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# Application and reliability analysis of DPM system in site investigation of HK weathered granite

*Zhuoying Tan*[1) *Meifeng Cai*1) *Zhongqi Yue*2),*L.G. Tham*2),*and C.F. Lee*2)

1) State Key Laboratory of High-Efficient Mining and Safety of Metal Mines (University of Science and Technology Beijing), Ministry of Education, Beijing 100083. China

2) Department of Civil Engineering, University of Hong Kong, Pokfulam Road, Hong Kong, China

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**Abstract:** A drilling process monitor (DPM) for ground characterization of weathered granite is presented. The monitor is portable and can be mounted on a hydraulic rotary drilling rig to record various drilling parameters in real time during normal subsurface investigation. The identification method for dominative and subsidiary interfaces has been established. The study reveals that the monitored drilling parameters are dependent on geotechnical materials and can be further applied to characterize ground interfaces. The t-test between manual logging and DPM logging has been carried out. The results show that the DPM has high accuracy in interfaces detection and well agreement with the manual logging. The findings show that the device and data analysis method are of potential application in subsurface drilling exploration in weathered granites. It also seems to have prospective uses in the determination of orebody boundary as well as in the detection of geohazards.

**Key words:** drilling process monitoring; hydraulic rotary drill; instrumented borehole drilling; geotechnical engineering; weathered granite

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## 1 Introduction

The drilling-process-monitor (DPM) is an instrumented drilling system that can log data while drilling. Its initial uses were found in oil and gas industry and it has been developed in both hardware and software since the invention of capacity pressure sensors in 1956. A logging-while-drilling (LWD) system, for the measurement in well deviation, torque and weight on bit and simple formation parameters, was put into use in 1980s. Its advances in technique and applications in petroleum field have been summarized in a recent publication by Stefan [1].

Due to the importance in site characterization, numerical control and quality control, the development and application of instrumented drilling in geotechnical engineering, is almost simultaneous as in well-boring. Since the 1980s, the use of microprocessor-based drill monitoring devices to allow sensing, acquisition, storage and processing of drill operational parameters has been recognized to be great potentials in ground characterizations *[2-7]*. Of these instrumented drilling systems, ENPASOL found its applications in ground investigation in 1970 [8], and then Rodio a PAPERO system [9] and Kajima a soil survey system vehicle [10].

Evidently, micro-electronics-based monitoring systems are able to record a variety of drilling parameters, such as bit torque, bit thrust force, rotary speed, penetration rate, pressure and flow of drilling fluid. The correlation analyses of the above parameters with borehole depth have been applied to reveal the strength and stratigraphical properties of geotechnical materials [9, 11-15].

Based on the achievement mentioned above, an innovative prototype digital DPM has been developed and applied to pneumatic percussion drill rig in soil nail drilling for slope stabilization in Hong Kong [16-18]. In order to expand its applications and to seek for a probability of integration for a variety of drill rigs, the DPM system has been applied to a hydraulic drill rig in ordinary geotechnical exploration. In this paper, the DPM system and the monitored drilling process

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**Corresponding author:** Zhuoying Tan, **E-mail:** markzhy_tan@ 163.com

associated with hydraulic rotary drill for typical ground investigation are discussed. The results as well as analysis of the monitored data of two routine subsurface investigation drillholes in weathered granite in Hong Kong are presented.

## 2 DPM system for hydraulic rotary drill

The DPM system includes three principal parts: (i) Process monitoring (PM); (ii) Data logging (DL); (iii) Data analysis (DA). The DPM system is described in **figure 1.**

The PM includes a sensing system for pressures, a laser distance meter for the displacement of bit and an electromagnetic-based rotation transducers for rotation. In the sensing system, five pressure sensors (S1, S2, S3, S4, and S5) are used respectively for the thrusting and adjusting pressure on the drill strings, the flushing pressure of fluid, and the moving pressures forward and backward horizontally on the drill rig.

