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Characterizing Rock Strength Along the Brisbane River

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ABSTRACT: *Surface geology and rock strength properties are discussed for the lower 50 km of the Brisbane River through a snapshot of cross sections along the river. The Brisbane River is tidal with a varied geological history which can be traced to the Triassic Period. River width and depth to bed level are compared as the river snakes through Brisbane City with a large drainage catchment. Statistical properties and correlations of some of the various rock units uncover the range and variability along the river, providing a basis for engineering design decisions and the assessment of project risk. Unconfined Compressive Strength (UCS) to Point Load Index ($I_{s(50)}$) and UCS to tangent modulus (E) correlations are developed.*

KEYWORDS: Rock strength, Unconfined Compressive Strength, Point Load Index, Brisbane River, Queensland, Australia.

SITE LOCATION: Geographic Database

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INTRODUCTION

The Brisbane River flows through the city of Brisbane, Queensland, Australia, and discharges into Moreton Bay. The river has a catchment area of approximately 13,506 km² (Eyre et al., 1998). Historically, the Brisbane River contained upstream bars and shallows and had a natural tidal limit of only 16 km (Abal et al., 2002). The current tidal limit extends 85 km upstream due to continual channel dredging and is shown in Figure 1.

There are many tributaries in the tidal Brisbane River catchment, including Breakfast, Bulimba, Norman, and Oxley Creeks. The Brisbane River catchment exports 450,000 tonnes (Abal et al., 2002) of suspended sediment into Moreton Bay every year from sub-catchments such as the Bremer and Lockyer, mostly after large storm events and heavy rainfall.

Some engineering characteristics of the river geometry and rock strength at sites in the lower 50 km are discussed in this paper. The study area is illustrated in Figure 2 and extends from Jindalee in the west, through Brisbane City, and to the eastern suburbs of Murarrie near Gibson Island at the beginning of the river delta. The river width triples over this distance, with the wetted perimeter increasing by a factor of two, and the depth to bedrock increasing by about 10 m. Rock types and properties also vary significantly over the distance.

The paper presents an initial overview of the Brisbane River geomorphology and geology with some key geological units. Rock strength characteristics and variability are presented at the five labeled sites shown in Figure 2. The unlabelled sites are used to inform geomorphology data in addition to the labeled sites, but without rock unit discussions.

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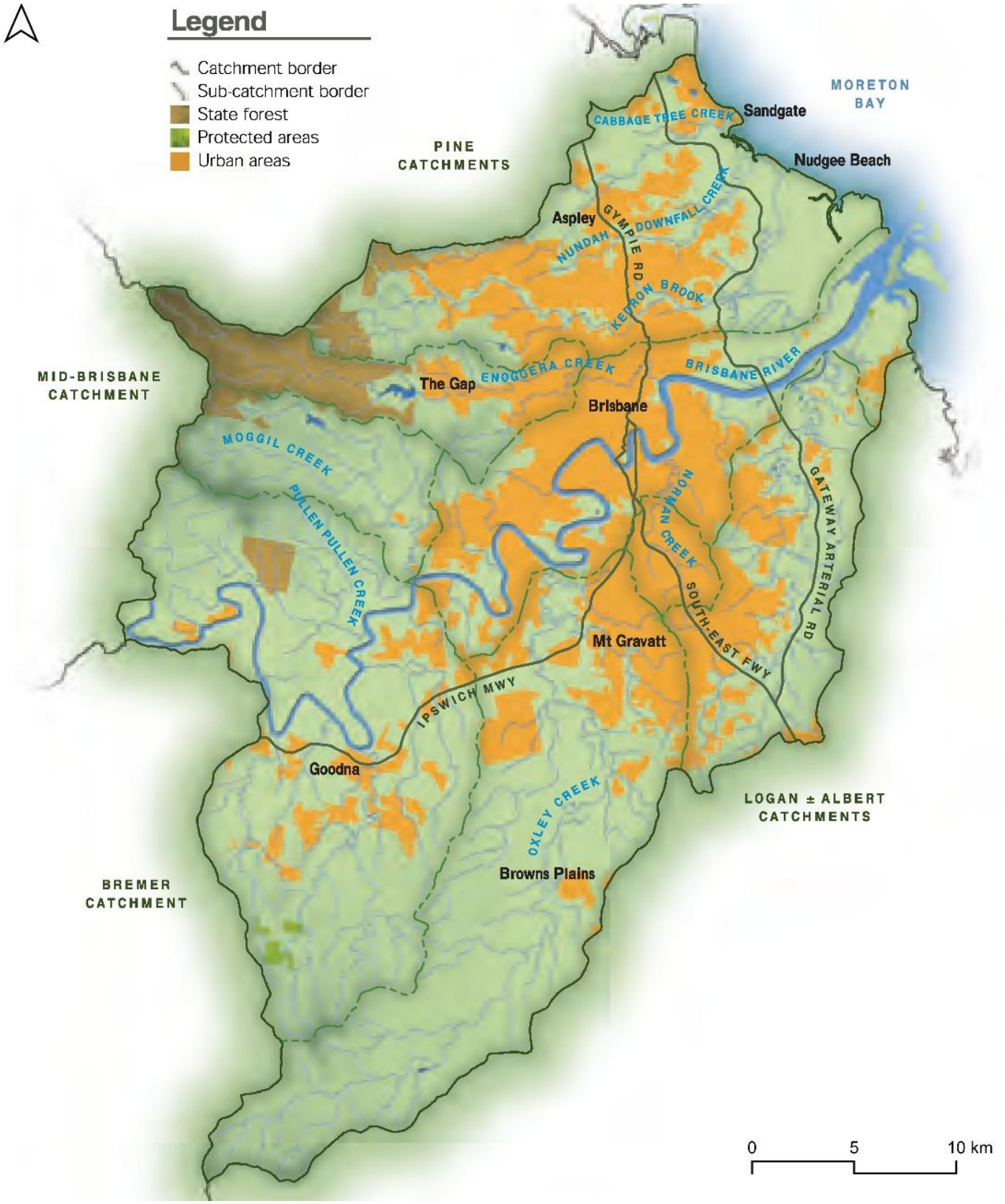

Figure 1. *Map of tidal Brisbane River catchment (Abal et al., 2002)*

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Figure 2. *Brisbane River study area*

SURFACE GEOLOGY AND GEOMORPHOLOGY

The Brisbane River traverses several geological units as described in Willmott (2012). These near-surface units are illustrated in Figure 3 and include:

- Neranleigh-Fernvale beds (DCf) and Bunya Phyllite (DCy). Sedimentary and metasedimentary rocks formed by 330 Ma (million years ago).
- Brisbane Tuff (Rif). Welded ignimbrite formed from Triassic pyroclastic flows about 226 Ma. Brisbane Tuff is famously exposed at the Kangaroo Point cliffs, a former quarry site opposite the central business district.
- Quaternary alluvial deposits (Qpa, Qa) from the past 2 Ma. There have been several fluctuations in sea level, including periods when Moreton Bay was dry. Alluvial terraces formed on either side of the valley, and younger alluvium was deposited with the most recent rise in sea level (Figure 4).
- Holocene-aged deposits (Qh) in the past 11,000 years, comprising softer and less consolidated sediments.
- Anthropocene (human) activity at Gibson and Bulwer Islands, as well as land reclamation at the Port of Brisbane in Moreton Bay.

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The history of the Brisbane River is described by Willmott (2012) and illustrated in Figure 4. Several small basins developed across southeast Queensland early in the Tertiary period (65 to 45 Ma). Deposits occurred in shallow freshwater lakes and swamps in the Sherwood – Oxley area (Oxley Group) and the Redbank Plains area (Booval Group). With fluctuations in sea level, the river linked the series of lakes and swamps.

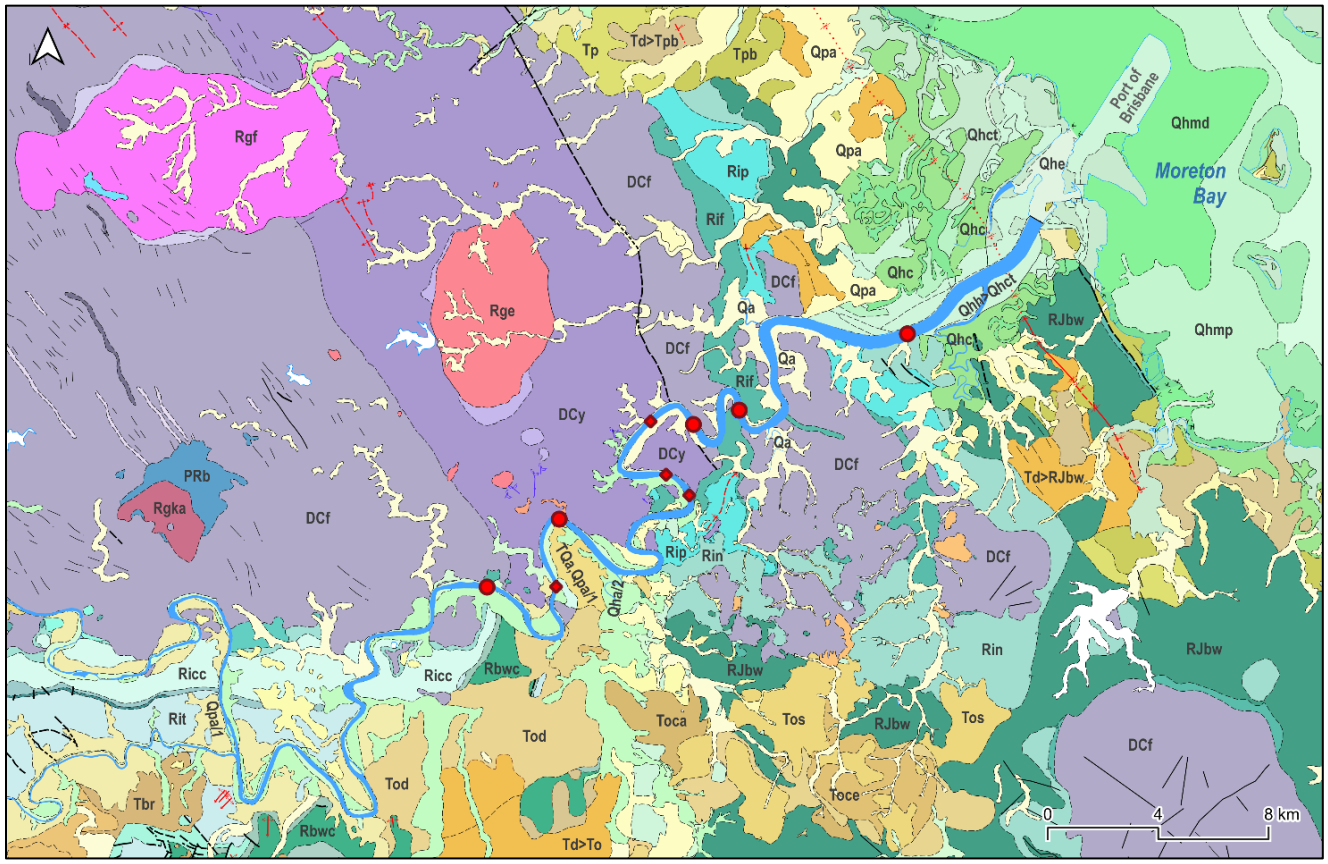

Figure 3. *Surface geology of the Brisbane River study area (Geological Survey of Queensland 2023)*

Extensive volcanic eruptions and intrusions of shallow dykes occurred between 28 and 20 Ma in areas surrounding Brisbane. After this volcanic period, erosion continued to remove the weaker rock to expose plugs across South East Queensland (SEQ). Although the local rhyolite and welded tuff rocks are generally stronger than the other rock types discussed herein, the tuff has an unconformity zone between various geological units. This zone becomes significant during tunneling operations when a sequence of weaker materials is present at the interface. This interface strength is not covered herein.

