PRELIMINARY STUDY ON THE POTENTIAL OF THE INVESTIGATIVE DRILLING (ID) METHOD FOR QUANTITATIVE SITE CHARACTERISATION

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ABSTRACT

Investigative drilling (ID) is a modern measurement while drilling (MWD) technique that has been effectively used in site investigations for several long corridor projects in Australia. The drilling data collected through the ID method has provided clients with valuable in situ strata verification for earthworks and footings. However, the use of drilling data from ID has been primarily qualitative. This paper presents a preliminary assessment of the ID method's potential for quantitative site characterisation through case studies involving soils and rocks. Comparative analysis with conventional boreholes demonstrates that ID data provides significant insights into ground conditions and can be used to characterise soil and rock properties. Specifically, the penetration rate, as a single drilling parameter, proves effective in identifying rock fractures, while compound indices such as the soil-rock resistance, Somerton index, and drilling energy correlate with the standard penetration test (SPT) values and rock strength. Despite the promising results, further rigorous testing is necessary to validate these findings, given the inherent uncertainties in subsurface conditions and conventional testing results.

Keywords: measurement while drilling; investigative drilling, site characterisation; SPT values; rock strength

1 INTRODUCTION

Site investigation is an essential process for assessing subsurface conditions and obtaining geotechnical parameter values for design and construction in civil engineering practice. Traditionally, geotechnical drilling is necessary to extract drill cores and soil/rock samples in the site investigation. The strata information and engineering properties are then obtained through field logging of the drill cores and laboratory testing of the soil and rock samples. In situ testing techniques such as the standard penetration test (SPT) and cone penetration test (CPT) can estimate engineering properties without the need for costly and time-consuming coring, sampling and laboratory testing (Stroud, 1974; Skempton, 1986; Robertson, 1990; Wu, 1996; Lunne, Powell and Robertson, 2002; Robertson, 2010). However, these methods are limited in penetrating hard layers such as gravel and rock. As a more versatile alternative, the measurement while drilling (MWD) technique integrates the benefits of both conventional geotechnical drilling and in situ testing, offering powerful penetration capacities and efficient ground assessment (Hamelin, Levallois and Pfister, 1983; Pfister, 1985; Girard *et al.*, 1986). During the MWD process, the drill bit interacts with geomaterials, and the integrated data sensors on the drilling rig monitor and collect real-time data on the strata's response, including feed force (or feed pressure), percussion pressure (in percussive drilling), torque (or rotation pressure), penetration rate, rotation rate, and flushing air/fluid pressure. Figure 1 illustrates a typical setup of the MWD technique. Dramatic fluctuations of MWD parameter values, such as penetration rate and thrust, reveal geological structures such as joints, fractures, and cavities in rock formations (Babaei Khorzoughi, Hall and Apel, 2018). The MWD data also offers valuable insights into the mechanical properties of the geomaterials. They allow for the estimation of the strength of soils and rocks, such as the undrained shear strength of clay, the friction angle of sand, and the unconfined compression strength of rocks, without the sampling and laboratory testing that are typically required by conventional geotechnical drilling methods (Gui *et al.*, 2002; Li and Itakura, 2012).

MWD, initially known as logging while drilling (LWD), was first attempted in the oil industry in the 1920s, but the first viable tools did not emerge until the 1960s (Meador, 2009). In the 1970s, MWD was extended to the mining industry to optimise blast design and mining operations (Peck and Vynne, 1993; Lucifora and Rafezim, 2013; Isheyskiy and Sanchidrián, 2020). Reporting of the MWD technique application in the civil industry dates back to the 1980s, especially following the advent of computerised recording of drilling parameters (Hamelin, Levallois and Pfister, 1983; Pfister, 1985; Girard *et al.*, 1986; Suzuki *et al.*, 1995; Nishi, Suzuki and Sasao, 1998). In recent decades, the MWD technique has gained increasing popularity in the civil industry. Yue *et al.* (2001) developed a drilling process monitoring (DPM) system. The DPM system was then used to identify weathered rock profiles and characterise rock quality and strength in Hong Kong and mainland China (Yue *et al.*, 2004; Yue, 2014; Wang *et al.*, 2023). Researchers at the University of Florida employed the MWD technique in pile shaft drilling to predict the shaft resistance of drilled piles with the specific drilling energy (McVay and Rodgers, 2016; McVay and Rodgers, 2020). They have recently extended their research to site investigation (Rodgers *et al.*, 2020; Rodgers *et al.*, 2021). Additionally, researchers at the University of New Hampshire have explored the potential of using MWD data for quantitative enhancements in geotechnical investigation and soil classification (Reiffsteck *et al.*, 2016; Reiffsteck *et al.*, 2018). Investigative drilling (ID) represents a recent advancement in MWD technology and has been successfully applied in site investigations for several long corridor projects in Australia (Duthy and Juett, 2020). ID has been providing clients with valuable strata information and footing recommendations at a significantly lower cost than conventional drilling. However, the utilisation of the drilling data from ID remains qualitative. This paper, for the first time, preliminarily assesses the potential of ID for quantitatively characterising ground conditions, including rock integrity and soil/rock properties.

