Subsurface profiling using horizontal drilling indices for guided boring method

Khondoker, Md. Tareq Hossain; Yi, Yaolin; Bayat, Alireza

2016

Khondoker, M. T. H., Yi, Y., & Bayat, A. (2016). Subsurface profiling using horizontal drilling indices for guided boring method. *International Journal of Geotechnical Engineering*, in press.

<https://hdl.handle.net/10356/84718>

<https://doi.org/10.1080/19386362.2016.1257415>

© 2016 Informa UK Limited. This is the author created version of a work that has been peer reviewed and accepted for publication in *International Journal of Geotechnical Engineering*, published by Taylor & Francis Group on behalf of Informa UK Limited. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<http://dx.doi.org/10.1080/19386362.2016.1257415>].

Downloaded on 26 Apr 2023 22:22:08 SGT

Subsurface Profiling Using Horizontal Drilling Indices for Guided Boring Method

Md. Tareq Hossain Khondoker¹, Yaolin Yi², Alireza Bayat³

¹M.Sc. Student, Department of Civil and Environmental Engineering, University of Alberta, E-

mail: mdtareqh@ualberta.ca

²Assistant Professor, School of Civil and Environmental Engineering, Nanyang Technological

University, E-mail: yiyaolin@ntu.edu.sg

³Associate Professor, Department of Civil and Environmental Engineering, University of

Alberta, 7-243 Donadeo Innovation Centre for Engineering 9211 116th Street, Edmonton,

Alberta, Canada, T6G 1H9, Phone: 1-780-492-5112, Fax: 1-780-492-0249, E-mail:

abayat@ualberta.ca (Corresponding Author)

Acknowledgement

The authors would like to thank the Consortium for Engineered Trenchless Technologies

(CETT) at the University of Alberta for their support and guidance. The assistance of Sheena

Moore at CETT for editing this paper is greatly appreciated.

Abstract

Guided Boring Method (GBM) is a widely used trenchless technique to install pipelines with grade precision. As the length of these projects is much smaller than other underground projects (e.g. tunnels), conducting geotechnical investigations for GBM becomes unjustified at times due to budget constraints. Therefore, contractors will often conduct GBM installations without performing a proper subsurface investigation, which may lead to unusual consequences for the project. Since GBM consists of an initial pilot tube installation with further borehole reaming, the drilling parameters during the pilot tube installation phase may be used for subsurface profiling, which can help operators select proper drilling tools for the next reaming stages. This paper investigates the effectiveness of drilling parameters during pilot tube installation for subsurface profiling using drilling indices for a GBM project in Edmonton, Canada. Six drilling indices, which were proposed for vertical drilling, were used to obtain the comparative strength of soil throughout the drive length. The results indicated that all six indices could identify the soil transitions in the drive length. However, the indices can only give a comparative strength measurement of soil throughout the drive length, not the exact soil strength.

Keywords: Pipeline installation; Guided boring method; Subsurface profiling; Drilling indices.

1. Introduction

Trenchless technique has recently become a popular method to install or rehabilitate pipelines with minimal surface disturbance (Najafi, 2005). Guided Boring Method (GBM) is a widely used trenchless technique to install pipelines with grade precision. Guided pilot tubes are initially installed to maintain line and grade precisely in GBM, followed by upsizing and product pipes

1
2
3
4 40 installation. This technology has grown from 0.10 m diameter to 1.22 m diameter pipeline
5
6 41 installation with a drive length of 121.92 m in range (Boschert, 2007). GBM has several
7
8
9 42 advantages over traditional pipe jacking/microtunnelling, e.g., the initial phase of pipe
10
11 43 jacking/microtunnelling is auger boring without pilot tube installation, which may lead to
12
13
14 44 deviation from the original line and grade. GBM is a three-step installation procedure, as shown
15
16 45 in Figure 1. The first step is to install pilot tubes on line and grade. The second step is to install
17
18
19 46 auger casings, followed by removal of pilot tubes one by one. The third step is to install product
20
21 47 pipes and remove auger casings (Boschert, 2007).
22
23
24 48