The present course of the river was established as a series of migrating meanders on a broad flood plain (Figure 4). At the end of the Pleistocene period (120,000 years ago), a rise in sea level resulted in a lower velocity stream and deposition of finer sediments. The Brisbane River delta grew over the last 6,000 years and now extends from Bulimba to Lytton.

Typically, one side of the riverbank comprises shallow or near-surface rock, often beginning with residual soil or extremely weathered (XW) to highly weathered (HW) rock, and becoming progressively less weathered with depth. The opposite side of the river is typically a flatter flood plain with deep alluvium overlying bedrock (Figures 5 and 6). As a first approximation, the top of moderately weathered (MW) rock in the riverbed is where the two riverbank slopes intersect.

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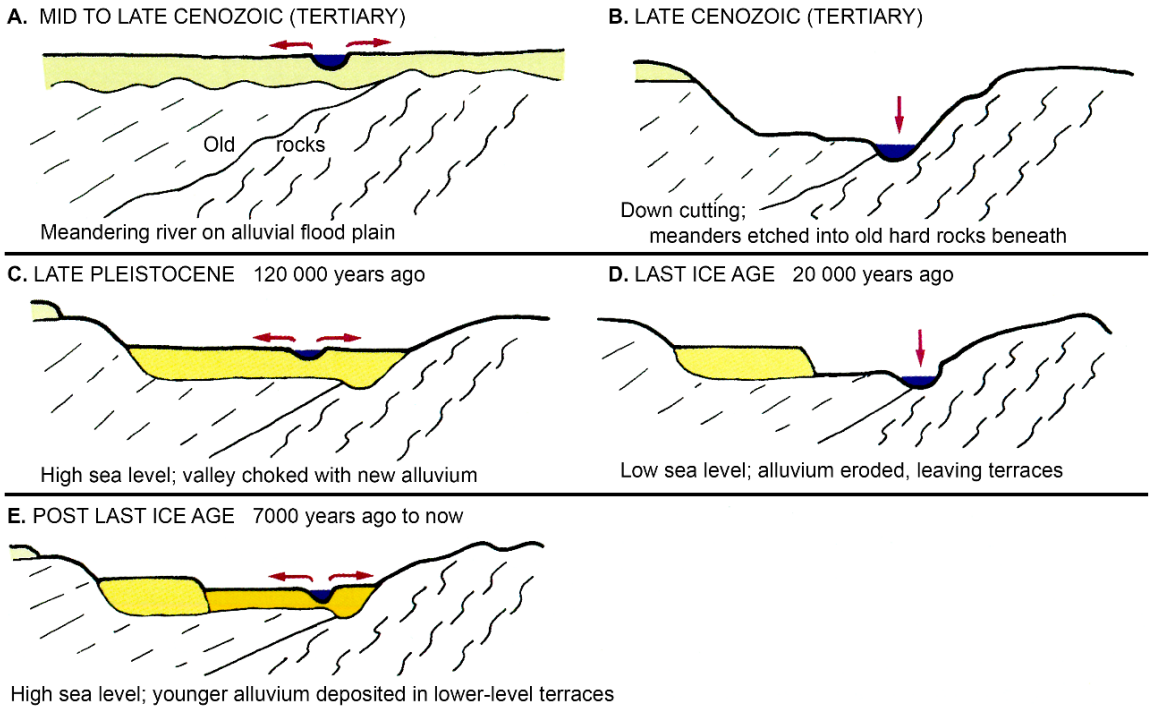

Figure 4. *Progressive development of the Brisbane River valley (Willmott, 2012)*

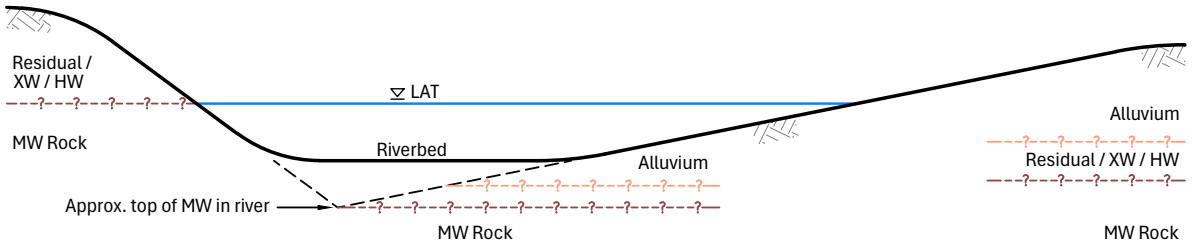

Figure 5. *Conceptual upstream geometry (facing Moreton Bay)*

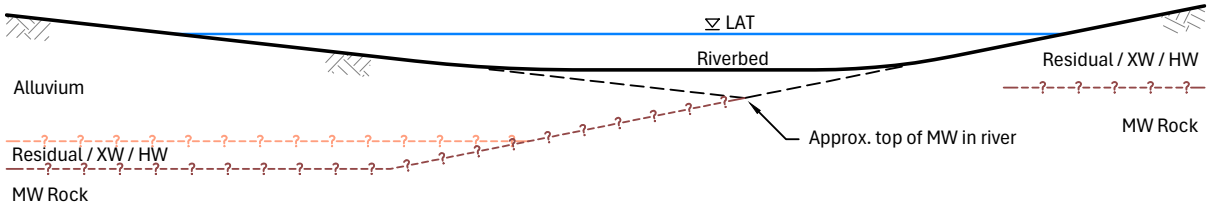

Figure 6. *Conceptual downstream geometry (facing Moreton Bay)*

The river width increases with proximity to the mouth of the river (Figure 7a), as can be expected, with a strong correlation. All areas adjacent to these snapshot locations (Figure 2) experienced flooding in the major 2011 event.

The depth to riverbed level with distance from the mouth of the river is weakly correlated (Figure 7b). The bed level is in a state of dynamic equilibrium and regularly changes with extreme events. The riverbed may then deepen by over 2 m due to bed erosion, but the material is typically deposited back to the previous levels within a few weeks.

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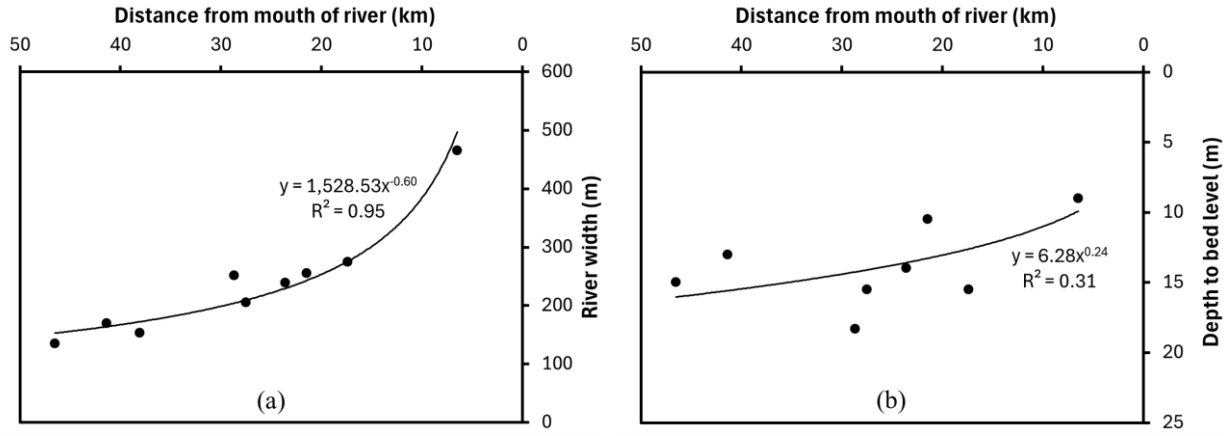

Figure 7. *Variation of (a) river width and (b) depth to riverbed level with distance from mouth of river*

The depth to rock and Reduced Level (RL in Australian Height Datum) of the rock are strongly correlated with distance from the mouth of the Brisbane River (Figure 8). This suggests that hydraulic forces dominate the equilibrium rock level as the material type and strength vary both along the river and across the width. As Quaternary deposits overlie the rock, the deepest rock level may extend for some distance away from the main channel flow. In other areas the rock is exposed at the riverbank level (e.g. Centenary Bridge, Indooroopilly, and Kangaroo Point Cliffs).

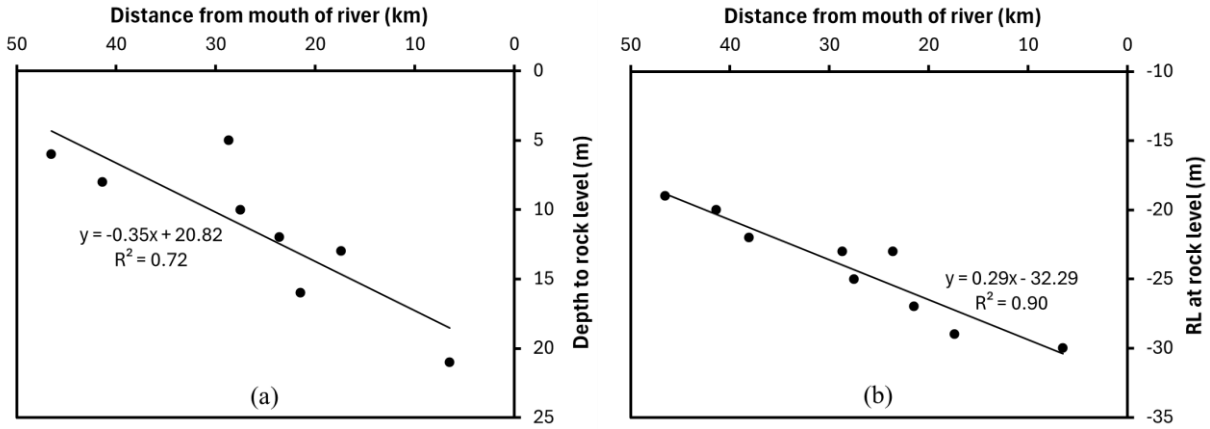

Figure 8. *Variation of (a) depth to rock level and (b) RL at rock level with distance from mouth of river*

QUEENSLAND ROCK TYPES

Figure 9 summarises an infrastructure database of 9,911 investigations showing the distribution of lithology across Queensland. This database was expanded from that used in Priddle et al. (2013), which was confined to southeast Queensland and focused on residual soil properties. Sedimentary rocks are predominant, at 61.7% within the database, and this is likely a low estimate as the dataset is geographically skewed to southeast Queensland, coastal areas, and major cities. Western Queensland is a large land area known to be dominated by sedimentary rock but is poorly represented in terms of infrastructure development for this database.