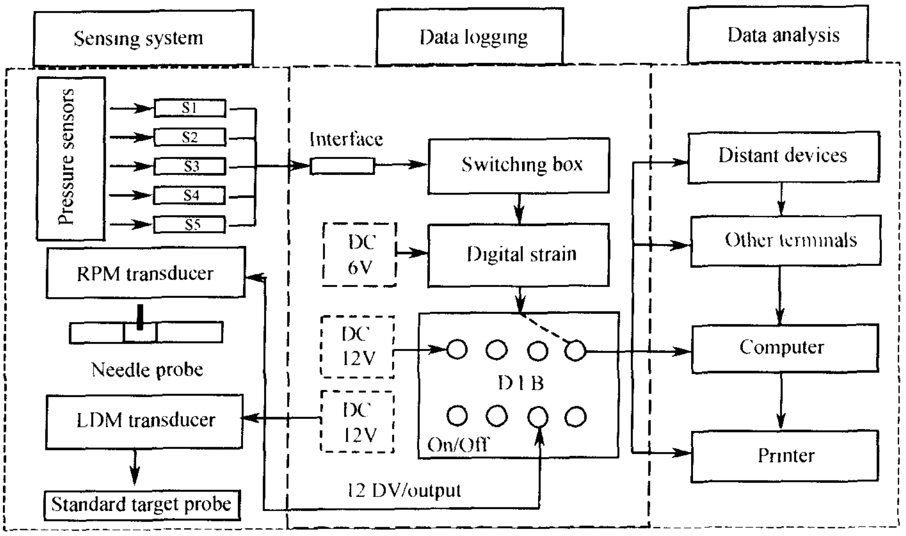

Figure 1 Design sketch of the DPM system.

The DL is an integration of a switching box, a digital strain meter and data transmission box. The PM and the DL together with a computer constitute the hardware of the DPM system. The DA is a data-processing unit of the system, which is an exclusive program package. In order to guarantee a high precision, all the sensors and transducers have been calibrated in laboratory before in situ monitoring.

## 3 Monitored results and analysis

### 3.1 Drillhole depths

The in-situ DPM monitoring work was carried out in a foundation investigation site. In order to check the accuracy of the DPM, the monitored drillholes were logged manually by engineering geologists so as to provide reliable data for verification. The results from two DPM monitored drillholes are shown in **table 1.** It indicates the extreme values between the manual logging and the DPM monitoring are [-0.132, 0.018] m in absolute error and [—0.37%, 0.06%] in relative error. It shows that the DPM system provides a high accuracy in the measuring of drillhole depth.

### 3.2 Phased characteristics of penetration depth with time (PDT)

The full graphs of PDT for the drillholes as mentioned above are shown in **figures** 2 and 3, respectively. In the figures, PDT is presented in the thick solid curve and the corresponding slope of the curve segment is described in a thinner line that equals the average penetration rate (APR) in numerical value.

Table 1 Comparison of drillhole depths between the manual and DPM logging (Mo Man Tin Site: Hong Kong)

| Borehole No. | BH1 | BH2 |
|---|---|---|
| $A$=DPM depth (m) | 35.668 | 31.868 |
| $B$=Manual depth (m) | 35.80 | 31.85 |
| Difference = $A-B$ | −0.132 | 0.018 |
| Relative difference=$(A-B)/B$ | −0.37% | 0.06% |

The relationship of the PDT in the drillhole BH1 is shown in figure 2. From the figure, a transition point exists at -19.95 m in depth which divides the curve into two general segments. Up the point, the curve is steeper and has a higher APR of 22.12 cm·min$^{-1}$. In contrasted to the upper segment, the lower part is gentler and has a much lower APR of 4.79 cm·min$^{-1}$. It is not hard to find from the logging that the stratum between 0.00 and -19.95 m is most strongly to very strongly decomposed granite (silty fine to coarse sand, grade IV to V), and the segment from -19.95 to -35.80 m is the slightly to moderately decomposed coarse granite (grade II to III). It is evident that the properties of the two strata are remarkably different.

