Seismic Response Perspective for the Proposed Subway Tunnel Near Kamalapur Railway Station

Tahmeed M. Al-Hussaini, Sagar Barua, and Mahbubah Ahmed

Abstract To mitigate ever-growing traffic congestion in Dhaka city, the Government of Bangladesh is implementing the Mass Rapid Transit (MRT) project. The MRT Project consists of several metro rail routes in the city, some of these routes are elevated rail, while some are planned to be partly elevated and partly underground. Construction of MRT Line 6 consisting of elevated rail is in progress, while the second route (MRT Line 1) being planned for construction consists of some underground portions. Bangladesh, located near the plate boundaries of the Indian Plate colliding with the Eurasian Plate, possesses significant seismic hazard. According to the latest updated version of the Bangladesh National Building Code (BNBC-2020), Dhaka city has a seismic zone coefficient of 0.20 (maximum considered earthquake) for rock sites. For local soil conditions, ground motions may exceed 0.25 g. This paper considers a site near Kamalapur Railway station, the Railway Hub in Dhaka city, where MRT Line 1 will end. The seismic response of a typical cross-section of subway tunnel is analyzed using the finite element software PLAXIS 2D. Time history analysis under 2D plane strain conditions is conducted for various intensity levels of earthquake motion incorporating site effects.

Keywords Subway tunnel · Seismic response · Site amplification · Dhaka MRT · FEM

1 Introduction

During an earthquake, underground structures move with the soil, while structures above ground are free to sway back and forth. For this, underground structures are less prone to damage in comparison to surface engineering works. From this belief for a long-time, underground structures were designed without seismic considerations. However, some significant damages of underground tunnels during recent strong earthquakes have drawn attention. Researchers have conducted different case studies on the damages of the tunnel due to different earthquakes. Damages in tunnel lining

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like cracking, spalling, collapsing have been identified after earthquakes [1]. Later, to minimize the damage suffered by tunnels during the earthquakes, many studies have been carried out. These studies recommend special treatment in designing tunnels for earthquake hazards. To obtain an optimum tunnel seismic design, a correct evaluation of stresses in tunnel lining and its relative displacement under seismic waves is necessary. The variation of internal forces induced in the tunnel lining during earthquakes can be calculated following several approaches that model in different ways the soil-structure interaction [2]. Although existing guidelines suggest pseudo-static or uncoupled dynamic analyses, usually adopted for a preliminary stage of design, it has been shown that full dynamic analyses must be performed of the soil-structure interaction taking into account the influence of the pre-existing stress state around the tunnel [3, 4].

The government of Bangladesh has undertaken massive infrastructure projects in the transportation sector across the country, including a Mass Rapid Transit (MRT) System in Dhaka city to ease traffic congestions in this densely populated megacity. An elevated metro rail (MRT Line 6) under construction is expected to be completed next year. This will be the first metro rail of the capital city. The second metro rail under planning is MRT Line 1, which has portions of it underground. This paper deals with the underground portion of MRT Line 1. A recent publication [5] addresses geotechnical considerations and prospects for underground construction, including the underground metro in Dhaka City. This study attempts to have an assessment of the seismic response of the proposed tunnel-soil system in Dhaka soil. Full dynamic analysis of the soil-structure system has been conducted using the finite element software PLAXIS 2D.

2 Site Information

2.1 Route Location

The MRT Line-1 will have both elevated rail and underground rail [6] as shown in Fig. 1. Line 1 will have two branches: (i) 16.5 km Airport line running from Dhaka airport southward to Kamalapur Rail Station and (ii) 10 km Purbachal line running from Bhatara (Natun Bazar) eastward to Purbachal. The major portions of Line 1 will be above ground. However, there will also be significant underground portions (shown in blue in Fig. 1): (i) Khilkhet to Bhatara (ii) Malibag to Kamalapur (iii) Bhatara to Bashundhara. A typical underground cross-section of MRT line-1 tunnel near Kamalapur railway station has been considered for analysis in our study.