25
26 49 For the past few years, contractors have been optimizing drilling in addition to reducing drilling
27
28
29 50 hazards and increasing drilling output in terms of time and cost. Consequently, a number of
30
31 51 drilling techniques, tools and machines have been introduced in the drilling sector to achieve
32
33 52 optimized drilling. A better knowledge of soil subsurface is essential to implement improved
34
35
36 53 drilling methods. The construction of large projects (e.g. tunnels) requires an extensive
37
38 54 investigation of ground to gain sufficient knowledge about soil. This investigation leads to
39
40
41 55 drilling a large number of holes for different in-situ tests, e.g. Cone Penetration Test (CPT).
42
43 56 However, as the length of these projects is much smaller than other underground projects, budget
44
45 57 constrains can make geotechnical investigations for GBM unjustified at times. Therefore,
46
47
48 58 trenchless contractors frequently take risks by performing GBM installations without proper
49
50 59 subsurface information, which often leads to unusual circumstances. Sometimes the installation
51
52
53 60 becomes immovable upon encountering an unusual soil layer; this costs the project even more
54
55 61 than the cost of a geotechnical investigation.
56
57
58 62

The use of drilling parameters can be an effective alternative tool for subsurface exploration in drilling. Recording and analyzing drilling parameters for drilling optimization has been used for a long time in the oil and gas industry (Gui *et al.*, 2002). Evidence based on theory as well as laboratory experiment shows that the compressive strength of drilled strata can be determined using the relationship between the observed values of drilling variables (Brown *et al.*, 1978). Laudanski *et al.* (2012) conducted an extensive experiment on a specially constructed test embankment to develop an empirical relationship between drilling parameters-based indices and test results from the Standard Penetration Test (SPT), as well as CPT. Real-time drilling surveillance software based on drilling parameters (e.g. ENPASOL) is being utilized to discover lithological transitions for vertical drilling. Trenchless technologies such as GBM or Pilot Tube Microtunnelling (PTMT) consist of an initial pilot tube installation with further borehole reaming. The process of pilot tube installation is similar to the process of CPT; hence, the drilling parameters gathered from the pilot tube installation may reveal the soil information along the drive length. Hence, profiling the subsurface using drilling parameters can be an effective alternative tool of geotechnical investigations for GBM or PTMT projects. In these types of projects, profiling the subsurface during the pilot tube installation phase can help operators select proper drilling tools for the next reaming stages.

2. Review of Vertical Drilling Indices

Using drilling data, different researchers have developed different indexes to create a relative soil profile, as shown in Table 1. The Somerton index (Somerton, 1959) is a measurement of resistance to drilling, which is an effective tool for rock mass classification. The Somerton index was initially proposed as a strength parameter for rock to correlate rock properties with drilling

parameters, and this tool proved to be very useful in differentiating weathered rock layers (Viana da Fonseca *et al.*, 2006). This index has no specific value range: a comparatively smaller value indicates softer soil, and a higher value indicates harder soil. Bingham (Bingham, 1965) proposed a Γ -hardness parameter that represents how hard it is to drill soil. A higher Γ -hardness value signifies the soil is hard to drill, which does not necessarily mean hard soil. Even clay may clog the drilling bits and increase the Γ -hardness value. The ease of removing drilled materials largely affects the measurement of soil hardness.

The Mechanical Specific Energy (MSE) proposed by Teale (Teale, 1965) is a widely used index for monitoring drilling efficiency. MSE is defined as the energy required for removing one unit volume of rock or soil. This index can be used as a tool for indirect assessment of soil strength. As the drilling progresses, abrupt variation of MSE represents inefficient drilling. This index has been used to increase performance and reduce time by adjusting drilling parameters in real time. Several factors may cause changes in MSE, e.g., bit balling, bottom hole balling, and vibrations (Bevilacqua *et al.*, 2013). In most of the cases, change in soil formation causes change in MSE; MSE can thus be used as a diagnostic tool to identify different geological formations (Bevilacqua *et al.*, 2013).

The alteration index was developed by Pfister (1985). This index provides a comparative strength measurement of soil using Weight On Bit (WOB) and penetration rate, but cannot specify the exact soil type based on a standard scale. This index, with values varying from 0 to 2, is very sensitive for low to medium strength soil; 0 is an indication of soft soil, while 2 is an indication of hard soil. Pfister (1985) also introduced the energy parameter used for drilling,

which is different from MSE developed by Teale (1965) since this index excludes jacking force parameter (Table 1). This energy parameter is very useful for hard soil and rock analysis. However, the omission of jacking force makes this index less effective than MSE to assess soil layers through a trenchless technique where the jacking force parameter is dominant. Celada *et al.* (2009) used MSE for rock mass characterization during a tunnel construction by measuring the drilling parameters of a Tunnel Boring Machine (TBM).

