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Strength estimation using an ultrasonic pulse velocity tester

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Abstract

Uniaxial compressive strength (UCS) is one of the basic and important descriptors for rock mechanics and rock mass strength determination. Field estimated strength (FES) – using International Society for Rock Mechanics and Rock Engineering published methodologies – and field testing are commonly used in conjunction with laboratory-tested UCS values for geotechnical design. Commonly used field testing techniques include point load testing and Leeb/Equotip testing. In support of field testing techniques, a number of existing publications deal with the correlation between rock strength and sonic velocity, measured as part of downhole geophysics surveys or from laboratory testing.

To add to this knowledge base, this paper demonstrates the application of sonic velocity measurements using a handheld ultrasonic pulse velocity (UPV) tester. UPV testing is an acoustic non-destructive test method most often used to evaluate the relative quality of rock or concrete structures, and to identify the presence of internal flaws such as cracks or voids.

For this paper, the UPV tester has been used to measure the sonic velocity on drill core to assist with rock strength estimation. Four case studies are given showing the correlation between the measured sonic velocity, FES and laboratory strength testing at the 4 sites. Because this is a relatively new application, the limitations found are presented, as well as suggested workflows and future applications.

Keywords: *rock strength, ultrasonic pulse velocity tester, field testing*

1 Introduction

Sonic velocity testing is a non-destructive method used to assess the strength and integrity of rock materials. The test involves sending high-frequency sound waves through a rock sample and measuring the time it takes for the waves to travel a known distance. The sonic velocity of the sound waves is influenced by the rock's density, elastic properties, porosity, and the presence of cracks or discontinuities, and can be correlated back to these rock properties. Higher sonic velocities typically indicate denser, more competent rock with fewer micro-fractures, while lower velocities may suggest weaker rock strength, more weathered rock, more fractured rock or rock with higher porosity.

Sonic velocity is commonly used in geotechnical engineering, mining, and petroleum exploration to evaluate rock quality, estimate uniaxial compressive strength (UCS), and assist in site characterisation. The advantages of sonic velocity testing include its non-destructive nature, speed, and ability to be carried out both in the laboratory and in the field (e.g. using borehole logging tools). However, accurate interpretation requires consideration of factors such as rock type, mineral composition, moisture content, and anisotropy.

The Surfer ultrasonic pulse velocity handheld tester (UPV tester) is a portable, simple to operate tool that provides sonic velocity based estimates of UCS on rock core and exposed rock faces over 150 mm in length. These estimates can be used to augment or replace existing field estimation techniques, such as point load

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testing, Leeb hardness testing and field estimated strengths, by providing proxy UCS values for improved spatial definition and population statistics in geotechnical design.

2 Field estimation of uniaxial compressive strength

This section summarises the estimation of UCS in the field to re-familiarise the reader with the concept, and then describes the measurement of sonic wave velocities and its application to estimating rock properties, followed by a description of the handheld sonic velocity tester.

2.1 Field estimated strength

Field estimated strength (FES) is obtained from core using the standard International Society for Rock Mechanics and Rock Engineering (ISRM) guidelines (Ulusay 2015), as shown in Table 1. In this, the strength of the core is tested using a knife to cut or scratch the core, or using a geological hammer to break the core. While this methodology is robust and used throughout logging programs world-wide, there is still some subjectivity, especially for higher rock strengths or for differentiating between units that are at the boundaries between classes.

Table 1 ISRM guidelines for estimating rock strength

ISRM grade	Term	UCS (MPa)	Field estimate of strength
R0	Extremely weak	0.25–1	Indented by thumbnail
R1	Very weak	1–5	Material crumbles under firm blow of geological hammer, can be shaped with knife
R2	Weak	5–25	Knife cuts material but too hard to shape into triaxial specimens
R3	Medium strong	25–50	Firm blow with geological hammer indents rock to 5 mm, knife just scrapes surface
R4	Strong	50–100	Handheld specimens broken by single blow of a geological hammer
R5	Very strong	100–250	Requires many blows of a geological hammer to break intact rock specimens
R6	Extremely strong	>250	Rock material only chipped under repeated hammer blows, rings when struck

2.2 Measurement of ultrasonic pulse velocity

UPV can be measured on solid rock specimens and, due to its non-destructive nature, is often collected prior to destructive testing such as the UCS testing to create co-located datasets. A sonic pulse velocity device is used, such as the one shown in Figure 1 (Humboldt 2025), consisting of a transmitter, receiver, signal generator, and digital timer. The transducers are usually piezoelectric and are positioned on opposite ends of the rock core, aligned along the longitudinal axis.

Figure 1 Ultrasonic pulse velocity tester

A coupling agent is applied between the transducers and rock surfaces to ensure good acoustic contact and minimise signal loss. A high-frequency ultrasonic pulse (usually between 20 and 100 kHz for rock samples) is emitted by the transmitter. The pulse travels through the specimen and is received on the opposite end. The transit time of the wave is recorded, and the pulse velocity is calculated using Equation 1:

$$V = L/T \tag{1}$$

where:

V = pulse velocity (m/s)

L = length of the rock sample (m)

T = transit time (s).

The pulse velocity is then correlated to UCS value through empirical relationships (ed. Ulusay 2015).

Sonic velocity is also commonly measured in in situ rock using geophysical methods using a full wave sonic tool which captures compression (P), shear (S), and tube wave properties as shown in Figure 2 (Mount Sopris 2025). The sonic velocity is determined by generating controlled sonic waves at a known source location along the device and detecting their arrival at one or more receivers placed at known distances.

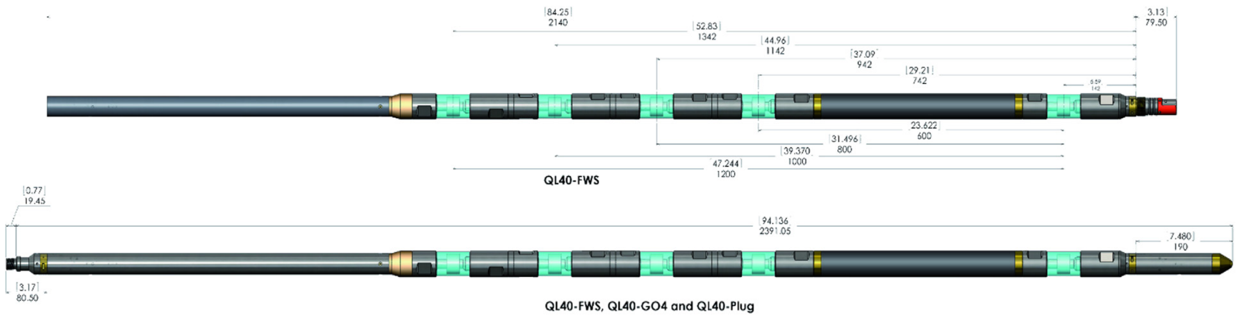


Figure 2 Example downhole geophysical full wave sonic tool

The travel time of the waves is recorded and used to calculate the velocity using Equation 2:

$$V = D/T \tag{2}$$

where:

V = pulse velocity (m/s)

D = distance travelled between transponder and receiver (m)

T = travel time (s).

The compressional (P-waves) and shear (S-waves) each provide different insights into the rock's elastic and mechanical properties such as the porosity, permeability, Poisson's ratio and bulk modulus. One of the benefits of this geophysical method is that continuous profiling can be undertaken to provide continuous velocity profiles with depth; however, the tools are limited to areas below the watertable and can be susceptible to interference if holes are not flushed sufficiently and wall cake (i.e. muds) remains on the drill surface. Density of the drilling fluid and hole details are required to achieve representative results, and careful interpretation is required.