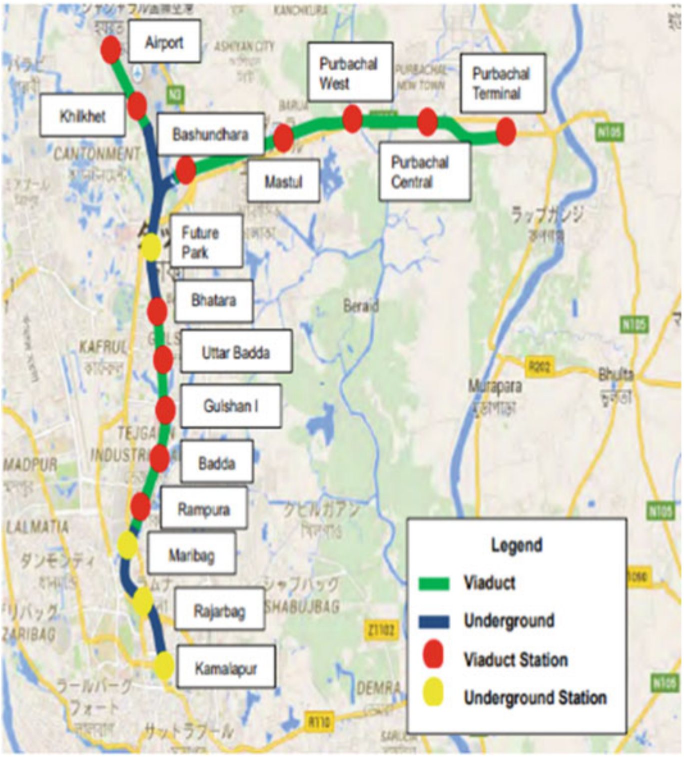

Fig. 1 Layout plan of MRT Line 1 [6]

2.2 *Soil Profile*

Soil investigations through 41 borings conducted under project feasibility study [6] provide information about the soil condition along the proposed route of MRT Line 1. A site (Borehole BH-1) near Kamalapur railway station is considered for this study (Fig. 2).

The subsoil information shows that there is 7.5 m of grayish brown medium stiff to very stiff clay on top of 3 m sandy silt layer. Below the sandy silt layer, 13.5 m of silty sand overlies firm support (N > 50) consisting of very dense sand or hard clay. Corresponding Standard Penetration Test (SPT) values are also shown in the figure.

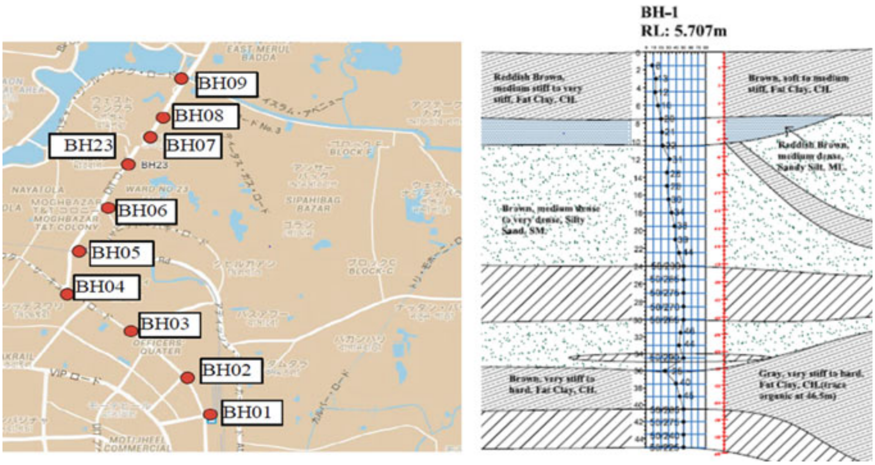

Fig. 2 Location of Borehole BH-1 and corresponding Bore Log [6]

3 Seismic Site Response Analysis

The software 'DEEPSOIL' has been used to conduct one-dimensional seismic site response analysis adopting the equivalent linear method. Shear wave velocities are estimated from SPT values of BH-1 using empirical relations given by the Japan Road Association [7].

Three earthquake records with different characteristics (listed in Table 1) but scaled to values consistent with Bangladesh's seismic zoning map have been used

Table 1 PGA (g) values obtained at 44 m depth from seismic site response analysis for different intensity levels of earthquakes

Earthquake Record	PGA (g) at 44 m depth		
	Case 1 $PGA_{rock} = 0.25$ g	Case 2 $PGA_{rock} = 0.2$ g	Case 3 $PGA_{rock} = 0.15$ g
January 17, 1995 $M_w = 6.9$ Kobe, Japan (PGA = 0.82 g)	0.15	0.12	0.08
October 15, 1979 $M_w = 6.4$ Imperial Valley, USA (PGA = 0.17 g)	0.18	0.14	0.1
January 17, 1994 $M_w = 6.9$ Northridge, USA (PGA = 0.22 g)	0.18	0.15	0.12

as input for site response analysis. The motions are hereafter termed as Kobe, Imperial Valley, and Northridge earthquake. The magnitude of the earthquakes and the peak ground acceleration (PGA) values of the three earthquake records are given in Table 1.