Sandstone (22%) is the most common sedimentary rock type. Several sites have more than one rock type, and Figure 9 should be viewed as indicative only. The Brisbane River is well represented with various lithologies, and all 3 rock groups will be covered for the sites examined further.

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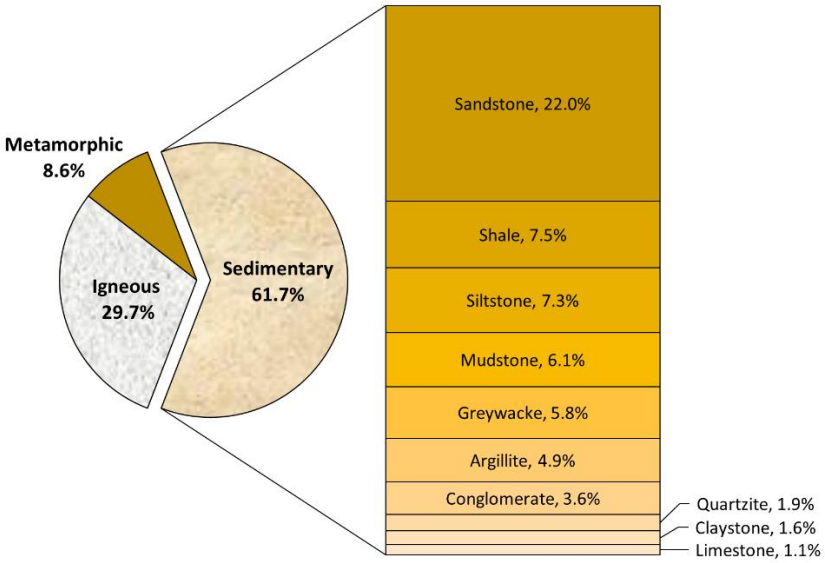

Figure 9. *Common lithologies for infrastructure related sites across Queensland*

ASSESSMENT OF ROCK STRENGTH PROPERTIES

Look and Griffiths (2001) investigated the correlation between Point Load Strength Index (PLI, $I_{s(50)}$) and Unconfined Compressive Strength (UCS) test results for rocks within the Brisbane area, and the effect that the direction of PLI testing had on reported $I_{s(50)}$ values. The key findings of that investigation were:

- The UCS to $I_{s(50)}$ multiplier of 24 commonly used at the time (2001) should not be applied for Brisbane rocks. This typical correlation was found relevant for high strength rocks with UCS > 20 MPa.

- UCS ~11.2 $I_{s(50)}$ applied for most Brisbane rocks (Figure 10a). It varies from 5 for the Phyllites to 18 for the Brisbane Tuff unit. The effect of test direction on the correlation is shown in Figure 10b.

- The $I_{s(50)}$ Coefficient of Variation (COV = standard deviation / mean) varied from 40% for tuff, 83% for the greywacke / argillite, and 102% for phyllite rocks across several projects.

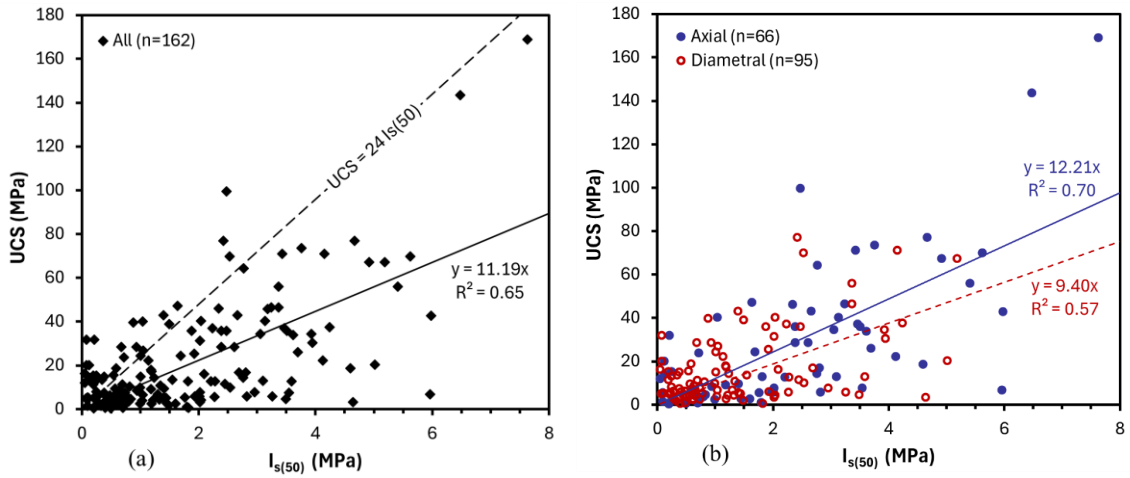

Figure 10. *Brisbane rock strength: (a) UCS to $I_{s(50)}$ correlation; (b) showing effect of anisotropy (Look and Griffiths 2001, 2004)*

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Look and Griffiths (2004a) further investigated the properties of the Brisbane rocks and found that the normal distribution does not apply to strength test results on intact rocks. The characteristic value chosen for design purposes is dependent on the type of distribution used. For the 12 different ways the study data was categorized and analyzed, the normal distribution was ranked between 12th and 13th out of 25 distribution functions trialed using goodness of fit statistical tests. The lognormal distribution was recommended to be used instead, as it usually ranked 1st to 5th.

Look and Griffiths (2004b) showed that for tests completed on meta-sedimentary (argillite, phyllite) and volcanic (tuff) rock materials with a reported rock strength of medium strength (UCS 6–20 MPa), or weaker, there is a bias between testing orientations. Axial-oriented tests repeatedly produced higher $I_{s(50)}$ values than corresponding tests completed in the diametral direction. The axial $I_{s(50)}$ value correlated better with UCS (Figure 10b), although this varied with rock type.

The rock properties by Look and Griffiths (2004) were specific to SEQ. This paper uses a similar approach but with different data for characterization of rock strength along the Brisbane River.

The variability of rock strength data at the Gateway Bridge was previously discussed in Look and Wijeyakulasuriya (2009) and fitted with statistical probability density functions (PDF). The effect of the PDF on the design and construction of the Gateway and Centenary bridges is discussed in Look (2024, 2025).

The database used in this study comprises laboratory test results obtained from rock core drilling investigations undertaken over a period exceeding 20 years. Core diameters were typically 52 mm, which is standard practice within the study area. All UCS and PLI tests were performed on cylindrical core specimens in accordance with Australian Standards (Standards Australia, 2007a, 2007b, 2013). Point load test orientation was recorded relative to the core axis, with axial (vertical) and diametral (horizontal) directions referenced to the drilled core orientation. Reported results represent individual test specimens. For UCS to $I_{s(50)}$ correlations, paired results were obtained from immediately adjacent core specimens. Consequently, some geological variability is inherent in the correlations and contributes to the reported scatter and coefficients of variation. Because the historical records did not consistently identify the orientation of bedding, foliation, or laminations relative to either the core axis or the applied test load, the influence of rock fabric anisotropy could not be explicitly isolated from the observed strength variability. Consequently, part of the scatter in the reported $I_{s(50)}$, UCS, and UCS to $I_{s(50)}$ correlations is likely attributable to variations in rock fabric orientation in addition to natural geological variability.

The assessment of rock properties was undertaken using box-and-whisker plots to both qualitatively and quantitatively compare rock material types and PLI test directions, and then by further developing standard UCS to $I_{s(50)}$ and modulus (E) to UCS correlations at each site where data were available. The COV for each site is also provided to show the strength variability of the rock units.

Figure 11 shows the key elements of the box-and-whisker plot. Whiskers extend to 1.5 times the interquartile range (IQR), and this represents 99.3% of results. Mild outliers are data that plot between 1.5 IQR and 3.0 IQR, while extreme outliers are greater than 3.0 IQR from the edge of the box. Where outliers exist, correlations should be used with care unless the outliers are removed from the analysis. This consideration is illustrated for the Gateway Bridge site with and without outliers. Where both outliers and a low number of samples occur, statistical correlations are likely to be in error.

Box and whisker plots provide a visual comparison of the variability of strength in the rock unit, while the COV provides a single numerical value to describe variability.

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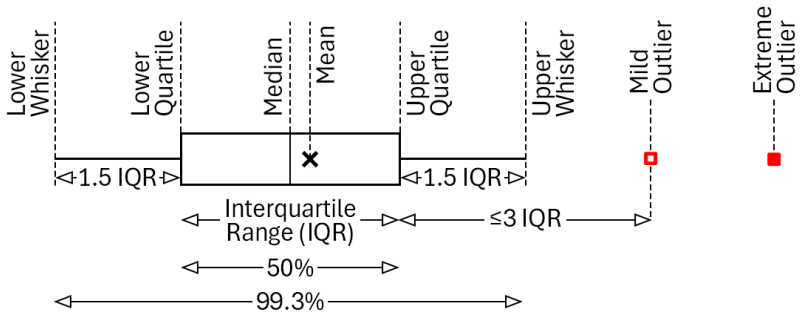

Figure 11. *Box and whisker plot key diagram*

SITE CENTENARY BRIDGE – 46.5 KM UPSTREAM

The upper end of this study is at the Centenary Bridge between Jindalee and Kenmore, approximately 46.5 km from the mouth of the river. There is exposed rock on the northern bank (left bank facing downstream) and a flood plain at the southern bank (right bank facing downstream). Shallow weathered agglomerate observed on the northern bank was inferred to be from the Brisbane Tuff (Rif) unit overlying mainly argillite and metagreywacke from the Neranleigh-Fernvale beds (DCf), as shown in Figure 12. The southern bank comprises alluvium (Qha/2) with a significant thickness of soft clay, and Holocene alluvium (Qhe) in the river itself.

$I_{s(50)}$ test results for each rock type and test orientation have been compared in Figure 13. The box plots show a significant variation in rock properties, suggesting a "uniform" rock model is unrealistic for geotechnical analysis purposes at this site, with the metagreywacke generally stronger than the argillite.

