Geological Prediction Ahead of the Tunnel Face by the Exploration Drilling System
During the Tunnel Excavation

T. Kuwahara¹, K. Hata¹
¹ Technical Research Institute, Obayashi Corporation, Tokyo, Japan

1. Introduction
For safe and rational mountain tunneling, it is essential to accurately survey the geology ahead of the tunnel face. In Japan, a wide variety of techniques for geological prediction ahead of the face have been employed, the most typical of which is geophysical exploration. However, issues have remained relevant to practicable depth of survey and accuracy, and time necessary for on-site measurements and data analysis. In these circumstances, non-core drilling exploration using a drifter mounted on a hydraulic wheel jumbo has been deemed a promising technique that can be always available without stopping face advance.

Non-core drilling exploration employs a specifically designed measurement system installed on the drifter, to acquire data of drilling velocity, impact pressure, rotation pressure, feed pressure and impact energy, thereby evaluating numerically the geological properties ahead of the face based mainly on the drilling velocity and impact energy. This technique of non-core drilling data is based upon the drilling theory developed in the area of mining [1]. The rotation pressure and feed pressure must be necessarily kept constant for allowing geological evaluation referring to the drilling velocity and impact energy. However, in a non-uniform zone, a fracture zone and a fault zone, the feed pressure tends to noticeably fluctuate, making it impossible to make accurate assessment.

The authors analyzed in detail the results of various experiments and drilling data, and developed a drilling velocity conversion analysis system capable of evaluation independent of feed pressure [2,3]. During non-core drilling exploration, the feed pressure is always varying. If, assuming the feed pressure to be constant, the equivalent drilling velocity must enable geological evaluation to be unaffected by feed pressure fluctuation. For developing this system, the relationship between drilling velocity and feed pressure was established, and the equivalent drilling velocity (referred to as “converted drilling velocity”) was calculated. The converted drilling velocity was normalized to be dimensionless to define a new parameter “Normalized Drilling Velocity Ratio.” The authors conducted a case study for geological prediction ahead of the tunnel face involving the Normalized Drilling Velocity Ratio and for validation of this technique [3,4,5], and verified the effectiveness of this analysis system. This paper provides a description of the comprehensive prediction of the geology ahead of the face by means of Conversion Analysis of Non-core Drilling Velocity.

2. Flow of exploration ahead of the face by the Conversion Analysis of Non-core Drilling Velocity
Fig. 1 is the schematic diagram of non-core drilling exploration and Fig. 2 the configuration and flow of the geological exploration ahead of the face by the Conversion Analysis of Non-core Drilling Velocity (referred to as “CANVEL”).

STEP 1: Determine the correlation between feed pressure and drilling velocity from non-core drilling data.
STEP 2-1: Based on the correlation determined by STEP 1, calculate the equivalent drilling velocity (converted drilling velocity) assuming that the feed pressure, which always fluctuates during non-core drilling, is kept constant.

STEP 2-2: Calculate the new parameter, Normalized Dimensionless Drilling Velocity Ratio (referred to as “NVR”) that is obtained by normalizing the converted drilling velocity.

STEP 2-3: Based on the NVR, find weak sections such as fault zones, weathering and hydrothermal alteration zones, and determine the engineering rock mass classification.

STEP 3: Determine the correlation between NVR and rock properties (evaluated by laboratory tests) at the tunnel face.

STEP 4-1: Using the correlation determined by STEP 3, calculate the competence factor in the tunnel rock mass (referred to as the “competence factor”) from the NVR and predict the squeezing and swelling tendencies.

STEP 4-2: Using again the correlation determined by STEP 3, calculate the reflection coefficient of seismic wave from the NVR, and verify the location of fault zones predicted by seismic imaging using seismic reflection waves such as HSP and TSP during tunnel excavation.

STEP 5: After implementing the geological exploration ahead of the face, conduct geological observation at the face and verify the prediction results, to grasp the relationship between initial design, prediction and actual results.