Sonic velocity data are used to determine lithological boundaries, estimate rock strength and stiffness, and calibrate geology and geotechnical models. Sonic logs are typically calibrated with laboratory data for improved accuracy and integrated with other geophysical data (e.g. density and resistivity logs) to enhance subsurface interpretation.

2.3 Handheld ultrasonic pulse velocity tester

This paper presents options for the use of a handheld UPV tester as an alternative method to measure the pulse velocity from diamond drill core. The device used in this study was the Surfer UPV tester (Hylec Controls 2025). The UPV tester is shown in Figure 3.

The UPV tester measures the pulse transit time from transmitter to receiver and computes the pulse velocity using the known distance (150 mm) between 2 dry-point-contact transducers brought into contact with the test object's surface. The ultrasonic pulse velocity can be measured without having access to opposite sides of the test object. In contrast with traditional pulse velocity instruments which measure through transmission, the UPV tester measures the compression wave time and speed (Vp) in the near-surface rock or concrete.

The manufactured purpose of the UPV tester is to assess concrete strength and uniformity, and to estimate the depth and extent of surface cracks. An additional stated use is for estimation of flexural strength of stone panels using correlations. It is this latter use that is of interest for geotechnical rock strength estimation.

Figure 3 Surfer ultrasonic pulse velocity tester

3 Correlations of ultrasonic pulse velocity

The previous chapter presented the tools to estimate UCS using sonic velocity measurements; this chapter presents the correlations of UPV with rock properties.

3.1 Correlation to elastic properties

The ultrasonic pulse velocity (Vp) of longitudinal ultrasonic stress waves is related to its elastic properties and density according to the equation as given in ASTM C597-22 (ASTM International 2022):

$$Vp = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{3}$$

where:

E = dynamic Young's modulus (GPa)

μ = dynamic Poisson's ratio

ρ = density.

3.2 Correlation to uniaxial compressive strength

The UPV does not measure rock strength. Strength is correlated indirectly, using the premise that there is a relationship between strength and elastic properties and density, and, like elastic properties, that the correlation will be different for different rock types.

A number of equations are provided in literature for the correlation between sonic velocity and UCS. The correlation commonly adopted in Australia (see Equation 4) was developed by McNally (1990) based on several hundred test results from 24 drill holes from the coalfields in eastern Australia:

$$\mathrm{UCS} = 1000 \times \mathrm{e}^{-0.035\mathrm{t}} \tag{4}$$

where:

UCS = uniaxial compressive strength (MPa)

t = interval time of the P-wave (μs/m).

3.3 Observations on correlations

UCS and sonic velocity correlations are widely used in the Australian coal mining industry to predict in situ rock strength, mainly because the measurements are cheap, fast and easy to produce, and have practical application in mine planning and design. Butel et al. (2014) present a review of the effectiveness of UCS/Vp correlations for in situ rock strength estimation, with data from 6 open cut coal mines and 2 development projects from eastern Australia. The sonic velocity was measured using a downhole sonic logging tool. It was concluded that the major downfall of the models is the large variation in UCS values at high sonic velocities; that there is significant variability in measured UCS values for a given velocity. The main sources of error identified in the paper included irregularities in UCS testing due to sample length being outside of the standard recommended ratio, clast size in sedimentary rocks (especially conglomerates) skewing results, and interbedded nature of sandstone, siltstone and shale resulting in the geophysical measurements spanning materials with different geomechanical properties.

Correlation between Vp and rock properties of quartz-mica schist was presented by Chawre (2018). The conclusion from this study was that general equations encompassing all types of rocks do not give reliable results of rock properties and showed large relative errors, ranging from 23 to 1,146%. The dominant rock type in the case study was quartz-mica schist, and the anisotropy of the rock was likely to have been the underlying cause of the variability in rock property testing. Chawre (2018) concluded that empirical correlations must be investigated separately for different types of rocks. The general empirical equations should not be used for the design and planning purposes before they are verified for each rock type from the project site, as they may contain large unacceptable errors.

4 Practical application of the ultrasonic pulse velocity tester

To test the validity of the UPV testing carried out to date, 4 case studies are presented below.

4.1 Case study 1: comparison of field estimated strength and Vp

The first case study was undertaken as part of the geotechnical investigation undertaken for a pit near Laverton, Western Australia. The proposed pit shape measured approximately 600 m across and 150 m deep.

Gold is hosted by a suite of granitoids with narrow shears that intruded intermediate to mafic volcanic and volcaniclastic rocks. Rock types logged in the geotechnical drill holes include syenite and monzonite. The regolith includes up to 20 m of transported sediments (colluvium and alluvium), 30–60 m of saprolite and saprock. Transition from saprock (highly weathered to moderately weathered rock) to slightly weathered and unweathered rock was rapid, and generally over a distance of less than 10 m vertically.

The geotechnical investigation included 5 oriented drill holes, planned and drilled specifically for geotechnical reasons. The holes were geologically logged by the site geologists, then geotechnically logged using the company-specific data collection system (Seery et al. 2018). Structural logging of the oriented core was also undertaken. A limited laboratory testing program, including 8 UCS tests, 5 multistage rock triaxial tests (Venter et al. 2016), and 5 multistage confined undrained triaxial tests with particle size distribution and Atterberg limits were carried out.

In addition to logging the rock strength using standard ISRM descriptions, the UPV tester was used to help assess rock strength. A reading was taken every 1 m in strong rock (strength R4 and above) and, where possible, in moderate and weak rock (R2 and R3). The tester generally could not take readings in R1 or weaker material as the lower velocity limit of the tester is 1,000 m/s. Sporadic readings through the R1 strength rock were obtained; however, these were from isolated corestones and not representative of the typical strength of this material.

Readings at these frequencies can be taken rapidly, and readings for a 150 m long hole were completed in less than 20 minutes. The UPV tester does not record depth, so that needs to be manually noted and added to the downloaded time and velocity readings. An example of the raw and processed data is given in Table 2. This shows the downhole depth of the reading, time and velocity, estimated UCS calculated using the McNally equation given in Equation 4, and rock lithology, weathering and logged FES. The FES was later adjusted using the Vp obtained, and the adjusted FES is also given.

Table 2 Examples of sonic velocity readings

Hole ID	Depth (m)	Time (µs)	Vp (m/s)	Estimated UCS from Vp (MPa)	Rock type	Weathering	Logged FES	Reassessed FES
GDD077	45	1,061	1,410	1	Saprolite	Saprolite	R0	R1
GDD077	53	483	3,100	32	Syenite	HW	R2	R3
GDD077	54	473	3,170	35	Syenite	HW	R2	R3
GDD077	56	441	3,400	43	Syenite	HW	R3	R3
GDD077	68	703	2,130	7	Syenite	HW	R3	R2
GDD077	73	829	1,810	3	Syenite	HW	R3	R2
GDD077	78	402	3,730	57	Syenite	MW	R4	R3
GDD077	79	338	4,440	90	Syenite	MW	R4	R4
GDD077	80	255	5,880	163	Syenite	SW	R5	R5
GDD077	81	253	5,930	165	Syenite	SW	R5	R5
GDD077	82	265	5,660	152	Syenite	SW	R5	R5
GDD077	83	267	5,620	150	Syenite	SW	R5	R5
GDD077	84	256	5,850	161	Syenite	SW	R5	R5
GDD077	85	260	5,760	157	Syenite	SW	R5	R5
GDD077	86	258	5,800	159	Syenite	SW	R5	R5
GDD077	87	259	5,790	158	Syenite	SW	R5	R5

HW – highly weathered, MW – moderately weathered, SW – slightly weathered.