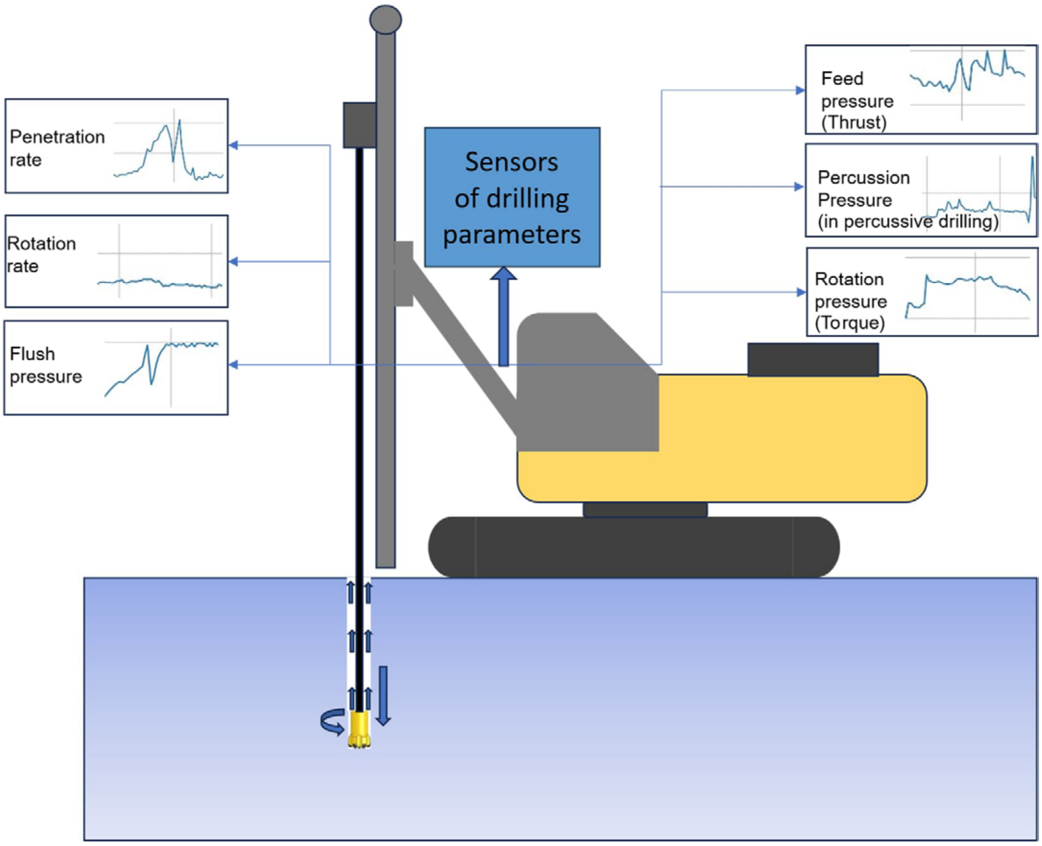


Figure 1: Drilling rig with an MWD system

2 BACKGROUND

2.1 INTRODUCTION OF ID

Although the MWD technique has been reported in applications within the mining industry in Australia (Li and Itakura, 2011; Li and Itakura, 2012; Khanal *et al.*, 2020), its application in civil engineering practice has not been publicly reported in Australia. Nevertheless, Civil Group has successfully applied ID in the site investigation of several long corridor projects. ID has several distinguishing features compared to conventional MWD techniques. Firstly, ID incorporates both rotary and percussive drilling, making it applicable in various ground conditions. In soils, rotary drilling with blade bits (drag bits) is employed, while in rocks, percussive drilling using down-the-hole (DTH) or top hammers and button bits is utilised. In both rotary and percussive drilling modes, compressed air is used to flush the borehole and remove drill cuttings. The air-flushed drill cuttings are collected and can be used for field logging. The second significant feature that sets ID apart from regular MWD techniques is that ID is performed by smart drilling rigs (Figure 2), such as SmartROC D65, which can achieve automatic drilling via an advanced rig control system. The ID rig can intelligently adjust the operational parameters such as feed pressure, rotation pressure, and percussion pressure to maintain an efficient drill penetration rate. Drill rods can also be automatically added with minimal downtime during drilling. The ID rig can typically complete a 15-meter deep borehole in about 10-20 minutes. The efficient, continuous, and automatic drilling of the ID method provides higher quality MWD data with less noise and less non-informative data, such as dramatic data variations caused by operator control and non-drilling data during resting and rod-adding (Scoble, Peck and Hendricks, 1989; Navarro Miguel, 2018). This salient feature of ID significantly reduces the effort required for data filtering. Otherwise, special signal processing techniques may be required to remove noise from the instrumented borehole drilling data (Gui, 2008). Thirdly, the drilling data is captured by a data acquisition system and displayed in real-time on the monitor in the cabin of the drill rig as illustrated in Figure 3. The data files can then be downloaded by the driller from the onboard computer onto a USB drive for further processing and analysis. The drilling parameters recorded by the ID rig include (Duthy and Juett, 2020):

- Penetration rate (m/min): the speed of drilling,
- Feed pressure (bar): down thrust hydraulic pressure in the feed cylinder,
- Percussion pressure (bar): the air pressure driving the DTH hammer to impact (only for DTH percussive drilling),
- Flush pressure (bar): the pressure of the air flushing the cuttings,
- Rotation pressure (bar): the hydraulic pressure driving the rig motor to rotate,
- Damp pressure (bar): the hydraulic back pressure, only recorded for top hammer percussion.

The rotation rate (revolutions per minute) is usually set to a fixed value before drilling and can be adjusted if the ground condition differs significantly from what was expected.

Figure 2: The ID rig at a drilling site

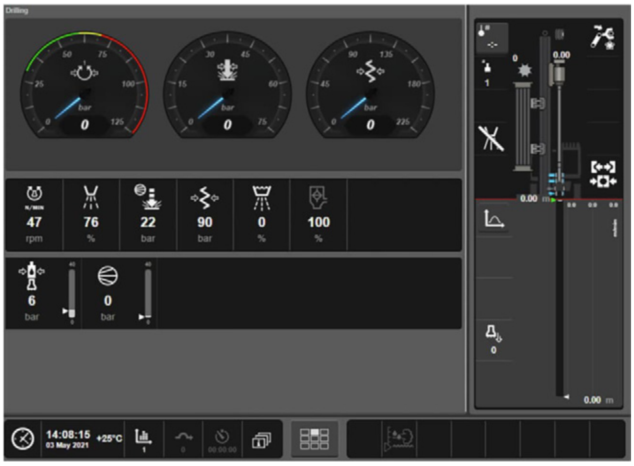


Figure 3: Monitoring during drilling operations (Epiroc, 2022)

The ID rig collects drilling data every 5 to 6 cm penetration depth, which can be adjusted to suit strata profiles being encountered to ensure appropriate data collection coverage along the drilling depth. Figure 4 demonstrates the typical profiles of drilling parameters collected from an ID borehole. Enabled with automatic and intelligent drilling functions, ID data displays considerably less noise than the drilling data collected by conventional MWD systems installed on regular drilling rigs, as shown in Figure 5.

