The Effect of Seismic Load on TBM Structures for Metro Line 3 in Hanoi, Vietnam

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ABSTRACT

Metro line 3 in Hanoi is being constructed using tunnels, which may affect nearby constructions. In addition, Hanoi's earthquakes also pose risks to this Tunnel Boring Machine (TBM) line. This paper studies the impact of TBM construction on the surrounding houses along the line, as well as the impact of earthquakes on this line. A 3D numerical model was developed to simulate the static and dynamic behavior of TBM at station 9 in Metro Line 3. The results show that the maximum settlement at the ground surface under seismic load is significantly reduced from 4.6 mm to 0.1 mm when using the jet grouting method.

Keywords-3D Plaxis; seismic; FEM; soil dynamic; structures

I. INTRODUCTION

The urban railway line 3 is a part of the Hanoi Metro network and is currently under construction. It will be the second line to be utilized in the Metro network, aimed to serve in and around Hanoi. The line will run from Nhon station to Hanoi station on a dedicated track with a total length of about 12.5 km, 8.5 km elevated and 4 km underground, and includes 12 stations in total. The line has two transfer stations. The elevated section of Metro Line No. 3 from Nhon to the S8 station at the University of Transport and Communications is 8.5 km long. The remaining 4 km-long underground section is under construction (S9 to S12).

For the underground section, the Tunnel Boring Machine (TBM) will be used and begin boring from the S9 station on Kim Ma Street to the S12 station at the Hanoi Train Station, which is located at the end of Tran Hung Dao Street. The TBM passes through a densely populated residential area with buildings above it between stations 9 and 10. The raft foundation type is commonly used in the buildings above Station 9. For Station 10, the foundation type varies depending on the height of the building. For buildings with a height of 5-7 floors, the foundation depth is about 10 m to 15 m and the driven pile foundation was used. For 7-story buildings, the foundation depth is about 15 m to 20 m and bored pile foundation was applied (Figure 1).

The construction of the TBM line passing through buildings can cause soil displacement and damage to the buildings' structure or foundation. This issue needs to be analyzed and monitored during the TBM construction process to ensure the safety of nearby structures [1-3].

The full dynamic analysis of tunnel structures under seismic loads has been studied extensively. The current trend is to use numerical analysis techniques. Authors in [4] used PLAXIS 3D to simulate the construction procedure of a TBM tunnel passing between existing piled footings located at variable distances from the tunnel. They concluded that the minimum distance between the tunnel and the piled footing was 3 m for piles with a diameter of 0.9 m and 2.5 m for a diameter of 1.5 m to minimize the effect of TBM construction on nearby pile foundations. In some cases, ground subsidence occurred when using TBM excavation, for example, in January 2008, while tunneling ring N0.200 of Chengdu metro line 1, ground subsidence occurred in one section. The distance between the surface and the top of the EPB TBM cutterhead was approximately 12.5 m. The maximum diameter of the subsidence area was 3 - 5 m behind the cutterhead [5]. Authors in [6] suggested that the variability in small-strain shear modulus of clay can have a significant impact on the seismic responses of the bending moment, shear force, and lateral deformation of rectangular tunnel walls to varying degrees. Authors in [7] evaluated the seismic loading of nearby structures according to the Czech technical standards. Authors in [8] suggested the economic earthquake resistance construction of high-rise buildings.

Fig. 1. TBM will pass through the houses above (from Station 9 to Station 10).

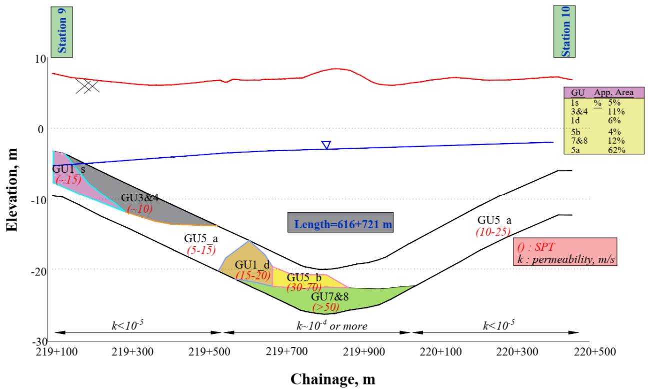
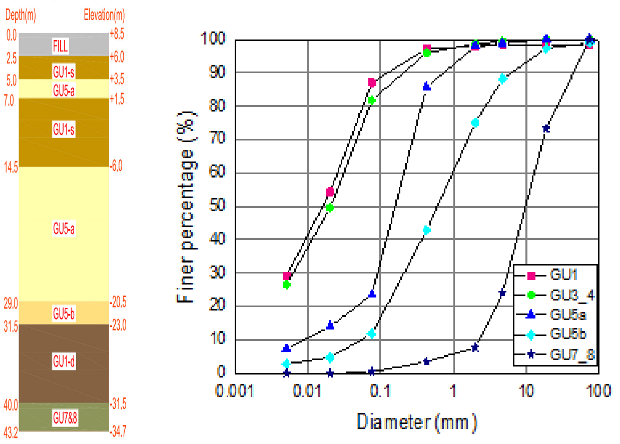


