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

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Abstract

During tunnel excavation, unexpected geological conditions and changes in the advancing direction present geological hazards and challenging problems during tunnel construction. In the study, real-time vibration monitoring is carried out on the surrounding rock during the excavation process using a tunnel boring machine (TBM) to study the changes in the vibrational response and geological conditions. The monitoring is performed on the Mae Tang - Mae Ngad - Mae Kuang Diversion Tunnel Project in Northern Thailand which is excavated using a TBM. The diameter of the tunnel is 4.74 meters, and the excavation is in general in rock conditions. The monitoring system consists of geophone sensors mounted on the Tunnel Boring Machine and on the segmented wall. Subsequently, velocity time histories are analyzed in the time domain and spectral frequency domain. The TBM vibrations during excavation in hard rock or mixed face ground conditions (MFC) in addition to the TBM parameters are related to geological conditions and results from the monitoring suggested that the geological conditions changed during the drilling process.

Keywords: (TBM real-time vibration monitoring, time domain, spectral frequency domain, geological conditions)

1. Introduction

When tunneling in rock with a tunnel boring machine (TBM), the geological conditions are an important factor in problematic geological such as mixed-face ground, faulting, fracturing, rock bursting, squeezing, swelling, and high-water inflow [2]. The influence of the TBM advance rate, rock fragmentation efficiency, cutter head wearing, and deformation or damage to the TBM surface is assessed with a borehole geological survey at sampling locations along the tunnel route. However, the interpolated geological maps do not sufficiently accurately predict the local geological variations and such complicated geological variations and potential geological hazards during tunnel construction can cause a great loss of life and property [3].

In this paper, field monitoring is carried out on the surrounding rock during the excavation process to validate the prediction of mixed face ground conditions in real time. The vibration data were obtained during TBM excavation under changing ground conditions in of Mae Tang - Mae Ngad diversion tunnel project in Northern Thailand as shown in Fig. 1. This work's primary objectives and contributions were summarized as follows: (1) to study the TBM vibration characteristics during tunneling under mixed face ground conditions (MFC).

Fig. 1 Location of Mae Tang-Mae Ngad diversion tunnel project Northern, Thailand.[1]

2. Study area and data acquisition

2.1 Project overview

The tunnel boring machine (TBM) vibration data were acquired from of Mae Tang-Mae Ngad diversion tunnel project in Northern Thailand. The total length of the tunnel is 25.26 km and is excavated by double shield TBMs, as shown in Fig.2 The double shield TBM parameters, which consist of cutterhead torque, axial thrust, cutterhead rotational speed, and advance rate used to perform the excavation in Table 1. This project encounters the complex geological condition which has highly 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

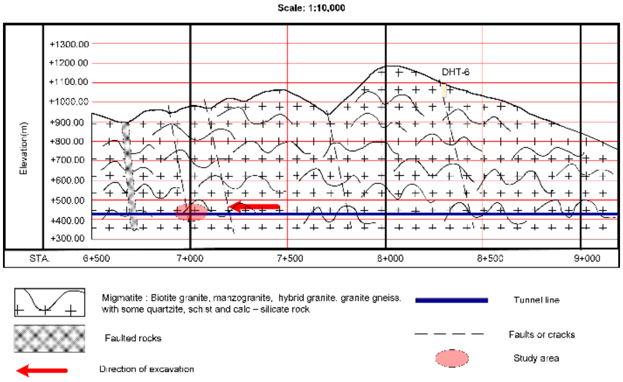

Fig. 3 The geological condition between STA:06+500 and 09+000

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

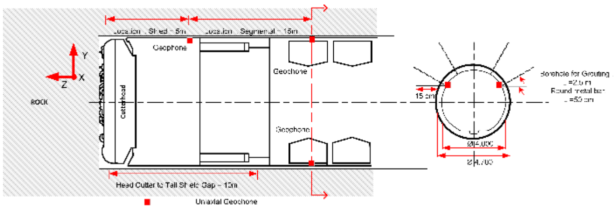

Fig. 4 The location of the Geophone location of the vibration measuring

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)