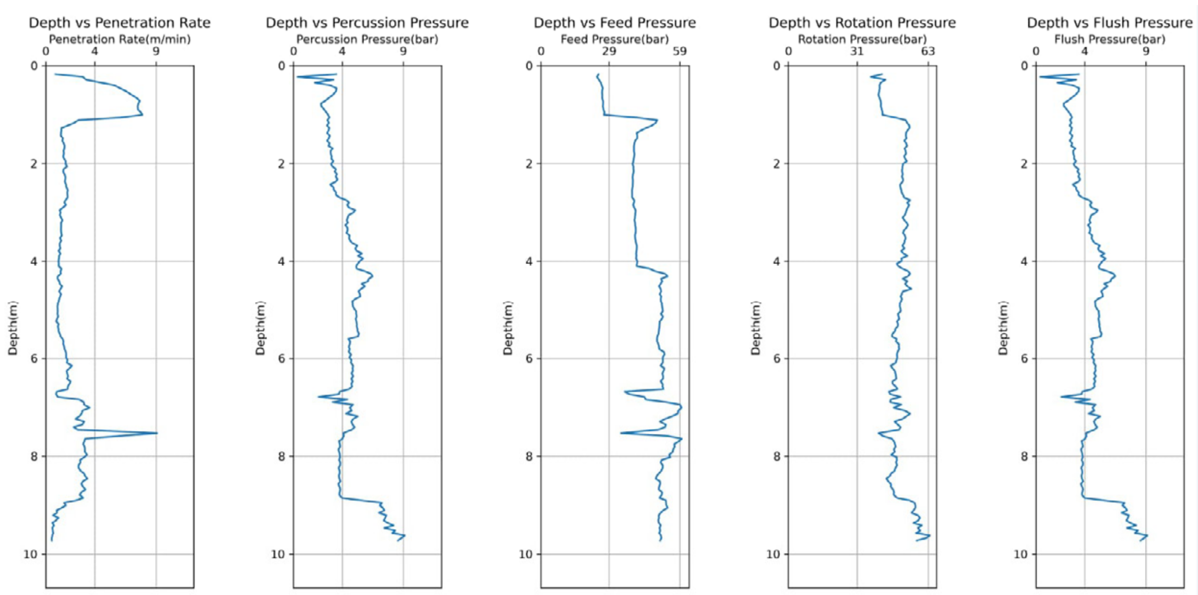
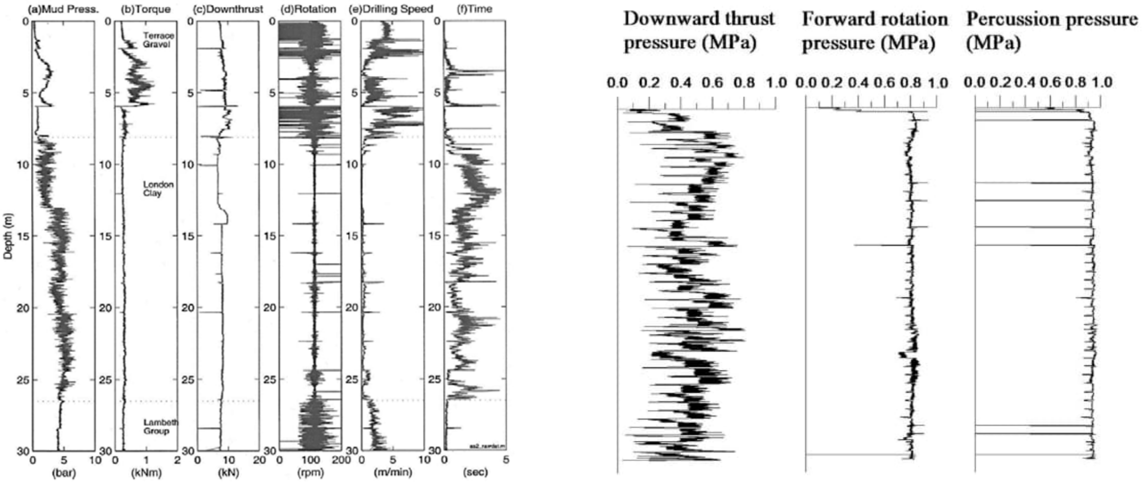


Figure 4: Typical profiles of the collected ID data



a) Raw MWD data produced by the ENPASOL-3 system (Gui *et al.*, 2002)

b) Raw MWD data produced by the DPM system (Chen and Yue, 2015)

Figure 5: Raw data profiles produced by conventional MWD techniques

2.2 METHODS FOR DRILLING DATA INTERPRETATION

Single drilling parameters, such as the penetration rate, feed force and torque, have been used to characterise rock quality (rock fractures and rock quality designation), strata boundaries and rock strength (Schunnesson, 1996; Kahraman, Bilgin and Feridunoglu, 2003; Yue *et al.*, 2004). However, single drilling parameters may not be able to fully reflect the ground condition because other drilling parameters can also influence them. For example, the penetration rate can be increased simply by applying more feed force in the same strata. In cases where most drilling parameters constantly change, compound indices containing two or more drilling parameters are more reasonable for MWD data interpretation.

The first compound index proposed for MWD is the Somerton index, S_d (Somerton, 1959) for rotary drilling. Several researchers have found that the Somerton index can be related to lithological variations and soil/rock strength (Laudanski *et al.*, 2012; Lonstein *et al.*, 2015; Reiffsteck *et al.*, 2018).

$$S_d = P_e \sqrt{\frac{V_r}{V_a}} \tag{1}$$

where $P_e = F / A$ is the feed pressure on the bit, F is the feed force, A is the cross-section area of the borehole, V_a is the penetration rate, and V_r is the rotation rate.