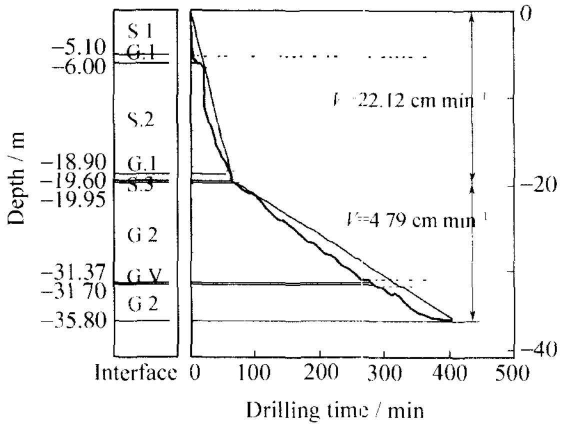

**Figure 2 Comparison of ground characterizations between the conventional manual logging and DPM logging in BH1. Note: S.1=Sand, grade V, very strongly decomposed GRANITE; S.2=Sand, grade V, decomposed coarse GRANITE; S.3=Sand, grade IV, strongly to very strongly decomposed GRANITE; G.1=Granite, grade III to II, moderately to slightly decomposed coarse GRANITE; G.2=Granite, grade II, slightly decomposed coarse GRANITE; G.V=Granite, grade II, slightly decomposed fine to medium grained GRANITE VEIN.**

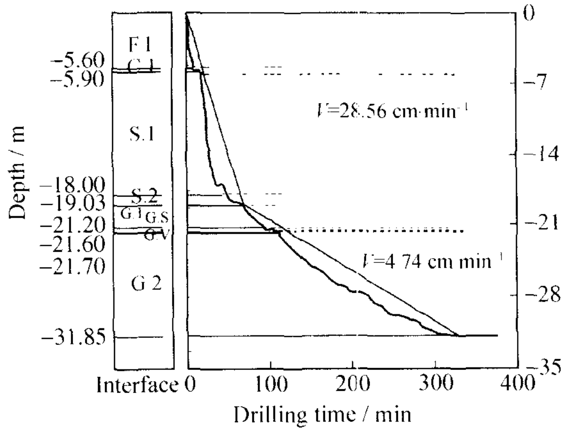

**Figure 3 Comparison of ground characterizations between the conventional manual logging and DPM logging in BH2. Note: F.1=Fill, silty fine to coarse SAND with occasional angular fine to coarse gravel sized rock fragments; C.1=Old concrete slab; S.1=Sand, grade V, very strongly decomposed GRANITE; S.2=Sand, grade V/IV, strongly to very strongly decomposed GRANITE; G.1 =Granite, grade IV/III, strongly to moderately decomposed coarse GRANITE; G.S.=Fractured Granite, grade IV, strongly decomposed coarse GRANITE; G.V.=Granite, grade II, slightly decomposed pegmatite VEIN; G.2=Granite, grade II, slightly decomposed coarse Granite.**

The same relationship for BH2 is described in figure 3. The upper segment, from 0.00 to -19.03 m in depth, has an APR of 28.56 cm·min$^{-1}$. The lower segment, from -19.03 to -31.85 m in depth, has an APR of 4.74 cm·min$^{-1}$. It gives a similar case in BH1 in the characteristics of the graph. In fact, the drillholes BH1 and BH2 are very neighboring holes at the same site. The central distance between the two holes is nothing more than 10.0 m. The drillhole record reveals that the upper segment, from the ground surface to the depth of -19.03 m, is comprised of fill soil which is the strongly to very strongly decomposed granite (silty fine to coarse sand) in grades of V to IV. The lower segment, from -19.03 to -31.85 m, consists of the strongly and moderately decomposed coarse grained granite in grades of IV to III, and locally and slightly decomposed pegmatite vein in a grade of II.