Figure 4 shows the plots of Vp and the logged and adjusted FES values in each of the 5 drill holes. The logged FES was undertaken before the Vp readings were taken. The FES was then adjusted using the Vp values and confirmed from core observations. From these, it can be seen that the depth between logged strength classes was more accurately described using the velocity readings. In addition, zones of higher alteration with lower strength were sometimes missed in the original log, and these were then captured by the adjusted log.

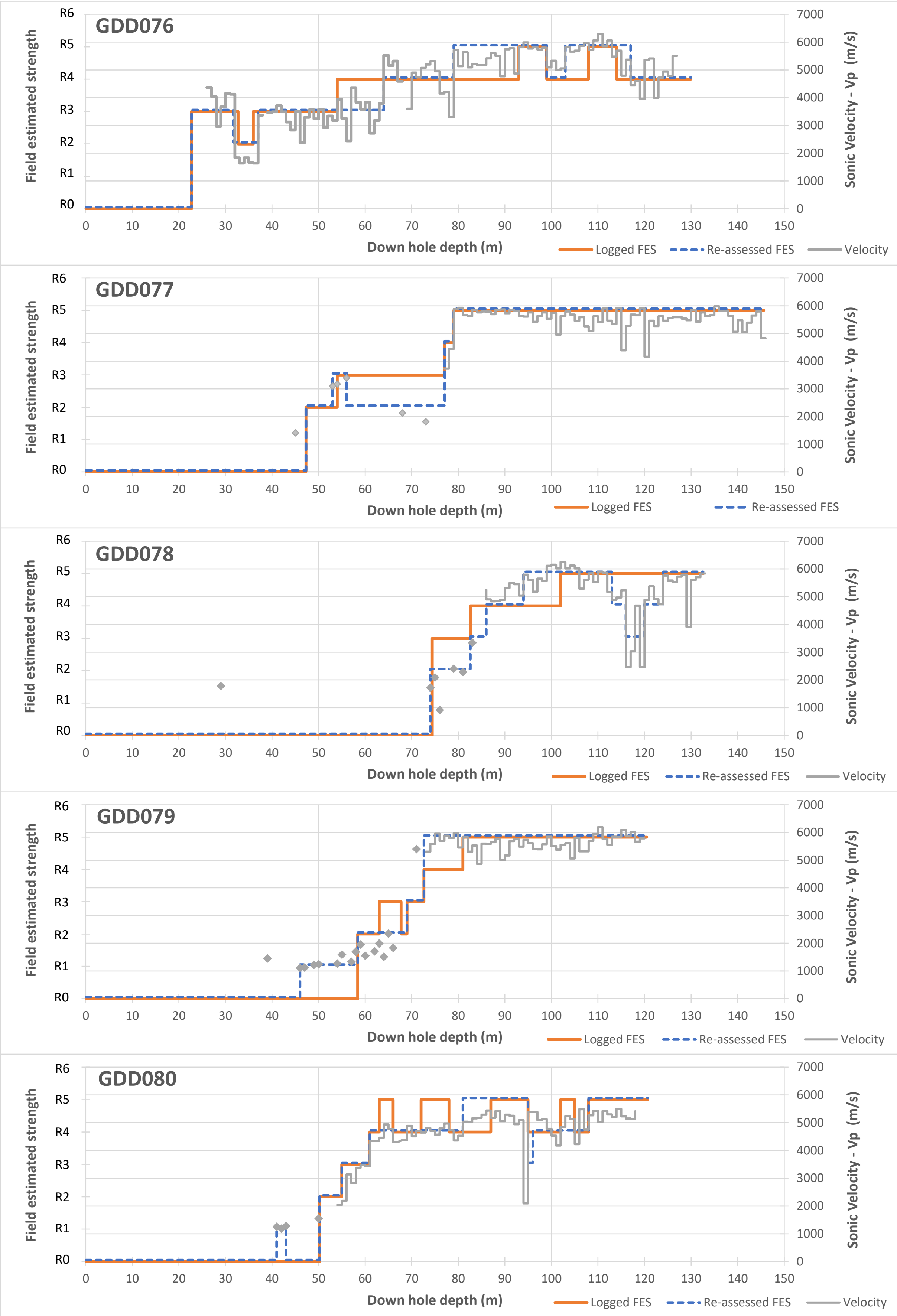


Figure 4 Plots showing logged and reassessed field estimated strength versus Vp – case study 1

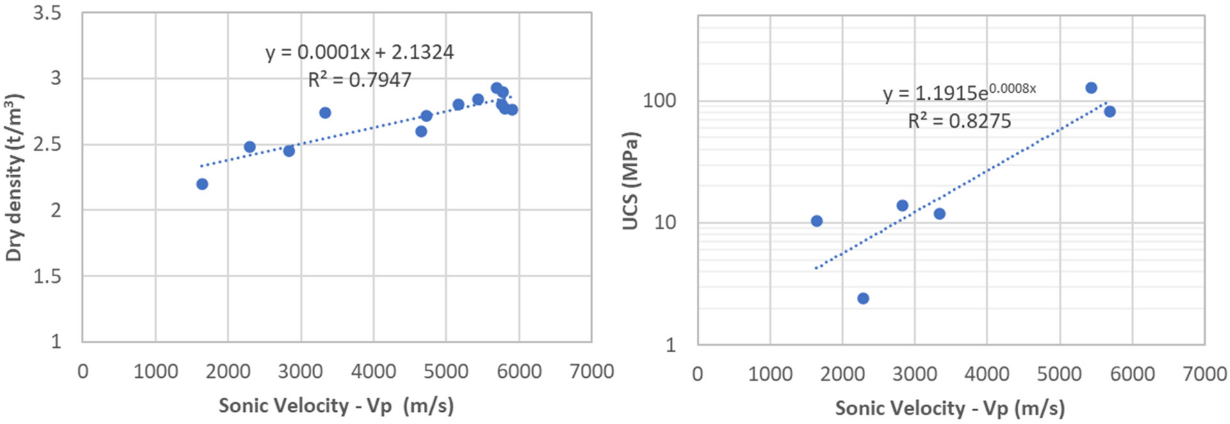
The Vp readings were then compared with laboratory-tested UCS and dry density, as shown in Table 3 and Figure 5. Only UCS tests with valid failure modes are plotted and used for correlations. All tests with density measured were plotted. The syenite and monzonite are both intrusive igneous rocks with similar density and geotechnical properties and were analysed together. However, if more data had been available, these would have been subdomained and analysed separately. Lines of best fit were added, and both sets of data show similar residuals (0.79 for the density, and 0.83 for the UCS tests). The UCS calculated using the McNally equation is higher than the laboratory-tested UCS, showing that rock type specific correlations are necessary.

Laboratory testing was limited and showed some data scatter even when all invalid test results were excluded. This is in line with conclusions found in other studies.

