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Procedia Engineering
Volume 143, 2016, Pages 1160–1168
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)
Procedia Engineering

Some Predictions of Deformations from Tram Track Construction in a Structure-Embankment Transition Zone

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Abstract:
Based on a construction project of a tram line in Nanjing City of China, the influence of a tram track construction on the deformation characteristics of an adjacent metro station and tunnels is investigated. Because a section of the tram track is designed to be constructed in the vicinity of the connection between a metro station and metro tunnels, the foundation of the tram track is changed from the station structure to the normal embankment. As a result, deformations from tram track construction in this structure-embankment transition zone will be serious. In order to protect the metro station and the twin tunnels from the construction-induced deformation and long term settlement caused by tram trains, a recommended treatment of the structure-embankment transition zone is suggested according to the property of the surrounding soils. The construction process of the tram track over the metro station and the tunnels is simulated by a finite element analysis (FEA) method. The deformation characteristics of the metro station and tunnels are calculated. Results indicate that with the recommended transition zone design the deformation response of the adjacent underground structures can be well controlled and the transition performance of the tram track transition zone can be improved.

Keywords: tram track, transition zone, metro tunnel, uneven settlement

1. Introduction

With the development of the modern urban rail transit technology, more and more tram lines are planned to be constructed in cities of China. As an important component of the public transportation system, the modern tram plays a significant role in solving problems of urban traffic jams, environmental pollution and energy shortage.

Most of the research works with regard to the tram system mainly focus on the traffic organization, connection with other traffic modes, alternative of the power supply system, the landscape impact and acoustics problems (Topp 1999, Real et al. 2011, Jolibois et al. 2015). However, hardly any

 Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016
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doi:10.1016/j.proeng.2016.06.129

publications that concerning with mechanical problems of the tram track construction can be found as well as the influence of the tram track construction on the adjacent structures. Consequently, in this paper the influence of the construction of a tram track on the deformation characteristics of a metro station and tunnels are investigated based on a project of a tram track construction in Nanjing, China.

Because the construction process of the tram track can be separated as steps of the foundation excavation, the subgrade filling and the track structure installation, this problem can be summarized as the deformation of the metro station and tunnels induced by soil unloading and loading process of adjacent tram track construction. Chang et al. (2001) took a case study on response of a Taipei rapid transit system tunnel to adjacent excavation. Movements of the ground, tunnel segments and track slabs were observed to provide reference for establishing criteria to regulate excavations adjacent to existing tunnels. Bilotta and Stallebrass (2009) evaluated the influence of an embedded wall placed near a tunnel on ground movements and tunnel stability by series of model tests and finite element analyses. Zhang et al. (2013) presented a semi-analytical method to evaluate the heave of underlying tunnel induced by adjacent excavation. Zheng and Wei (2008) investigated the influence of overlying excavation on existing tunnels by 2D FE method. Shi et al. (2015) took a parameter study to investigate the influence of excavation geometry, sand density, tunnel stiffness and joint stiffness on tunnel responses due to overlying basement excavation by 3D FE method. Hu et al. (2003) presented the design and construction of a deep excavation for building foundations in saturated soil. Sharma et al. (2001) reported the deformation of two Mass Rapid Transit (MRT) tunnels due to a nearby large excavation measured by monitoring system. Doležalová (2001) examined the effect of a deep open excavation on the underlying tunnel with 2D FE method. Zhang et al. (2013) presented a simplified analytical approach to analyze the deformation response for adjacent tunnels due to soil unloading in excavation engineering. Huang et al. (2013) presented a parametric study on tunnel behavior caused by adjacent deep excavation in Shanghai with 3D FE method. Dai et al. (2006) investigated the effect of construction loads on longitudinal deformation of adjacent metro tunnels with finite difference method.

Most of existing researches on tunnel deformation induced by adjacent constructions mainly focus on the excavation cases, in which only the soil unloading process is considered. Since the construction of the tram track is very complicated, both the soil unloading and loading process should be considered. Consequently, the influence of the complex construction process on deformation characteristics of adjacent metro station and tunnels is worth to be studied, especially for the connection between them. Due to the stiffness differences between the station and the tunnel, the deformation responses of them are different.