As discussed above, it is apparent that the PDT curve goes steadily and smoothly when the penetrated stratum is nearly homogeneous, while the curve fluctuates when the stratum is diverse. However, the most difference is the slope of the curve. It is higher in soil/sand (grade V or IV) than that in rock (grade IV to II). It indicates that the smoothness and slope of the curve can reveal the stability, grade and drillability of the penetrated stratum. The more homogeneous the stratum, the smoother the curve. The stiffer the stratum, the smaller the penetration rate and the gentler the slope of PDT curve. So, a phased characteristic will be presented in a PDT curve when it goes through different strata. In order to reveal a general law of the penetrated strata, smoothed polygonal lines were used to describe the firmness.

### 3.3 Identification of a dominative interface

A dominative interface may be defined as a boundary between two geological materials of apparent stratigraphic characteristics. Such interfaces from the drillhole record are shown in the histograms in the right part of figures 2 and 3, respectively.

In order to identify these interfaces, a significant index is defined to describe the extent of change in lithology. The significant index ($S_i$) is numerically a change rate ($P_r$) of slope ($P$ ) of the PDT graph.

$$S_i = P_r = \frac{P_1 - P_2}{P_1} \times 100\% = (1 - \frac{P_2}{P_1}) \times 100\% \tag{1}$$

where the step-length of the borehole depth is set to be 0.50 m. $P_1$ and $P_2$ *are* the slopes of PDT graph in two adjacent step-lengths, respectively. It is evident that the precision of identification in interfaces is dependent of significant index and step-length. **In** order to satisfy the demand of geotechnical engineering, $5_i$ is set to be more than or equal to 10.0% for the dominative interface.

As shown in figure 2, there are seven dominative interfaces from the drillhole record in BH1. From these interfaces, significantly abrupt changes occur at the PDT curve. In order to give an understandable comparison, the recorded interfaces are shown in solid lines in the right side of the curve, while interpreted interfaces of the monitored results from the DPM are presented in the broken line on the left side. As a general rule, the penetration rate under specific energy, in the same conditions of drill and tools, will decrease with the increasing in firmness and strength. It is evident that break points may exist between the interfaces when the bit penetrates from one layer to another one. For example, the PDT graph goes in another direction at a depth level of -19.95 m. The stratum changes from sand to granite at the point. Similarly, such change happens at -19.03 m in figure 3. It is noted that it is not always true when divide a PDT graph into two segments. It depends on the complexity of the penetrated ground and whether it is separated discontinuously by different strata and/or weak planes. These interface values from drillhole records and interpretations from the DPM system are listed in **table 2.**

**Table 2 Comparison of the depths of dominative interfaces between the manual logging and DPM**

| Drillhole No. | Parameters | Depth values at the dominative interfaces | | | | | | |
|---|---|---|---|---|---|---|---|---|
| BH1 | $u_i$ / m | −5.10 | −6.00 | −18.90 | −19.60 | −19.95 | −31.37 | −31.70 |
| | Grade change at interface$^{+}$ | V<br>-III/II | III/II<br>-V | V/IV<br>-III/II | III/II<br>-IV | IV<br>-III/II | II<br>-Vein* | Vein*<br>- II |
| | $v_i$ / m | −5.36 | −6.67 | −18.58 | −19.50 | −19.95 | −31.08 | −31.92 |
| | $x_i=(u_i-v_i)$ / m | 0.26 | 0.67 | −0.32 | −0.10 | −0.00 | −0.29 | 0.22 |
| | $\lvert x_i \rvert$ / m | 0.26 | 0.67 | 0.32 | 0.10 | 0.00 | 0.29 | 0.22 |
| | $\eta_i$ / % | 5.10 | 11.17 | 1.69 | 0.51 | 0.00 | 0.92 | 0.69 |
| BH2 | $u_i$ / m | −5.60 | −5.90 | −18.00 | −19.03 | −21.20 | −21.60 | −21.70 |
| | Grade change at interface$^{+}$ | Old concrete slab<br>Old concrete slab | | V<br>-V/IV | V/VI-<br>VI/III | VI/III<br>-IV | VI<br>-Vein# | II<br>-Vein# |
| | $v_i$ / m | −5.42 | −6.09 | −17.87 | −19.00 | −21.33 | −21.51 | −21.68 |
| | $x_i=(u_i-v_i)$ / m | −0.18 | 0.19 | −0.13 | −0.03 | 0.13 | −0.09 | −0.02 |
| | $\lvert x_i \rvert$ / m | 0.18 | 0.19 | 0.13 | 0.03 | 0.13 | 0.09 | 0.02 |
| | $\eta_i$ / % | 3.21 | 3.22 | 0.72 | 0.16 | 0.61 | 0.42 | 0.09 |