Fig. 2. TBM for station 9 to station 10 (modified from [12]).



(a) (b)

Fig. 3. (a) Geological profile, (b) grain size distribution curve for soils.

Limited research has been conducted in Vietnam on tunnel structures subjected to seismic loads. The analysis of TBM only considers settlement and horizontal displacement. For instance, the ground surface settlement profile associated with the twin tunnels was analyzed using Plaxis 2D software in [9]. The numerical back-analysis was carried out using contraction and stress reduction methods. Other studies concentrated on the assessment of soil liquefaction [10, 11].

Further in-depth studies are required to investigate the stability calculations as an appropriate acceleration spectrum has not yet been provided. Therefore, this paper will study the impact of the construction stage of TBM on nearby buildings and the effect of earthquakes on TBM structures.

II. GROUND CONDITION

The geological units encountered along the tunnel alignment were collected from technical documents. There is a total of 6 soil layers in the project area (Figure 3). The summarized general description for each layer follows:

- Backfill: Sandy clay, brick, sand. This layer distributes on the ground surface in all boreholes. The thickness of the backfill layer varies from 1.0 to 3.5 m, with an average thickness of 1.93 m.
- Fine-grained materials:
  - GU1: Lean clay with lenses of silt or clayey silt (CL, CH) located at a depth less than 25 m from the surface. The thickness varies from 2.0 to 12.3 m, with 5.3 m average thickness. SPT value in average is $N_{30} = 16$.
  - GU3&4: Organic fat and elastic clay (CH, MH, ML, CL). The thickness varies from 1.7 to 14.9 m and the average thickness is 7.74 m. The SPT value in average is $N_{30} = 4$.
- Coarse-grained materials:
  - GU5_a: Loose to medium dense fine sand or silty sand (SC, SC-SM, SP), N_{spt} <30. The thickness varies from 7.7 to 15.7 m, the average thickness is 11.93 m. The SPT value in average is $N_{30} = 20$.
  - GU5_b: Dense fine sand or silty sand (SP, SC-SM, SW). The thickness varies from 1.0 to 7.7 m and the average thickness is 3.6 m. The SPT value in average is $N_{30} = 43$.
  - GU7&8: Very dense sand and gravel (GP, SM). The thickness varies from 7.4 to 8.9 m and the average thickness is 8.3 m. The SPT value in average is N_{30} >50.

During the soil investigation, the groundwater level was monitored using standpipe piezometers and observation wells. Based on the groundwater monitoring results at standpipe piezometers, the groundwater table was found to range from 10 to 12 m below ground level. This paper focuses on the analysis of the TBM line from Station 9 to Station 10 as shown in Figure 3. The typical section of geological at Station 9 is shown in Figure 3(a). The grain size distribution curves of the soil layer are shown in Figure 3(b).

III. CONSTRUCTION METHOD

Based on the soil distribution curve (Figure 3(b)), it is recommended that an Earth Pressure Balance (EPB) TBM is used for the construction of the Nhon - Hanoi train station. It is the first of its kind to be used in Hanoi. The TBM is designed to tunnel through highly urbanized areas and avoid collapses on the above surface. It is over 100 m long and weighs about 850 tons [12]. The TBM includes earth pressure balance shields that minimize impact on geological features, and it is expected that local houses will not be affected during the boring process.

IV. DYNAMIC ANALYSIS OF TBM

A. *Input Parameters for Soil Layers and TBM Model*

An 80 m × 80 m × 40 m soil strata was considered for modeling (Figure 4).