2. Background

The Nanjing Tram Line 1 is planned to be constructed in the Hexi new city area of Nanjing, China (refer to Fig. 1). The central and southern regions of the new city area will be connected by this new constructed tram line, which consists of 13 stations with a total length of 7.8km.

The tram train structure is shown in Fig. 2 with the axle load of 125 kN and the operation speed of 50 km/h. The channel rail with linear mass of 50 kg/m is employed and the longitudinal level irregularity limit is 20mm.

The layout of the Tram Line 1 between Olympic Center East Station and Yuantong Station is parallel to the existing Metro Line 2. Because the Yuantong Station (highlight in Fig.1) is a transfer station of these two transit systems, the tram track should be constructed over the underground metro station. As a result the tram track foundation changes from the metro station structure to the normal embankment on the south of the Yuantong station as shown in Fig. 3. And in this section the tram line is no more parallel to the existing metro line. The horizontal distance between the tram track and the metro tunnel increases with the longitudinal distance from the station (refer to Fig. 3).

Because the long term consolidation settlements of tunnels measured in the Hexi new city area are larger than those of other area in this city, the settlement control of the metro tunnel in this area is very important, especially for uneven settlement between the tunnel and the station structure. Consequently, protection measures of the metro station and tunnels should be employed when the construction of the tram track is in the vicinity of the connection between the metro station and tunnels. On the other hand, the uneven settlement of the tram track in this transition zone between the station structure and the embankment should also be well controlled. Consequently, in this paper a transition zone design of the tram track is introduced and the protection effect is investigated by FE method.

