Experimental and Numerical Analysis of Vibrations Induced by a Twin Tunnel, Underground Railway

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Abstract: Many underground railway lines around the world consist of twin tunnels. One of the environmental vibration problems caused by these subways is the effect of the existence of loads in the two tunnels simultaneously. For example, measurement of the vibrations induced by two trains simultaneously in the field tests is rare. In this study, a 3D finite element model was built to investigate the ground vibrations induced by the subway twin tunnels and was verified against field measurements. A site measurement was performed on Line 1, Tabriz Metro. Furthermore, the influence of the second tunnel with various separation distances in the soil layer containing the different elastic modulus (for 3 values of 60, 150, and 400 MPa) on the surface vibrations is examined. The results show that when the elastic modulus of the soil decreases, the distance between two tunnels which the effect of the second tunnel disappears increases. So that, for the soil layer with an elastic modulus of 60, 150, and 400 MPa, the separation distance is obtained about 8, 9, and 10 times of the tunnel radius. In addition, a correction factor of +6 dB has been proposed for the field measurement data of the twin tunnels, which was determined from one of the trains.

Keywords: twin tunnels; railway vibration; situ measurement; numerical analysis

1 Introduction

Subway structure is undergoing increases in many cities in order to reduce the urban traffic. Subways usually run beneath the space of residential areas, which may cause disturbances to nearby buildings and their residents. The interaction between the wheel and the rail induces dynamic force, and causes vibrations, which that propagate through the tunnel and the surrounding soil into buildings. The induced vibration from the underground railway causes vibrations in the frequency range of 1–80Hz and re-radiated noise in the range of 1-200 Hz. [1]. To design a new railway or checking the vibrations from existing lines, the induced vibrations must be determined and compared with the standards. Then, according to the obtained values, vibration reduction solutions should be taken. In addition, the mitigation effects of the proposed methods need to be evaluated. However, the prediction model is necessitated to achieve the above goals [2].

In the past decade, several numerical and analytical models have been established to predict ground vibrations induced by underground railways. These studies have investigated vibration in single and twin tunnels. Numerous prediction models and field measurements have been performed for assessments of vibration induced by single tunnel and isolated systems [3-9]. While a common simplifying assumption adopted in these studies is to neglect the presence of a neighboring tunnel. However, most underground railway lines around the world consist of twin tunnels: one for the outbound direction and one for the inbound direction. For example, in London, Copenhagen, Washington DC, Shiraz, and Isfahan the metro lines are included twin tunnels. To date, few numbers of models are available in the literature, which accounts for the effect of second tunnel on induced vibration by another tunnel.

Kuo et al. have presented the formulation of a model for underground-railway vibration induced from twin tunnels based on the single-tunnel Pip in Pip model. The superposition method has been used to determine of interaction between neighboring tunnels [10]. Hamad et al. have investigated the vibration response of the twin tunnels by two different methods, a fully coupled approach, and a superposition approach. The accuracy of the two methods is assessed [11]. He et al. present a 2.5D theoretical model for the solution of dynamic interaction between two parallel tunnels in a multi-layered half-space. The influence of soil layering and the stiffness of the soil above the tunnels were investigated [12]. Yuan et al. have proposed an analytical method for calculating vibrations from a twin tunnel in a saturated poroelastic half-space. The results show that the surface vibration from the half-space model is larger than those of the full-space model [13]. In another study, Yuan et al. have presented an analytical solution for estimating twin tunnels vibrations, which considers the multiple scattering effects between the two tunnels. The second tunnel has a small influence on the soil displacement at the low frequencies, while in the high frequencies the neighboring tunnel has significant scattering effects [14]. Heidary et al. have investigated the effect of axle load and speed of trains on the ground surface vibration, while two trains passed each other in the opposite direction in the twin tunnels [15]. Heidary et al. have studied the effect of surrounding soil layers and lens properties on the ground-borne vibration induced from twin tunnels. In the following, the results of the twin tunnels model have been compared with the single tunnel model [16].

Because of complexity of vibration source, uncertainty of transmission path and existing of different materials, study on vibration needs of reliable experimental data for the verification of numerical or analytical models. To date, several field studies of the single tunnel have conducted in previous works, but the evidence in the literature of a field measurement, which accounts for the vibrant interaction between neighboring tunnels, does not exist. In this study, measurements are carried out to study the influence of the twin tunnels-induced vibration on the ground surface. At Tabriz, Iran, microtremor instrumentations on the ground surface and inside the underpass tunnel were carried out in order to evaluate train-induced vibrations. These results were used to verify the 3D numerical model in the time domain. The effects of the existence of the second active tunnel and tunnels separation distance on the ground vibration were then investigated. The goal of this study is to determine the minimum separation distance of the two tunnels, that the effect of the second tunnel on the ground surface vibration is eliminated. Also, one of the study gaps in the field measurement of the twin tunnels has been investigated in this study. The possibility of recording vibrations from both trains simultaneously in the field measurements is very low. Therefore, in this study, the correction factor for this issue is determined.