The dimensions of the model considered the effect of the depth tunnel and diameter of TBM [13]. The model boundaries were considered as free at the top and completely hinged constraints at the bottom, right, and left of the model edges. Standard fixities and absorbent boundaries were applied to reduce wave reflection at the boundaries. To model the soil behavior, the Hardening Soil (HS) model was used for all soil layers. The properties of the different soil layers are given in Table I. The dynamic load is assigned as the modified acceleration of the Dien Bien earthquake [14].

TABLE I. SOIL PARAMETERS IN PLAXIS 3D

	GU1_s,d	GU3,4	GU5_a	GU5_b	GU7,8
Layer	**Lean clay**	**Organic clay**	**Loose to medium dense fine sand**	**Dense fine sand**	**Very dense sand or gravel**
Model	HS	HS	HS	HS	HS
Drained type	UD	UD	UD	D	D
γ (kN/m^3)	19	18	20	21	21
Effective cohesion c' (kPa)	15	10	0	0	0
Internal friction angle ϕ' (deg)	25	20	32	33	40
v	0.2	0.2	0.3	0.3	0.3
E_{50}^{ref} (MPa)	10	7	10	15	45
E_{oed}^{ref} (MPa)	10	7	10	15	45
E_{ur}^{ref}	30	21	50	75	135
m	1	1	0.8	0.8	0.5
Cc	0.0345	0.05	0.0345	0.023	0.007
Cs	0.01	0.015	0.006	0.004	0.002

Note: c', ϕ' from CU-Triaxial test, UD: Undrained, D: Drained

TABLE II. TBM INPUT PARAMETERS

Parameter	Unit	Value
Tunnel diameter (inner/outer)	m	5.7/6.3
Modulus of elasticity of tunnel concrete	kPa	3.5E+7
Poisson's ratio	-	0.2

The studied section considers tunnels of 6.3 m diameter and -23 m from the ground level. The input parameter of TBM for analysis in Plaxis 3D is shown in Table II. The model for the lining tunnel is the linear elastic model. The material of the lining tunnel is the plate element in Plaxis 3D. In PLAXIS 3D, it is feasible to conduct a dynamic analysis after a series of plastic calculations. The dynamic load applied is the product of the input value of the defined dynamic load and the corresponding dynamic load multiplier. The basic equation for the time-dependent movement of a volume under the influence of a (dynamic) load is:

$$M\ddot{u} + C\dot{u} + Ku = F \qquad (1)$$

where M is the mass matrix, u is the displacement vector, C is the damping matrix, K is the stiffness matrix, and F is the load vector. Displacement u, velocity $\dot{u}$, and acceleration $\ddot{u}$, can vary with time.

In this research, the modified accelerations for Hanoi city were used to analyze the TBM structure between S9 and S10 for underground sections.

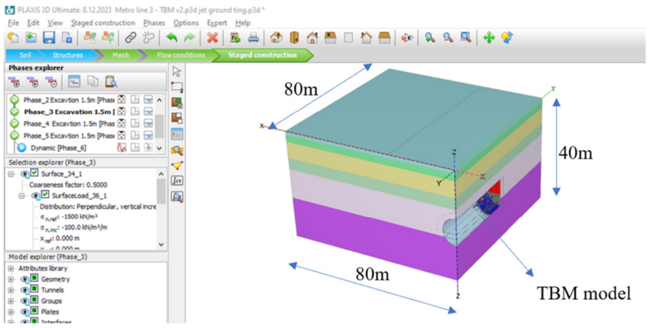


Fig. 4. Details of the TBM model in Plaxis 3D.

B. *Plaxis 3D Calculations*

The calculation of the model was conducted in 3 cases:

- Case 1: Tunnel excavation without jet grouting.
- Case 2: Tunnel excavation using TBM, ground improvement by using jet grouting.
- Case 3: Earthquake.

The construction sequence taken into consideration in the numerical model is:

- Step 1: Condition initialization.
- Step 2: Tunnel lining construction simulation by activating the tunnel lining and deactivating the soil clusters inside the tunnel.
- Step 3: Contraction simulates the volume loss, which was taken as 0.5%.
- Step 4: Seismic loading is applied for TBM (the modified acceleration for Hanoi city was applied, using Dynamic multipliers in Plaxis).

V. RESULTS

The maximum value for the static case was obtained from the last stage, while for the dynamic case, it was obtained from the response spectrum. The analysis results are summarized in Table III.

A. Static Analysis

The calculation results of the 3D model show that the vertical displacement u_z when using jet grouting decreases significantly compared to the case without soil improvement (Figures 5-6). This result is in accordance with [2, 15].