When the rotation rate is constant, the Somerton index can be simplified to

$$S_d = \frac{P_e}{\sqrt{V_a}}\,. \tag{2}$$

Teale (1965) introduced another popular compound index known as the specific energy (E_s), quantifying the energy required to drill a unit volume of rock in rotary drilling.

$$E_s = P_e + C_R \frac{V_r}{V_a} \tag{3}$$

where C_R is the torque. The specific energy consists of two components: the thrust component F / A and rotary component $C_R V_r / V_a$, with the rotary component typically constituting the majority of the total drilling energy and often used as a proxy for the specific energy (Pfister, 1985; Tan, Yue and Cai, 2007). Teale's research, along with subsequent studies, demonstrated that the specific energy, or its modified form, strongly correlates with the unconfined compressive strength (UCS) of rocks (Huang and Wang, 1997; Finfinger *et al.*, 2000; Dagrain, 2001; Li and Itakura, 2011; Li and Itakura, 2012; Richard *et al.*, 2012; Jaime *et al.*, 2015; Kalantari, Baghbanan and Hashemalhosseini, 2019; Wang *et al.*, 2019; Kolapo, 2021).

Mathis (1975) proposed an index, the rock quality index, to evaluate the quality of the rocks being drilled in an unpublished report. This concept was then adopted by the MWD standard ISO 22476-15 (British Standards Institution, 2016), and renamed as the soil-rock resistance R_{sr}.

$$R_{sr} = \frac{P_e}{V_a} \tag{4}$$

For percussive drilling, Sugawara *et al.* (2003) proposed a simplified index called the percussion index P_i to represent the specific energy for percussive drilling introduced by earlier researchers (Paone, Madson and Bruce, 1969; Hustrulid and Fairhurst, 1971; Hustrulid and Fairhurst, 1972; Schmidt, 1972; Tandanand and Unger, 1975).

$$P_i = \frac{P_p}{V_a}\left(\frac{D}{100}\right)^{1.5} \tag{5}$$

where P_p is the percussion pressure, and D is the borehole diameter or bit diameter.

In addition to the compound indices mentioned above, several other indices are outlined in the MWD standard (British Standards Institution, 2016). As previously mentioned, ID employs two different drilling modes depending on the ground being drilled: rotary drilling for soils and percussive drilling for rocks. Therefore, this paper presents two case studies: one involving drilling in soils and the other in rocks. For percussive drilling in rocks, the penetration rate was used to explore its potential in identifying rock fractures. Compound indices, the soil-rock resistance (R_{sr}) and percussion index (P_i), were selected to investigate their relationships with the rock strength. For rotary drilling in soils, compound indices, including the Somerton index (S_d), drilling energy (rotary part of the specific energy $C_R V_r / V_a$) and soil-rock resistance (R_{sr}) were used to assess their correlations with the SPT values.

3 CASE STUDIES

3.1 ID IN SOILS

3.1.1 Case study background

The first case study in this paper focuses on the application of ID in soils. ID was used in the site investigation for a long corridor project in New South Wales in Australia. Both conventional drilling and ID were conducted for this project. According to the site investigation results, the strata within the drilled depth consist mainly of soils, including clay, silt, sand, gravel and mixed soils such as sandy clay and clayey sand. Consequently, the rotary drilling mode with a blade bit was adopted in this project. The rotation rate was set to around 70 rpm.

Compound indices, including the soil-rock resistance, Somerton index and drilling energy, were calculated using the original units of the ID drilling parameters introduced in the previous section. The depth recorded for each SPT value represents the end depth of the test, and the associated MWD index values in the correlation analysis were averaged over the 30 cm testing interval of the SPT. Two pairs of comparative boreholes with the smallest distance between them (0.4 m and 0.9 m) were selected to minimise the uncertainties arising from spatial variation in ground conditions.

3.1.2 Correlations between soil SPT values and MWD indices

Figure 6 andFigure 8 demonstrate the three calculated compound MWD indices with depth for boreholes S1 and S2, respectively. The SPT values at the corresponding depths are plotted as well for comparison. The SPT values align well with all three MWD indices for borehole S1, except for the noticeable discrepancies at the depth of 16.45 m. To further explore the correlations between the selected MWD indices and the SPT values of borehole S1, a regression analysis was conducted and presented in Figure 7. An outlier is detected on each scatter plot, corresponding to the discrepancy at the depth of 16.45 m in Figure 6. The coefficient of determination R^2 is relatively low (0.02~0.15) for all three correlations when the regression includes the outlier. However, excluding this outlier, very high correlations are observed between the soil-rock resistance, Somerton index and drilling energy and SPT values, with R^2 values of 0.88, 0.89 and 0.86, respectively. In view of the fact that flushing air becomes less effective in cleaning the borehole with increasing depth, the actual consumed drilling energy would be significantly higher than what is needed to cut the soils if too many drill cuttings accumulate within the borehole. This might explain the discrepancy that drilling parameter values are significantly higher than SPT values at the deeper section of the borehole.

The correspondence between the selected MWD indices and SPT values of borehole S2 in Figure 8 is lower than that for borehole S1, although no individual large discrepancies are observed. Figure 9 shows a higher scatter pattern between the three MWD indices and SPT values, with R^2 values around 0.38, indicating a moderate correlation ($0.25 < R^2 < 0.49$), based on the criteria proposed by Mukaka (2012). In general, all three selected indices demonstrate similar performance when used to correlate with soil SPT values. This case study indicates that there are indeed some extents of correlations between compound MWD indices and soil SPT values. However, correlations may be adversely affected by the inherent uncertainty of the SPT method and potential stratigraphical variations between comparative boreholes. More comparative studies are needed to establish reliable correlations.