Note: $u_i$—manual logging; $v_i$—DPM logging; $\eta_i = \frac{\lvert x_i \rvert}{\lvert u_i \rvert} \times 100\%$. *—Strong, light pink, slightly decomposed fine to medium grained Granite; #=Strong, slightly decomposed pegmatite; +—It expresses the grades of the neighboring strata separated by the dominative interface. The upper symbol of the dash is the proceeding stratum and the lower the following stratum.

Generally, PDT graph will go steeply when penetrating from a strong, hard and low drillable geological material into a weaker, soft and high drillable one, and the inclination will turn into gentle when under an adverse condition. The break points are important symbols for the detection of such interfaces. The extent of complexity and number of break points in PDT graph can be used to reveal the homogeneity of the penetrated strata. The more frequently it fluctuates, the worse homogeneous the strata would be.

### 3.4 Identification of a subsidiary interface

When a bit is penetrating through an incrementally changed stratum without an evident boundary, the graph will tend to be gentle and without abrupt turns. Here a subsidiary interface can be defined as another type of boundary in such an incrementally changed stratum. Unlike the dominative interface, a subsidiary interface happens at some small local regions in the same stratum where either the decomposed or metamorphic extent of rock is seriously changed. Based on the analysis in dominative interface, $S_i$ is set to be more than or equal to 3.0% but less than 10.0% here.

As discussed above, the PDT graph will turn its strike at a depth where ground characterization changes. These interfaces from both the manual logs and the DPM record are made into a combined histogram in **figure 4,** and their corresponding interface values are listed in **table 3.** Figure 4 shows, from the manual logs, four subsidiary interfaces alone exist in BH1 and BH2. These interfaces are successfully detected by the DPM in BH1. Table 3 shows that the extreme values between the manual logs and the DPM records are [-0.38, 0.53] m in absolute error and [1.53%, 2.91%] in relative error. However, for BH2, not four but two of the subsidiary interfaces were detected by the DPM when the lower limit value of the significant index ($S_i$) is 3%. It indicates that the precision of the DPM in interface detection is $S_i$ -dependant.