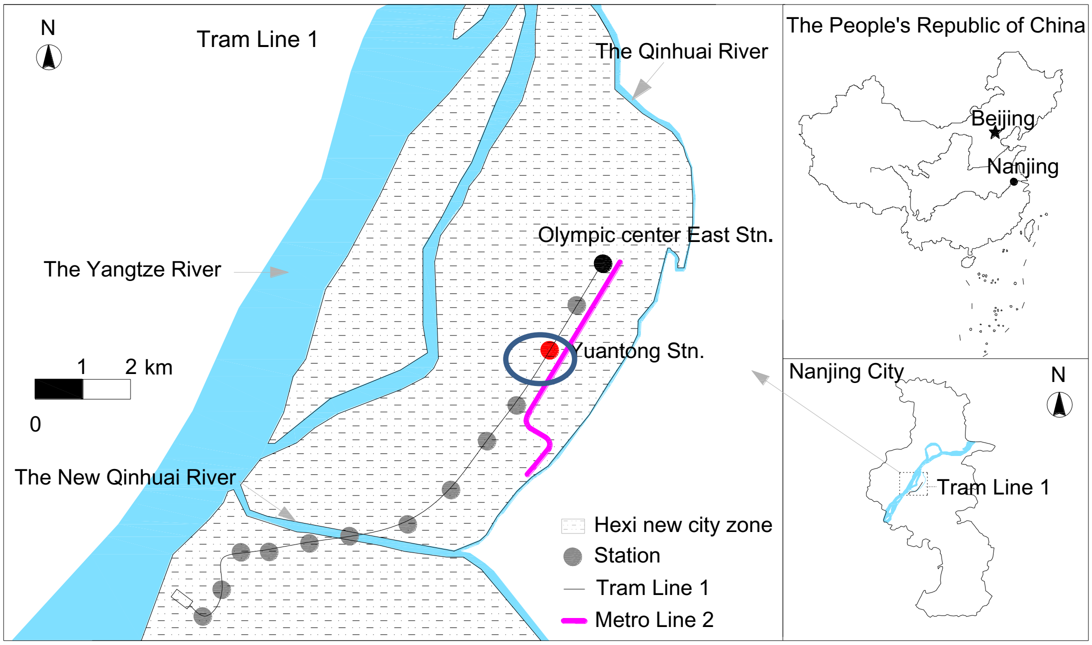


Figure 1: Location of Nanjing Tram Line 1

Figure 2: Tram train system

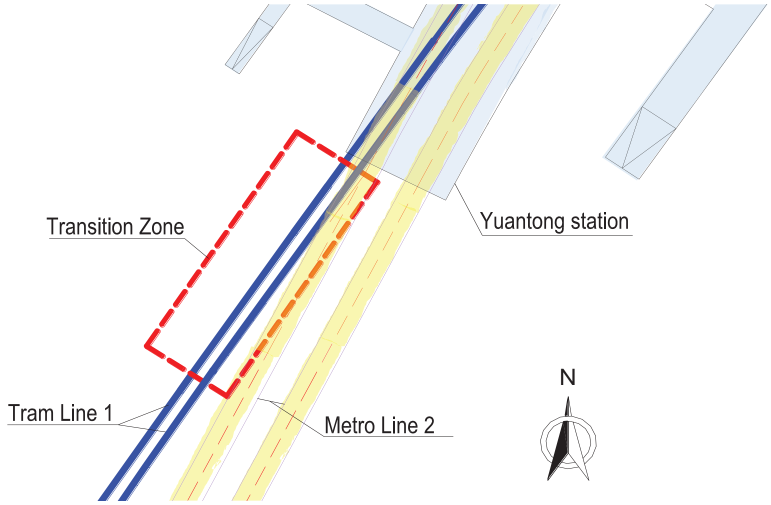
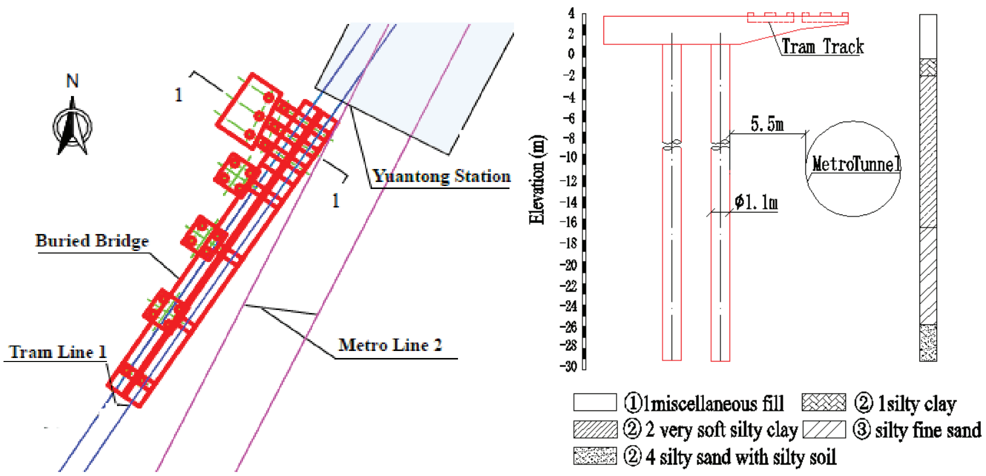


Figure 3: Layout of the planned Tram Line 1 and the existing Metro Line 2

3. Transition Zone Design of the Tram Track

In order to protect the metro station and the twin tunnels from the construction-induced deformation and long term settlement caused by tram trains, it is proposed to install a cover on the top of the underground structures. In this way the new constructed tram track will be supported by this cover structure but not the surrounding soils of tunnels. Dynamic interactions between tram and metro trains can also be cut off. In order to realize this design, a buried continuous beam bridge is recommended to be constructed in the transition zone between tram tracks on the metro station and the embankment. The plan and elevation views of adjacent structures in the transition zone are shown in Fig. 4. The minimum distance between piles (bored piles) and the tunnel is 5.5m and the buried depth of metro tunnels in this section is 13.7 m. Bearing platforms are designed to be constructed on top of piles and the continuous beam will be installed on platforms. Finally, the tram track structure will be constructed on top of the metro station, the buried bridge and the normal embankment.



a) Plan view of the transition zone design b) Cross section 1-1 of the transition zone
Figure 4: Buried continuous beam bridge in the tram track transition zone