According to the updated version of the Bangladesh National Building Code (BNBC-2020), Dhaka city has a seismic zone coefficient of 0.20, implying PGA = 0.2 g at rock site [8] for maximum considered earthquake (MCE). For local site conditions consisting of alluvium, site amplification is expected, which is assessed by conducting seismic site response analysis. For this analysis, three different intensity levels are considered with PGA_{rock} equal to 0.25, 0.2, and 0.15 g. Each of the records of Imperial Valley, Northridge, and Kobe earthquakes scaled down to 0.25, 0.2, and 0.15 g are chosen as input (outcrop) motion in DEEPSOIL. As a result, nine sets of earthquake motion are considered. Through one-dimensional wave propagation analysis adopting an equivalent linear method, ground motion at a depth of 44 m is obtained. Table 1 also presents PGA values obtained at 44 m depth for nine sets of input earthquake motion. It is observed that the Imperial Valley and Northridge earthquake result in significantly greater PGA compared to that for the Kobe earthquake. The ground motion records obtained for 44 m depth are finally used as input to the base of the soil-tunnel system's numerical model for further numerical analysis in PLAXIS 2D.

4 Seismic Tunnel Response Analysis

4.1 Numerical Model

Figure 3 presents a schematic view of the tunnel-soil system considered for numerical analysis. A 7 m diameter tunnel with a reinforced concrete lining thickness of 0.3 m is assumed to have 8 m of overburden soil. High-strength concrete (fc' = 7000 psi) is considered for the tunnel lining. The soil profile up to firm soil is considered here, i.e., up to 44 m depth. The ground motion obtained through site response analysis (Sect. 3) is applied here at a depth of 44 m. As shown in Fig. 3, the soil profile is divided into eleven layers. The corresponding shear wave velocity and density are also shown.

A 2D plain strain model adopting 15-noded triangular elements is used to generate the finite element mesh for the problem shown in Fig. 3. The mesh, as developed in PLAXIS-2D, is shown in Fig. 4. The model is provided with viscous boundary conditions on the vertical boundaries described as absorbing boundary conditions in [9], while input motion (acceleration time history) obtained from site response analysis (Sect. 3) is applied to the base of the model as shown in Fig. 4.

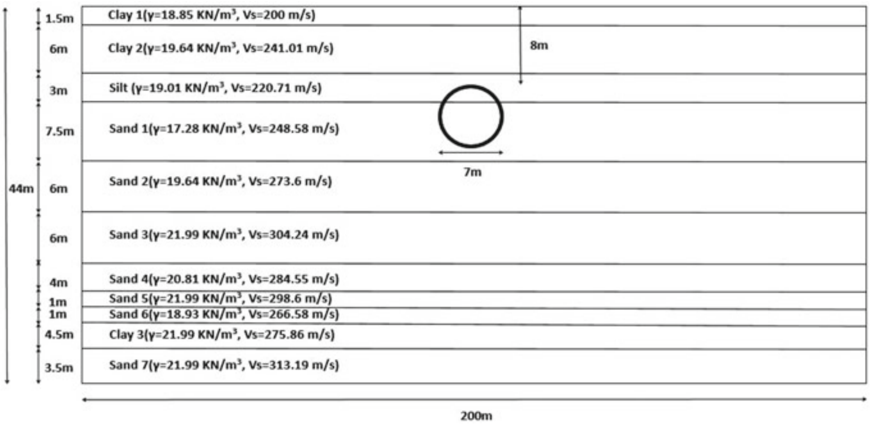

Fig. 3 Schematic view of the soil-tunnel system

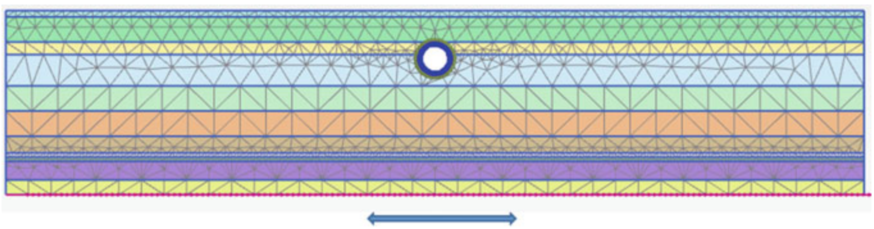

Fig. 4 PLAXIS 2D plain strain model with generated mesh

4.2 Numerical Results

Time history analysis is performed in PLAXIS-2D to evaluate the seismic response of the tunnel-soil system. Two parameters are considered in this paper, which affects the tunnel lining design:

(i) Induced horizontal distortions.
(ii) Induced moments.