3. Geological evaluation using the new parameter “Normalized Drilling Velocity Ratio (NVR)”

3.1 Correlation between drilling velocity and feed pressure
To learn the correlation between drilling velocity and feed pressure, a study was conducted in three steps (Fig. 2 STEP 1)
1) Drilling test with various drilling parameters, using a test specimen (1 x 1 x 2 m) of uniform large granite
2) Drilling test at the tunnel face, varying the feed pressure stepwise in a single zone where the geology and engineering rock mass classification are estimated to be almost the same.
3) Detailed analysis of previous data of non-core drilling exploration made repetitively with varying feed pressure in each of the zones estimated to be composed of the same geology and rock mass class.

The study above demonstrated that the drilling velocity decreases as the feed pressure diminishes, and inversely as the feed pressure increases, the drilling velocity becomes higher. This fact is schematically shown in Fig. 3. The correlation between drilling velocity and feed pressure was interpreted as the correlation between difference in drilling velocity \( V \) and that in feed pressure \( F \) (\( \Delta V \sim \Delta F \)) to obtain a three-dimensional polynomial regression equation.

3.2 Definition and calculation of the NVR
The calculation procedures and definition of the NVR are shown below (Fig. 2 STEP 2).

In the following equations,

\( i = I^{th} \) drilling data, \( F(i) = \) feed pressure (MPa), \( Fc = \) reference value of feed pressure (MPa), that is 4.9 MPa, \( V(i) = \) drilling velocity (cm/min), \( V'(i) = \) equivalent drilling velocity, that is converted drilling velocity (cm/min).

1) Calculate the difference between measured feed pressure and reference feed pressure.
   \[ \Delta F(i) = F(i) - Fc. \]  

2) Calculate the correction value for obtaining the converted drilling velocity \( V' \).
   \[ \Delta V(i) = a (\Delta F(i))^3 + b (\Delta F(i))^2 + c \Delta F(i) + d \]  
   \[ \Delta V - \Delta F \) correlation formula above mentioned and shown in Fig. 4, \( a, b, c, d = \) coefficients.

3) Calculate the converted drilling velocity \( V' \).
   If \( \Delta F(i) \leq 0, V'(i) = V(i) + \Delta V(i). \)  Eq. (3)
   If \( \Delta F(i) \geq 0, V'(i) = V(i) - \Delta V(i). \)  Eq. (4)

4) Calculate the Normalized Drilling Velocity Ratio.
   \( NVR(i) \propto \frac{V'(i)}{(V'(max) - V'(min))} \)  Eq. (5)
   where \( 0.0 \leq NVR(i) \leq 1.0. \)

4. Geological evaluation based on the correlation between the NVR and bedrock properties

4.1 Correlation between the NVR and bedrock properties
Along with non-core drilling exploration, rock was sampled from the tunnel face and laboratory tests were conducted. As a result, the following equations give the correlation of laboratory test results between NVR – unit weight, elastic wave velocity and unconfined compressive strength, as shown in Fig.5 (Fig. 2 STEP 3).

\( \gamma(i) = -47.4 NVR(i) + 40.5. \)  Eq. (6)
\( Vpc(i) = -21.3 NVR(i) + 11.7. \)  Eq. (7)
\( \sigma c(i) = -642,000 NVR(i) + 297,000. \)  Eq. (8)
In the equations

\( i = 1 \) through drilling data and relevant property data, \( NVR(i) \) = Normalized Drilling Velocity Ratio, \( \gamma(i) \) = unit weight \((\text{kN/m}^3)\), \( Vpc(i) \) = elastic wave (ultrasonic wave) velocity obtained from laboratory test \((\text{km/s})\), \( \sigma c(i) \) = unconfined compressive strength \((\text{kN/m}^2)\).