Table 3 Results of laboratory testing

Hole ID	Depth (m)	Rock type	Weathering	Test	Mode of failure	Dry density (t/m^3)	UCS (MPa)	FES logged	FES adjusted	Sonic velocity (m/s)	Estimated UCS from Vp (MPa)
GDD078	81.1	Monzonite	HW	UCS	Conical	2.48	2.4	R3	R3	2,290	9.5
GDD076	37.0	Monzonite	MW	UCS	Shear	2.20	10	R3	R2	1,640	1.5
GDD080	58.3	Syenite	MW	UCS	Shear	2.45	14	R3	R3	2,830	23
GDD079	92.4	Monzonite	FR	UCS	Axial splitting	2.93	83	R5	R5	5,690	153
GDD077	132.7	Syenite	FR	UCS	Axial splitting	2.84	128	R5	R5	5,430	140
GDD078	84.1	Monzonite	HW	UCS	End splitting	2.74	11.8[1]	R3	R3	3,340	41
GDD076	124.0	Syenite	FR	UCS	Shear on defect	2.72	15.3[1]	R4	R4	4,720	104
GDD078	124.7	Monzonite	FR	UCS	Shear on defect	2.80	16.3[1]	R5	R5	5,760	157
GDD076	86.1	Monzonite	FR	HKTX	Shear	2.80		R4	R4	5,170	127
GDD077	104.8	Syenite	FR	HKTX	Shear	2.77		R5	R5	5,800	159
GDD079	89.0	Monzonite	FR	HKTX	Shear	2.90		R5	R5	5,780	158
GDD078[1]	111.1	Monzonite	FR	HKTX	Shear on defect	*2.76*		*R5*	*R5*	*5,900*	*164*
GDD080[1]	73.7	Syenite	SW	HKTX	Shear on defect	*2.60*		*R5*	*R4*	*4,650*	*101*

[1] Invalid failure modes, UCS not representative of intact rock strength.
HW – highly weathered, MW – moderately weathered, SW – slightly weathered, FR – fresh, HKTX – Hoek triaxial test



(a) (b)

Figure 5 Correlation with (a) laboratory-testing density and (b) UCS – case study 1

Figure 6 shows box and whisker plots of sonic velocity per logged FES, and the adjusted FES. The former shows fair correlation but with overlap at the border between strength categories. This may show that the original log underestimated strength, especially for weak and moderate strength intervals. The second plot shows much tighter groupings, and after reassessment of the results against the drill core photographs, these adjusted FES values were adopted for use in rock mass rating calculations and geotechnical characterisation.

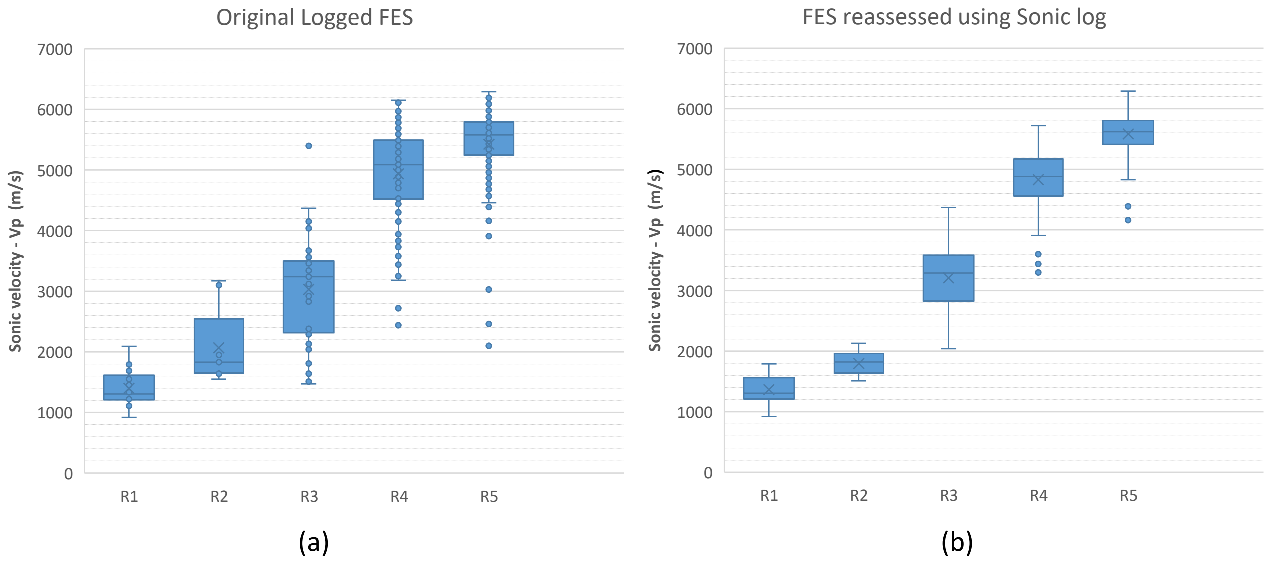


Figure 6 Correlation with (a) original logged field estimated strength and (b) adjusted field estimated strength – case study 1

Suggested sonic velocity ranges for each FES class are given in Table 4. This correlation appears to be suitable for this site (for intrusive igneous rocks) and would need to be tested for different rock types as site-specific correlations may be required, as reported by other authors in sonic velocity data studies.

Table 4 Suggested classes for correlation velocity to field estimated strength – case study 1

Strength class	UCS range (MPa)	Suggested sonic velocity range (m/s)	Comment
R0	<0.5	n/a	No measurements possible
R1	0.5–5	1,000–1,600	Sporadic measurements only
R2	5–25	1,600–2,600	Readings limited by core stick length and condition
R3	25–50	2,600–4,000	Readings limited by core stick length and condition
R4	50–100	4,000–5,200	Continuous readings
R5	100–250	5,200–6,500	Continuous readings
R6	>250	>6,500	Assumed, no data from case study

Overall findings from this case study show the sonic velocity readings were very good for slightly weathered and unweathered intervals with strength R4 and R5. Continuous readings of one reading per metre allowed the variability in strength to be more accurately assessed than by FES alone. Readings could not be taken every 1 m in moderately and highly weathered rock with strength R2 and R3 because of the high prevalence of veining and micro-fractures which caused readings to fail. Wider-spaced readings were recorded through intervals with these rock strengths. In highly fractured rock, the sticks of core were not long enough to take a Vp reading. In these cases, the FES was a better indication of rock strength than a 'null' value which could indicate low rock strength.

Zones of lower velocity in the fresh intervals were reviewed and found to be caused by higher alteration (which was not initially logged) or due to higher percentage of veins and veinlets. This allowed the FES to be adjusted and a more accurate estimate to be made.

FES ranges were adjusted based on the sonic velocity values to better define the boundaries between different strength classes, which was more robustly defined by the Vp values than by the logged FES value.

Laboratory testing was limited and showed some data scatter even when all invalid test results were excluded. This is in line with conclusions found in other studies. A fair correlation is found for both density and UCS.

While the data trends are more important than individual or precise measurements, the sonic velocity readings allowed a more accurate assessment of rock strength than estimation of FES using ISRM methods alone.

4.2 Case study 2: second comparison of field estimated strength and sonic velocity

The second case study is from the geotechnical investigation for satellite pits at the Sunrise Dam operations.

The geology of this area is interpreted as being in the immediate hanging wall of the regional thrust system. Mineralisation is predominately associated with the felsic intrusive and andesite unit contacts, with discrete high-grade zones within the felsic intrusive, and as supergene mineralisation near the base of completely weathered rock. Pit walls will be within andesite and banded iron formation rock types. The regolith includes variable thickness of transported soil (alluvial/colluvial), a well-developed saprolite profile overlying saprock and fresh rock. The majority of the pit walls will be within saprolite and saprock, with limited fresh rock exposed at the base of the pit.

The geotechnical investigation included 4 oriented geotechnical drill holes, which were geotechnically and structurally logged, and a laboratory-testing program.

The downhole plots of FES and sonic velocity values for each of the 4 drill holes are shown in Figure 7. A number of outliers with low sonic velocity values are present in hole NVGT001. These represent readings taken in highly altered zones with a higher frequency of veinlets and micro-fractures, and the sonic velocity values may be representative of the cemented defect strength, not the unaltered rock strength. These data give information on strength variability through the altered rock zones. Hole NVGT002 shows the deepest ~10 m was logged as R6 strength, which is not supported by the sonic velocity readings. These FES values should have been readjusted to R5 to reflect the additional data source. Hole NVGT003 shows only sporadic readings were taken at depths 42–78 m. The reason for this is that the rock was highly fractured, and sticks of core long enough for UPV testing were not always present. In these zones, the FES is considered the more reliable data source. The lack of Vp data is because of closely spaced fractures, not because of low rock strength.