E method, also known as exponent method, was introduced by Gui *et al.* (2002) to indicate stratigraphic changes. This method was modified from “*d-exp*” method developed by Jordan *et al.* (1978) to track the profile of rock strength using one dependent variable, drilling speed; but the equation was dimensionally incorrect. Gui *et al.* (2002) assumed a relationship between velocity ratio and force ratio to obtain dimensional consistency of the original “*d-exp*” method proposed by Jordan *et al.* (1978). E method or exponent method is mathematically defined as the exponential relationship between velocity ratio and force ratio for profiling soil strength; the relation is a power curve. A summary of different indices is presented in Table 1.

3. Objectives

As explained earlier, on one hand, GBM projects usually lack geotechnical investigation. On the other hand, GBM consists of drilling of a pilot borehole that is further reamed for pipe installation. In this context, this study, for the first time, attempts to monitor the drilling parameters of the pilot tube installation stage and use them for subsurface profiling for the next reaming stage during a GBM project.

In order to investigate the applicability of the proposed principle, this study conducted a case study of a GBM project in Edmonton, Alberta, Canada. Drilling parameters for this project were recorded using sensors during the pilot tube installation. The strength of soil throughout the drive length was investigated using the six indices in Table 1, incorporating recorded drilling parameters. The intent is to use drilling parameter analysis to identify lithological changes of the soil being drilled. Although the six indices were proposed by previous researchers for vertical drilling, but they have not been applied to horizontal drilling, especially not in conjunction with the pilot tube installation stage of GBM. The objectives of this study are (1) to form a geotechnical investigation tool that can provide a reliable pattern of comparative soil strength, and (2) to compare indices for subsurface profiling. This is a primary work which only explores relative strength measurement of soil, but provides opportunity for future researchers to define exact values of indices for particular strengths of soil.

4. Field Instrumentation

4.1 Project Overview

The GBM project was located at the intersection of 90th Avenue and 110th Street, Edmonton, Alberta, Canada. The project consisted of installing two HDPE pipelines, one for a sanitary line and the other one for a storm line, as shown in Figure 2 and 3. The pipe diameter for the sanitary line was 0.41 m with a casing diameter of 0.71 m, and the drive length was 39.93 m. The pipe diameter for the storm line was 0.61 m with a casing diameter of 0.91 m, and the drive length was 38.71 m (Figure 3). The distance between the two lines was 0.76 m (Figure 3), but there was no elevation difference.

1
2
3
4 155 A 12.80 m × 3.66 m × 6.10 m sized launch shaft was prepared to drive the pilot tubes through the
5
6
7 156 ground (Figure 3). A total of 14 piles were used to support the excavation of the launch shaft.
8
9 157 The piles were 3.96 m long and penetrated 1.50 m into the soil (Figure 3). The excavated soil
10
11
12 158 was sandy, but no geotechnical investigation was conducted to determine exact ground
13
14 159 conditions. There was no presence of ground water. No disruption of traffic and no sound
15
16 160 restriction had been implemented on the site. An Akkerman 240A jacking frame (Figure 2) was
17
18
19 161 used to insert the pilot tubes into the ground and a P100Q power pack was used to provide the
20
21 162 pressure. Later, a Detroit diesel auger machine was used to drive augers through the soil. The
22
23
24 163 length of one auger casing was 6.10 m. Auger casings were welded to each other during
25
26 164 installation. Two 0.02 m diameter small pipes were installed on top of the casings (Figure 3).
27
28
29 165 One pipe was used to convey water and ease the drilling process, and the other pipe was used to
30
31 166 convey bentonite and support the borehole. Two distinct manholes were used as reception shafts
32
33 167 for the installations, as shown in Figure 4(a). In Figure 4(a), the left manhole was used for the
34
35
36 168 sanitary line and the right manhole was used for the storm line. Only one person was able to
37
38 169 enter the manhole to facilitate the pilot tube removal (Figure 4(b)).
39
40
41 170
42
43 171 The product pipes installation in this project differed from the conventional GBM principle.
44
45 172 According to GBM principle, installation of product pipes and removal of auger casings occur
46
47
48 173 simultaneously. However, at the mid-length of the storm line project, the soil to the left side of
49
50 174 the auger casing appeared softer than the rest of the length, thus pulling the auger casings slightly
51
52
53 175 to the left. The alignment was later maintained by removing and reinstalling the auger casings.
54
55 176 To prevent product pipes deviating from their courses in the future, the auger casings were kept
56
57
58 177 inside the soil, as shown in Figure 5.
59
60
61
62
63
64
65