4.2 Calculation of the competence factor

The competence factor represents the relationship between unconfined compressive strength of the ground at the excavation location to the ground pressure (overburden pressure). It is one of the indices to assess the stability of the tunneling face. Practically it is not easy to measure the ground pressure, evaluation is made by the ratio of unconfined compressive strength to overburden pressure. The competence factor is given by the following equation.

\[
\text{Competence factor} = \frac{\sigma c}{(\gamma \cdot H)} \quad \text{Eq. (9)}
\]

where \( \sigma c = \) unconfined compressive strength of ground \((\text{kN/m}^2)\), \( \gamma = \) unit weight of ground \((\text{kN/m}^3)\), \( H = \) overburden height \((\text{m})\).

For each data sample in the non-core drilling, the terms necessary for calculation of Eq. (9) are determined, as follows (Fig. 2 STEP 4). The overburden height \( H \) \((\text{m})\) is given in the tunnel design document (longitudinal tunnel section). The unconfined compressive strength of ground \( \sigma c \) \((\text{kN/m}^2)\) and the unit weight of ground \( \gamma \) \((\text{kN/m}^3)\) are obtained by Eqs. (6) and (8).

4.3 Calculation of reflection coefficient elastic wave

The intensity of the reflected elastic wave from the interface is given in terms of the reflection coefficient. The reflection coefficient \( r_i \), which is defined as the amplitude ratio of reflected wave to incident wave, depends on difference in acoustic impedance at the interface, given by Eq. (10).

\[
r_i = \frac{(Z_{i+1} - Z_i)}{(Z_{i+1} + Z_i)} = \frac{(\rho_{i+1} V_{i+1} - \rho_i V_i)}{(\rho_{i+1} V_{i+1} + \rho_i V_i)} \quad \text{Eq. (10)}
\]

where, supposing the wave coming from the \( i \)th layer normally to (\( i+1 \)th layer, \( Z_i = \) acoustic impedance= \( \rho_i V_i \), \( \rho = \) density, \( V = \) elastic wave velocity obtained from seismic exploration \((\text{km/s})\).

Denoting by \( r'_i \), the reflection coefficient obtained from the non-core drilling data (Fig. 2 STEP 4), we obtain

\[
r'_i = \frac{\gamma_i Vpc_{i+1} - \gamma_{i+1} Vpc_i}{\gamma_i Vpc_{i+1} + \gamma_{i+1} Vpc_i} \quad \text{Eq. (11)}
\]

where \( \gamma = \) unit weight of ground \((\text{kN/m}^3)\), \( Vpc = \) elastic wave (ultrasonic wave) velocity obtained from laboratory test \((\text{km/s})\). These values are given by Eqs. (6) and (7).
5. Cases of geological evaluation by the Conversion Analysis of Non-core Drilling Velocity (CANVEL)

5.1 Overview of the case studied
This case study was made on a fault zone, using the results of the pilot boring (core observation), velocity logging (P wave), TSP (Tunnel Seismic Prediction) and geological survey at the heading face, to validate the geological evaluation involving the NVR, calculated competence factor and reflection coefficient.

5.2 Analytical results by the CANVEL
Fig. 6 shows the measurement and analysis results of the non-core drilling data. In this figure are also given drilling velocity, feed pressure, impact energy and the NVR, competence factor and reflection coefficient, obtained by the CANVEL.

The drilling velocity tends to increase in weak ground zones, for example, fault zone and weathering and hydrothermal alteration zone. However, as learned from Fig. 6, it is difficult to determine the geology based on this criterion in some cases. The graphs suggest that, with feed pressure fluctuation, the geology cannot be correctly predicted from the drilling velocity and impact energy.

The value of NVR increases as tunneling ground is weaker. In the fault zone (III in the figure) and shear zone (VII), the NVR increases abruptly, whereas the competence factor drops suddenly, and with these steep variations, a larger reflection coefficient appears, representing the geological specificity of these zones. The competence factor was validated separately [5].