Figure 8 shows a box and whisker plot of all sonic velocity values and FES as logged during the field campaign. While there is overlap between classes, the majority of the data plots in discrete classes, showing that the UPV is effective in differentiating strength classes. Suggested ranges are given in Table 5. When compared with Table 4 it can be seen that there are some differences in the suggested range for each strength class, which indicates that data classes need to be established and calibrated for each site.

Figure 9 shows the plots for sonic velocity against laboratory measured dry density and UCS. Good correlations are obtained, with R-squared values greater than 0.9 for density and 0.8 for UCS, albeit for very small population size.

Future work should focus on expanding the application of the UPV tester to a broader range of rock types and refining correlations for different failure modes and strength ranges.

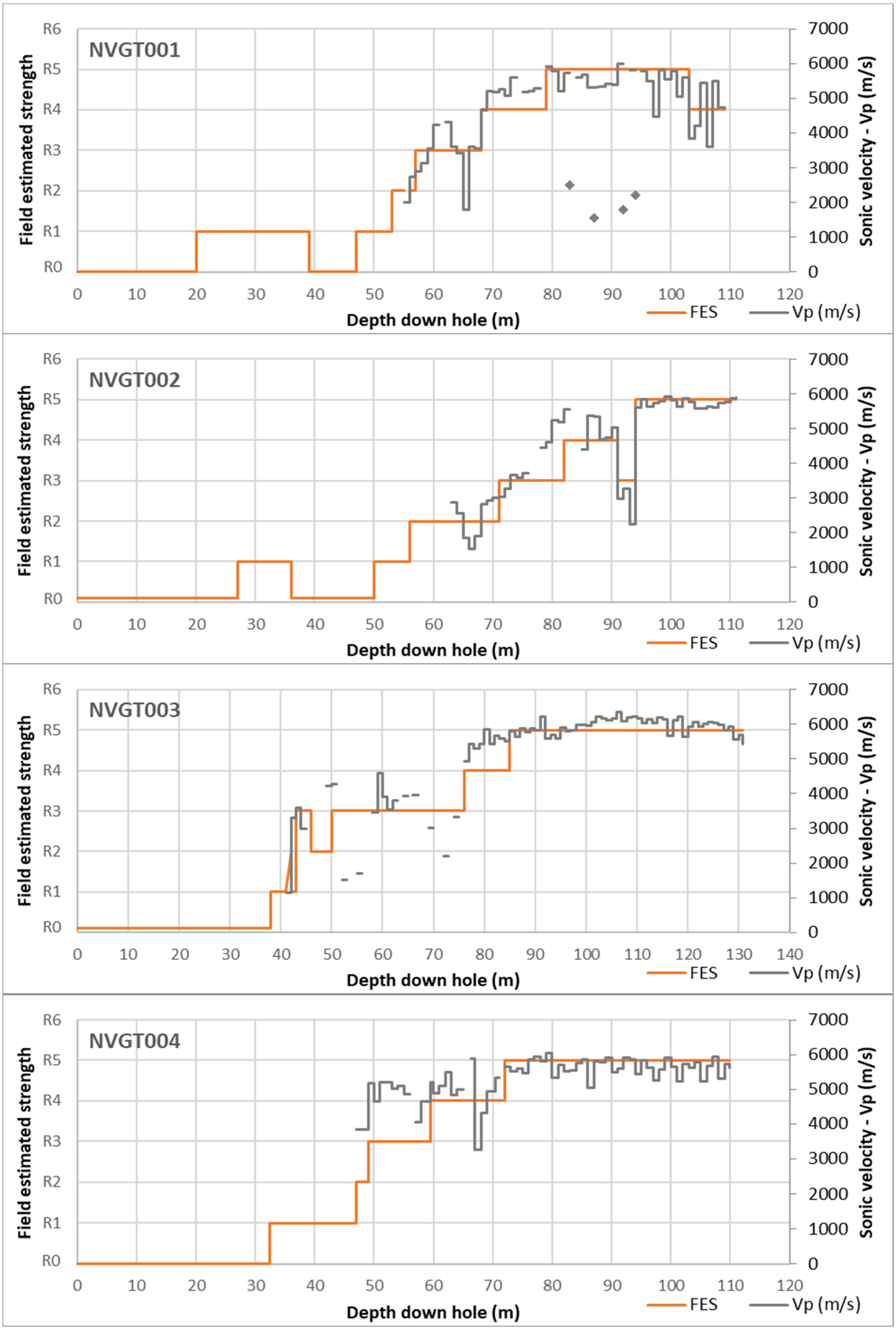


Figure 7 Plots showing logged field estimated strength and sonic velocity – case study 2

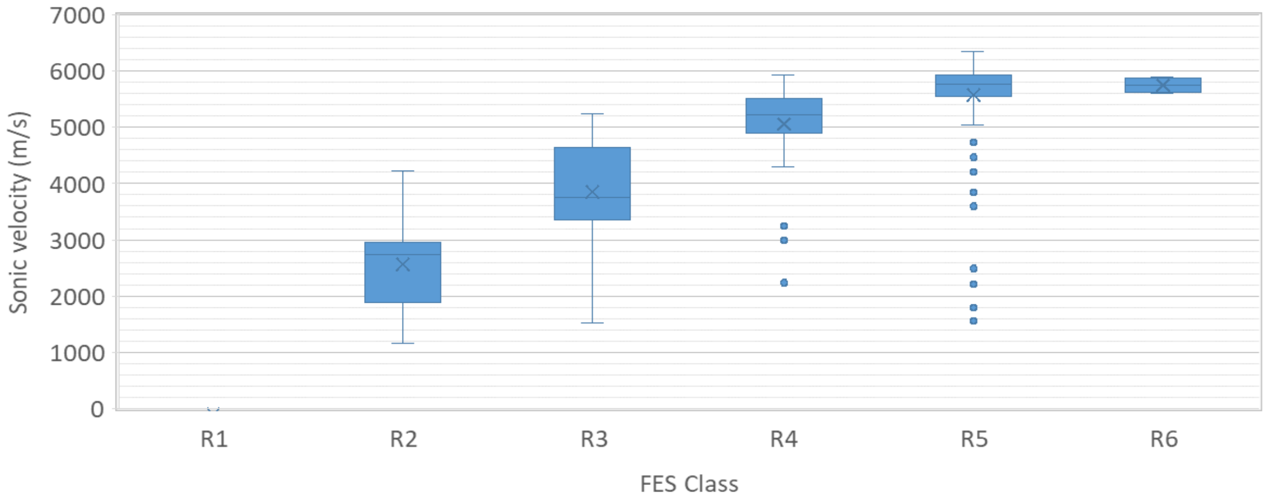


Figure 8 Correlation with logged field estimated strength – case study 2

Table 5 Suggested classes for correlation velocity to field estimated strength – case study 2

Strength class	UCS range (MPa)	Suggested sonic velocity range (m/s)	Comment
R0	<0.5	n/a	No measurements possible
R1	0.5–5	n/a	No measurements possible
R2	5–25	1,800–3,000	Readings limited by core stick length and condition
R3	25–50	3,000–4,800	Readings limited by core stick length and condition
R4	50–100	4,800–5,400	Continuous readings
R5	100–250	5,400–6,500	Continuous readings
R6	>250	>6,500	Assumed, case study data did not support R6 estimate

