	26.5	7.6	69.3	78
Brisbane Tuff	34	Weibull	30.5	16.9	13.4	53.4	55
Sandstone	26	Laplace	17.4	11.4	4.4	30.4	66
Spillite	18	Laplace	73.6	35	33.8	113.4	48

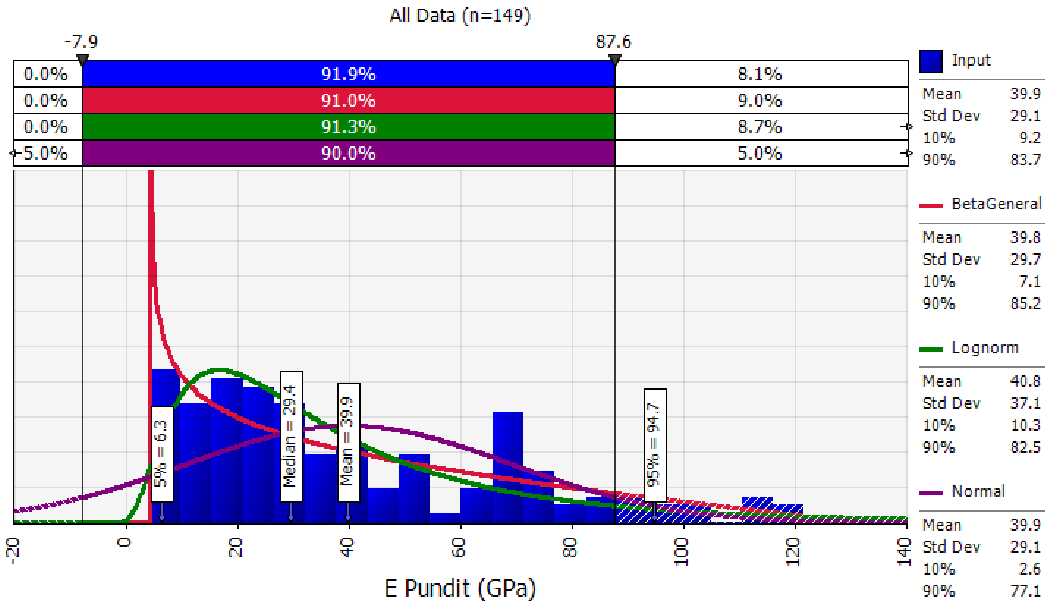

Figure 3. Probability Distribution of All E – Pundit data.

Table 2. Summary of E_o (GPa) Pundit Fit Comparisons

Rock Type	No. of Samples	Best Fit Distribution	Mean	Standard Deviation	Percentile		Coefficient of Variation (CV, %)
					10^{th}	90^{th}	
All Data	149	BetaGeneral	39.8	29.7	7.1	85.2	75
Argillite	55	Triangular	46.7	24.6	17.2	83.3	53
Brisbane Tuff	34	Logistic	23.3	8.7	12.8	33.8	37
Sandstone	27	BetGeneral	24.8	17.2	5.9	50.2	69
Spillite	18	Laplace	90.8	24.3	63.2	118.4	27

The normal distribution if applied would have a 5 percentile value of −8.4 MPa which shows the error in assuming a normal distribution. The lognormal, while not best ranked, closely follows the best fit distribution and would not produce the errors of the normal distribution (Look 2015). The results of the UCS fit comparisons are summarized in Table 1.

The data for E_0 obtained from the Pundit was analyzed in a similar fashion (Figure 3). The CV for all combined data is 75% with a mean of 39.8 GPa. The normal distribution, if applied, would have a 5 percentile value of −7.9 GPa. This negative value again shows the error in assuming a normal distribution. The results of the E Pundit fit comparisons are summarized in Table 2. Overall, less variation is obtained for the modulus as compared with the UCS.

A higher ratio applied to the low strength rocks, while a lower ratio applied to the high strength rocks, excluding Sandstone. The sandstone and Tuff have a relatively minor change in E_0/UCS ratios, while the argillite and Spillite have a very high ratio difference between low to high strength rocks.

Tables 1 and 2 show that lumping all data together results in a large spread of results with a CV of 82% and 75% for the UCS and modulus respectively. When that data is analyzed for Spillite only, the spread of results reduces to as low as 48% and 27% for the UCS and E, respectively.

The results from the UCS/ E Pundit PDF analysis from Tables 1 and 2 were then combined to calculate E_0/UCS ratios for rock type and overall PDF (Figures 4 and 5, respectively).