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

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

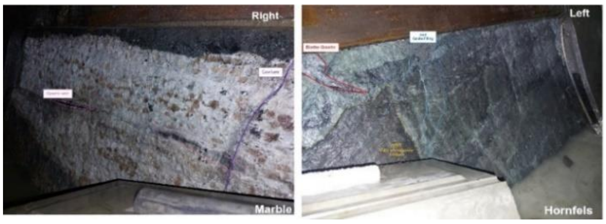

Fig. 7 Geological images after excavation on Head Cutter to tail shield gap Ring Nos. 4371, 4372, 4374

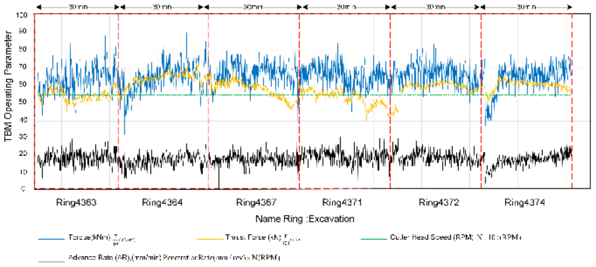

Fig. 8 TBM operating parameters in during excavation.

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 - 130 HZ indicate that the maximum vibration amplitude in the perpendicular direction to the cutter-head face (GYV) reaches 2.81 $x10^{-3}$ which is higher than those in the other two (GXR, GXL) directions (i.e., 8.33 $x10^{-4}$and 4.51$x10^{-4}$). The frequencies 155 -160 Hz indicate that the vibration amplitude in the direction perpendicular to the cutterhead face (GYV) reaches 2.41x $x10^{-3}$. which is higher than those in the other two (GXR, GXL) directions (i.e., 3.61 $x10^{-4}$and 1.58 $x10^{-4}$). At GXR and GXL as the distance from the cutterhead increases, the vibration energy is concentrated in a lower spectrogram in the frequency domain and amplitudes. The analysis reveals distinct frequencies in the TBM working in MFC vibration response, including Fig. 10-11. Differences in conditions geological conditions. Fig. 6-7. That the stronger the hard rock, the larger the amplitude and the more concentrated the frequency. The larger the difference in rock strength within the stratum, the larger the amplitude difference [10]. Comparison of TBM vibration time frequency characteristics in different ground MFC conditions. By comparing the vibrations of Rings 4363-4364 and 4371-4372. At data perpendicular direction to the cutter-head face (GYV). The analysis found the same frequency of 125-130, 155-160, and 200-250 Hz. At of Ring 4371-4372. This maximum vibration in amplitude 2.1 $x10^{-3}$,3 $x10^{-3}$,1.6 $x10^{-3}$. The ring 4363-4364. This is because, with a lower amplitude reaches 1.3$x10^{-3}$,2.2 $x10^{-3}$,1.6$x10^{-3}$.

5. Conclusion

In this study, Monitoring the Vibration Response of a Tunnel Boring Machine for Real-Time Detection of Geological Conditions. The data analysis methods have been applied to in-situ monitoring. The conclusions are:

1. The frequency-domain analysis with a duration of three minutes during TBM boring without thrust force can identify the frequencies that directly affect the analysis results based on cutterhead rotating speed and can be considered as one of the influence parameters on cutterhead vibration considering that during the actual tunneling process the TBM works in MFC vibration response.
2. The vibrations in the tunneling in the perpendicular direction to the cutter-head face (GYV) direction are more intense than those in the lateral two (GXR, GXL) direction. The frequencies of vibration energy are predominantly concentrated at approximately 125-160 Hz, and at (GYV) those of the medium-low vibration energy are concentrated at approximately 200-250 Hz. At GXR and GXL as the distance from the cutterhead increases, the vibration energy is concentrated in a lower frequency and amplitudes.
3. Monitoring the vibration response of heterogeneous strata primarily affects the amplitude and frequency content of the vibrations. Moreover, a difference in the band of frequencies around the predominant frequencies varies and may be an indicator of mixed ground conditions.