4.2 Instrumentation and Data Collection

Two hydraulic pressure transducers were used to record the jacking pressure and rotational pressure data of the jacking frame. Both of the transducers were installed on a P100Q power pack. A CR 800 datalogger was used to measure the data (Figure 6). The datalogger scanned data at 80-ms intervals and recorded data at 2-s intervals. Within a 2-s interval, the datalogger recorded the maximum, minimum and average values of jacking and rotational pressures. A laptop was initially connected to the datalogger to verify that the datalogger was recording data properly. Later, a SC 115 CS I/O 2G flash memory was connected to the datalogger to store data. The CRBASIC editor software was later used to extract the data from the flash drive and input it into an Excel sheet. Data was converted from rotational pressure to torque and from jacking pressure to jacking force for analysis. The data showed a clear pattern for each pilot tube installation, including preparing time and jacking time.

5. Result Analysis

The six commonly used indices, as shown in Table 1, interpreted the field data for this GBM project. Pressure transducers recorded the jacking force and torque during drilling. The length of each pilot tube was 0.76 m, and recorded data provided the length of time needed to penetrate each pilot tube. The average rate of penetration for each pilot tube was calculated from previous pilot tube length and time information. Revolution Per Minute (RPM) was not recorded during drilling. An average value of 37.5 RPM was used to calculate indices, since 25–50 was the range of RPM value used for the GBM 240A jacking frame. The recorded data is plotted in Figure 7 to show the variation of each drilling parameter except RPM throughout the drive length. Jacking

pressure remains almost constant, but the rotational pressure varies because the diameter of the pilot tube was 0.10 m, which was easier to penetrate through the soil. Since maintaining proper alignment was more crucial than jacking during the drilling process, the rotational pressure became dominant over jacking pressure. Figure 7 shows that where the rotational pressure was higher, the rate of penetration was lower and vice versa. Soil was not the same strength throughout the length, and comparatively hard soil increased the rotational pressure value and decreased the rate of penetration.

Alteration index is presented in Figure 8. The value of the alteration index is controlled by jacking force and rate of penetration (Table 1). The jacking force remained almost constant in the recorded data, so the rate of penetration became the only controlling parameter for the alteration index in this project. This may account for the similar pattern between the alteration index and rate of penetration. The highest average rate of penetration of a pilot tube was considered the maximum rate of penetration in calculating the alteration index. From Figure 8, the drive length can be divided into three sections of approximately equal time slots. The first two slots show a nearly similar increasing pattern in alteration index, which indicates comparatively lower strength soil to higher strength soil. But in the last time slot, the index value remains almost constant, which indicates the strength of soil is almost constant.

The lower boundary of the alteration index, 0, represents soft soil, and the higher boundary, 2, represents hard soil. If the penetration reaches an immovable condition, then the index value becomes 2 and the WOB reaches its maximum value. Conversely, if a jacking force of almost 0 creates maximum rate of penetration, then the index value becomes 0. For soil index, a value of 0

is almost impossible. An index value close to 0 represents substantially soft soil. Although the strength profile provided by the alteration index is a relative one, it still gives a significant amount of information about soil strength. A value of 1 can be used as a benchmark for medium-strength soil during the interpretation of an alteration index profile. In Figure 8, the index value reaches approximately 0.20 at one stage, indicating the existence of soft soil layers. Throughout the drive length, the index value persistently remains below 1; therefore, the soil was generally of low strength for most of the drive length. In the first two-thirds segment of the drive length, the index value shows an increasing trend in its value, indicating that the soil was harder for few parts of the drive length. The highest index value is around 1.4.

Γ -hardness parameter is controlled by four drilling parameters and bit diameter. Therefore, the result of Γ -hardness is more reliable than the alteration index as it includes rotational pressure, jacking pressure, and rate of penetration. Figure 9 presents the calculated Γ -hardness parameter for this project. Since the fluctuation of Γ -hardness parameter is not so intense, Figure 9 does not show as clear a pattern of soil formation change as the alteration index in Figure 8. Regardless, the last one-third segment of Figure 9 shows no variable peaks compared with the rest of the drive length, which means the soil type for the last one-third segment was of consistent strength. As discussed earlier in the Result Analysis, the alteration index also reveals similar results in which the soil type for the last one-third segment is consistent. Although there is no clear baseline trend for the first two-thirds segment of the profile, the peaks exhibit an imaginary increase in Γ -hardness value.