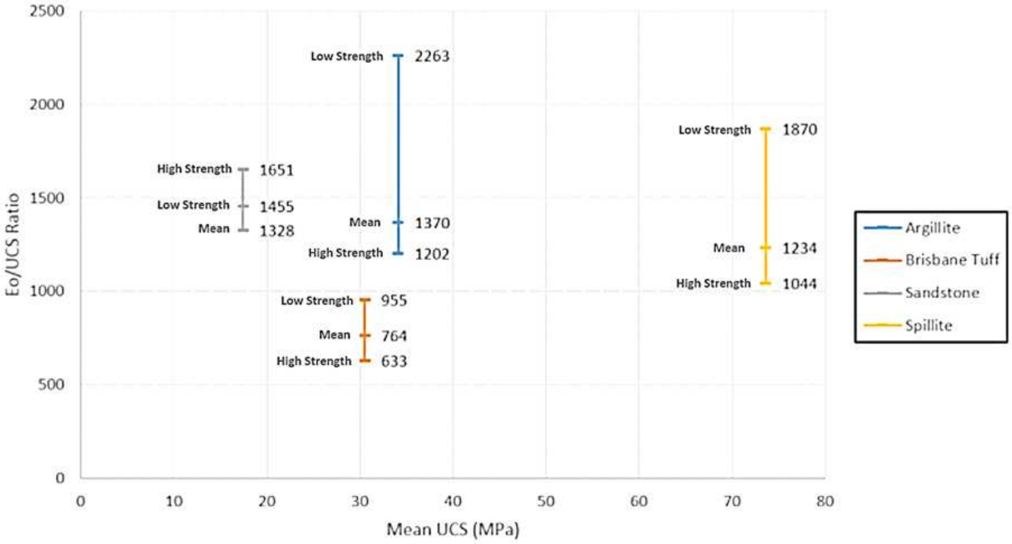

Figure 4. E_0/UCS Ratio for Rock Types.

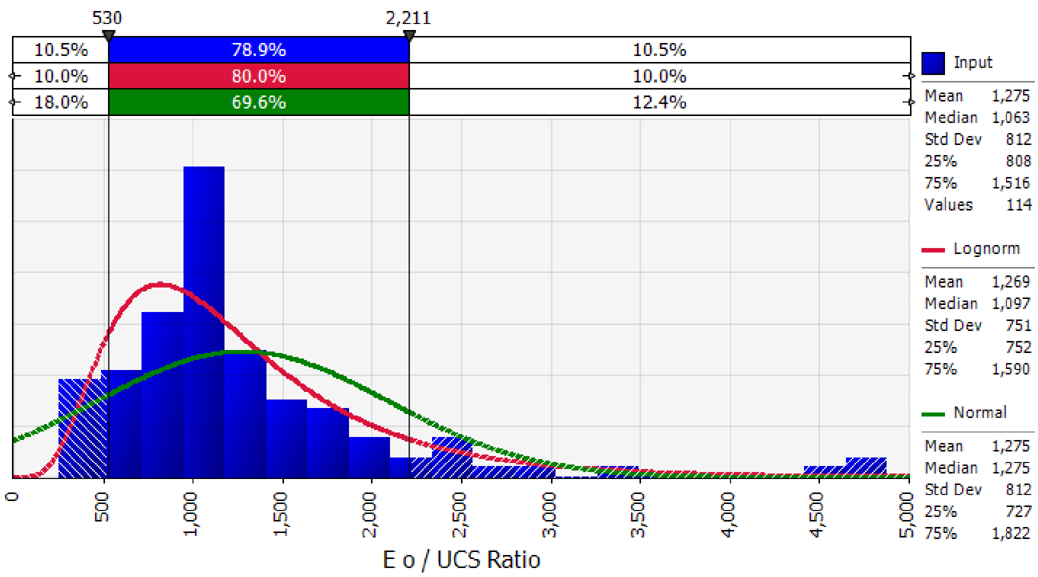

Figure 5. PDF of E_0/UCS Ratio for combined data.

The Poisson's ratio obtained through the velocity testing was also analyzed for each rock type. Using all the data (n=149) the best fit distribution is the normal. The CV is 23% with a mean of 0.22 for rocks in the Brisbane region.

4.2 *Primary Velocity versus Young's Modulus Correlation*

The primary velocity, measured by the Pundit, was correlated with the Young's Modulus (both secant and tangent), obtained through laboratory testing (Figure 6). The secant Modulus is measured at 0% to 50% of maximum UCS while the tangent Modulus is at 50% of UCS. There is an excellent exponential relationship (R^2 =0.9) between primary velocity and Young's modulus, using all data.