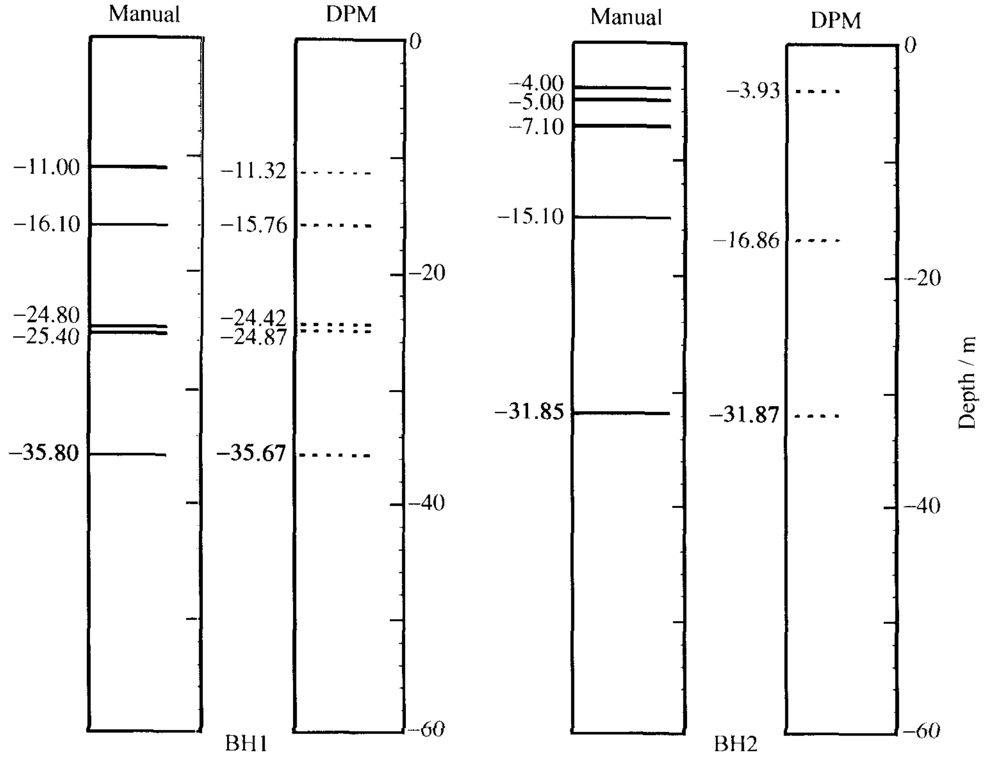

**Figure 4 Comparison of subsidiary interface depths between the manual and DPM logging in BH1 and BH2. Here, the numbers of the black font are the depth values at the bottom of the drillholes. Note: Solid level lines for the interfaces from the drillhole records and dotted level lines for interpretations from the monitored results of the DPM.**

**Table 3 Comparison of subsidiary interfaces between the manual logging and DPM**

| Drillhole No. | Parameters | Depth values at the subsidiary interfaces / m | | | |
|---|---|---|---|---|---|
| BH1 | $u_i$ / m | -11.00 | -16.10 | -24.80 | -25.40 |
| | Grade change at interface* | V-V | V-V/IV | III/II-IV/III | IV/III-II |
| | $v_i$ / m | -11.32 | -15.76 | -24.42 | -24.87 |
| | $x_i=(u_i-v_i)$ / m | 0.32 | -0.34 | -0.38 | 0.53 |
| | $\lvert x_i \rvert$ / m | 0.32 | 0.34 | 0.38 | 0.53 |
| | $\eta_i$ / % | 2.91 | 2.11 | 1.53 | 2.09 |
| BH2 | $u_i$ / m | -4.00 | -15.10 | — | — |
| | Grade change at interface* | Fill | V-V | — | — |
| | $v_i$ / m | -3.93 | -16.86 | — | — |
| | $x_i=(u_i-v_i)$ / m | -0.07 | 1.76 | — | — |
| | $\lvert x_i \rvert$ / m | 0.07 | 1.76 | — | — |
| | $\eta_i$ / % | 1.75 | 11.66 | — | — |

Note : $u_i$—manual logging; $v_i$—DPM logging; $\eta_i = \frac{|x_i|}{|u_i|} \times 100\,\%$ *—It expresses the grades of the neighboring strata separated by the subsidiary interface. The left symbol of the dash is the proceeding stratum and the right the following stratum. Subsidiary interfaces alone exist in BH1 and BH2. These interfaces are successfully detected by the DPM in BH1.