Drillability is the opposite of hardness (Solberg, 2012). There is no specific range of maximum and minimum Γ -hardness values, but a higher Γ -hardness value tends to slow the drilling process. The only thing that can be detected from a Γ -hardness profile is the variation of index value, which indirectly implies a change in soil strength. Figure 9 undoubtedly shows two segments of a higher Γ -hardness value, suggesting the soil was comparatively hard.

To determine how effective this tool can be in differentiating soil layers, Figure 10 shows the calculated Somerton index for this GBM project. This index has three drilling parameters, excluding torque. In the recorded data, jacking force remained almost constant; the RPM value was also considered constant. As a result, the rate of penetration became the driving parameter in calculating the Somerton index in this GBM project.

The drive length of Figure 10 can also be divided into three equal time slots based on index value patterns. The first segment of the drive length shows several peaks, but the base line index value exhibits a slightly increasing trend in index value. The trend for the middle segment is similar to the first segment, and in the case of the last drive length segment, the base line index value remains almost constant in spite of having few peaks. Overall, the minimum index value line represents a clearly visible pattern showing transition in soil strength. The peaks of the index form an imaginary but transparent wavy pattern, similar to the baseline trend pattern; the pattern ensures the variation in soil strength during drilling. This index value has no specific range to judge the exact strength of soil, so it is only helpful in determining the transition of soil layers.

MSE has been used as an indicator of efficiency in vertical drilling for a long time. MSE for this GBM project is plotted in Figure 11. Several factors can create a variation of MSE. For instance, the appearance of hard soil layers causes vibrations of the drill bit and leads to an increase in MSE (Teale, 1965). Additionally, the appearance of clay layers creates bit balling so the bits become less effective at drilling, causing an increase in MSE (Teale, 1965). The plotted MSE profile exhibits a common and visible trend line irrespective of lower and higher index values. The MSE profile during drilling is more straightforward to interpret than the Somerton index and Γ -hardness profile since there is no complexity regarding a base line trend and imaginary peaks trend. In Figure 11, the MSE increased as the drilling advanced up to one third of the total drive length time. The index value then dropped, which was an explicit indication of new soil layer emergence since there was no evidence of bit balling which could affect the index value. For the last one-third time segment in Figure 11, the MSE remained almost constant, representing a homogenous soil layer. This evaluation of soil strength by the MSE tool throughout the drive length matches the results of the alteration index, Somerton index and Γ -hardness parameter. Since there is no specific MSE value to correlate with a soil of specific strength, an extensive laboratory test of drilling on various types of soil is required to correlate soil strength with MSE. Still, as an initial study, MSE can be used to identify drilling efficiency involved in different soil layers.

Energy used for drilling, proposed by Pfister (1985), is plotted in Figure 12 for this GBM project. Because of the nearly constant jacking force value of the project, the change of index value along the drive length is nearly identical to MSE. This is evident since the absence of jacking force is the only difference of energy from MSE used for drilling. The fluctuations of

this drilling energy index in Figure 12 show the index value increased gradually, then dropped, but remained stable for the last part of the drive length. An unchanged drilling energy clearly refers to a consistent soil layer. A gradual increase in energy indicates drilling from soft soil to hard soil. Although further research is needed to correlate a specific energy value with a specific type of soil, this index profile gives a direct measurement of energy for drilling. The variations of energy value in Figure 12 signifies a heterogeneous soil profile. The drilling operator can therefore judge the soil strength onsite in real time by evaluating the amount of energy required for drilling. Figure 11 and Figure 12 show comparatively higher index values for MSE and energy used for drilling at 1200 s of x-coordinate. An increase in MSE or energy used for drilling value is directly proportional to an increase in jacking force and torque value as per equations in Table 1. At around 1200 s, abrupt peaks of MSE and energy used for drilling caused by higher values of jacking force and torque represent appearance of harder soil. In this case study, this phenomenon can be explained as the appearance of small rocks during drilling. The other indices are either solely dependent on jacking force or inversely proportional to torque. So an increase of jacking force as well as torque value does not form an abrupt increase in the indices values.

