Monitoring the Vibration Response of a Tunnel Boring Machine for Real-Time Detection of Geological Conditions

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varied the type of rock and fractures including joint and faults. Fig.3



Fig. 2 The double shield TBM used in the TBM construction section https://www.rtco.co.th/portfolio

Table 1 Specifications of double shield TBM.

Parameter		
Machine Diameter (m)	4.74	4.93
Number of machines	2	1
Cutter (inch)	17	19
Number of disc cutter	32	30
Recommended cutterhead thrust (kN)	8,000	9,069
Cutterhead speed (RPM)	9.0	12
Available cutterhead torque (kNm)	1570	2552
Thrust cylinder stroke length(m)	1.4	1.4
Cutterhead weight (ton)	411.2	299.0

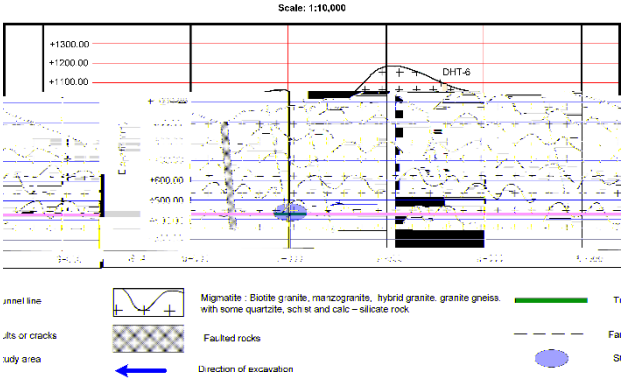

Fig. 3 The geological condition between STA:06+500 and 09+000

3. Measurement setup

3.1 Geophone

The vibrations are monitored using a geophone which is a passive velocity sensor, inexpensive, and highly sensitive for detecting very small amplitudes of vibration. The geophone consists of a magnetic mass moving within a wire coil surrounded by a casing. The relative movement of the magnetic mass to the wire coil from a vibration source induces a voltage that can be converted to the velocity. The uniaxial geophone used to capture the vibration is the SM-24 model, which have a frequency range varying from 10 to 240 Hz. Its sensitivity is 28.8 V/m/s, and the natural frequency is 10 Hz as shown in Table 2 Data logger used to record the data is the PCD-320A model connecting with control software to the computer with the USB interface. In this study, the maximum frequency recorded is 1000Hz based on the work of [4]. The investigated the vibration response of the TBM under MFC. At location 1, the geophone is installed on the shield (Font of the tunnel machine) in the vertical Y-direction. the Geophone uniaxial vertical (GYV) could measure the velocity in orthogonal directions vertical. At location 2 installed segments the left and right wall at segments the X-direction is horizontal, the Geophone uniaxial horizontal in Right and Left (GXR, GXL). Two uniaxial geophones are mounted on a steel rod in the borehole at a depth of approximately 15 -20 cm with a length of 50 cm. In orthogonal directions vertical to the TBM axis in left and right wall at segmental. Tunnel direction TBM advancing direction Z. All analyses concerning directions used the coordinates XYZ. For geophone no.1, the installation location is attached to the shield part of the TBM to record the vibration in the Y direction. Instruments no. 2 and 3 are installed at the segment wall zone to capture the vibration behind the TBM shield. The installed geophones on the segment wall, a steel rod is used as shown in Fig. 4-5. The installation of vibration measurement and data acquisition due to the geophone vibration environment in the excavation site at the geophone is close to the vibration origin, the results are more accurate.

Table 2 Specification is Uniaxial Geophone was SM-24

Sensitivity	28.8 V/(m/s) (0.73V(/in/s))
Tolerance	±2.5%
RtBcfn	6,000 W Hz
Moving mass	11 g (0.38 oz)
Maximum coil excursion p.p.	2 mm (0.08 in.)
Standard	375 W
Tolerance	±2.5%
Physical characteristics	
Diameter	25.4 mm (1 in.)
Height	32 mm (1.26 in.)
Weight	74 g (2.6 oz.)
Operating temperature range	-40°C to +100°C

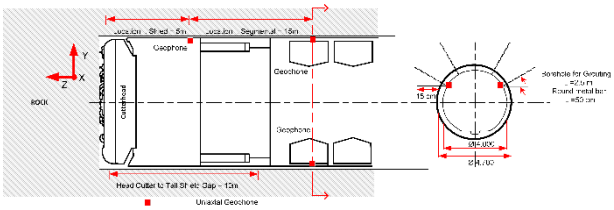

Fig. 4 The location of the Geophone location of the vibration measuring



Fig. 5 (a) GYV, (b) GXR, (c) GXL

3.2 Time-domain and frequency domain analyses

The fast Fourier transform (FFT) is a commonly used method to transform a signal in the time domain to a frequency domain. FFT computes the discrete Fourier transform (DFT) and its inverse. by Eq. (1)

$$\boldsymbol{X[h] = \sum_{i=0}^{N-1}\left(x[i]W_N^{ih}\right), W_N = e^{-\frac{j2\pi}{N}}} \quad (1)$$
$$\boldsymbol{h = 0, 1, 2, \ldots, N-1}$$

The FFT algorithm is used to convert a signal (x) with length (N) from the time domain into a signal in the frequency domain (X), since the amplitude of vibration is recorded based on its evolution versus the frequency.