## 4 Statistical analysis of the monitored data

### 4.1 Error analysis

The monitored contents of DPM system include: (1) operational parameters of the drill, (2) penetrated depth, and (3) interfaces. The penetrated depths have been discussed in section 3.2, while the monitoring of the operational parameters is based on calibration, and their errors are enacted in regression equations. So, the dominative and subsidiary interfaces are analyzed here and their results are listed in tables 2 and 3.

The depth values at the dominative interfaces from the manual logging and the DPM system are shown in table 2. The changes in the ground characterization at the interfaces can be obtained from the table. As shown in the grade row, the grades of neighboring strata at the interfaces will alternate in order. This alternation at interfaces in grade will be reflected as the break points in PDT graph. The identification of the points by naked eyes in the graph depends on the penetrated thickness of the same grade. However, by use of program, any tiny changes can be detected successfully by the parameters setting for interfaces, such as an increment or decrement of the angle during a certain depth.

From table 2, the maximum absolute error and relative error happened in the drillhole BH1 are 0.67 m and 11.17%, respectively. Besides, table 3 gives the subsidiary interfaces and results by error analysis. As the same as in dominative interfaces, the maximum absolute error and relative error in the drillhole BH2 are 1.76 m and 11.66%, respectively.

### 4.2 *T-test* for confidence

As known, error analysis only reflects the deviation extent of an individual sample. Besides that, one needs to know the deviation extent of sample population. In order to check the accuracy of the DPM system, a *t*-test was carried out in the ensuing monitored results.

Assuming that there are two methods used for drillhole recording, one is manual logging, *u*. The other is automatically monitoring by the DPM system, *v*. Their observed values are the logged interfaces $u_i$ and the monitored $v_i$, respectively. The question is whether or not there is any significant difference in the values between the above two methods.

According to the t-test theory, if the two methods play the equal role in identifying the interfaces, then the difference in each pair of the observed data is created by random errors. The difference variable can be taken as a normal distribution of zero mean. So, the question, *i.e.,* whether or not there is any significant difference between the two methods, can be simplified to answer by judging the following mathematical question: whether or not the variable $x = u\text{-}v$ follows the normal distribution with zero mean, $N(0,\sigma^2)$, where, the population variance $\sigma^2$ is unknown and $x$ is a difference variable and a new independent observed value.

The above question can be answered by testing the following hypothesis under a certain level of significance α (α = 0.01). Assuming the mean value $E(x)$ of variable $x$ to be zero, then

$$E(x) = 0 \tag{2}$$

The rejection field under the test is

$$|\bar{x}| > \frac{s}{\sqrt{n}} t_{\alpha/2}(n-1) \tag{3}$$

where $\bar{x}$ is an average value of the observed sample, s the sample standard deviation, $n$ the the sample capacity. From these parameters, $s$ can be determined as below:

$$s^2 = \frac{1}{n-1}\sum(x_i - \bar{x})^2 \tag{4}$$

where $x = \frac{1}{n}\sum x_i$ .

For carrying out the t-test, the data in tables 2 and 3 about $u$, $v$ and $x$ were used. The results of the t-test are shown in **table 4.** From table 4, for all the drillholes BH1 and BH2, $\bar{x}$ values are all excluded from their rejection regions, whether dominative interfaces or subsidiary interfaces. Therefore, it can be concluded that there are no significant differences between values from the two methods under the assumed significance level.

Table 4 Results of the *t-test* **and the** degree **of** confidence at the interfaces **from DPM with** respect to manual logging

| Interface | Drillhole No. | $n$ | $a$ | $\sum x_i$ | $\bar{x}$ | $S^2$ | $S$ | $t_{a/2}(n-1)$ | $\frac{S}{\sqrt{n}} t_{a/2}(n-1)$ | $100(1-\alpha)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Dominative | BH1 | 7 | 0.01 | 0.440 | 0.063 | 0.1223 | 0.3497 | 3.7074 | 0.4900 | 99 |
| | BH2 | 7 | 0.01 | –0.130 | –0.019 | 0.0182 | 0.1350 | 3.7074 | 0.1891 | 99 |
| Subsidiary | BH1 | 4 | 0.01 | –0.930 | –0.233 | 0.1424 | 0.3773 | 5.8409 | 1.1019 | 99 |
| | BH2 | 2 | 0.01 | 1.690 | 0.845 | 1.6745 | 1.2940 | 63.6574 | 58.2465 | 99 |

When the DPM system and the associated data analysis method are used for the determination of ground characterizations, the confidence degree can reach 99% with respect to the manual logging by engineering geologists.