Figure 13 exhibits stratigraphic changes by E or exponential method introduced by Gui *et al.* (2002). Changes of E are associated with soil formation and thereby soil strength change. The relationship of velocity function and force function changes in different soil types, so the dimensionless plot of velocity function and force function can locate the transition of soil layers. In Figure 13, the value of E fluctuates significantly at several places throughout the drive length. From 250-400s, 800-1100s, and 1200-1400s, the values of E jump from baseline. This map of stratigraphy is a clear indication of the existence of interlayers of soil. A consistent value of E

represents soil layers of similar strength or single soil layer. Appearance of soil layers of different strength drives E value to go up or down.

Knowing geotechnical information plays an important role in selecting the proper drill bits or Powered Cutter Head (PCH) for the reaming stages of GBM projects. Hard soil layers resist penetration of drill bits, which results in the application of more force, and excessive weight on drill bits may cause buckling of the drill stem and wear of bits. Too little knowledge about the soil profile may lead to improper selection of drill bits, resulting in a low rate of penetration. The energy requirement for auger penetration is influenced by strength of soil. In this GBM project, the operators assumed the soil was hard because it was taking more time to penetrate one pilot tube through the ground relative to their experience. As a result, they selected a drill bit for auger casings installation which was compatible for hard soil, but this bit selection could have been more accurate with the knowledge of a soil profile. Regardless of experience, all trenchless personnel associated with drilling ahead of reaming can benefit from using indices for subsurface profiling. A proper drill bit selection accelerates the rate of penetration, but on the other hand, improper bit selection can lead the project to an immovable condition. Soil information also helps select the jacking frame and increase the overall project speed. This knowledge reduces the probability of a project stopping due to the appearance of unusual soil layers and increases the confidence level in the entire drilling process. This preliminary study indicates that the drilling parameters of the pilot tube installation stage can be used as alternative costly geotechnical investigation, which can reduce the amount of risks associated with drilling for GBM projects lacking traditional geotechnical investigation.

6. Conclusion

In this study, subsurface profiling using horizontal drilling parameters during pilot tube installation has been implemented in a GBM project without geotechnical information. All the six indices could identify the soil transitions in the drive length, and provide practitioners an explicit knowledge of ground conditions without any traditional geotechnical investigation. Among the six indices, subsurface profiling is more transparent using the alteration index, MSE and energy used for drilling, which are therefore recommended. The preliminary study of indices for horizontal soil drilling in this paper can enhance the specific contributions of drilling parameters over conventional geotechnical investigations in the future; nevertheless, more field data is strongly suggested for further validation. Also, the indices only give a comparative strength measurement of soil throughout the drive length but cannot give the exact strength of soil. Further studies are required to correlate the indices to soil strength first through laboratory investigations, then validate through field tests.

7. References

- Bevilacqua, M., Ciarapica, F. E. and Marchetti, B. 2013. Acquisition, processing and evaluation of down hole data for monitoring efficiency of drilling processes, *Journal of Petroleum Science Research*, **2**(2), 1-8.
- Bingham, M. G. 1965. A new approach to interpreting rock drillability, Technical manual reprint, *Oil & Gas Journal*, 93 P.

- Boschert, J. 2007. Pilot tube microtunneling explodes in the U.S. using vitrified clay jacking pipe, in International Conference on Pipeline Engineering and Construction, 1-9, Boston, American Society of Civil Engineers (ASCE).
- Brown, E. T. and Barr, M. V. 1978. Instrumented drilling as an aid to tunnelling site investigations, in Proceedings of 3rd Congress of the International Association of Engineering Geology, 21-28, Madrid, International Association of Engineering Geology (IAEG).
- Celada, B., Galera, J. M., Muñoz, C. and Tardáguila, I. 2009. The use of the specific drilling energy for rock mass characterisation and TBM driving during tunnel construction, in ITA-AITES World Tunnel Congress, 1-13, Budapest, ITA-AITES.
- Gui, M. W., Soga, K., Bolton, M. D. and Hamelin, J. P. 2002. Instrumented borehole drilling for subsurface investigation, *Journal of Geotechnical and Geoenvironmental Engineering*, **128**, (4), 283-291.
- Jordan, J. R. and Shirley, O. J. 1978. Application of drilling performance data to overpressure detection, *Journal of Petroleum Technology*, **7**, 987-991.
- Laudanski, G., Reiffsteck, P., Tacita J. -L., Desanneaux, G. and Benoît. J. 2012. Experimental study of drilling parameters using a test embankment, in Proceedings of the Fourth International Conference on Geotechnical and Geophysical Site Characterization, 435-440, Porto de Galinhas-Pernambuco, CRC Press.
- Najafi, M. 2005. *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*, New York, McGraw-Hill.