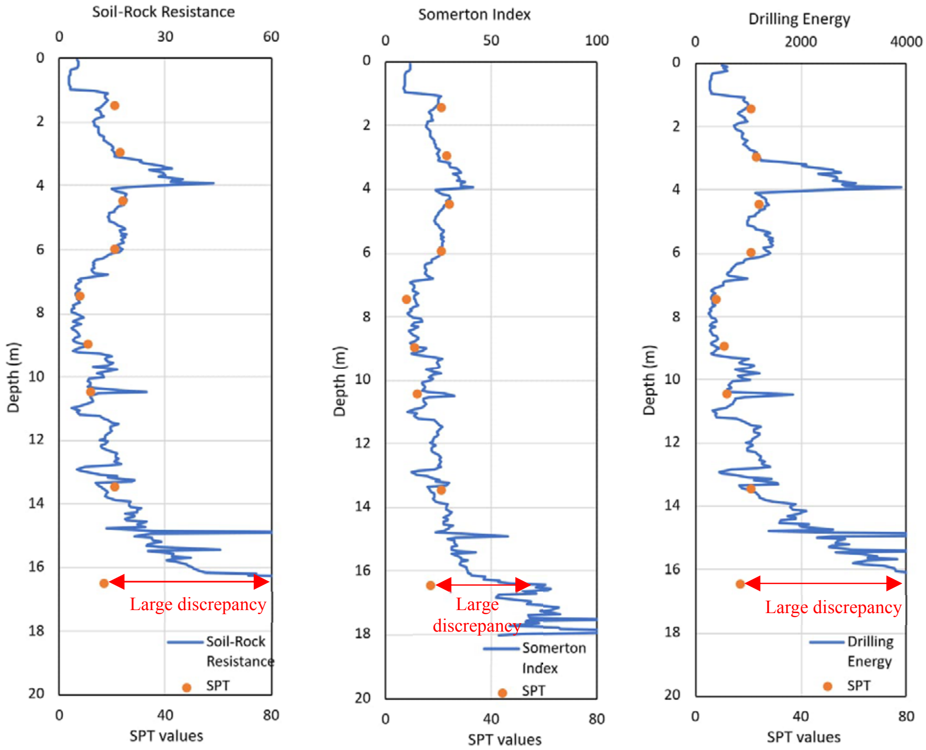


Figure 6: Comparison between MWD indices and SPT values with depth (Borehole S1)

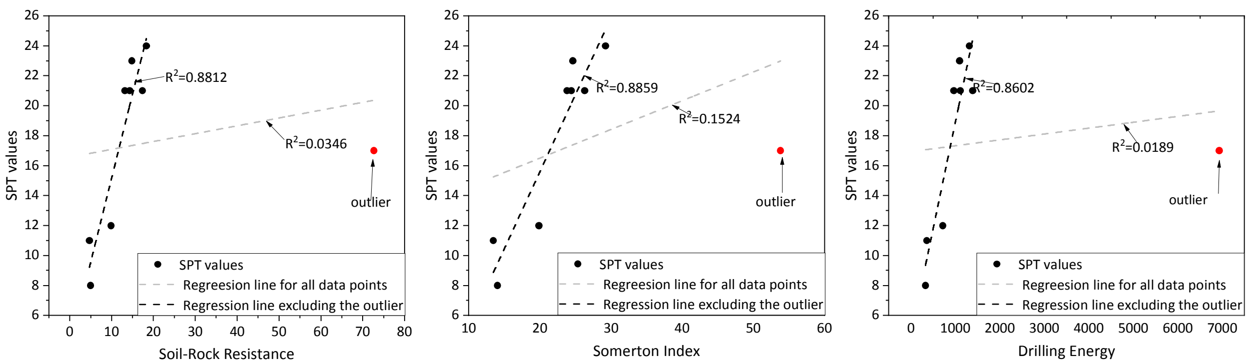


Figure 7: Correlations between MWD indices and SPT values (Borehole S1)

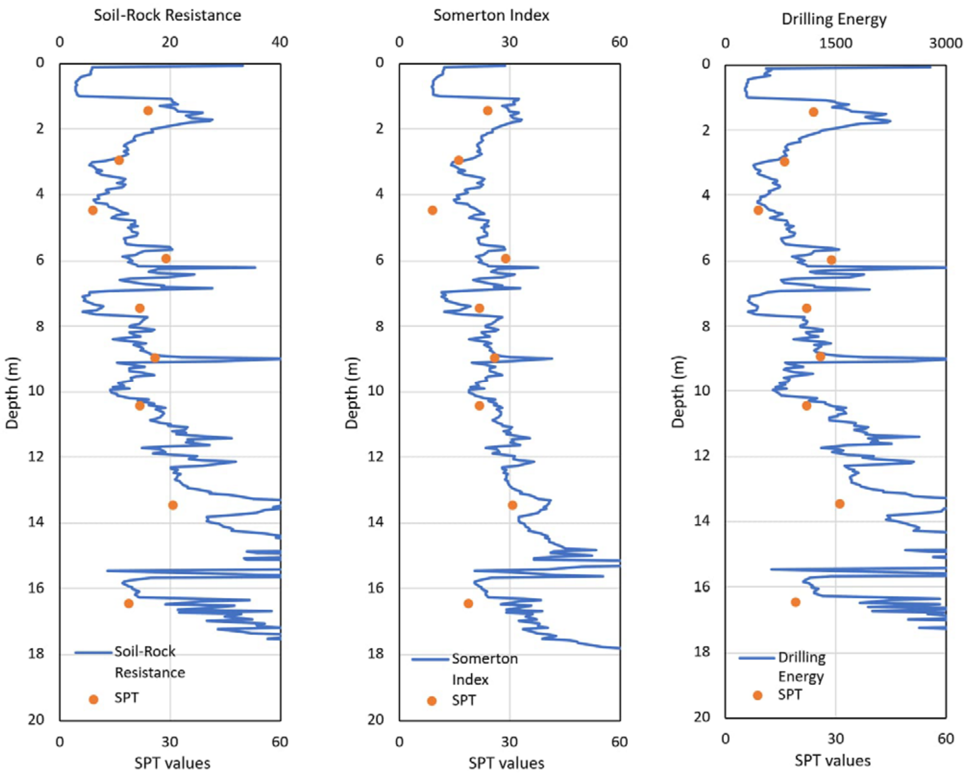


Figure 8: Comparison between MWD indices and SPT values with depth (Borehole S2)