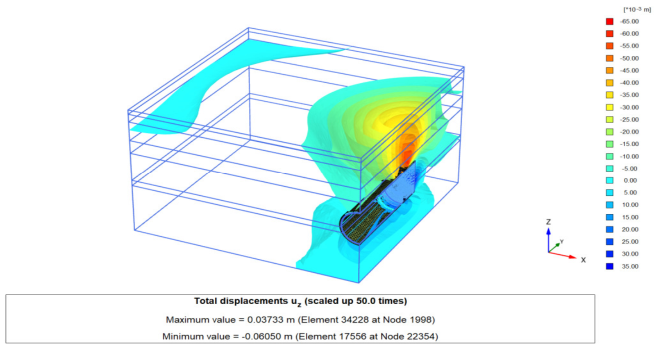


Fig. 5. Total displacement during TBM excavation in case 1.

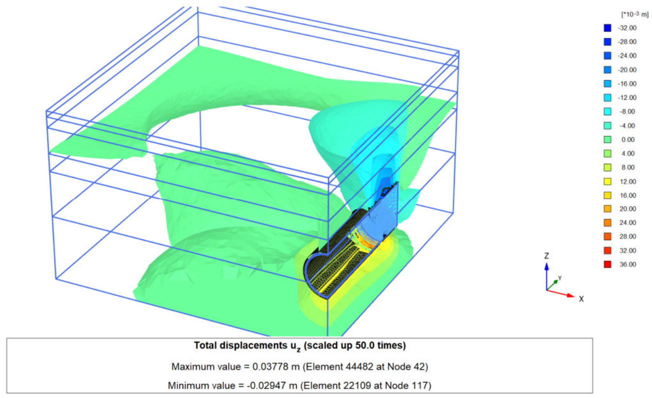


Fig. 6. Total displacement during TBM excavation in case 2.

B. Dynamic Analysis

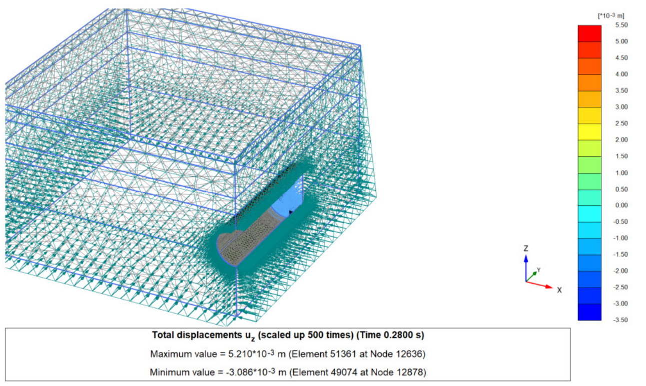


Fig. 7. Vertical displacement due to seismic loading for normal conditions without jet grouting (case 3).

The maximum settlement at the ground surface is significantly reduced from 4.6 to 0.1 mm under seismic load. Figure 7 presents the vertical displacement of the soil due to seismic loading. A small value of displacement was observed and it did not affect the settlement of the house. The maximum velocity of the two cases is still less than that requirement for civil engineering (20 mm) [16].

TABLE III. RESULTS FOR STATIC AND SEISMIC CONDITIONS OF TBM

Parameter	Under static conditions		Under seismic loading	
	Without jet grouting	With Jet grouting	Without jet grouting	With jet grouting
Vertical displacement, u_z (mm)	60	37.8	5.2	4.7
Maximum settlement at ground level (mm)	21	6.5	4.6	0.1
Velocity v_x at ground level (mm/s)	-	-	7	0.8
Moment M11 of TBM (kN.m/m)	118	104	-	-

VI. CONCLUCION

The current study employed a complete 3D FEM model of a single TBM to investigate the influence of effective EPB-TBM parameters during excavation. The TBM construction of Metro Line 3, Hanoi, Vietnam under both normal and earthquake conditions was considered.

The maximum vertical displacement is 60 mm and 37.8 mm for the cases without and with jet grouting, respectively. It is necessary to monitor this displacement value during the construction process.

According to the results of Plaxis 3D analysis, the maximum settlement at the ground surface was reduced significantly from 4.6 to 0.1 mm under seismic load. Although a small value of displacement was observed, it had no effect on the house settlement. The maximum velocity when considering earthquake was considered was less than 20 mm, therefore it does not affect the structure. Additional future analysis should be performed to compare monitoring results and numerical analysis results.

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