## 5 Average penetration rates (APR) for weathered granite

**Table 5** presents the distribution of time consumed and corresponding penetration rates both in weathered soil and weathered rock. From the table, the APRs in soil are 22.12 and 28.56 $\text{cm min}^{-1}$ at BH1 and BH2, respectively. It is evident that the APR in bedrock at BH1 and BH2 are almost equal. This may reveal that the firmness characterizations at BH1 and BH2 are similar. However, the soil penetration rate at BH2 is higher than that at BH1, which may indicate that the soils in BH2 are weaker than that in BH1. Such DPM results are confirmed by the manual logs. It shows that there is a top fill layer up to a depth of 7.10 m in BH2 while that in BH1 is much thinner and about 1.00 m. The penetration resistance is considered to be weaker in loose fills than that in undisturbed weathered granitic soils.

Table 5 Comparison of the average penetration rates for soils and rocks from the DPM data

| Borehole No. | Drilling in soils | | | Drilling in rocks | | |
|---|---|---|---|---|---|---|
| | Thickness / m | Used net time / min | APR / (cm·min$^{-1}$) | Thickness / m | Used net time / min | APR / (cm·min$^{-1}$) |
| BH1 | 19.95 | 90.2 | 22.12 | 15.85 | 331.0 | 4.79 |
| BH2 | 19.03 | 66.6 | 28.56 | 12.82 | 270.3 | 4.74 |

In addition, the APR in bedrock is much lower than that in soil. From table 5, they are 4.79 and 4.74 cmmin$^{-1}$ in BH1 and BH2, respectively. Such results have shown that the weathered granite in BH1 and BH2 are similar. The manual logs show that the granites are similar at BH1 and BH2, which is the slightly decomposed coarse granite. It indicates that the penetration rate agrees well with the characterization of geotechnical materials.

## 6 Management of drilling work

Another important use of the DPM system is for the quantitative management of drilling production. The applications in this aspect include the file management of drillholes and construction time management.

The DPM system records the total time and the distributions in real-time for each sub-procedure throughout the drilling process. An understanding of the time distributions can assist operator, engineer and manager to make plans and well control the progress of the project. For example, the monitoring results show that sampling is a time consuming process. As shown in table 6, the total time for advancement of the bit (net penetrating time) were less than 30% of the total drilling time. The total time did not cover the time spent on both moving of the drill rig at the beginning and its relocation after the completion of the drilling work.

Table 6 Comparison of total drilling time with net penetrating time

| Borehole No. | BH1 | BH2 |
|---|---|---|
| Total time, $A$ / h | 24.50 | 22.67 |
| Net time, $B$ / h | 7.02 | 5.62 |
| $B/A$=ratio | 28.65% | 24.79% |

## 7 Conclusions

The DPM system can accurately monitor the operational parameters of the drill. It can obtain detailed quantitative information on site characterizations in addition to those from the conventional manual logging because of its capability of continuous monitoring in real time with high precision. The site characterizations of weathered granites from the system agree well with those from the manual logs. The results of t-test have shown that the confidence level of the DPM system is up to 99% with respect to the manual logs. Besides, the DPM can be used in operational management of drilling work. Therefore, the system has prospective uses for ground characterizations in geotechnical investigation and for the determination of orebody as well as the detection of geohazards such as karst hazards in geological engineering. However, there is still a lot of testing and calibration work to do when the DPM system is popularized in non-granite sites.

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