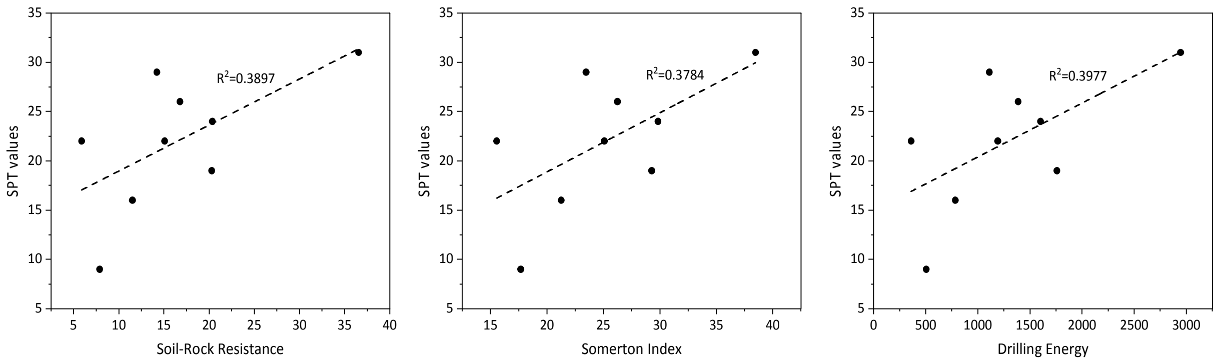


Figure 9: Correlations between MWD indices and SPT values (Borehole S2)

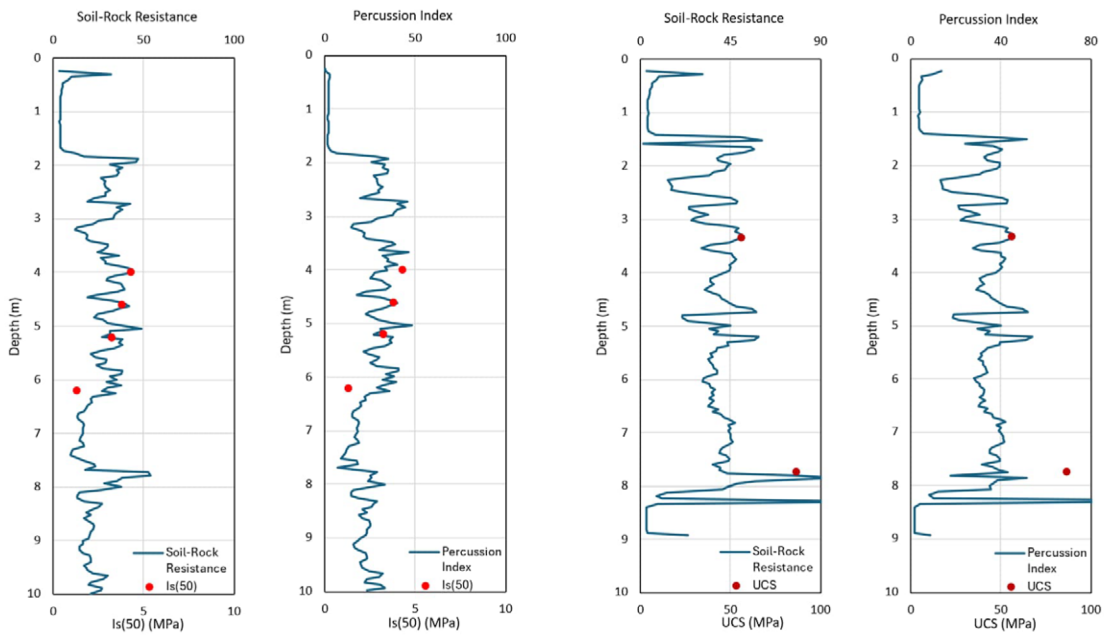
3.2 ID IN ROCKS

3.2.1 Case study background

Another long corridor project in rocky ground in Victoria, Australia, is selected in this section to investigate the potential of ID data for rock characterisation. The project site primarily consists of basalt rock with varying degrees of weathering, overlain by a thin layer of soil. Percussive drilling mode with DTH hammers and button bits was utilised for this project. Drill cores were recovered by conventional drilling and photographed by the site engineer. UCS and point load strength index tests were conducted on the rock core samples. Two pairs of comparative boreholes with UCS and point load strength index test results were selected for the correlation study between MWD indices (the soil-rock resistance and percussion index) and rock strength. Additionally, two more pairs of comparative boreholes were selected—one located in relatively massive rock with good rock mass integrity, and the other in fractured rock with poor integrity—to investigate the potential of using the ID penetration rate to detect rock fractures. All selected MWD indices were calculated with the original units of the drilling parameters, with pressure measured in bars and penetration rate in meters per minute (m/min).

3.2.2 Correlations between rock strength and MWD indices

Figure 10 demonstrates the profiles of MWD indices, the soil-rock resistance and percussion index, as well as the point load strength index ($I_{s(50)}$) and UCS values of two comparative boreholes, R1 and R2. The scales of each MWD index are adjusted to produce the best match. In Figure 10a, both the soil-rock resistance and percussion index profiles exhibit similar variation patterns with depth in borehole R1, and they generally align with $I_{s(50)}$ values, except at the depth of 6.2 m. It also can be known that $I_{s(50)}$ is approximately 10% of the soil-rock resistance and percussion index values. Figure 10b shows that the soil-rock resistance aligns with both UCS values at depths of 3.3 m and 7.7 m in borehole R2, whereas the percussion index corresponds to only one of the UCS values. Due to the limited UCS data, it is not possible to draw definitive conclusions about the relationships between rock UCS values and the MWD indices at this stage.



a) Comparison between MWD indices and $I_{s(50)}$ (R1) **b) Comparison between MWD indices and UCS (R2)**

Figure 10: Comparison between MWD indices and rock strength

3.2.3 Identification of rock fractures by the ID penetration rate

The penetration rate profiles of two other comparative boreholes (R3 and R4) are plotted alongside the drill core photographs in Figures 11 and 12, respectively. The rock mass quality at borehole R3 is relatively good, with a few widely spaced fractures. By contrast, the rock mass quality at borehole R4 is relatively poor, with numerous closed spaced fractures and several highly crushed sections.