The outline of the paper is as follows. Section 2 introduces the test site in Tabriz (Iran) and addresses the determination of the soil, train and track characteristics. The 3D finite element model is presented in Section 3, and the experimental results are compared to results obtained by 3D FE modeling. Additional simulations are performed for the investigating of the tunnels separation distance effect in section 4. Also, the effect of a neighboring tunnel on the propagation of surface ground-borne vibrations is studied in Section 5.

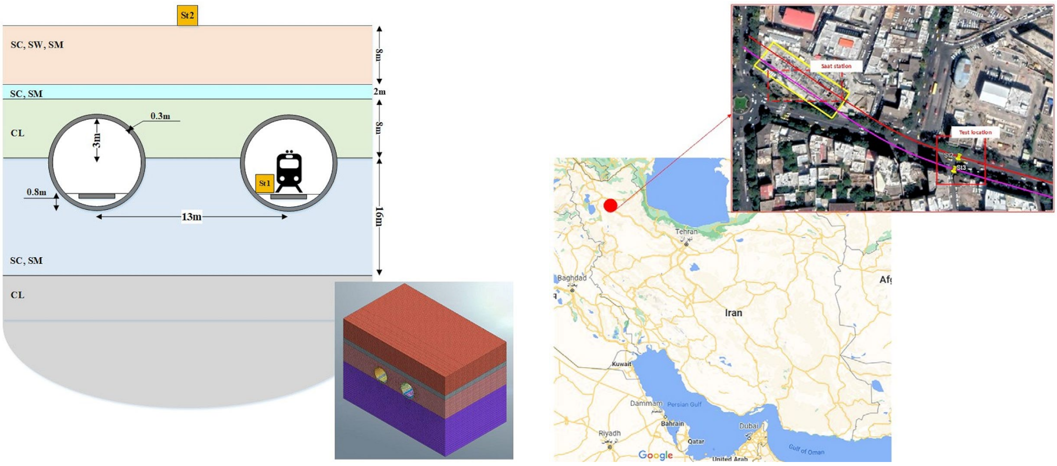
2 In-situ Measurements

Underground Line 1 in Tabriz, Iran was designed in about 2002 to allow connection west to east with a length of 17.2 km and 17 stations. This line consists of twin tunnels, used for the outbound and inbound directions, respectively. The tunnel on this line is a deep-bored tunnel with a concrete lining and a single track in each tunnel. The tunnels were excavated in a clay stone and tuff soils, using a tunnel boring machine (TBM) at a depth of about 15-25 m below the surface. In the test site, the two tunnels are built as circular section with inner radius 3 m, outer radius 3.3 and burial depths 15 m. The two tunnels are separated by a transverse distance 13 m (Figure 1).

2.1 Track and Train Specifications

The rails are placed on the slab with rail pads, and the slab is connected to the tunnel invert by rubber mat. The distance between the rail pads is 0.6 meters, and the rail type is a S49.

The line 1 trains are a normal passenger train, consisting of 5 cars: a driving motor car, three non-driving motor cars, and a driving motor car. The length of a motor car is 21 m, while the length of a trailer car is 19.5 m. The bogie and axle distances on all cars are 12.6 and 2.2 m, respectively. The total length of the test train is 100 m (Figure 2). Considering the mass of a wagon and the bogies, the axle load is 9.5 tons.



(a) (b)

Figure 1
(a) Cross section of the tunnels on line 1 and FE model, (b) location of field measurement

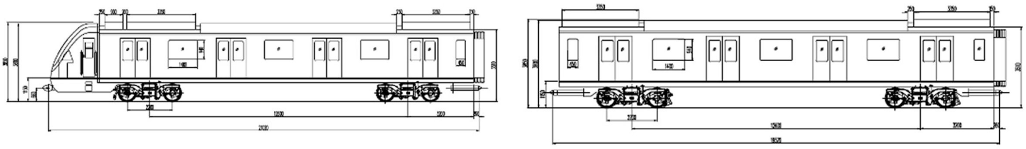


Figure 2
The configuration of the train

2.2 Geodynamic Characterization

The test site is located on line 1 of the Tabriz metro, between the Beheshti and Saat stations. The mechanical characteristics of the surrounding soil were determined using the Downhole seismic test.