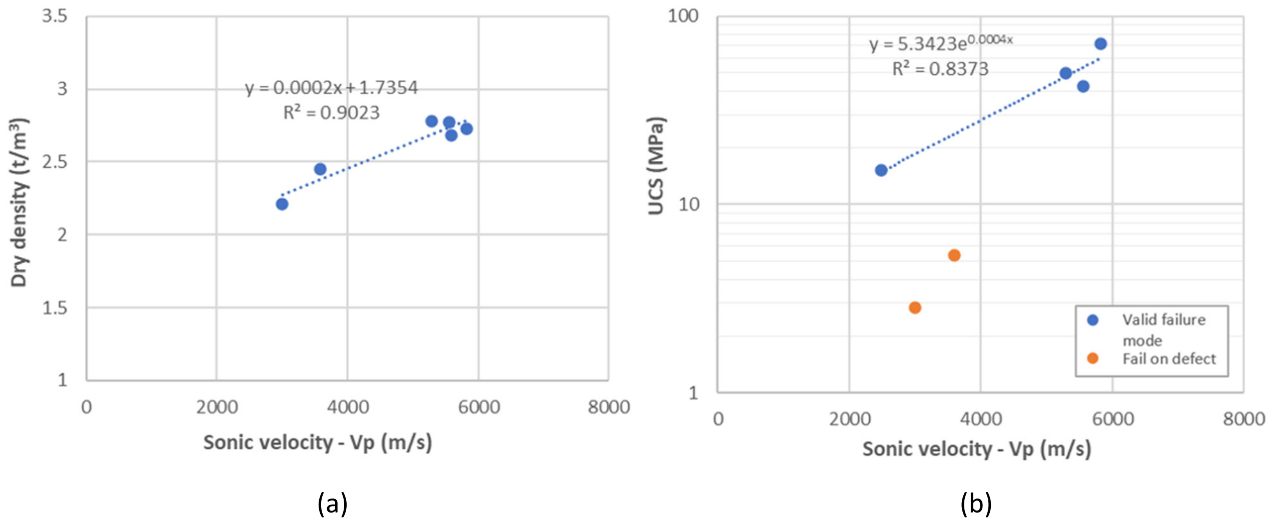


Figure 9 Correlation with (a) laboratory-testing density and (b) UCS – case study 2

4.3 Case study 3: quality control of Surfer Vp/UCS relationships

Another of AngloGold Ashanti's project areas is hosted in weak epithermal tuffs where the risk of sample disturbance during transport was a concern for the calibration of site-specific curve fitting. In this case, a

Surfer unit was sent to the laboratory with the samples to allow for readings just prior to UCS testing. The deposit in question is highly fractured and highly altered with different clay, silica or both present in samples. This results in the majority of samples failing along pre-defined structures, which would typically result in results being discarded as invalid, but are considered representative of the rock mass unit in this particular case and have been deemed valid for the use case.

Three readings per sample were taken, and then averaged, and compared against the theoretical distance–time relationship to filter out erroneous data based on the 150 mm nominal distance between probes (i.e. making use of the basic velocity equation of distance divided by time as shown in Equation 2). An arbitrary cut-off value of 50 m/s deviation from the theoretical fit was used to filter 'good' data and outliers.

Results of the laboratory values are reproduced in Table 6, with readings designated as outliers bolded in the outliers column. This process is also shown visually in Figure 10.

Table 6 Laboratory ultrasonic pulse velocity Vp results

Time (µs)	Velocity (m/s)	Exact relationship fit (m/s)	Residuals (m/s)	Outliers	UCS50 (MPa)	Alteration	Weathering	FES	Failure type	Failure mode
32.7	4,623	4,587	−36	Good	**202**	Clay	MW	R3	M	**A**
36.18	4,167	4,146	−21	Good	**91**	Silica	SW	R4	M	**A**
36.13	4,163	4,152	−11	Good	47	Silica	MW	R4	M	S
36.4	4,120	4,121	1	Good	34	Clay	SW	R5	P	S
37.1	4,043	4,043	0	Good	54	Clay	FR	R3	M	S
39.9	3,763	3,759	−4	Good	39	Clay	SW	R3	P	S
42.6	3,523	3,521	−2	Good	30	Silica	SW	R4	M	S
43.2	3,473	3,472	−1	Good	29	Clay	FR	R3	M	S
43.67	3,473	3,435	−38	Good	**158**	Silica	SW	R5	C	**M**
43.8	3,432	3,425	−7	Good	42	Clay	MW	R3	M	S
44.2	3,420	3,394	−26	Good	34	Clay	MW	R3	M	S
44.5	3,373	3,371	−2	Good	**41**	Clay	FR	R3	M	**A**
44.8	3,353	3,348	−5	Good	50	Clay	FR	R3	M	S
44.79	3,350	3,349	−1	Good	**30**	Clay	SW	R3	M	**A**
45.1	3,327	3,326	−1	Good	24	Clay	SW	R5	M	S
45.23	3,320	3,316	-4	Good	44	Clay	SW	R5	P	S
45.8	3,273	3,275	2	Good	38	Clay	FR	R3	M	S
46.6	3,260	3,219	−41	Good	27	Clay	FR	R3	M	S
47.2	3,177	3,178	1	Good	26	Clay	SW	R5	W	S
48.6	3,083	3,086	3	Good	33	Clay	FR	R3	W	S
48.7	3,080	3,080	0	Good	**21**	Clay	FR	R4	M	**A**
53.6	2,797	2,799	2	Good	29	Clay	SW	R4	M	S
55.7	2,697	2,693	−4	Good	21	Clay	MW	R3	M	S
56.1	2,677	2,674	−3	Good	25	Clay	FR	R4	M	S
56.2	2,670	2,669	−1	Good	17	Clay	MW	R3	M	S
56.5	2,660	2,655	−5	Good	44	Clay	SW	R4	C	S
56.7	2,647	2,646	−1	Good	7.1	Clay	FR	R4	P	S
57.4	2,610	2,613	3	Good	20	Clay	SW	R3	M	S
62.7	2,400	2,392	−8	Good	17	Clay	SW	R3	C	S
62.6	2,397	2,396	−1	Good	19	Clay	SW	R3	M	S

Time (µs)	Velocity (m/s)	Exact relationship fit (m/s)	Residuals (m/s)	Outliers	UCS50 (MPa)	Alteration	Weathering	FES	Failure type	Failure mode
63.4	2,370	2,366	−4	Good	**259**	Clay	SW	R5	W	**A**
65.02	2,309	2,307	−2	Good	19	Clay	MW	R3	M	S
65.1	2,300	2,304	4	Good	*14*	Clay	SW	R4	P	S
65.4	2,293	2,294	1	Good	11	Clay	SW	R4	P	S
66.7	2,250	2,249	−1	Good	18	Clay	SW	R3	P	S
67.3	2,230	2,229	−1	Good	9.6	Clay	SW	R4	P	S
67.8	2,207	2,212	5	Good	20	Clay	MW	R3	M	S
68.9	2,187	2,177	−10	Good	17	Clay	MW	R3	M	S
69.44	2,161	2,160	−1	Good	23	Clay	SW	R4	M	S
69.9	2,150	2,146	−4	Good	**53**	Silica	SW	R5	W	**C**
71.26	2,130	2,105	−25	Good	13	Clay	MW	R4	C	M
71.26	2,130	2,105	−25	Good	13	Clay	MW	R4	C	M
71.36	2,130	2,102	−28	Good	13	Clay	MW	R4	C	M
71.36	2,130	2,102	−28	Good	13	Clay	MW	R4	C	M
70.9	2,123	2,116	−7	Good	11	Clay	HW	R2	M	S
76.2	1,970	1,969	−1	Good	11	Clay	SW	R3	P	S
81	1,890	1,852	−38	Good	12	Clay	SW	R3	C	S
79.6	1,887	1,884	−3	Good	16	Clay	MW	R5	M	S
82.3	1,830	1,823	−7	Good	8	Clay	HW	R2	M	S
85.5	1,750	1,754	4	Good	19	Clay	SW	R3	P	S
100.8	1,490	1,488	−2	Good	3.2	Clay	HW	R1	M	S
102	1,473	1,471	−2	Good	5.8	Clay	MW	R3	M	S
102	1,470	1,471	1	Good	2.5	Clay	MW	R2	P	S
35	4,354	4,286	−68	**Outlier**	**149**	Silica	SW	R4	M	S
89.46	1,740	1,677	−63	**Outlier**	**4.9**	Clay	TM	R2	M	S
100.4	1,557	1,494	−63	**Outlier**	**3.7**	Clay	HW	R3	C	S
32.3	3,219	4,644	1,425	**Outlier**	**108**	Clay	FR	R4	M	A
86.5	3,220	1,734	−1,486	**Outlier**	**8.9**	Clay	MW	R4	P	S
55.63	2,829	2,696	−133	**Outlier**	**18**	Clay	SW	R5	M	S
56.38	2,729	2,661	−68	**Outlier**	**34**	Clay	SW	R3	M	S
63.42	2,609	2,365	−244	**Outlier**	**19**	Clay	MW	R3	P	S