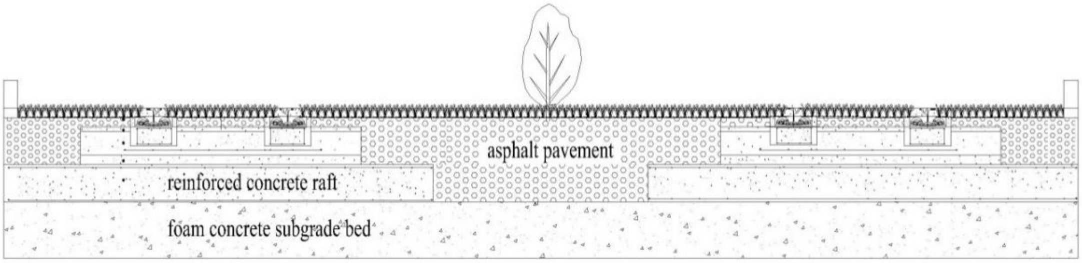
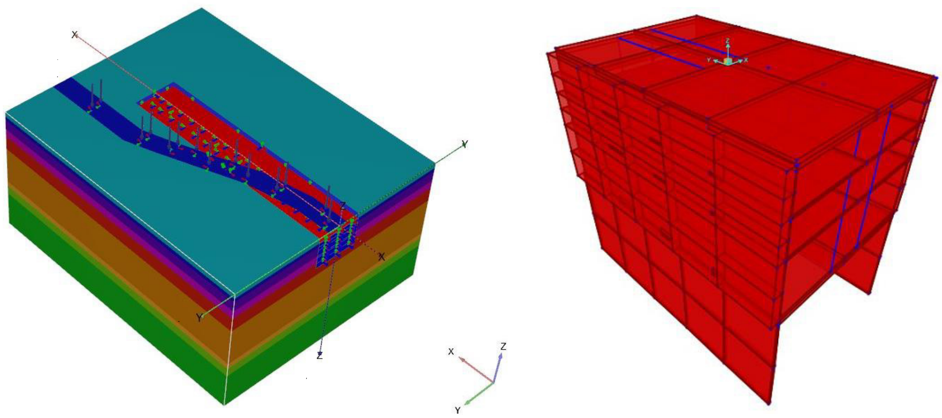


Figure 5: Tram track structure

The tram track consists of the foam concrete subgrade bed, reinforced concrete raft, concrete slabs, pads, fasteners and rails. The geometries of the components are illustrated in Fig. 5.

4. Model, Boundaries and Calculation Process

A 3D FEA model is employed. The length (X direction), the width (Y direction) and depth (Z direction) of the model are 180m, 160m and 80m, respectively. The material model of the soil is hardening soil model. With this model, the shear hardening and volumetric hardening behaviors of soils can be well simulated as well as the dilatancy of the sand. Stiffness attenuation characteristics under different strain levels can also be obtained and a Mohr-Coulomb failure criterion is employed. While for metro station structure, shield tunnel segment, buried continuous beam, bearing platforms, piles and tram track components, the linear elastic model is implemented. The segments and the station structure are simulated by plate element. The tram track components, buried continuous beam, bearing platforms, piles, embankment filler and soils are simulated by solid elements. In order to simulate the interaction of the soil and the structure, contact elements are employed on the interface between soils and structures. The coordinate axes X, Y, Z represent the longitudinal, transverse, and vertical direction of the tram track, respectively (refer to Fig. 6). Material parameters are shown in Table 1 and Table 2. Soil material parameters listed in Table 1 are in consonance with the geological investigation report for this region. The water table in this area is 0.7 m underground and the corresponding water pressure has been applied in this model.



a) Over view of the tram track and the station b) Metro station structure

Figure 6: Finite element model of the tram track and the metro station

stratum	density (kN/m³)	cohesion (kPa)	internal friction angle	Young 's modulus (Mpa)	Poisson ratio
①1 miscellaneous fill	1890	25	16.8	18.9	0.33
②1 silty clay	1950	23	19	25.7	0.35
②2 very soft silty clay	1750	12	20.5	22.7	0.33
②4 silty sand with silty soil	1860	9	31.4	67.4	0.31
③1 silty fine sand	1910	8	31.8	81	0.28
③2 silty fine sand	1910	8	31	77.4	0.29
④ clay	1940	40	15	72	0.31

Table 1: Soil material parameters

	Density (kg/m³)	Elastic modulus (MPa)	Poisson's ratio
tunnel segments	3000	45e3	0.17
metro station	2800	40e3	0.18
buried bridge	2800	40e3	0.18
track components	3000	45e3	0.17

Table 2: Material parameters of structures

Nodes on the bottom surface of the model are fixed. For the nodes on the side surfaces, the displacement of the X and Y directions are fixed and only the Z direction is free.