- Pfister, P. 1985. Recording drilling parameters in ground engineering, Journal of Ground Engineering, **18**, (3), 16-21.
- Solberg, S. M. 2012. Improved drilling process through the determination of hardness and lithology boundaries, M.Sc. Thesis, Norwegian University of Science and Technology, Norway.
- Somerton, W.H. 1959. A laboratory study of rock breakage by rotary drilling, Petroleum Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers, 92-97, Society of Petroleum Engineers (SPE).
- Teale. R. 1965. The concept of specific energy in rock drilling, International Journal of Rock Mechanics and Mining Sciences & Geomechanics, **2**, (1), 57-73.
- Viana da Fonseca, A. and Coelho, S. 2006. Characterization of highly variable rock weathering by using DPR, in GeoShanghai International Conference, 127-134, Shanghai, American Society of Civil Engineers (ASCE).

Table 1. Summary of indices.

Index	Equation	Description of parameters
Somerton index (Somerton, 1959)	$S_d = W \times (N/V)^{1/2}$	<p>S_d = Somerton index</p> <p>W = weight on bit (thrust – retention force + weight of rods and bit) (kN)</p> <p>N = rotation speed (rpm)</p>

		$V = \text{drilling speed (m/s)}$
Hardness parameter (Bingham, 1965)	$\Gamma\text{-hardness} = NFD^2/VT$	$N = \text{rotation speed (rps)}$ $F = \text{thrust applied on the drilling bit (kN)}$ $D = \text{bit diameter (m)}$ $V = \text{drilling speed (m/s)}$ $T = \text{rotation torque (kN}\cdot\text{m)}$
MSE (Teale, 1965)	$E = F/A + 2\pi NT/AV$	$E = \text{Mechanical specific energy}$ $F = \text{thrust on bit (kN)}$ $A = \text{area removed by drill bit (m}^2\text{)}$ $N = \text{rotation speed (rps)}$ $T = \text{rotation torque (kN}\cdot\text{m)}$ $V = \text{drilling speed (m/s)}$
Alteration index (Pfister, 1985)	$A = 1 + \left(\frac{W}{W_{\max}} \right) - \left(\frac{V}{V_{\max}} \right)$	$A = \text{Alteration index}$ $W = \text{weight on the bit (thrust – retention force + weights of rods and bit) (kN)}$ $W_{\max} = \text{theoretical maximum value of } W \text{ (kN)}$ $V = \text{drilling speed (with maximum value } V_{\max} \text{) (m/s)}$
Energy used for drilling (Pfister, 1985)	$W = TN/V$	$W = \text{Energy used for drilling}$ $T = \text{value of the rotation torque}$

		(kN·m) N = rotation speed (rps) V = drilling speed (m/s)
E or Exponent method (Gui <i>et al.</i> , 2002)	$E = \log \Gamma_v / \log \Gamma_f$ $= \log \frac{V}{ND} / \log \frac{WD}{T}$ $\text{or } \Gamma_v = \Gamma_f^E$	V = drilling speed (m/s) N = rotation speed (rps) D = bit diameter (m) W = weight on the bit (kN) T = value of the rotation torque (kN·m)

Figure captions

Figure 1: Three-step installation procedure of GBM

Figure 2: Pilot tubes installation for sanitary line

Figure 3: Auger casing installation for storm line

Figure 4: (a) Manholes as reception shafts and (b) pilot tubes removal from manhole

Figure 5: Product pipes installation

Figure 6: Continuous measurement of data using datalogger

Figure 7: Recorded jacking pressure, rotational pressure, and rate of penetration

Figure 8: Change of alteration index vs. time

Figure 9: Change of Γ -Hardness parameter vs. time

Figure 10: Change of Somerton index vs. time

Figure 11: Change of MSE vs time

Figure 12: Energy required for drilling defined by Pfister (1985) vs time

Figure 13: Change of E vs. time

Figure 1

Figure 6

[Click here to download Colour figure \(online only\) Figure 6.tif](#)

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 13

Figure 12