Failure type: M – through matrix, P – along weakness plane, C – combination, W – weakness network
Failure mode: A – axial splitting, S – shear rupture, M – mixed splitting and shear, C – spalling/chipping
TM – transported material, HW – highly weathered, MW – moderately weathered, SW – slightly weathered, FR – fresh

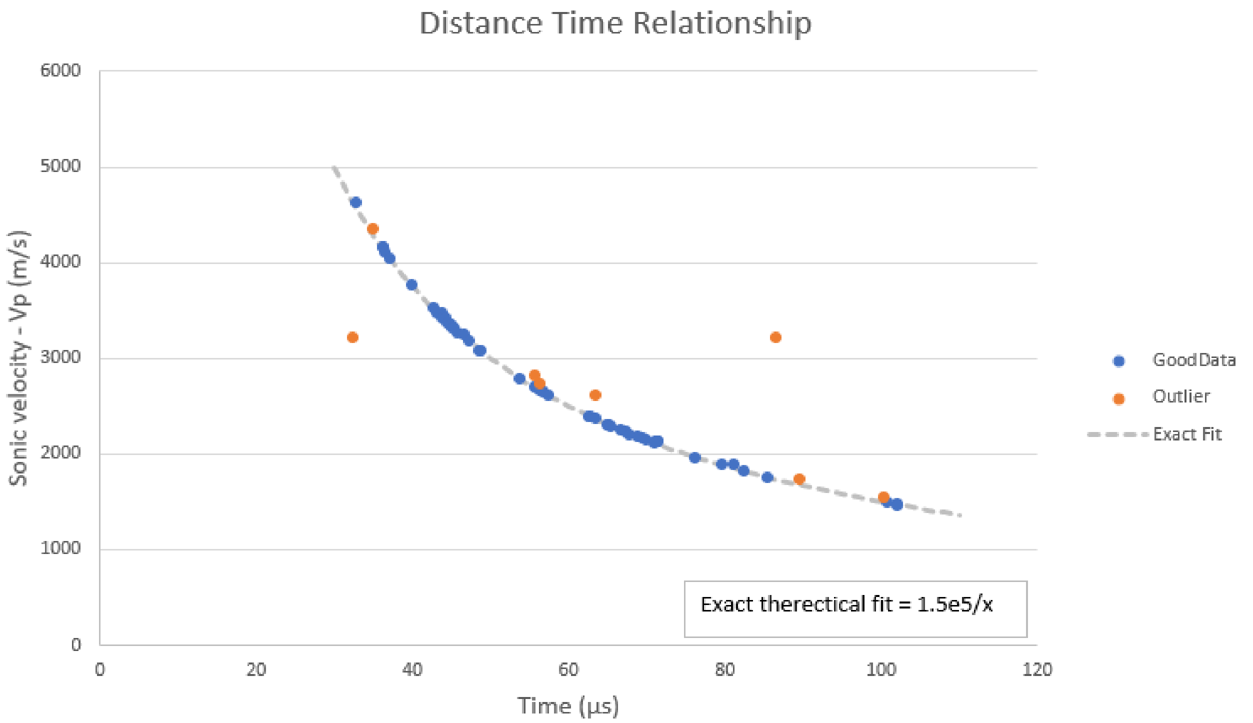


Figure 10 Distance–time relationship for Surfer ultrasonic pulse velocity readings

The resulting filtered data compared to the size-corrected UCS is pictured in Figure 11. Additional filtering was completed based on the mode of failure. This was required for axial splitting, as illustrated by the grey dots in Figure 11 where the results did not fit the trend. This can be explained by the high silica presence in these samples which results in a brittle failure mechanism and where microdefects were less likely to be present, as shown in Figure 12. This indicates that the mode of failure may result in a different curve and site-specific calibrations should take place considering the geological knowledge available.

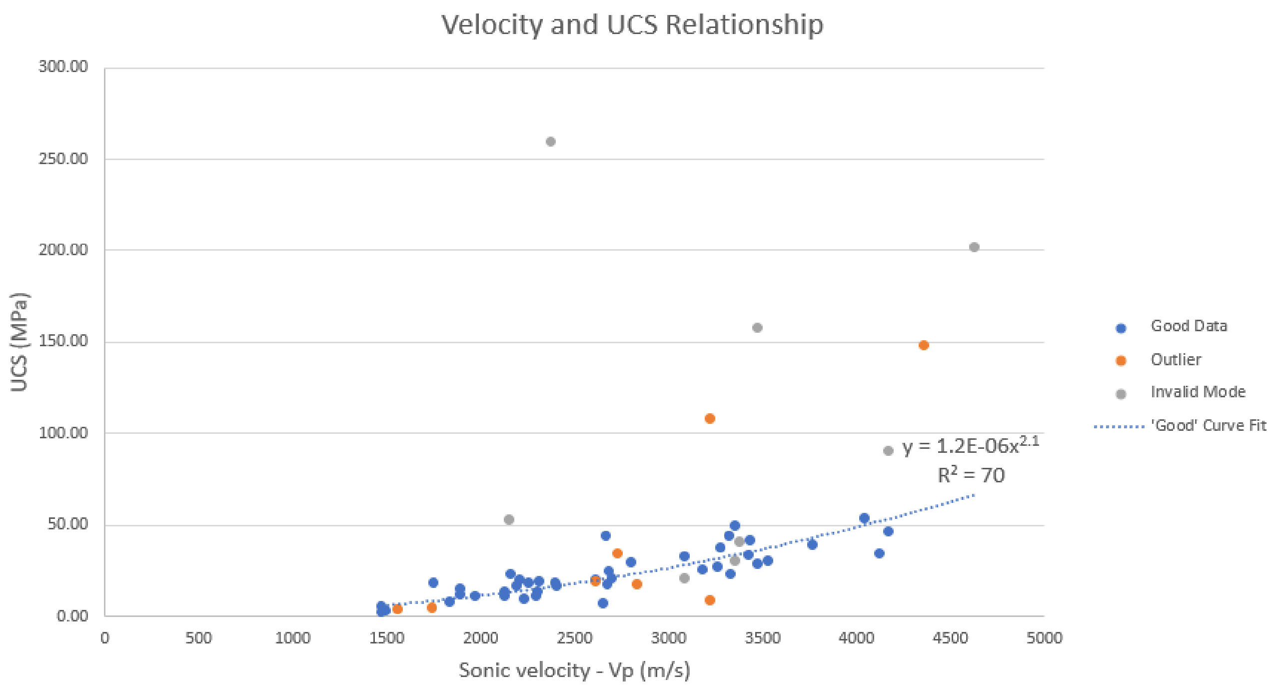


Figure 11 Filtered velocity/uniaxial compressive strength (UCS) results and curve fitting of the data

(a) (b)

Figure 12 Typical sample failure modes axial splitting, and in shear for (a) a silica altered sample and (b) a clay altered sample

The site-specific curve was then used to validate the logged FES against the laboratory and UPV values for the 'good' data as shown in Table 7. A comparison of the different FES types was created by taking the relative measure of the ISRM FES and assigning a positive or negative integer value of the difference in assigned grade. Unsurprisingly, the UPV versus laboratory UCS values shows the best correlation with the sum of all values being the closest to zero (i.e. a perfect correlation). This simple comparison also shows that the UPV tester can accurately identify the FES class and would be a useful tool in the field to classify FES, particularly where ambiguity exists in the ISRM hammer techniques (i.e. >R4).

