ABSTRACT

It is essential to know the properties of the rock ahead of the face when digging a tunnel. We examined long-hole exploration drilling as a method of determining the rock properties with the objective of establishing an improved procedure for such surveys. This report describes the results of the development of an improved system for exploration drilling. For convenience, the system, including its data-storage package, was designed to be mounted on a drill jumbo. A large-diameter rod was used at the tip of the extension rods to prevent deviation of the hole, after testing had indicated that this was an issue. A rod with an integrated coupling sleeve was employed to reduce the time required for the test. Dedicated software was also developed to enable semi-automated processing of the data. The above features make the system convenient to use, and provide accurate data of the rock properties ahead of the tunnel face.

Keywords: Tunnel, Rock properties, Rock drill, Sleeve coupling, Exploration

1. INTRODUCTION

Geological surveys are necessary at sites of planned tunnels. It is not uncommon for such surveys to be incomplete, however, due to technical limitations and the desire to minimize costs. In such cases, the survey must be performed during actual tunneling operations.

Exploration drilling is one method that can be used to survey the rock ahead of the face during tunneling. This approach involves a minimal delay time and is a comparatively simple procedure. Several issues remain to be refined in this method, however, due to a number of influences that remain uncontrolled as the holes are drilled to greater depths ahead of the rock face.

As test methods have shifted from pneumatic drifters to laboratory equipment, many reports have described the characteristics of holes drilled with drifters. Hustrulid et al. (1971a, 1971b) proposed an equation for predicting drilling speed on the basis of research into the capabilities of drifters; they found that drilling speed is influenced by the magnitude of thrust. The U.S. Bureau of Mines (1959) and Clark et al. (1979, 1982) investigated the relation between drilling performance and rock properties, based on theoretical and experimental research. Lundberg (1982, 1987) published various numerical calculations for a rod-and-bit system, and examined the influence on drilling performance of the ratio between the impedances of the rod and bit. Schunnesson (1998) investigated the performance of in situ long-hole drilling.

There have been few investigations of systematically organized in situ long-hole drilling data from previous reports. We have gathered all the available data on long-hole drilling in an attempt to develop a procedure for assessing rock properties from the drilling data. This report describes the exploration drilling system that we constructed to efficiently gather and process data from long-hole drilling surveys.

2. HISTORY PRIOR TO SYSTEM DEVELOPMENT, GOALS OF DEVELOPMENT

Tunnel seismic prediction (TSP) is capable of revealing some of the rock properties up to 100–150 m ahead of the face. The obtained results represent the locations where the elastic waves are reflected; however, it is difficult to “read” the details of the rock properties using this approach. This method is particularly vulnerable to weak rock, which strongly attenuates elastic waves; consequently, its application is limited.

Increasingly, tunneling operations are using exploration drilling in place of TSP. A hydraulic drifter applies both percussion and rotating forces to the rod; the bit transmits these forces to the rock in order to fracture the surface. Some drifters are equipped with a damping mechanism to further increase drilling efficiency. The performance of drifters has been greatly improved in recent years, and it is now possible to drill holes up to 50 m in length, regardless of the rock properties.
Nevertheless, at the initiation of this study, considerations of instrumentation, measurements, assessment procedures and other aspects of the measurement of rock properties had yet to be systemized. This shortcoming was the motivation for seeking to systemize exploration-drilling procedures. The following conditions were set to ensure a more convenient and efficient exploration process.

1) The system shall contain a drill jumbo.
2) Drilling data shall be collected automatically.
3) The rock properties obtained from the drilling data shall be expressed numerically.
4) Drilling data shall be processed quickly.
5) The optimal rod shall be selected.

3. TEST VERSION OF THE DRILLING SYSTEM

We began by developing a test version of the drilling survey system to be driven by a drill jumbo. This was employed at three tunnels, and its operability and durability to withstand the tunneling environment were observed. Quantitative observations of rock properties were also collected.

The operating hydraulic pressure, rotation speed, thrust force and damping pressure were recorded, as was the drilling depth.

The data were measured over a drilling depth of 4 m in order to provide an envelope for the standard rod length of 3.6 m.

Most drifters rely on the extension of a hydraulic cylinder (see Fig. 1). The extension of the cylinder used in this system was estimated from the volume of inflow of hydraulic fluid. In drilling a long hole, additional rods were attached to the end of each rod, such that the appropriate multiple of rod length was added to obtain the actual drilling depth.

The data were obtained at a frequency of 1 Hz to take account of the volume of data to be stored. The following conditions were specified to avoid unnecessary fouling of the tunnel environment.

1) The test equipment was installed on a drill jumbo.
2) Waterproof and dustproof equipment were employed.
3) Shock-absorbing mounts were placed between the drill jumbo and the test equipment.
4) The power for the test equipment was supplied from the drill jumbo.

Figure 2 shows a diagram of the drilling survey system. The system was used in three tunnels, and data were recorded with regard to equipment operability, durability, rock properties, and measurement procedures.

4. IMPROVEMENT OF THE DRILLING SYSTEM

A number of improvements were made to the system after problems were discovered in the course of the test.