It has the strengths of fast calculation and distinct physical meaning and frequency domain analysis over time-domain analysis is its ability to identify and isolate certain frequency content of interest. [5] The vibration frequency varies during the machine operation and geological conditions. The Fourier transform algorithm determines the frequencies corresponding to the large amplitudes (or high energy) of these fundamental sinusoidal signals (or cosine signals) and then detects the frequency and amplitude distribution features of the vibration signals. Therefore, the Spectral FFT frequency domain analyses the spectral amplitudes among the frequencies 160 Hz - 170 Hz, 200 Hz - 210 Hz, and 220 Hz - 230 Hz are larger than those at the other frequencies. Hence, to avoid resonance, the frequencies of the TBM equipment should not coincide with these frequencies.[6] Therefore, the frequency content during a field test in the Frequency-domain during TBM boring without thrust force is investigated. The authors obtained the Fourier spectra using the MATLAB code, adopting the FFT Discrete Fourier Transform as the data processing method.

4. Results and Analysis.

4.1 In-situ monitoring for the interaction between the surrounding rock and TBMs operating parameter

The monitoring for vibrating on surrounding rock conditions is monitored during boring at the Chainage 07+56.77 - 07+ 39.07. The TBM measurement was performed at six rings in the concerning section, including Ring Nos. 4363, 4364, 4367 ,4371, 4372 and 4374. The surrounding rock at this monitoring location is biotite, granite, hornfels, and impure marble with the presence of local faults, etc., with changes in ground conditions the critical TBMs operating excavation perimeters showed that the surrounding rock is of mixed ground conditions with soft and hard rock. On-site testing using the Schmidt hammer (SH) on rock mass at the tail shield gap is used to determine uniaxial compressive strength through the index method of the SH. SH rebound readings are considered consistent and reproducible, fast, non-destructive, and for evaluations of rock material [7]. The uniaxial compressive strength of the rock with a high alteration degree is with an average result of 115.751 - 129.250 MPa, Fig.6-7. The operation parameters of the TBM during excavation are shown in Fig.8. Operation parameters (OP) of TBM are measured, namely the advance rate (AR), cutterhead torque (T), cutterhead rotation rate (N) and axial/thrust force (F). The highly dependent on the TBM operation and monitoring of measured vibration data with each cycle lasting for 30 minutes



Fig. 6 Geological images after excavation on Head Cutter to tail shield gap Ring Nos. 4363, 4364,4367

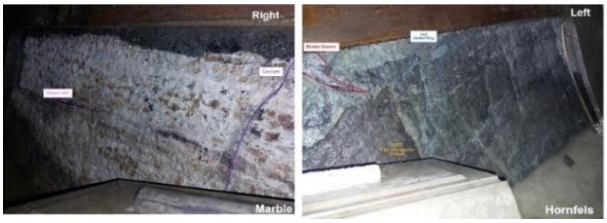

Fig. 7 Geological images after excavation on Head Cutter to tail shield gap Ring Nos. 4371, 4372, 4374

Fig. 8 TBM operating parameters in during excavation.

4.2 Time-Frequency Under MFC

The ambient noise produced by the TBM can influence the accuracy of the analysis of the signal caused by the excavation. Therefore, the magnitude and frequency of ambient noise during TBM operation with and without thrust force are investigated and shown in Fig. 9. The vibration monitoring frequency-domain analysis at 3 min during TBM boring without thrust face showed predominant frequencies of 50,126, 156 Hz, with single Sided Amplitude Spectrum of 4.747 $x10^{-4}$ and 1.4x $x10^{-4}$. The cutterhead torque is 194.631kNm, and the cutterhead rotational speed is 5 rpm. The vibration energy of the cutterhead is distributed in the frequency range of 0–130 Hz, whereas that of the main girder is distributed in the range of 0–100 Hz [8]. If the power source frequency is under the basic frequency of 50 Hz, the drive motor output torque is kept constant, while the rotation speed increases until the output power runs up to the rated horsepower. [9].