Figure 5 presents horizontal distortion in the tunnel lining, which is defined as the relative lateral displacement between the tunnel left and tunnel right. For different intensity levels of earthquake, the relative displacement is found to be of the order of mm. The maximum distortion is found to be around 4.5 mm, which corresponds to the Imperial Valley earthquake. It may also be noted that the distortion is not proportional to the different intensity levels for the same earthquake. It is also worth mentioning that the Northridge earthquake has the maximum PGA value (Table 1) but still results in minimum distortion.

As shown in Fig. 6, the Kobe earthquake which has the lowest PGA (Table 1) results in the maximum bending moment (88.06 kN-m/m) in the tunnel lining. The

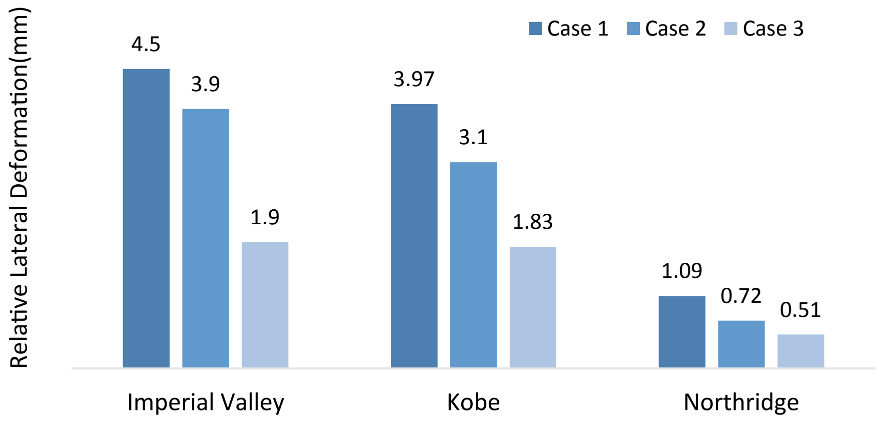

Fig. 5 Maximum relative horizontal deformation for various earthquake intensity levels

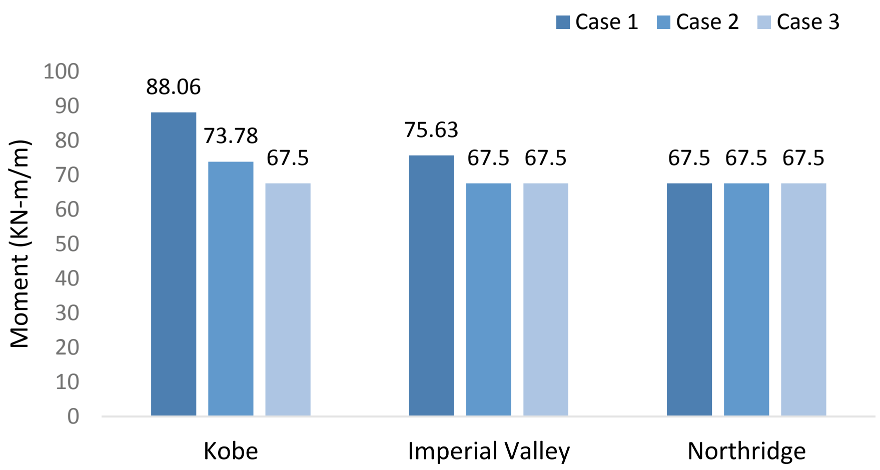

Fig. 6 Maximum bending moment in tunnel lining for different earthquake intensity levels

value of the bending moment without any earthquake is around 62.5 kN-m/m. Hence, the increase in bending moment is 5 to 25.56 kN-m/m, whereas corresponding input PGA at 44 m depth increases from 0.08 to 0.15 g. Hence, the bending moment increases by a much larger factor.

5 Conclusions

This paper presents preliminary results on ongoing research work for seismic response analysis for a typical tunnel-soil section for the proposed underground metro Line 1 near the Kamalapur Railway Station in Dhaka city. The study includes a two-step procedure with a seismic site response analysis to obtain ground motion at a certain depth, which is then used to perform finite element analysis on the tunnel-soil system using PLAXIS-2D. A variety of earthquake records with varying intensity levels have been considered. The seismic motion may generate appreciable bending moment in the tunnel lining, whereas the induced horizontal distortion is not that significant. The bending moment can increase at a much higher rate than the increase in the rate of intensity level. It is also observed that the earthquake with the lowest PGA at the bottom yields the largest bending moment. This highlights the importance of characteristics of earthquakes other than PGA. The results presented here are expected to be useful for conducting further studies on assessing the effect of an earthquake on tunnel design in the context of Dhaka City.

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