Table 1 summarises the fracture detection results for borehole R3. Four out of the seven fractures were successfully detected by the penetration rate peaks, with depth differences within 0.3 meters. Allowing for the offset distance between the comparative boreholes and dipangles of rock fractures, this extent of mismatching and depthdrifting is reasonable. Detection results for the borehole R4 are detailed in Table 2. All the highly crushed zones were detected by the major peaks on the penetration rate profile, while the fluctuating sections of the penetration rate curve reflect two of the four fractured zones. It is noted that the penetration rate missed some closed fractures in both boreholes R3 and R4. To address this issue, other drilling parameters may need to be considered, together with the penetration rate, for rock fracture detection in future research. Figure 13 further investigates the penetration rate response in integral and fractured rocks with corresponding penetration rate profiles and core photographs. It shows that the penetration rate curve in the integral rock is relatively flat and smooth, while it is much more fluctuating in the fractured rock. Future research using quantitative metrics such as the standard deviation will be conducted to further characterise the rock integrity from the penetration rate.

From the above comparative analysis, it can be concluded that the penetration rate can potentially be used to identify rock fractures in percussive drilling. However, since the penetration rate can also be affected by other drilling parameters, such as the feed pressure and percussion pressure, detection becomes more reliable when these parameters are generally kept constant or when the penetration rate is normalised by them. Alternatively, borehole televiewers could be used in the same ID boreholes in future research to accurately capture the rock mass conditions. This approach would mitigate uncertainties caused by stratigraphical changes between comparative boreholes, leading to a more reliable and trustworthy evaluation of the ID method.

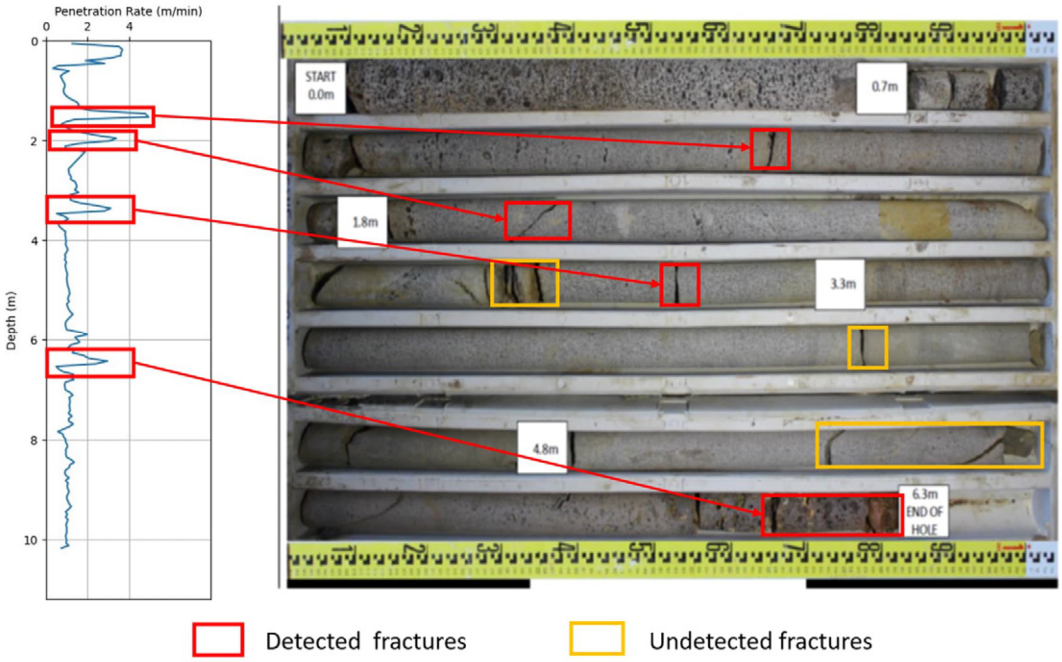


Figure 11: Rock fracture detection using the penetration rate (Borehole R3)