Surrounding rock conditions during the vibration monitoring on 10-11 June 2021 between the station 07+56.770 and 07+44.732. The vibration monitoring frequency-domain analysis at 30 min. The analyzed and the spectrogram is shown in the frequency domain Fig.10-11. The analysis reveals distinct frequencies in the TBM working in MFC vibration response. These frequencies are evident in primarily three clusters with frequencies of 125-130, 155-160, and 200-250 Hz, without the frequencies in the range of 200-250 Hz on right and left segments. The frequencies of 125 - [(ke)7(pt)6( )-352-352-352-352-352-352-352-35q0.00000887t(546(d)] TJ-T(e)-8( )] TJ3(3)-4( )-33)7( )-83(st)3(Qb0.0

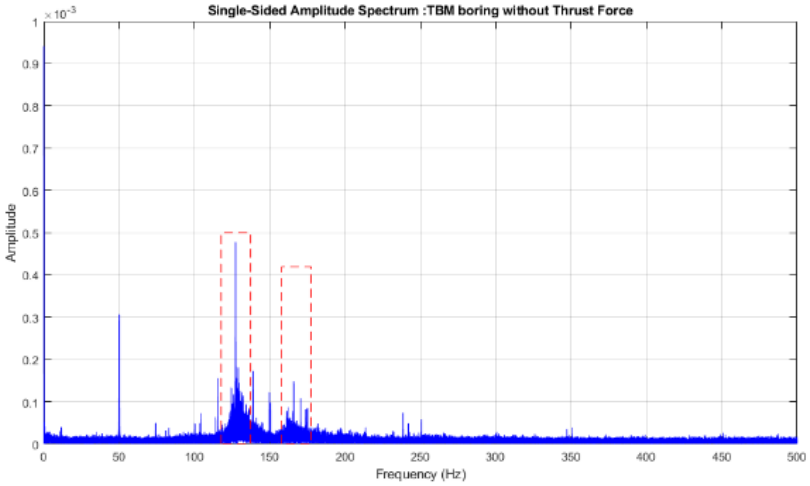

Fig. 9 Frequency-domain analysis during TBM boring without Thrust Force

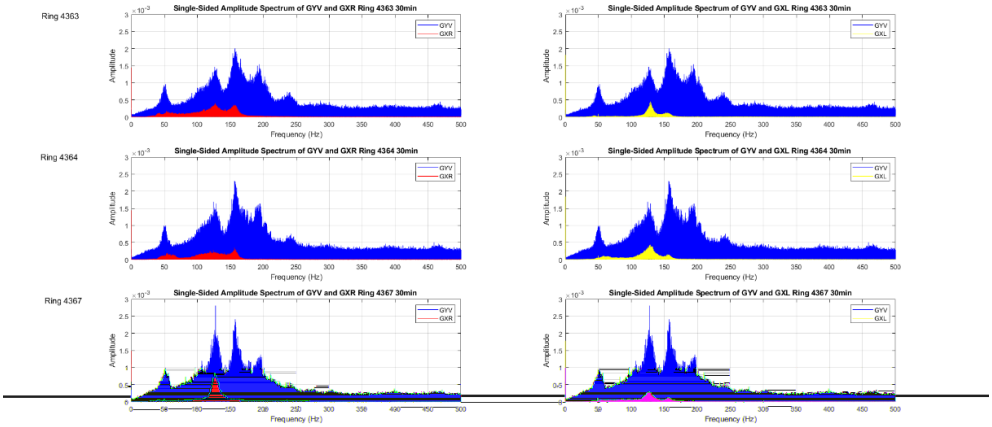

Fig. 10 Frequency-domain analysis under different ground conditions. Frequency - Amplitude between at Shield, Right wall, and Left wall segment. Ring Nos. 4363, 4364, 4367

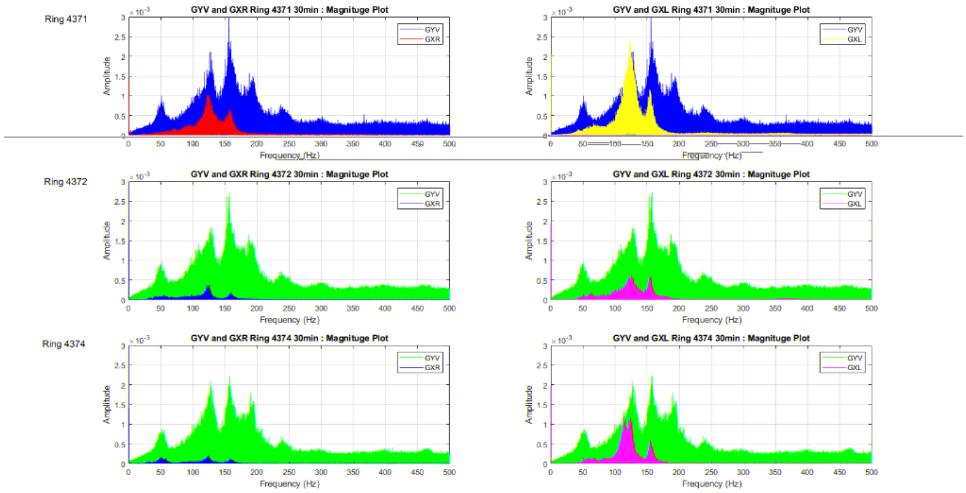

Fig. 11 Frequency-domain analysis under different ground conditions. Frequency - Amplitude between at Shield, Right wall, and Left wall segment. Ring Nos. 4371, 4372, 4374

4. The mixed ground conditions influenced the TBM dynamic response depending on geological changes, i.e., the amplitude and frequency of vibration are larger in the hard rock conditions. Also, the different ground conditions are identified on the right and the left side of the tunnel.

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