Table 7 Comparison of field estimated strength values from laboratory, core logging and ultrasonic pulse velocity

UCS lab (MPa)	UPV UCS (MPa)	Lab FES	Logged FES	UPV FES	FES lab vs logged	FES UPV vs lab	FES UPV vs logged
202	80	R5	R3	R4	2	−1	1
91	64	R4	R4	R4	0	0	0
47	64	R3	R4	R4	−1	1	0
34	62	R3	R5	R4	−2	1	−1
54	60	R4	R3	R4	1	0	1
39	52	R3	R3	R4	0	1	1
30	45	R3	R4	R3	−1	0	−1
29	44	R3	R3	R3	0	0	0
158	44	R5	R5	R3	0	−2	−2
42	43	R3	R3	R3	0	0	0
34	42	R3	R3	R3	0	0	0
41	41	R3	R3	R3	0	0	0
50	41	R4	R3	R3	1	−1	0
30	40	R3	R3	R3	0	0	0
24	40	R2	R5	R3	−3	1	−2
44	40	R3	R5	R3	−2	0	−2
38	39	R3	R3	R3	0	0	0
27	38	R3	R3	R3	0	0	0
26	36	R3	R5	R3	−2	0	−2

UCS lab (MPa)	UPV UCS (MPa)	Lab FES	Logged FES	UPV FES	FES lab vs logged	FES UPV vs lab	FES UPV vs logged
33	34	R3	R3	R3	0	0	0
21	34	R2	R4	R3	−2	1	−1
29	28	R3	R4	R3	−1	0	−1
21	26	R2	R3	R3	−1	1	0
25	25	R2	R4	R3	−2	1	−1
17	25	R2	R3	R3	−1	1	0
44	25	R3	R4	R2	−1	−1	−2
7.1	25	R2	R4	R2	−2	0	−2
20	24	R2	R3	R2	−1	0	−1
17	20	R2	R3	R2	−1	0	−1
19	20	R2	R3	R2	−1	0	−1
259	20	R6	R5	R2	1	−4	−3
19	19	R2	R3	R2	−1	0	−1
14	18	R2	R4	R2	−2	0	−2
11	18	R2	R4	R2	−2	0	−2
18	18	R2	R3	R2	−1	0	−1
10	17	R2	R4	R2	−2	0	−2
20	17	R2	R3	R2	−1	0	−1
17	17	R2	R3	R2	−1	0	−1
23	16	R2	R4	R2	−2	0	−2
53	16	R4	R5	R2	−1	−2	−3
13	16	R2	R4	R2	−2	0	−2
11	16	R2	R2	R2	0	0	0
11	13	R2	R3	R2	−1	0	−1
12	12	R2	R3	R2	−1	0	−1
16	12	R2	R5	R2	−3	0	−3
7.8	11	R2	R2	R2	0	0	0
19	10	R2	R3	R2	−1	0	−1
3.2	7.4	R1	R1	R2	0	1	1
5.8	7.2	R2	R3	R2	−1	0	−1
2.5	7.2	R1	R2	R2	−1	1	0
Totals					−42	−1	−43
Filtered failure mode results removed					−45	6	−39

4.4 Case study 4: quantification of transport damage

At another operation, highly variable weak (R2) to strong (R5) rock was required to be transported long distance via road to get to the testing facilities. Sample degradation during transport was a concern, so index readings using Equotip and UPV taken prior to shipment and at the laboratory were compared to quantify sample quality. A reliable fit between values before and after shipping with the UPV device is apparent, as illustrated in Figure 13a. Of note, three samples with reduced readings at the laboratory all failed through weakness networks, indicating that sample damage was incurred during transport and the resulting test work is likely unrepresentative of in situ conditions.

A similar exercise was completed using Equotip (i.e. Leeb hardness) values gathered during routine collection and from values collected at the laboratory prior to rock mass testing (Figure 13b). In the Equotip data, a greater spread in results is shown which can be attributed to the point data collection, surface conditions, and transport-related damage.

From this exercise, it can be concluded that both UPV and Equotip can be used to quantify sample damage during the transportation process. The UPV provides a cleaner and more reliable dataset than Equotip, possibly due to its sampling methodology that takes readings over an entire sample rather than the point estimate method provided by Equotip, which is highly dependent on where and how the instrument is placed.

(a) (b)

Figure 13 Damage-related damage quantification using (a) ultrasonic pulse velocity readings and (b) Equotip readings

5 Conclusion

Sonic velocity testing is a non-destructive method used to assess the strength and integrity of rock materials. Sonic velocity is commonly measured using in situ geophysical methods or from rock specimen as part of laboratory testing. Sonic velocity correlates with elastic properties and rock density, which can be used to estimate UCS indirectly. Empirical relationships, such as the equation presented by McNally (1990), are commonly used for this correlation, and site-specific calibration is often necessary.

This paper explores the use of a handheld UPV tester to estimate rock strength of diamond drill core and geotechnical laboratory samples. Four case studies are given to demonstrate the application and limitations of the UPV tester in geotechnical investigations.

The first 2 case studies showed correlation of the UPV readings with the FES. In both cases, UPV readings were attempted to be taken every 1 m downhole for the length of the diamond drill holes. Readings could be taken every 1 m in the slightly weathered and unweathered rock with strength R4 and R5. Readings could not be taken every 1 m moderately and highly weathered rock with strength R2 and R3 because of the high prevalence of jointing and micro-fractures which caused readings to fail. Wider-spaced readings were recorded through these intervals, but the readings obtained were still found to accurately represent the material strength. The tester generally could not take readings in R1 or weaker material as the lower velocity limit of the tester is 1,000 m/s.

The UPV readings allowed the contact between strength classes to be more accurately picked. Intervals of lower strength associated with increased weathering, veining and alteration were better identified from the UPV readings than from initial logged FES. This shows the UPV tester removes subjectivity from the picking of FES values in-field and can be considered a more reliable dataset than ISRM FES testing methods alone.

Correlations of UPV readings with both FES and laboratory-tested UCS values are presented. Suggested sonic velocity ranges for each FES class are given. It was noted that correlations may be different for different rock or alteration types, and that site-specific correlations may need to be developed at different sites.

The third case history was a detailed comparison of laboratory UCS testing compared with the logged FES and UPV measured for each sample. This comparison showed that the UPV tester can accurately identify the strength class as obtained from laboratory testing, and was more accurate than the FES logging alone. This shows that it is a useful tool in the field to classify FES – particularly where ambiguity exists in the ISRM hammer techniques (i.e. strength classes lower than R4).

The fourth case history demonstrated quantification of transport damage of weak samples. Index readings on laboratory samples prior to shipment and at the laboratory were compared. This allowed samples which had deteriorated during transportation to be identified. The resulting test work was likely unrepresentative of in situ conditions, and could thus be excluded from analysis.

Overall, the UPV tester improves reliability of strength estimation, reducing the subjectivity inherent in the ISRM estimation method. Future work should focus on expanding the application of the UPV tester to a broader range of rock types and refining correlations for different failure modes and geotechnical properties.

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