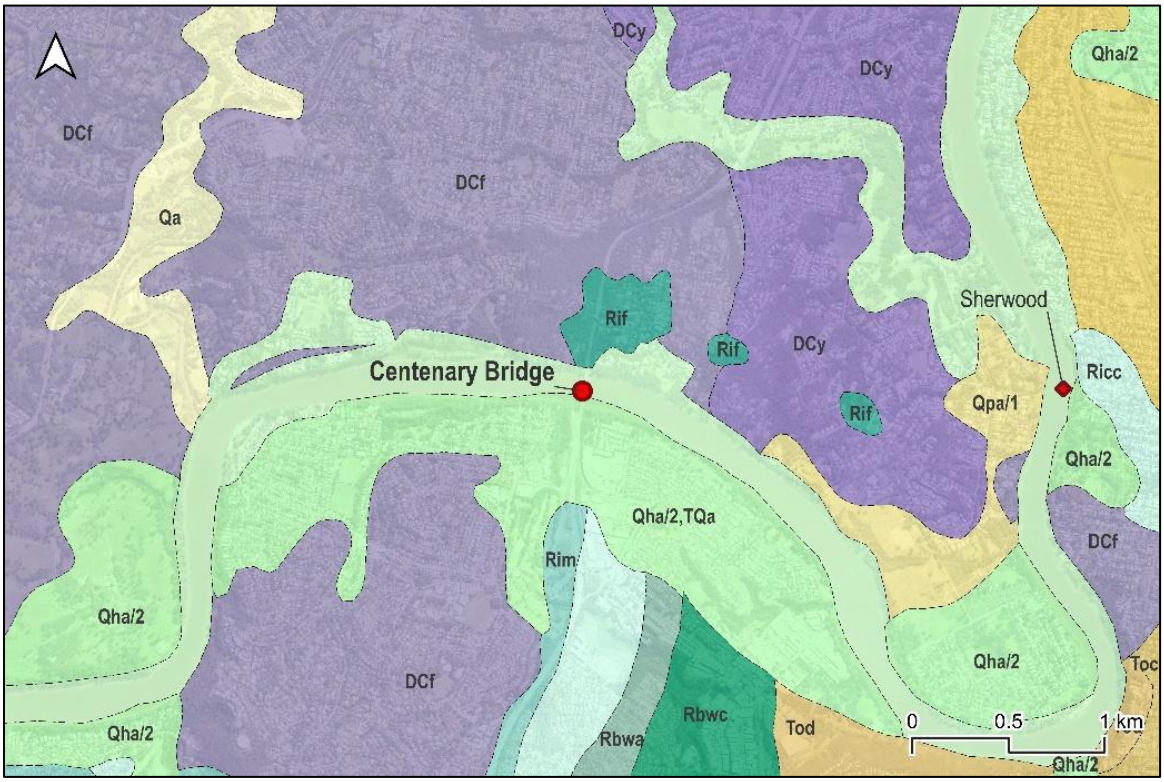

Figure 12. *Centenary Bridge surface geology (Geological Survey of Queensland 2023)*

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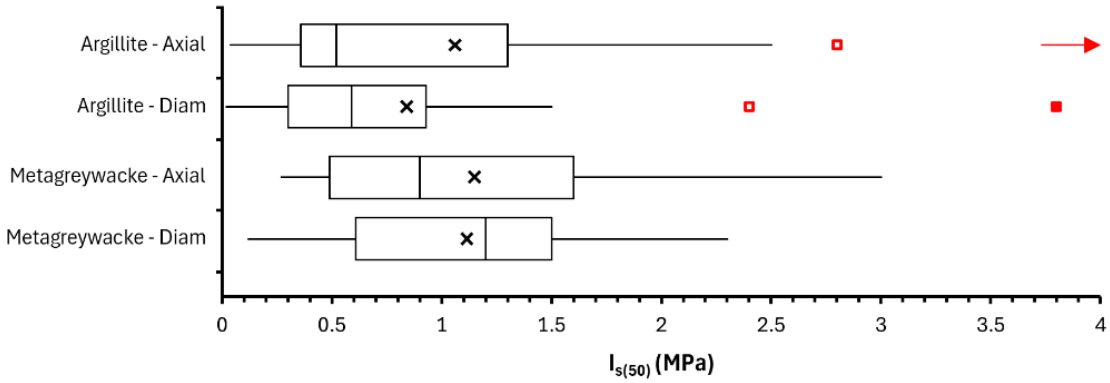

Figure 13. *Centenary Bridge variation of $I_{s(50)}$ results with rock material type and test direction*

The variability in rock strength, even for this single site, is apparent when the strength and COV values are compared from both axial and diametral $I_{s(50)}$ test results across the river (Table 1). The right bank (facing downstream) had significant alluvium overlying the rock, and the alluvium thickness decreases across the riverbed. The underlying rock has greater variability at the right bank and reduces toward the left bank. This suggests that obtaining a singular design value for this site and rock type is difficult with such variability, and variable rock strength interpretation would also potentially occur during construction verification.

Table 1. *Centenary Bridge typical point load index properties*

Property	Orientation $I_{s(50)}$	Left (North) Bank	Mid River	Right (South) Bank
No. of tests	Axial	17	80	17
Median (MPa)		0.5	0.9	0.8
COV (%)		73%	90%	105%
No. of tests	Diametral	20	80	17
Median (MPa)		0.5	0.7	0.6
COV (%)		52%	87%	142%

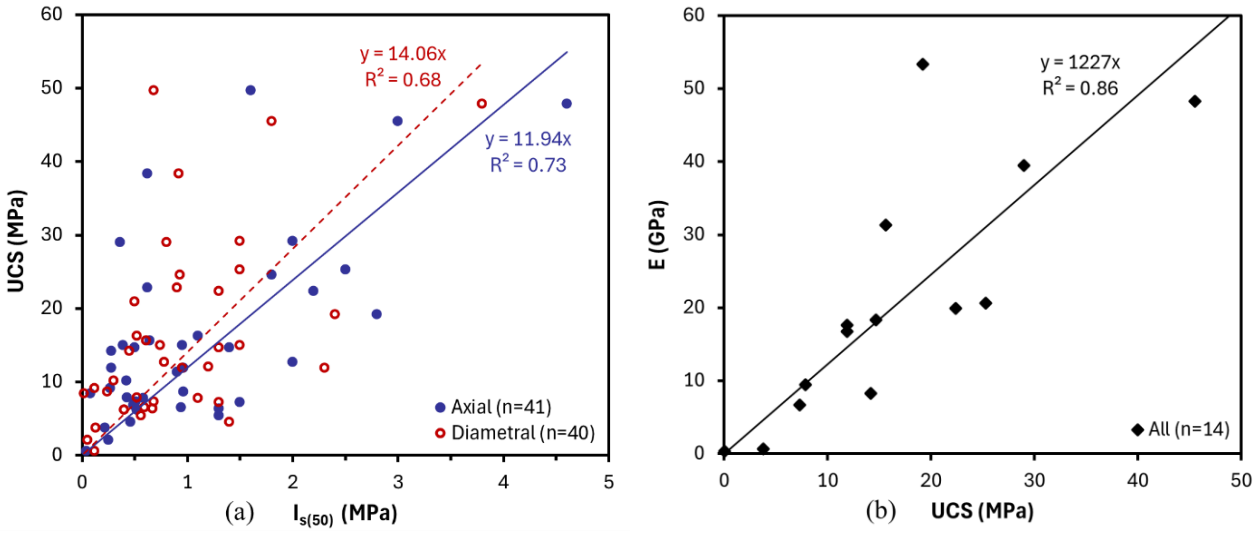

Figure 14. *Centenary Bridge (a) UCS to $I_{s(50)}$ correlations and (b) E to UCS correlation*

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Correlations between UCS and axial and diametral $I_{s(50)}$ have been developed in Figure 14a, with UCS = 14.1 $I_{s(50)}$ in the axial and 11.9 $I_{s(50)}$ in the diametral direction.

Correlation between modulus and UCS, or the modulus ratio (E / UCS), was calculated as approximately 1200 (Figure 14b), which is much higher than the typical 200 to 500 ratio, although metamorphic rocks may be expected to have a higher ratio (Vallejo & Ferrer, 2011).

E is the tangent modulus as interpreted on the laboratory certificate, typically between 20% and 35% of the maximum UCS value. Modulus (E) tests for this and other sites represent less than 25% of the UCS tests undertaken.

SITE INDOOROOPILLY – 38.1 KM UPSTREAM

There are several bridge structures near the sharp river bend at Indooroopilly. Bunya Phyllite (DCy) is exposed on the northern bank, along with rhyolite (Ri/r) intrusions, and an alluvial (Qpa, Qha/2, Qhe) flood plain is present on the southern bank (Figure 15). At this site, the river has an abrupt right-angle bend, which results in a narrower width and an increased depth to riverbed level (Figure 7). Lee (2005) suggests that at such locations, potential scour depths are increased.

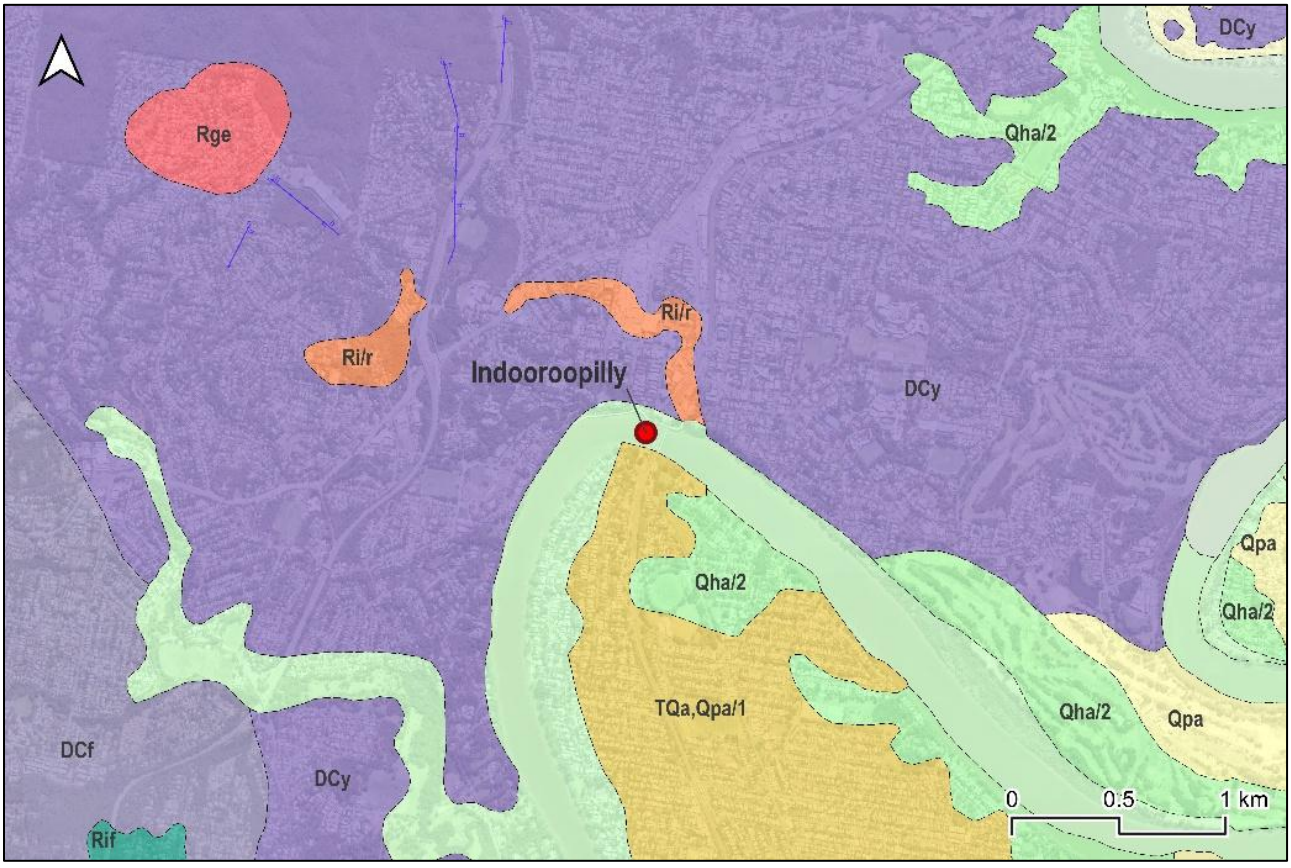

Figure 15. *Indooroopilly surface geology (Geological Survey of Queensland 2023)*

The available dataset was from a cycle bridge that runs parallel to the river bank, which means data was only available for the northern (left) bank, with a total of 160 axial and 42 diametral $I_{s(50)}$ results. The $I_{s(50)}$ test results for each rock type and test orientation have been compared in Figure 16. The box plots show that the rhyolite-derived material has a very large

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strength range and that, generally, diametral $I_{s(50)}$ results were somewhat higher than in the axial direction for these metamorphic rocks, which is the reverse anisotropy of what is commonly encountered in bedded sedimentary rocks.