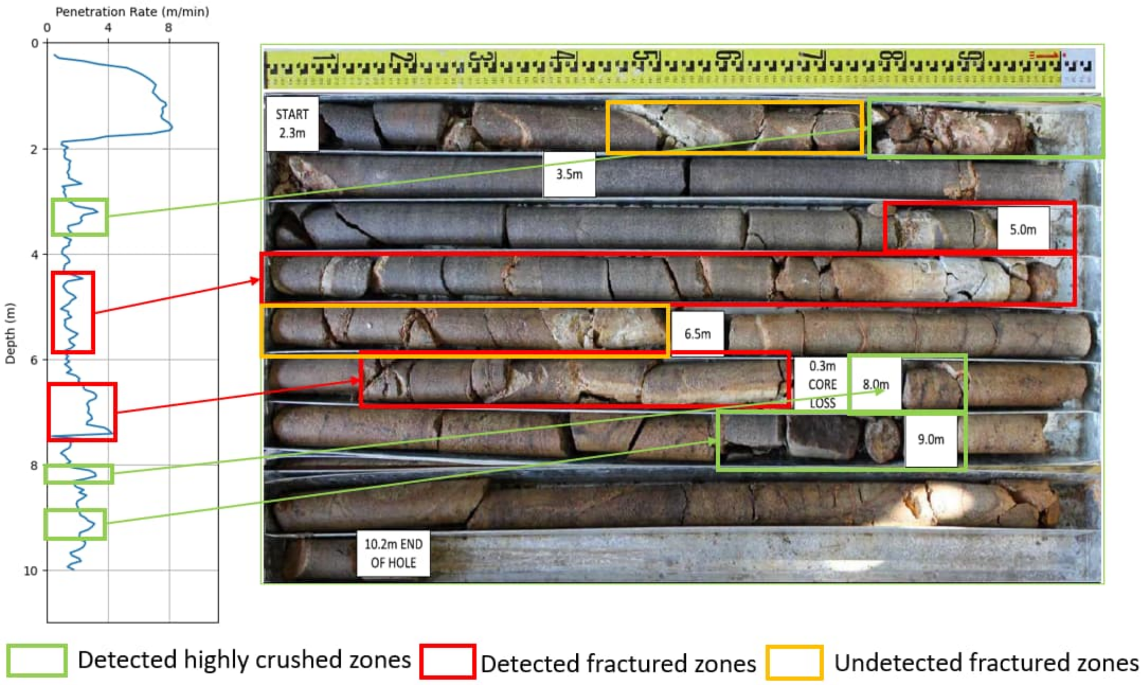


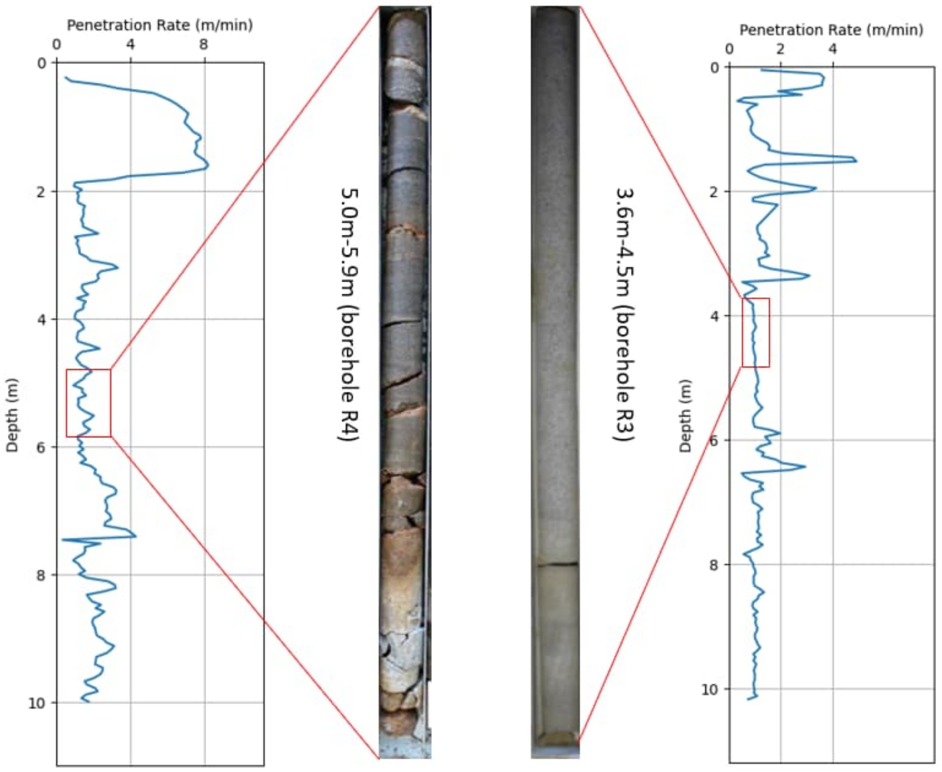
Figure 12: Rock fracture detection using the penetration rate (Borehole R4)

Table 1: Fracture detection results for borehole R3

Fractures on the drill core photograph	Peaks on the penetration rate profile	Detection results
1.5 m	1.5 m-1.6 m	Detected
2.0 m-2.1 m	1.9 m-2.0 m	Detected
2.9 m-3.0 m	No peak	Undetected
3.1 m	3.2 m-3.3 m	Detected
4.2 m	No peak	Undetected
5.1 m-5.4 m	No peak	Undetected
6.1 m-6.3 m	6.3 m-6.5 m	Detected

Table 2: Fracture detection results for borehole R4

Fractured or crushed zones on the drill core photograph	Peaks on the penetration rate profile	Detection results
2.7 m-3.0 m	No major peak	Undetected fractured zone
3.0 m-3.2m	3.0 m-3.2 m	Detected highly crushed zone
4.8 m-6.0 m	4.4 m-5.9 m	Detected fractured zone
6.0 m-6.5 m	No major peak	Undetected fractured zone
7.1 m-7.7 m	6.9 m-7.7 m	Detected fractured zone
7.7 m-8.1 m	8.0 m-8.3 m	Detected highly crushed zone
8.7 m-9.0 m	9.1 m-9.3 m	Detected highly crushed zone



a) Borehole R4 b) Borehole R3

Figure 13: Comparison of penetration rate curves in integral and fractured rocks

4 CONCLUSIONS

ID is a new type of MWD technique that has been applied in several site investigation projects in Australia. Featuring intelligent and automatic drilling functions, ID can efficiently produce higher-quality drilling data compared to conventional MWD techniques. This paper initially assessed the potential of ID data for quantitative site geotechnical characterisation. The first case study of ID in soils shows that the three selected MWD indices, the soil-rock resistance, Somerton index and drilling energy, are correlated with soil SPT values. The correlation level is very high if any noticeable outliers are excluded. The case study in rocks demonstrates that the soil-rock resistance and percussive index can be linked to rock strength ($I_{s(50)}$ and UCS), with the soil-rock resistance exhibiting a slightly better performance. Generally, $I_{s(50)}$ is equal to 10% of the two studied MWD indices of rocks. In the rock fracture detection analysis, it is found that the peaks on the penetration rate profiles can be used to identify discrete fractures or highly crushed zones in rocks for percussive drilling. While demonstrating promising results, some discrepancies are also found in the soil and rock characterisation in this study, highlighting the necessity to conduct more comparative testing in controlled environments to validate and enhance the findings from the case studies. Beyond the applications discussed in this paper, future research on the ID method will explore its potential for soil classification. Additionally, in the future, machine learning could be employed to process multi-dimensional and large-scale drilling data, complementing the traditional MWD indices used for data interpretation in this study.

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CRediT authorship contribution statement

Fei Huang: Formal analysis, Writing - original draft, Writing – review and editing**.** **Hongyu Qin:** Supervision, Writing - original draft. **Masoud Manafi:** Writing – review and editing. **Ben Juett:** Writing – review and editing. **Ben Evans:** Writing – review and editing.

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