The calculation process comprises 6 steps as shown in Table 3. Because the initial stress of the soil already existed, the soil stress will be changed due to the tram track construction process. Consequently, the initial stress of the soil under gravity should be computed prior to the simulation of the construction process. The coefficient of soil lateral pressure in this simulation can be expressed as

$$k_0 = 1 - \sin\varphi \quad (1)$$

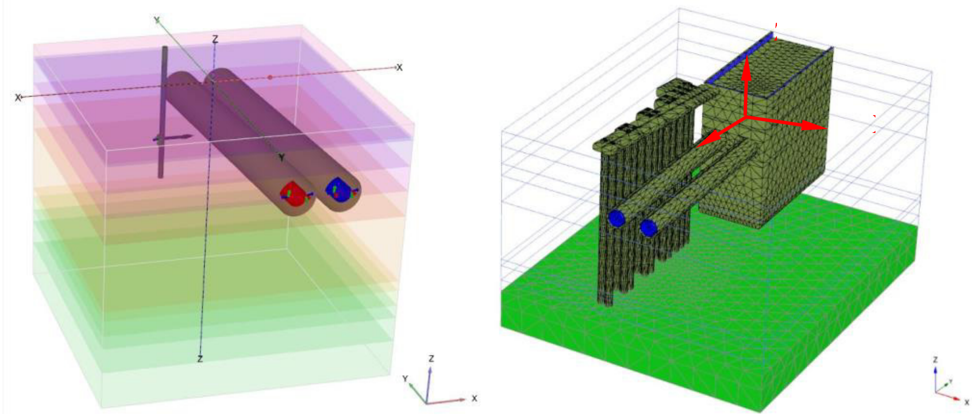
where, k_0 is the coefficient of soil lateral pressure and φ is internal friction angle of soil.

step 1	To calculate the initial geostress and displacement field of the ground
step 2	To excavate the internal soil of the tunnels and install tunnel segments and the station structure
step 3	To remove the displacement induced by Step 1 to Step 2
step 4	To construct piles
step 5	To excavate the foundation of the bearing platforms, continuous beam and the tram track
step 6	To construct the bearing platform, continuous beam and the tram track components successively

Table 3: Calculation steps

5. Results

Firstly, the influence of the buried bridge construction on the adjacent tunnel displacement is calculated. Due to the construction of the piles the horizontal (X direction shown in Fig. 7 b) and vertical (Z direction) displacements of the tunnel are -0.33 mm and -0.53 mm, respectively. The symbol '-' represents the negative direction of the coordinate. The tunnel displacements induced by the excavation of the foundation of the bearing platforms and the continuous beam are -0.38 mm in horizontal and 1.27 mm in vertical, respectively. After the installation of the bearing platforms, the continuous beam and the track components, the final horizontal displacement of the tunnel is -0.35 mm and the vertical value is -0.44mm.



a) Construction of the piles b) Construction of the buried bridge

Figure 7: Simulation of the transition zone construction process

Secondly, the deformation response of the metro station structure to the construction of the tram track, which is constructed on the top of the station, is investigated. Results indicate that the maximum displacement of the station structure due to the excavation process of the tram track foundation is 0.8 mm. After the installation of the tram components, the maximum displacement of the station structure is -0.34 mm.

Thirdly, the displacements of the metro tunnel due to the construction of the tram track in the normal embankment section are calculated. In this section the minimum distance between the tram track and the metro tunnel is 9.2 m and the buried depth of the metro tunnel is 19.2 m. The horizontal distance between the tram track and the metro tunnel increases with the longitudinal distance from the station. The final displacement of the tunnel is -0.14 mm in horizontal and -0.24 mm in vertical, respectively.

The deformation response of the metro station and tunnels to the adjacent construction of the tram track is summarized in Table 4.

	vertical displacement/mm	horizontal displacement/mm
Station	-0.34	
tunnel adjacent to tram track transition zone	-0.44	-0.35
tunnel adjacent to tram track embankment	-0.24	-0.14

Table 4: Deformation response of the station and the tunnel

Results indicate that with the special design of the tram track transition zone, the influence of the construction of the tram track on the adjacent metro station and tunnels is limited. The tunnel and the station structure in the vicinity of the tram track transition zone can be well protected by the buried continuous beam bridge.