The UCS to axial and diametral $I_{s(50)}$ correlations at the Indooroopilly site vary from UCS = 12.4 $I_{s(50)}$ for the axial direction up to 19.8 $I_{s(50)}$ in the diametral direction (Figure 17a); however, this is not based on a large dataset, with only n = 7 suitable pairs of UCS with $I_{s(50)}$ for analysis in the diametral direction. At this site, the modulus ratio (E / UCS) was calculated as 340 (Figure 17b), which is within the typical range but on the low side for metamorphic rocks, and significantly lower than for the Centenary Bridge site.

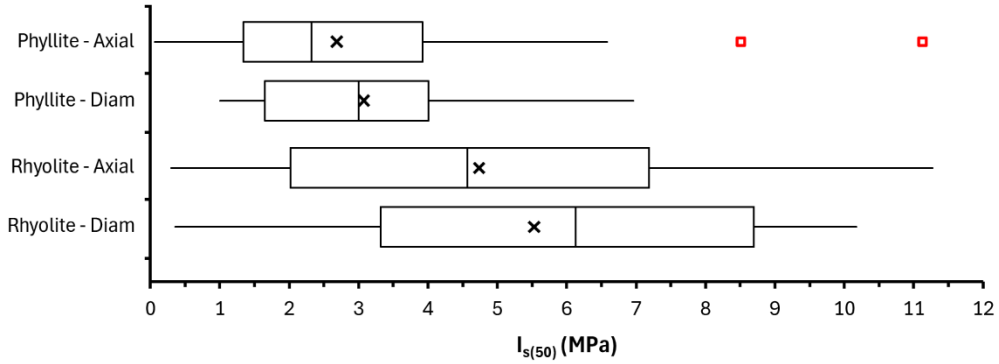

Figure 16. *Indooroopilly variation of $I_{s(50)}$ results with rock material type and test direction*

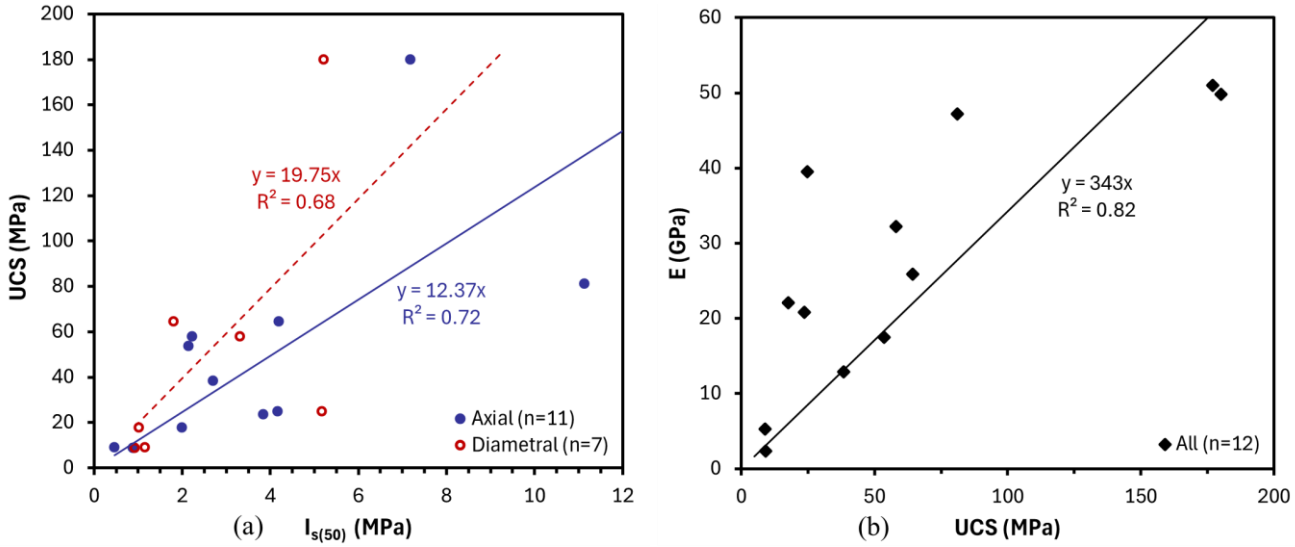

Figure 17. *Indooroopilly (a) UCS to $I_{s(50)}$ correlations and (b) correlation between modulus and UCS*

SITE CITY / SOUTH BANK – 21.5 KM UPSTREAM

The several bridges between Brisbane City and South Bank / South Brisbane typically traverse argillite of the Neranleigh-Fernvale beds (DCf) on the city (north) side, through Holocene alluvium in the river, and Quaternary alluvium (Qa) overlying Bunya Phyllite (DCy) on the South Bank / South Brisbane side (Figure 18).

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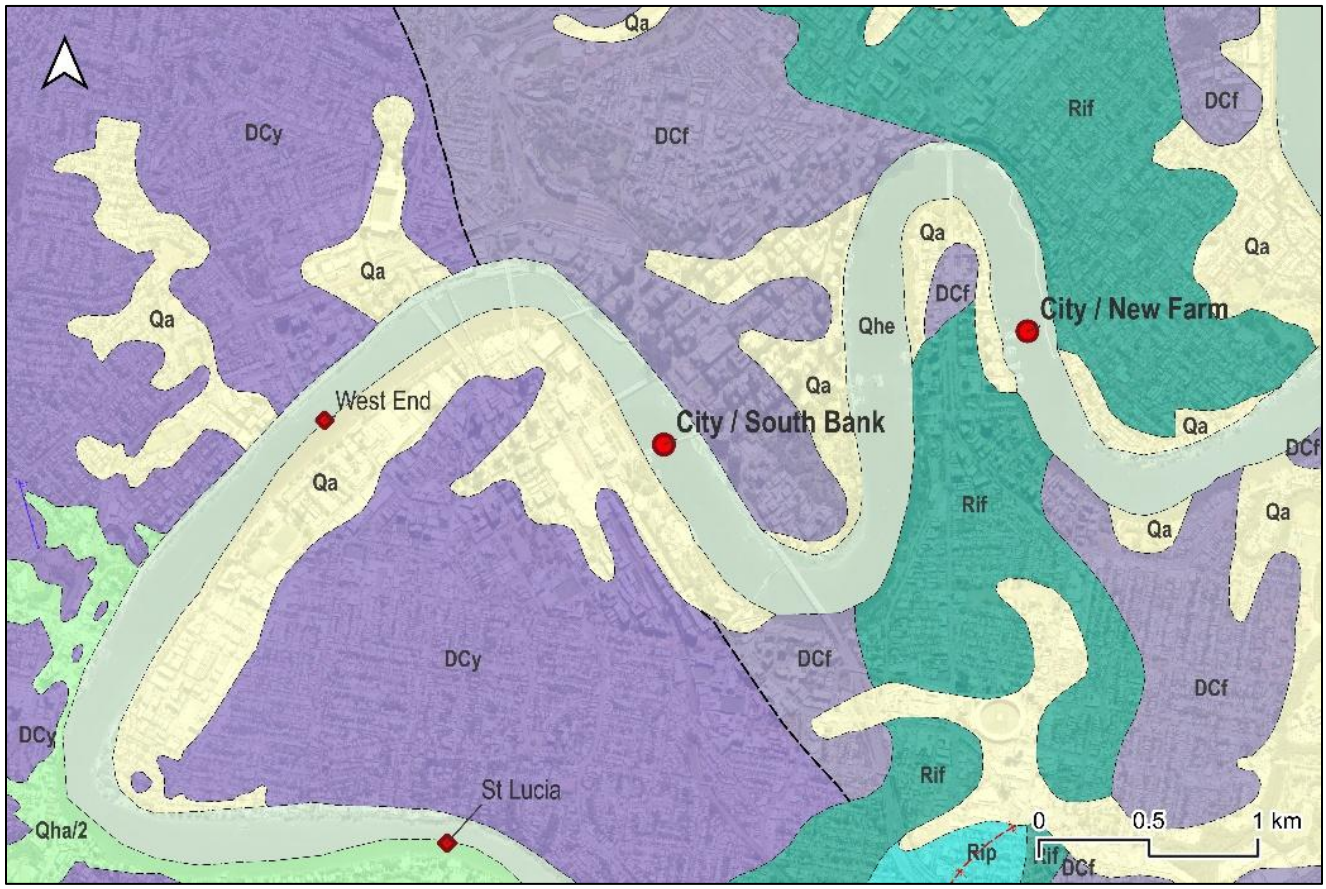

Figure 18. *City / South Bank surface geology (Geological Survey of Queensland 2023)*

$I_{s(50)}$ test results for each rock type and test orientation have been compared in Figure 19. The box plots show that the metasiltstone material encountered in the middle of the river is significantly stronger in the axial direction than the more typically encountered argillite from the Neranleigh-Fernvale beds (DCf) or Bunya Phyllite (DCy). These rock units vary across the river as shown in Table 2, but the calculated COV is significantly less than at the Centenary Bridge location. The limited number of tests (n=6) for the left bank suggests these values should be used with caution, and those values were included for completeness only.

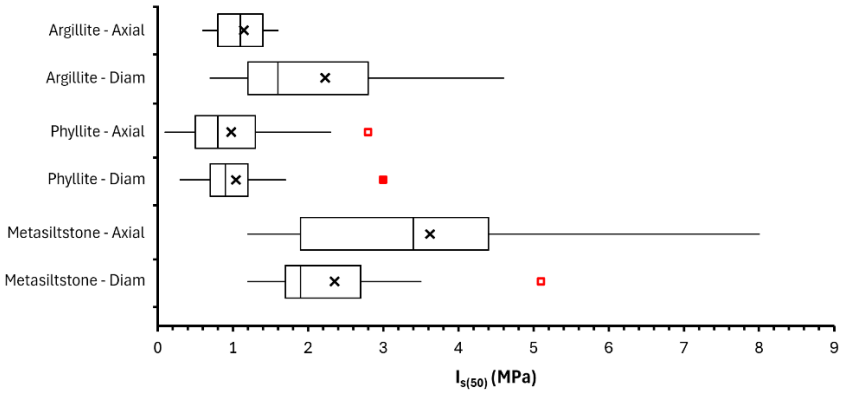

Figure 19. *City / South Bank variation of $I_{s(50)}$ results with rock material type and test direction*

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At this City / South Bank location, the UCS to axial and diametral $I_{s(50)}$ correlation varies from 8.8 to 12.2, respectively (Figure 20a). Insufficient UCS with modulus test results were available in this dataset to determine an E to UCS correlation. Land-based data in the South Bank / Brisbane City area were used in Look and Griffiths (2001). This data for nearby fresh (FR) Neranleigh–Fernvale beds test results is shown in Figure 20b. The calculated E/UCS ratio of 360 is within typical ranges, but the plot shows significant scatter.