4.3 *Young's Modulus (Pundit) versus Young's Modulus (Lab Tested)*

The Young's modulus obtained with the Pundit is a low (0%) strain (E_0 value), whereas the laboratory tested Young's modulus (E_{Lab}) is at a measured strain relative to ultimate failure. Therefore, E_0 was correlated with E_{Lab}, (Figure 7) to determine the appropriate reduction for this strain difference (Figure 1).

Table 4 outlines the reduction factor required to convert E_0 to E_{Lab} for different modulus values and the typical rock associated weathering. Higher strength rocks requires less of a reduction factor, whereas lower strengths rocks require a greater reduction is required.

There was little difference between the secant and tangent modulus.

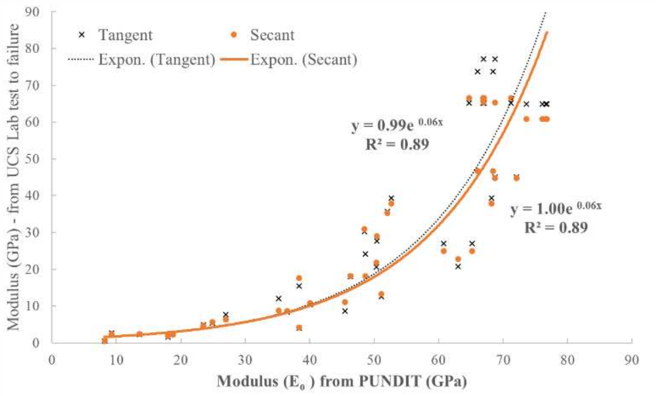

Figure 6. Lab Modulus from UCS testing vs Primary Velocity.

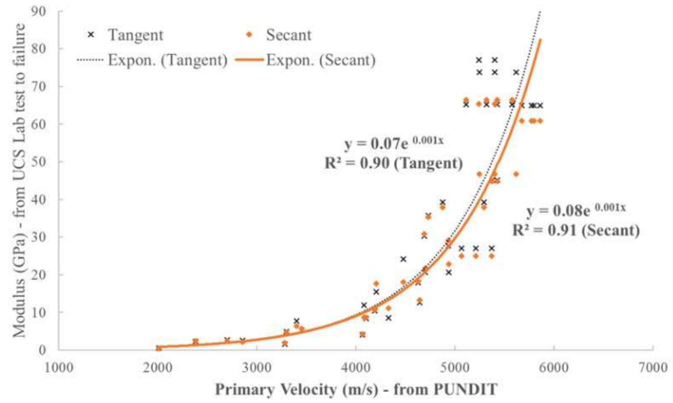

Figure 7. Lab Modulus from UCS testing vs Modulus (Pundit).

Table 3. E_{Lab} / E_0 Ratio

E_0 Pundit (GPa)	Typical Weathering	E_{Lab} (GPa)	E_{Lab} / E_0
20	DW	3.2	0.2
30	DW - SW	5.8	
40	SW	10.3	0.3
50	SW - Fr	19	0.4
60	Fr	33	0.6
70	Fr	60	0.9

Figure 8 shows the $E_{Lab\ Failure}$ / $UCS_{Lab\ Failure}$ of 800 (median) to 900 (mean) for all data, are significantly higher for this data set, compared to the typically reported values of 200 to 500. The Lognormal PDF is used in the evaluation.

An alternative approach with reduction factor applied to E_0 (Figures 4 and 5) shows this E/ UCS ratio typically varies from 750 to 1,600 for individual data (Table 4) but varies between rock types.

Table 4. Modulus / Strength Ratio

	Rock Type	Strength	E_0/UCS	E_{Lab}/E_0	E_{Lab}/UCS
Sedimentary	Sandstone	Low (15 MPa)	1400	0.16	~ 220
	Argillite	Typical (35 MPa)	1300	0.3	~ 400
	Spillite	High (70MPa)	1200	0.9	~ 1,000
Igneous	Brisbane Tuff	Low	900	0.2	~ 180
		Typical (35 MPa)	900		~ 150
		High	750		~ 110

5 CONCLUSIONS

The results show the PUNDIT is a reliable tool for measuring rock core properties. Figure 9 compares the traditional strength modulus conversion method versus the UPV method which measures Modulus directly. The latter seems to be more reliable approach to obtain the rock properties with less uncertainty for obtaining UCS and the Modulus. However this is offset by introducing a strain reduction factor. The UCS ~ E_0 /1200 but this varied with rock, type, strength and weathering. Understanding this requires more research.