5.3 Validation of the CANVEL involving data of various surveys of the geology ahead of the face
Fig. 7 shows NVR, rock species and engineering rock properties of the drilling core, RQD (Rock Quality Designation), P wave velocity and reflection surface distribution determined by the TSP. Eight weak ground zones were extracted from the results of pilot boring, velocity logging and TSP (I to VIII in the figure). These weak ground zones include fault zone, weak zones composed of fragments, breccias and clay, low RQD zones, low velocity zones, and reflection surface zones.

The relationship between these weak ground zones and characteristic variations of NVR are as follows.

1) A distinct and correct correspondence of anomaly of NVR was found at five sections among eight weak ground sections, and correspondence with slightly positional incorrectness at one section, and no correspondence at two sections.
2) In the five sections (II to IV, VI, VII in the figure) where distinct correspondence was found, to the clayey core, fragmentation and low RQD, whereas correspondence to low velocity zones and reflection surface zones TSP was not clear in some cases.
3) In terms of the NVR, the anomaly magnitude is in the order of III+IV, VII, VI, II. Sections III + IV are clayey and breccias shale and granitic cataclasite of the principal fault section. Zones VII and VI, slightly apart from the principal fault zone, are composed of breccias and granitic cataclasite. Zone II is the boundary between alternation of sand stone/shale and lapilli tuff before the principal fault zone. These sections correspond to the low RQD zones and also to the low velocity zones. Therefore, anomalies in terms of NVR detect essential geological variations within an accuracy of about one meter.
4) The standard relationship between NVR and engineering rock mass classification [6] was proposed [3]. The prediction of the engineering rock mass classification showed geological conditions more adverse than that in the initial design, over an extended range including a fault zone. The results of the excavation were almost the same as the prediction.

Summarizing the above description, we can state that the geological evaluation by the CANVEL agrees very well with the results of surveys ahead of the face by other techniques, and the geological observation results of the face during excavation and with the records of tunneling.
Fig. 6  Conventional exploration drilling data and analysis results by the CANVEL
Fig. 7  New parameter “NVR” and geological characteristics

Two weak zones inferred from the following different methods.

- ▼: CANVEL
- ▼: Seismic imaging

Fig. 8  Reflection coefficient calculated from the NVR and seismic imaging
5.4 Comparison between reflection coefficient calculated from the NVR and seismic imaging using seismic reflection wave

Fig. 8 shows the comparison of the distribution of the reflection coefficient of elastic wave calculated from the NVR with the TSP results. With both techniques, a large reflection coefficient appears at four spots, corresponding to a fault zone and a shear zone (shown as III and VII in Figs. 6 and 7), but there are positional differences between the results of both techniques.

With respect to the reflectance surface nearer to the tunnel face, the positional difference is 1 to 3 m, but for the further reflection surface, the difference is larger, 10 to 16 m. These differences are attributable to setting error of analysis velocity, frequency bands of reflection waves and multiple reflection. Combination of one-dimensional non-core drilling exploration and two- or three-dimensional seismic imaging using seismic reflection waves, is effective for geological prediction ahead of the face. The results discussed here suggest effectiveness of cross checking of the seismic imaging referring to non-core drilling exploration.

6. Conclusions
The record of the utilization of the CANVEL is as follows. The number of cases of geological surveys ahead of the face using this technique totals 10, including the plans for 2010, solely in Japan until the time of preparation of this paper, with the survey distance spanning about 14 km.

The geological conditions surveyed are two cases of accretionary prism, one case of fault zone including cataclastic rock, three cases of granitic rocks, four cases of volcanic and tuffaceous soft rocks of Tertiary and Quaternary Age. The main purposes of the survey are detection of fault zones, fracture zones and weathering and hydrothermal alteration zones, engineering rock mass classification for selecting a support pattern and prediction of swelling and squeezing tendencies of soft bedrock.

The authors are accumulating information on the relationship between the NVR and auxiliary stabilizing methods. For use of this analysis technique for construction management, a framework has been well established to create an analytical diagram by the use of specific analysis software and an ordinary personal computer with easy operation.

References