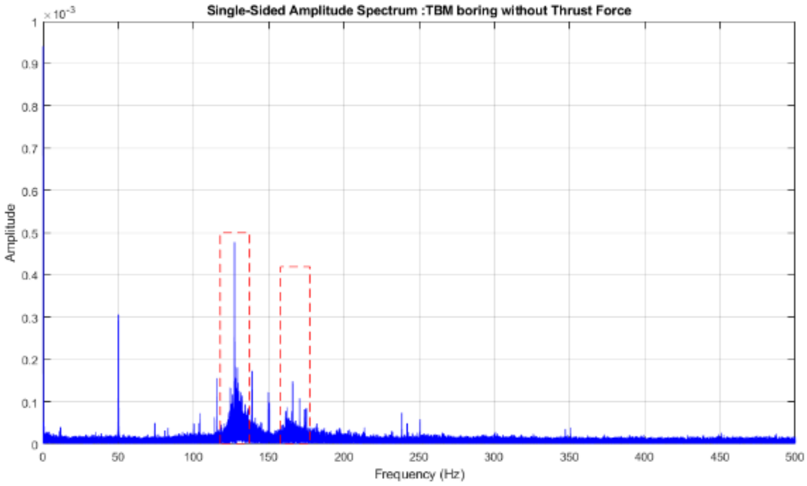

Fig. 9 Frequency-domain analysis during TBM boring without Thrust Force

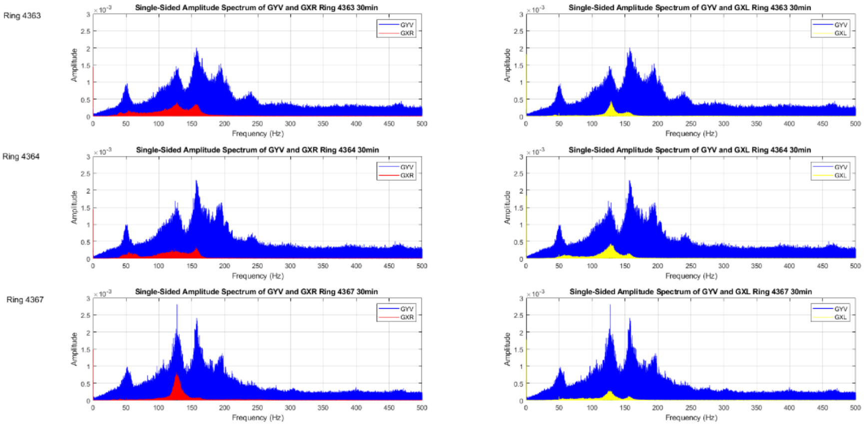

Fig. 10 Frequency-domain analysis under different ground conditions. Frequency - Amplitude between at Shield, Right wall, and Left wall segment. Ring Nos. 4363, 4364, 4367

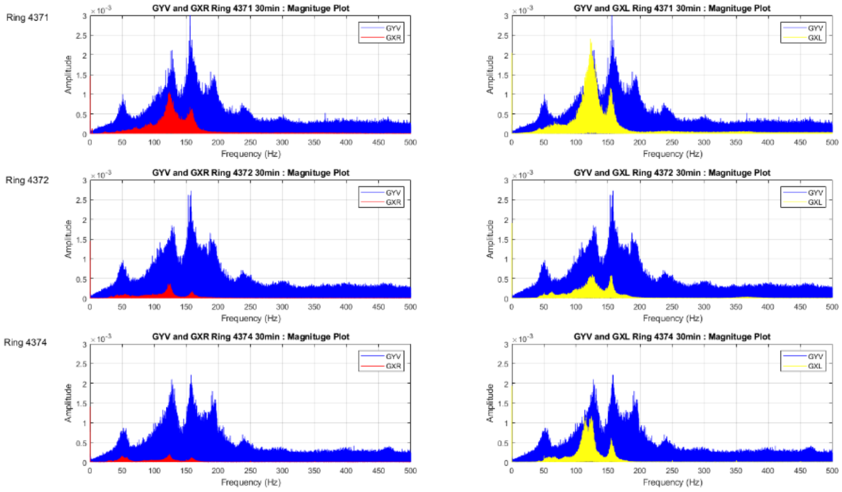

Fig. 11 Frequency-domain analysis under different ground conditions. Frequency - Amplitude between at Shield, Right wall, and Left wall segment. Ring Nos. 4371, 4372, 4374

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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