4.1 Data recorder

Given that the data recorder selected initially was rather large, it was planned to install it on the roof of the drill jumbo cabin; however, not all drill jumbos have convenient access to their cabin roofs, and it is possible that the space requirements for the equipment would be even tighter in tunnel boring machines (TBM). Therefore, the initial floppy-disk-based recorder was replaced with one that stored data on PC cards (Fig. 3). The new recorder offered greater storage capacity and superior resistance to vibration. Shock-absorbing mounts were installed, and the cards in the recorder were reinforced with silicone rubber.

4.2 Materials used for long-hole drilling

A drill jumbo was necessary for long-hole drilling, and tunnel excavation should be stopped while testing. It is therefore essential to minimize the testing time as far as possible. In a usual drilling, a rod threaded at each end and a coupling sleeve to connect adjacent rods is used. These drilling tools were used for the prototype of the present system; however, a time study revealed that much of the drilling time required when these tools are used. Therefore, the drilling tools were replaced with rods as shown Fig. 4. The new drilling tools do not require a coupling sleeve and save the time for connecting rods.

Figure 5 shows one of the problems inherent in long-hole
drilling, namely deviation. Not only does deviation accelerate wear at the threads of the rods, it also inevitably affects the precision of the survey. We encountered a deviation of over 3 m in a hole of less than 20 m depth, as shown in Fig. 6; such magnitudes are not uncommon. One of the ways to suppress this effect is to stiffen the rod tips, which is known to improve the straightness of the hole. The diameter of the rod that held the bit was increased to 45 mm to improve its stiffness as shown in Fig. 7, making it considerably stiffer than the connecting rod with a diameter of 32 mm.

4.3 Organization of data

The rod attachment time was recorded for this test, in addition to drilling time. The first task in organizing the recorded information was to extract only the drilling time data. Commercial spreadsheet software was used in the initial experiment, but it required much time and experience to obtain the times; consequently, we switched to dedicated software that partially automated this task to save time during data processing.

5. EXPLORATION DRILLING SYSTEM

Depending on the drilling conditions in the tunnel, it generally takes about 2 hours to carry out an exploration drilling survey to a depth of 30–50 m (including preparation and takedown time). The following procedure was employed in taking measurements for a hole of 30 m depth with a drill jumbo using measurement equipments, as shown in Fig. 8.

![Figure 4. Male-Female extension rods.](image)

![Figure 5. Examples of bended long-holes (Atlas Copco, 1997).](image)

![Figure 6. Deviation from the target position in percussive long-hole drilling.](image)

![Figure 7. First and middle extension rods.](image)

![Figure 8. Measurement equipments mounted on a drill jumbo.](image)
1) The drill jumbo is placed at the face and the desired number of rods (1 bit holder and 9 connecting rods) and the bit (diameter: 64 mm) are brought to the tunnel.

2) The data recorder is turned on.

3) The hydraulic pump of the drill jumbo is activated and the bit holder is installed with the bit attached.

4) The rod tip is oriented in the desired drilling direction.

5) The thrust and percussion pressures are adjusted to the desired values.

6) Data recording is initiated.

7) The hole is drilled while holding the thrust and percussion pressures constant.

8) Detritus is sampled, as shown in Fig. 9, and the color of the slurry is recorded.

9) Operations 7) and 8) are repeated as new connecting rods are added.

10) The desired drilling is completed.

11) Data recording is stopped.

12) The rods are withdrawn.

13) The hydraulic pump is turned off once all the rods have been recovered.

14) The rods and bit are removed from the tunnel.

15) The drill jumbo is moved from the face and parked.

Software was written specifically to obtain the fastest possible organization of the data, and the drilling speed and specific energy of cutting (energy consumed/drilled volume) were calculated. The drilling speed showed a high correlation with the rock properties when similar drifters were used under similar drilling conditions (Fukui et al., 2004). The specific energy of cutting is a widely used parameter, along with digging efficiency and the rock mass evaluation system (in mechanical digging), for evaluating tunneling equipment such as TBM and boom-type roadheaders as well as drifters.

Figure 10 shows a flow chart of the method employed in processing the data; a sequencing analysis in Fig. 10 takes about 1.5 hours. The first step is to select the drilling time data from the measurements. From this information, the variations in elapsed time due to drilling distance, driving pressure, percussion pressure, damping pressure, feed pressure, and drilling speed are plotted. Data selection can be performed automatically or manually. For automatic selection, data is chosen when it exceeds a pre-set threshold value, as determined by the user.

A graph is then made showing drilling data (rotation, percussion, feed drilling speed, and specific energy of cutting) versus the drilling distance on the horizontal axis. The results of the observations are entered at this time.

If previous observations yielded relationships between the specific energy of cutting and rock properties, it is possible to show the calculated rock properties in the boring region. The final output screen is displayed once the job has been completed. The user can choose between the values indicated at the 1 Hz measurements, or the mean values for the boring region.
6. SUMMARY

This report describes the process involved in the development of a rock survey system and the design goals. The system was improved on the basis of testing; these improvements are also described. The following features of the new system were noted.

1) Preparation for surveying was simplified by improving the durability of the survey equipment.
2) The system suppressed deviation of the borehole and was used to carry out long-hole drilling surveys.
3) Special software was developed to increase the speed of data processing.

These features enable the user to obtain data from long-hole drilling surveys with greater speed and convenience than is possible with currently available systems.

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REFERENCES