Table 2. *City / South Bank typical point load index properties*

Property	Orientation $I_{s(50)}$	Left Bank (City)	Mid River	Right Bank (South Bank)
Predominant rock		Argillite	Metasiltstone	Phyllite
No. of tests	Axial	6	26	18
Median (MPa)		1.3	2.5	0.7
COV (%)		33%	67%	50%
No. of tests	Diametral	6	27	19
Median (MPa)		2.1	1.7	1.1
COV (%)		64%	60%	40%

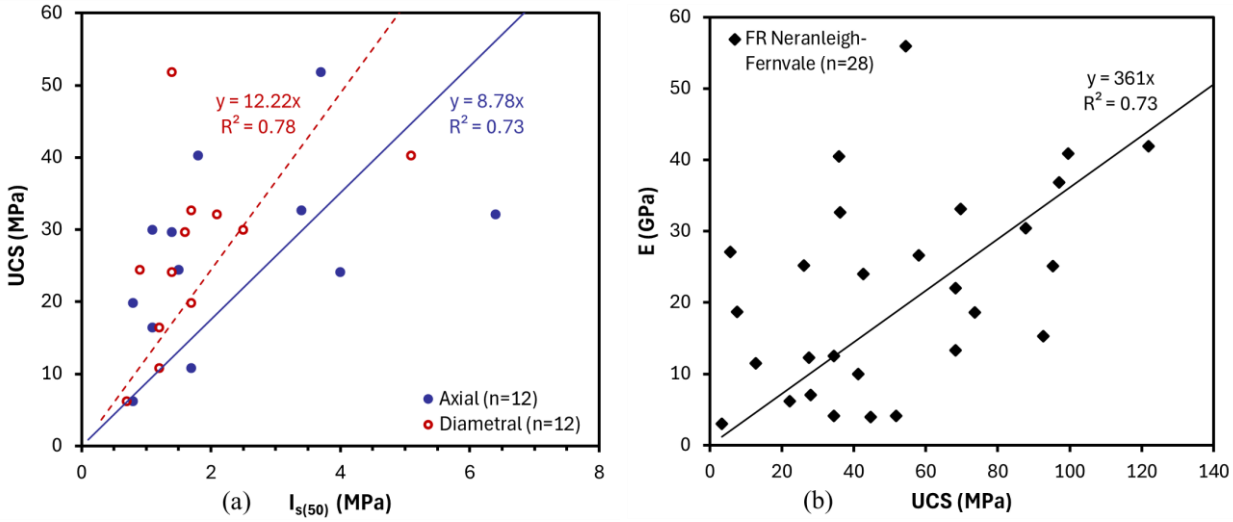

Figure 20. *City / South Bank (a) UCS to $I_{s(50)}$ correlations and (b) correlation between modulus and UCS for Fresh Neranleigh-Fernvale beds (Look and Griffiths 2001)*

SITE CITY / NEW FARM – 17.4 KM UPSTREAM

Brisbane Tuff (Rif) is observed along the Brisbane River at Kangaroo Point and New Farm (Figure 21). This geological unit was derived from ash flows in the late Triassic period (226 Ma) and is more recent than the other sedimentary or meta-sedimentary units along the Brisbane River. The Neranleigh-Fernvale beds (DCf) underlie both the alluvium and tuff and comprise the basement rocks in the area.

Data from adjacent sites (offset from the river) were used in the following analysis, as usable data in the Brisbane River were not available. $I_{s(50)}$ test orientations have been compared for the tuff unit in Figure 22, and these box plots indicate relatively little difference between test directions. There were 68 test results for each axial and diametral $I_{s(50)}$ orientation, but all tests were on the city (left/north) side of the river. Both axial and diametral $I_{s(50)}$ tests had the same COV of 59%.

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The UCS to axial and diametral $I_{s(50)}$ correlation for the Brisbane Tuff unit varies from 13.3 to 13.8, respectively (Figure 23a). This rock unit shows the most similar UCS to $I_{s(50)}$ relationship between test orientations, which, along with the box plots, suggests little anisotropy. Look and Griffiths (2001) found that an UCS to $I_{s(50)}$ ratio of 18 applied to Brisbane Tuff, which was on a different data set of samples over 10 m deeper than this data. This difference between nearby sites in the same geological unit suggests that the correlation is not constant for a given rock type, and general correlations have limited reliability when applied to new sites.

For the tuff dataset, the modulus ratio is E = 250 UCS (Figure 23b), which is within the typical 200–500 range and shows a stronger correlation ($R^2 = 0.92$) than for other datasets in this study.

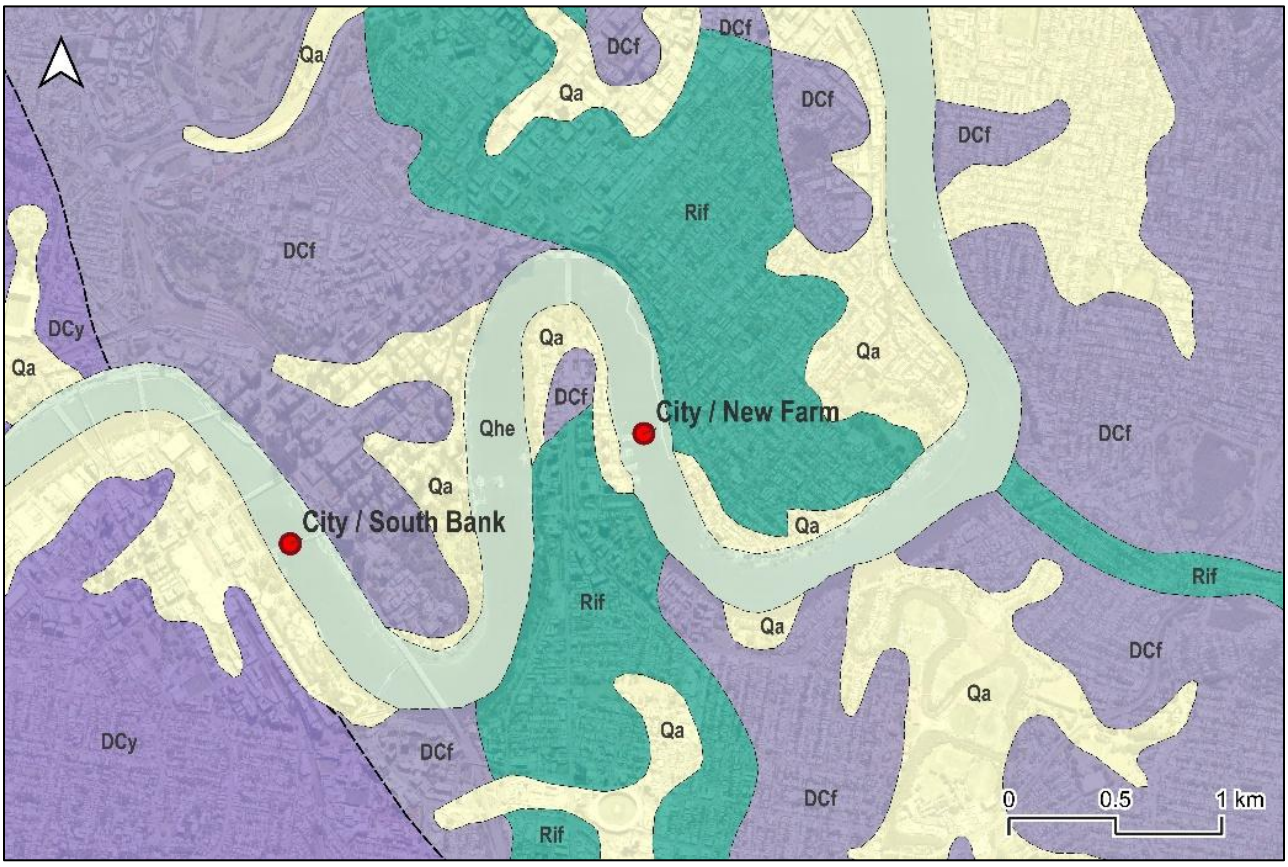

Figure 21. *City / New Farm surface geology (Geological Survey of Queensland 2023)*

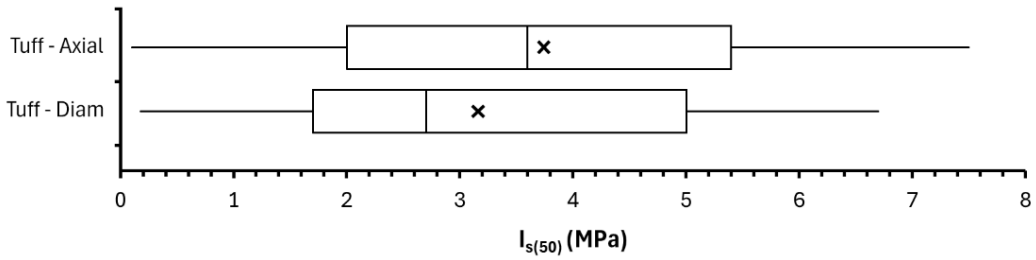

Figure 22. *City / New Farm tuff variation of $I_{s(50)}$ results with test direction*

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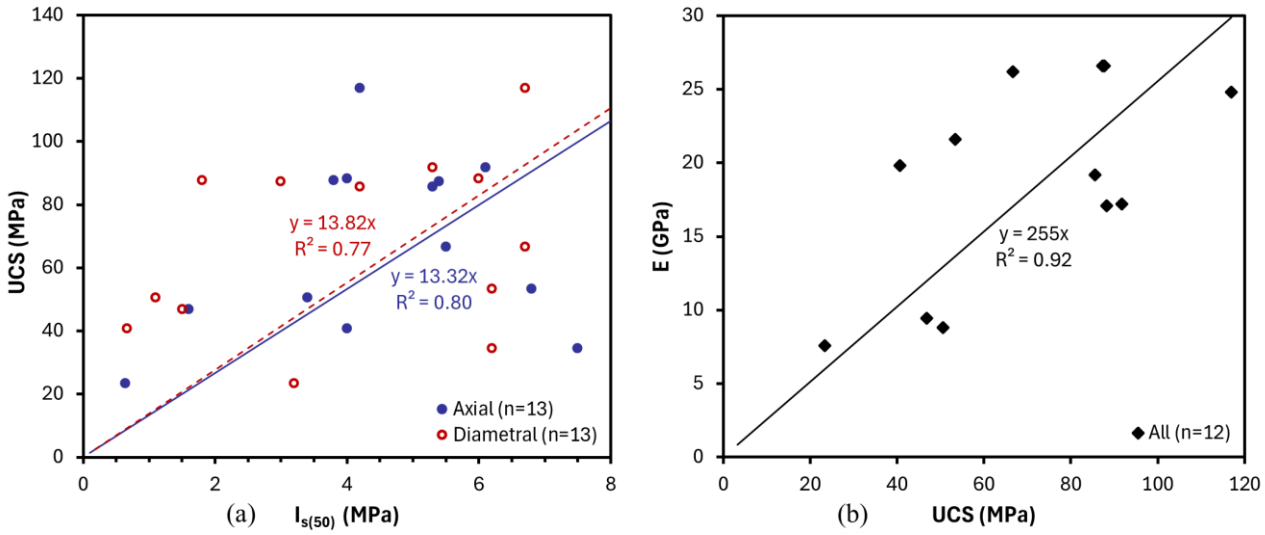

Figure 23. *City / New Farm tuff (a) UCS to $I_{s(50)}$ correlations and (b) correlation between modulus and UCS*

SITE GATEWAY BRIDGE – 6.5 KM UPSTREAM

The Gateway Bridge (GB) is located 6.5 km from the river mouth, and the site and rock properties have previously been described in Day et al. (2007) and Look and Wijeyakulasuriya (2009). The key geological features were:

- The basement rock consisted of Triassic-aged material of the Tingalpa Formation (Rin). This includes layers of sandstone, siltstone, mudstone, and low-grade coal formed about 220 to 180 Ma. This unit does not have any significant folding but is known to have faulting due to crustal tension in the Tertiary period.