After the investigation of the deformation response of the adjacent metro station and the tunnel, the vertical displacement of the tram track in the transition zone induced by the passing tram trains is calculated. A transient analysis with a 3D finite element model is taken. The passing trains are simulated as moving loads. Each moving wheel load of tram trains is chosen as 62.5 kN (half of the axle load of 125 kN). The axle base is 1.85 m and the distances between bogies are shown in Fig. 2. Fig. 8 shows the rail vertical displacement of the tram track as a function of the coordinate Y (refer to Fig. 7, the origin of the coordinate lies in the connection of the metro station and the transition zone).

The distribution discipline of the tram rail vertical displacement in the case with the buried bridge is compared with the distribution discipline of rail vertical displacement in the case without the buried bridge.

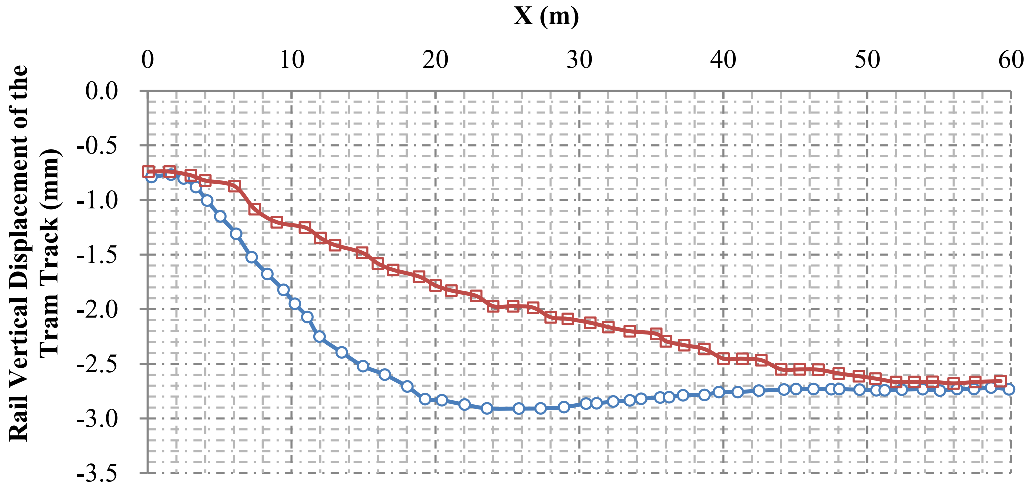


Figure 8: Rail vertical displacement of the tram track as a function of the distance from the station: the case without the buried bridge; the case with the buried bridge

As shown in Fig. 8, the rail vertical displacement of the tram track in both cases increases from the metro station to the embankment. Although the quantitative increases for both cases are the same, from 0.76 mm to 2.73 mm, the qualitative behaviors of the curves are different. The transition zone displacement in the case without the buried bridge increases in the region of the first 20 meters, while that of the case with the buried bridge changes smoothly in a range of 50 meters. Consequently, with the buried bridge the differential rail vertical displacement of the tram track in the transition zone can be well controlled.

6. Conclusion

In this study the deformation characteristics of the metro station and the twin tunnels induced by the nearby construction of the tram track are investigated with a FEA method. The completed soil unloading and loading procedure is simulated. After that the rail vertical displacement of the tram track due to the load of passing trains is investigated. Two conclusions can be drawn:

1) With the special design of the tram track transition zone, the largest vertical displacements of the metro station and the twin tunnels due to the adjacent tram track construction are -0.34 mm and -0.44 mm, respectively. The influence of the tram track construction on the deformation response of the adjacent underground structures is small due to the existence of the buried continuous beam bridge.

2) The curve of the rail vertical displacement in the case with the buried bridge is smoother than the curve in the case without the buried bridge. The transition performance of the tram track transition zone can be well improved by the construction of the buried bridge in this region.

In this study the tram trains are simplified as moving loads. As a result the vehicle-track interactions cannot be considered. In the next step, a completed vehicle model will be employed to investigate the influence of the tram track transition zone on the vehicle system dynamics. Furthermore, the long term uneven settlement of the tram track transition zone induced by dynamic train loads and the foundation soil consolidation is a sophisticated objective for future analyses. All investigations should be validated by in-site measurements in the future.

Acknowledgement

This research was supported by the Fundamental Research Funds for the Central Universities (Project No.: 2014KJ016 and 10247201571) and the Science and Technology Committee of Shanghai (Project No.: 15YF1412800), the People's Republic of China.

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