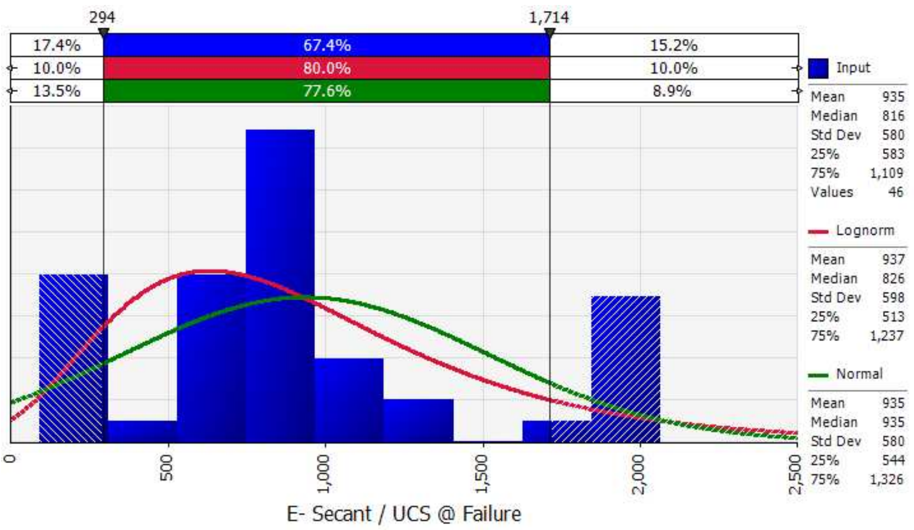

Figure 8. PDF for E (Secant) vs UCS at failure

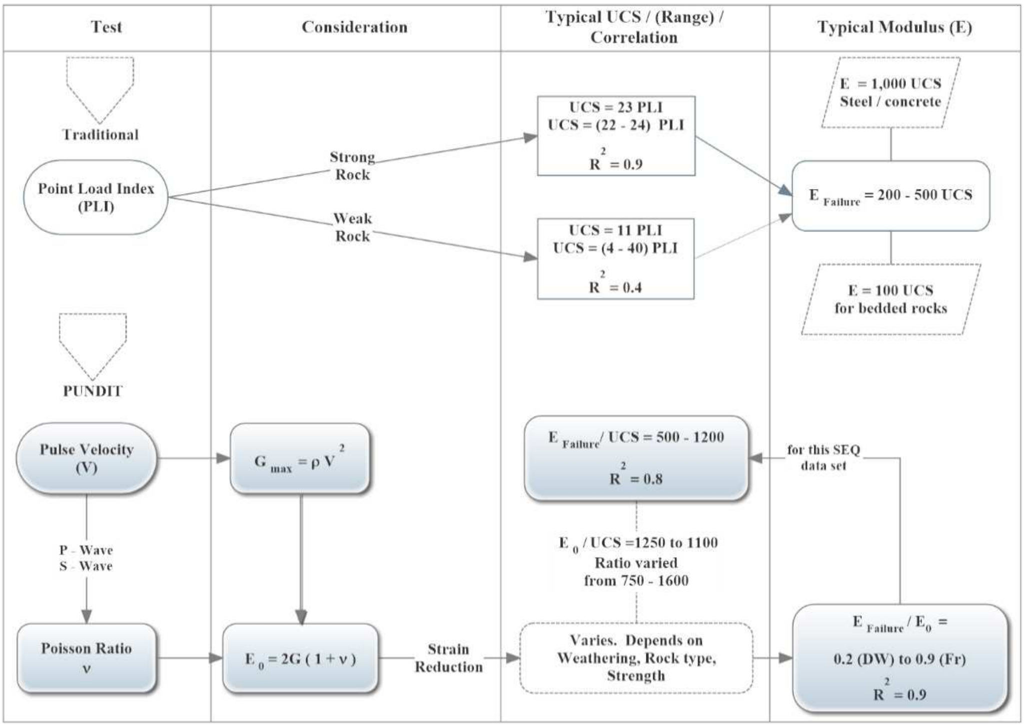

Figure 6. Traditional Method vs UPS method to indirectly determine UCS and modulus.

The E_{Lab}-V_p correlation relationship was less affected by rock type, specimen length, weathering or RQD, whereas the UCS-V_p relationship was heavily influenced by these parameters.

On a cost basis, this UPV approach would be comparable with using the PLI with its correlations for obtaining UCS or Modulus values.

6 ACKNOWLEDGEMENTS

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