- Deposition of Quaternary-aged alluvium (Qa) occurred in the recent past. This site is located close to the mouth of the Brisbane River and generally has younger Holocene (Qh) overlying the older Pleistocene (Qp) alluvium.

The geological units are shown in Figure 24, with the Holocene (Qh) / Anthropocene (Qhh) extending to the northern (left) bank, with Tingalpa Formation exposure at the southern (right) bank. The river width is approximately 465 m.

For this study, only data from a major river pier, "Pier 6," was analyzed. Two main rock units have been considered in the analysis, comprising interbedded sandstone–siltstone and interbedded sandstone–mudstone. $I_{s(50)}$ test results for each rock type and test orientation have been compared in Figure 25 at Pier 6 in the river. The box plot shows significant anisotropy between PLI test directions, with axial results significantly higher than the diametral direction, and the sandstone–mudstone unit being stronger overall (Table 3).

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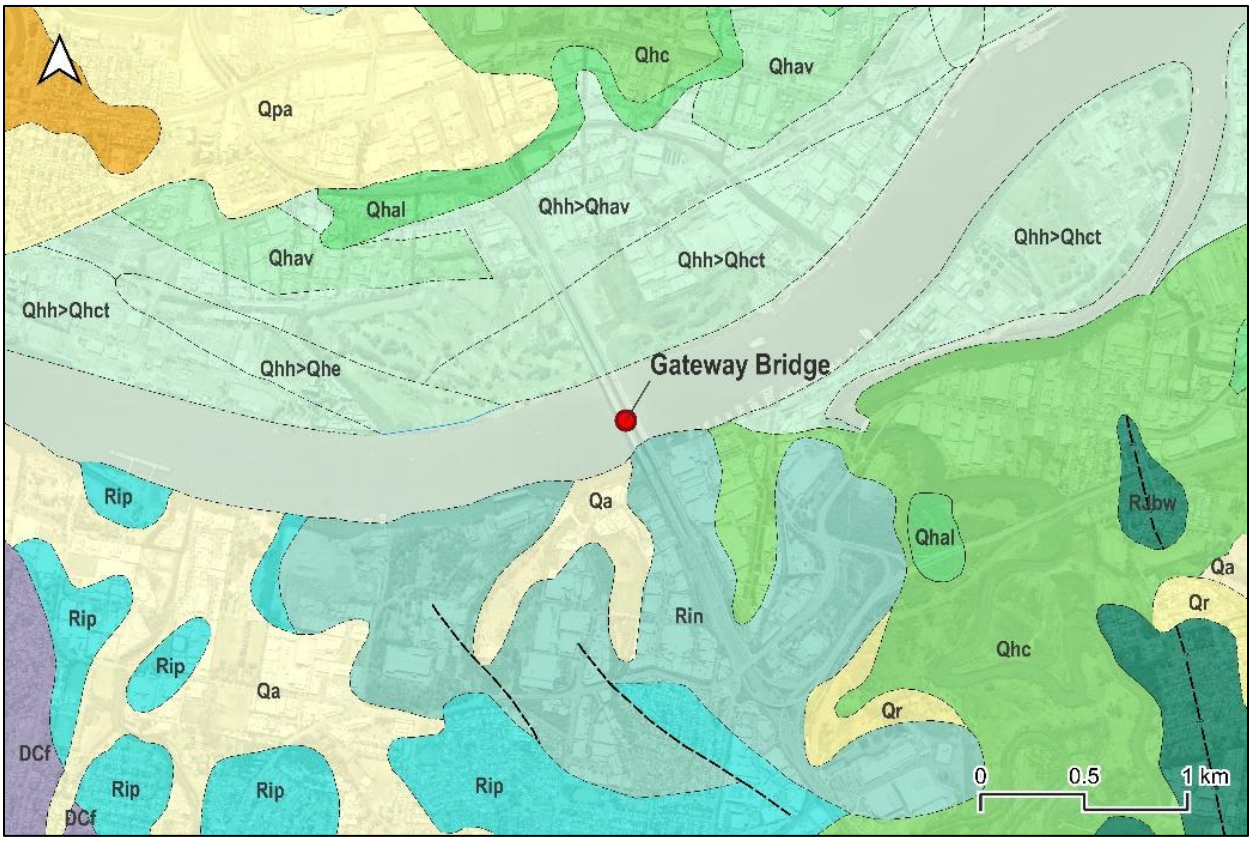

Figure 24. *Gateway Bridge surface geology (Geological Survey of Queensland 2023)*

Table 3. *Gateway Bridge typical point load index properties for middle of river only*

Property	Orientation $I_{s(50)}$	Mid River – Pier 6	
Predominant rock		sandstone–siltstone	sandstone–mudstone
No. of tests	Axial	25	32
Median (MPa)		1.0	1.5
COV (%)		52%	48%
No. of tests	Diametral	26	35
Median (MPa)		0.6	0.7
COV (%)		77%	50%

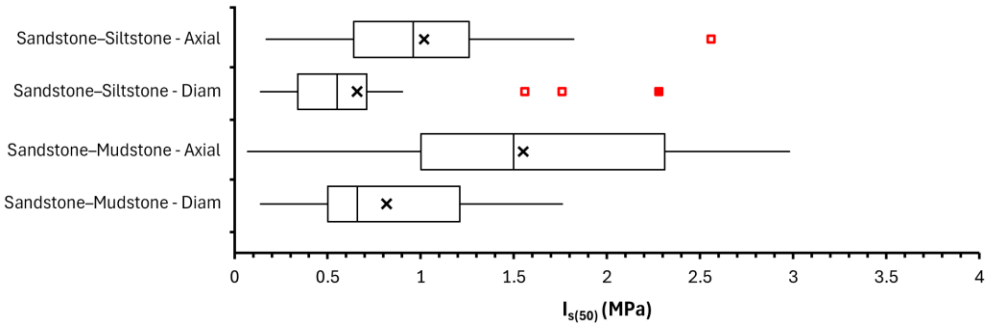

Figure 25. *Gateway Bridge variation of $I_{s(50)}$ results with rock material type and test direction*

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Look, and Wijeyakulasuriya (2009) showed the results of linear regression between the UCS and $I_{s(50)}$ on vertical core specimens for the interbedded sandstone–siltstone layer, with outliers eliminated using judgment to enhance confidence in the linear coefficient of determination, R2 (Figure 26a and b). Reliance on automatically generated spreadsheet regression lines without the application of engineering judgment may produce questionable relationships (Figure 26a), and in other cases may coincidentally not cause significant errors, as shown in Figure 27 for another rock unit. A strong anisotropy between axial and diametral orientations was observed in the sandstone–siltstone results, inferred due to the sub-horizontally bedded nature of the rock. For this rock unit, the ratio of UCS = 27 $I_{s(50)}$ in the axial direction and 42 $I_{s(50)}$ in the diametral direction.

The interbedded sandstone–mudstone rock unit also showed a high anisotropy with a ratio of UCS = 22 $I_{s(50)}$ in the axial and UCS = 39 $I_{s(50)}$ in the diametral direction (Figure 27); this was generally attributed to rock bedding.

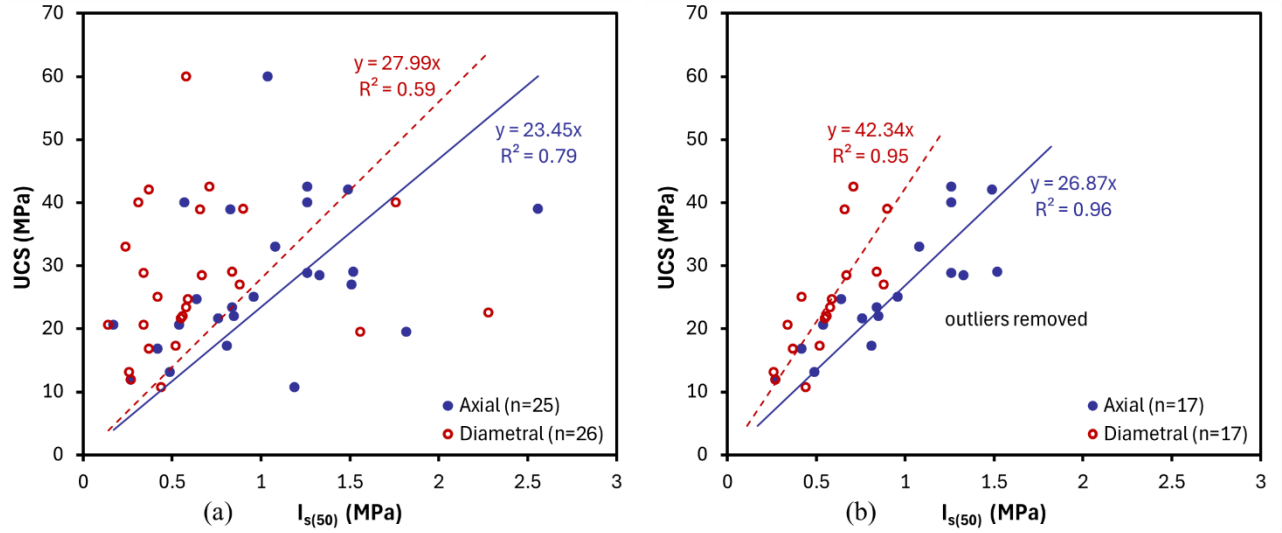

Figure 26. *Gateway Bridge sandstone–siltstone UCS to $I_{s(50)}$ correlations (a) with outliers, (b) without outliers (Look and Wijeyakulasuriya 2009)*

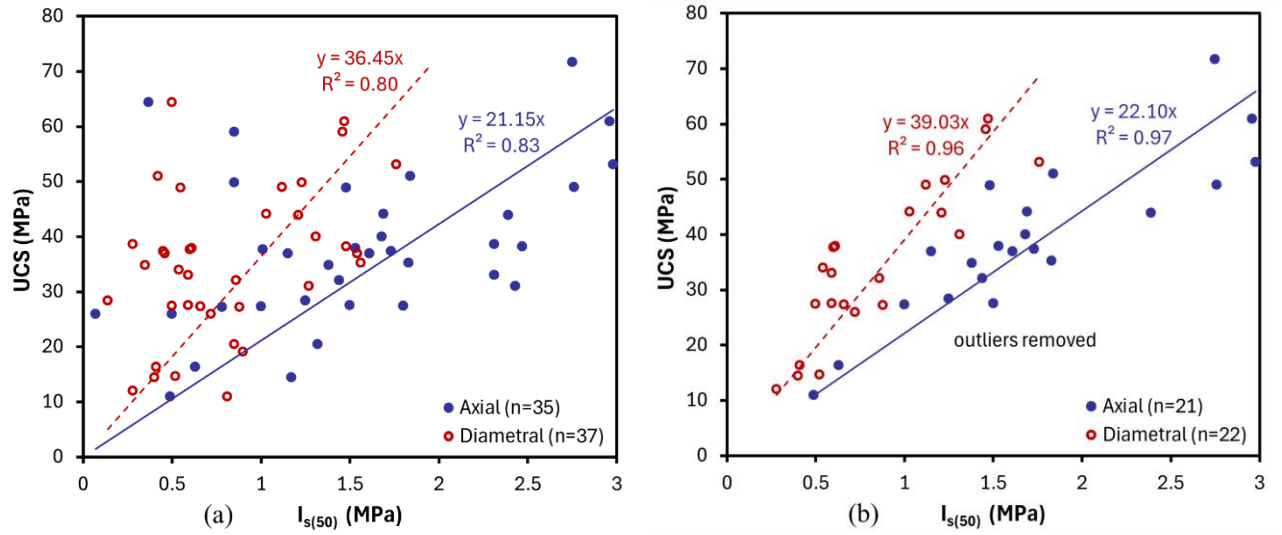

Figure 27. *Gateway Bridge sandstone–mudstone UCS to $I_{s(50)}$ correlations (a) with outliers, (b) without outliers (Look and Wijeyakulasuriya 2009)*

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Modulus to UCS correlations were comparable for the sandstone–siltstone and sandstone–mudstone rock units (Figure 28) with ratios of 102 and 120, respectively. There were only 3 coal samples tested, and while no trend line is shown, the coal E to UCS values seem to fit visually within a similar range as for the other rock units. These sedimentary rocks at the mouth of the Brisbane River have a significantly lower modulus to UCS ratio as compared to the metamorphic rocks further upstream.

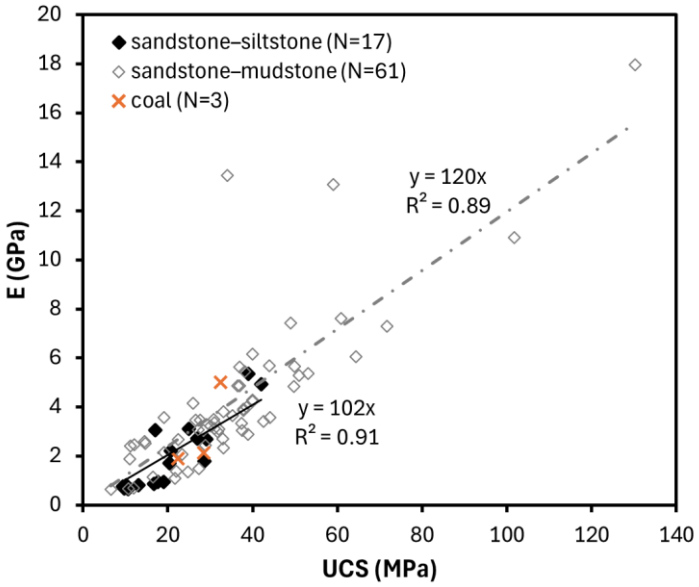

Figure 28. *Gateway Bridge correlation between modulus and UCS*

CONCLUSION

This geotechnical journey along the lower reaches of the Brisbane River characterized some of the key rock units and their engineering strength properties, with the resulting UCS to $I_{s(50)}$ and E to UCS correlations summarised in Table 4. The river geometry in terms of width and depth to rock level was found to be well correlated with the distance from the mouth of the river and therefore not significantly controlled by rock type and strength. The presence and nature of rock is, however, observed to vary on the riverbank slopes, often with shallow or exposed rock on one side.

Table 4 highlights the pronounced spatial variability of intact rock strength and stiffness correlations along the Brisbane River. Both UCS to $I_{s(50)}$ and E to UCS relationships differ significantly between the identified rock units, suggesting that geological setting exerts a strong control on engineering behavior. The substantial variation observed between sites reinforces the value of developing site-specific correlations wherever sufficient test data are available and highlights the importance of considering local geological conditions when deriving engineering parameters for design and construction adjacent to the Brisbane River.

The variations summarised in Table 4 should not be interpreted as a causal relationship between rock properties and distance from the river mouth. Rather, distance provides a spatial reference for a sequence of contrasting geological units at the analyzed sites. The available test results at the upstream sites included metamorphosed and locally intrusive rocks, whereas younger interbedded sedimentary rocks were encountered near the river mouth. Differences in mineralogy, degree of metamorphism, depositional fabric, weathering, and discontinuity orientation therefore provide more plausible controls on the rock strength observations and relationships than distance alone. Accordingly, the apparent spatial trend in Table 4 primarily reflects changes in geological setting along the river rather than a systematic downstream change in rock behavior.

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The principal observations from the analyzed sites, together with their engineering implications, are summarised below:

1. The top of moderately weathered rock is likely to be at the intersection of the two riverbank slopes, or deeper.

2. Rock strength appears greater beneath the river than on the riverbank. This is interpreted as more erosion of weathered rock has occurred within the river to stabilize at the stronger rock, while on the riverbank erosion of the weaker, more weathered rocks would continue to occur over time. This may provide a secondary control on rock strength by influencing which part of the weathering profile is preserved and sampled at each location.

3. The variability of rock strength. This was illustrated using box and whisker plots and numerically by the COV at select sites. Even at individual sites, a large variation in rock strength properties was observed.

4. The UCS to $I_{s(50)}$ ratio is not constant for a given rock type and varies between diametral and axial orientations due to inherent rock anisotropy.

5. Similarly, the calculated modulus-to-UCS correlations varied significantly. The lowest ratio was observed in sedimentary rocks near the mouth of the Brisbane River and the highest ratio further upstream in metamorphic rock units.

6. As the amount of available test data changes, the correlations may also change, which suggests limited reliability of general correlations and supports development of site-specific correlations.

7. The best-fit linear trend line represents the least error across the sample size. However, for a correlation to be geotechnically valid and to avoid inference errors, one must evaluate outliers and non-normality uncertainty. The effect of outliers was illustrated with the Gateway Bridge site data only, as there was little outlier effect for the other sites.

A key outcome of this study is that neither UCS to $I_{s(50)}$ nor E to UCS relationships were constant across the investigated Brisbane River sites. Even where similar lithologies were present, the derived correlations varied substantially. This finding highlights the limitations of adopting generic regional correlations for design purposes. While published correlations remain useful for preliminary assessment, the results support development of site-specific relationships for detailed design and construction.

Table 4. *Summary of intact rock strength and modulus correlations along the Brisbane River study area*

Location	Distance from Mouth of River	Rock Material	UCS / $I_{s(50)}$ Axial	UCS / $I_{s(50)}$ Diametral	Tangent E / UCS
Centenary Bridge	46.5 km	Argillite / Metagreywacke	12	14	1200
Indooroopilly	38.1 km	Phyllite / Rhyolite	12	20	340
City / South Bank	21.5 km	Phyllite / Argillite / Metasiltstone	9	12	360
City / New Farm	17.4 km	Tuff	13	14	250
Gateway Bridge	6.5 km	Sandstone–Siltstone	27	42	100
		Sandstone–Mudstone	22	39	120

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The first author will always remember the 1980s lectures of John Hutchinson, Professor of Engineering Geomorphology at Imperial College, who inspired first understanding the site geomorphology. The data analyzed in this paper were collected over a period of more than 20 years by various companies. Data quantity and quality varied for those projects, and this paper attempts to “unify” such variable data.

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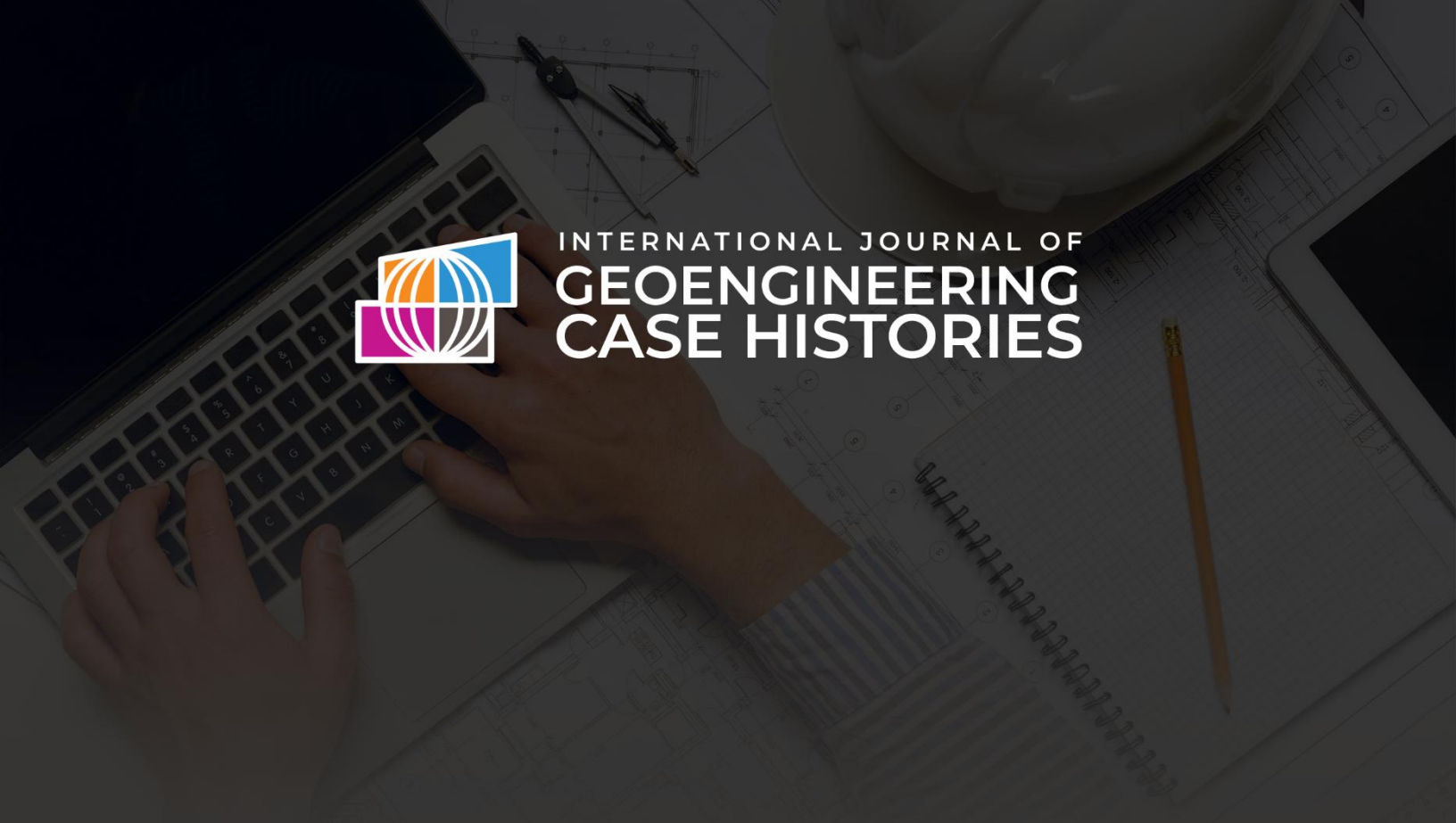

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