Figure 1 shows the locations of two parallel tunnels through the scheme of soil layers. The soil is defined as a superposition of seven horizontal layers. Soil layers include silty sand and silty clay upper the clay soil, the uppermost layer is formed by a sand mixture. The soil parameters are summarized in Table 1, for the 5 layers, in terms of Young's modulus E, density ρ, Poisson's ratio ν and wave velocity Vs.

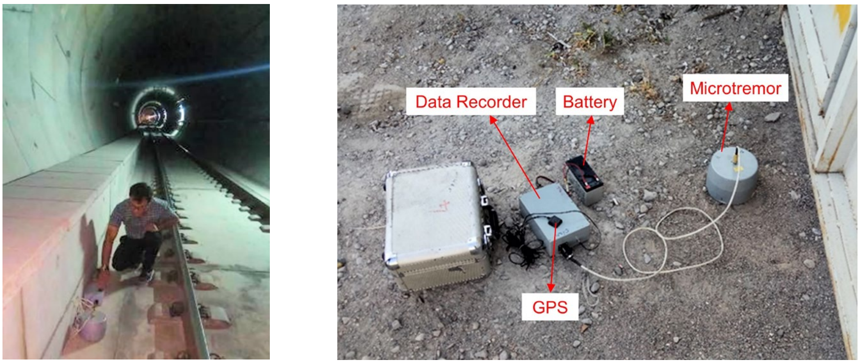
Table 1

Dynamic soil characteristics

Layer	E(Mpa)	ν	ρ (kg/m^3)	Vs(m/s)
1	300	0.39	1600	250
2	500	0.37	1800	300
3	700	0.37	1800	370
4	1350	0.36	1800	500

2.3 Measurements and Data Processing

The experimental measurements were carried out with the three vertical velocimeters (microtremor). These velocimeters were established on the ground surface and tunnel inside. The connected equipment includes a data recorder, power supply, and GPS are shown in Figure 3.



(a) (b)

Figure 3

(a) Railway track, (b) Microtremor equipment

The velocity responses were obtained at the tow points on the ground surface and one point on the slab. Points on the ground surface were located above the active tunnel and between a distance of the two tunnels. Three detection points were defined and are shown in Figure 1.

Field measurements were performed at the time with lowest passing surface road traffic. Nevertheless, data processing was implemented which includes eliminating noise signals, baseline correction, and the appropriate frequency range. The frequency range for the recorded data was set between 0 to 100 Hz.

3 Numerical Modeling

To predict the vibration responses, two 3D FE models were built with the FE code Midas GTS NX, one used for verification and the other used for other paper objectives. The model includes the soil layers, twin tunnels, and train load. To keep the model as simple as possible, also to decrease the model run time, superposition principle is applied for trainload. For this purpose, it is necessary to know the axle distribution and the train speed [17-19]. To simplify the cross-section of the rail in the numerical model, it is considered as a rectangle section with a contact surface equal to the width of the original rail foot. Moreover, the inertia must be equal to that of the original rail. [18].

The dimensions of the 3D model are considered to be 35*35*30 m. In addition, the mesh size of the soil layers surrounding the tunnels is 0.5 m. The sensitivity analyses were performed in another paper by the same authors to study the effect of model dimensions, mesh size, and time increment [15]. The absorbing boundary was used to prevent the wave reflection from the model boundaries.

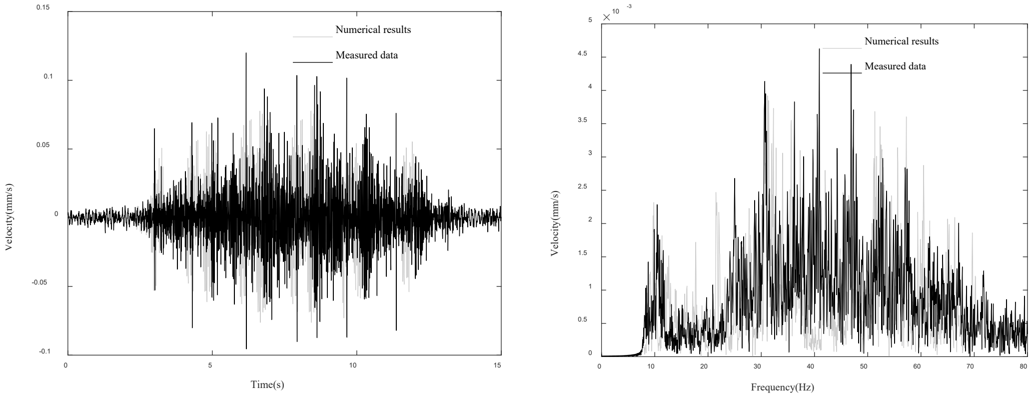
Rayleigh damping theory used in the model includes a damping matrix [C] which can be calculated as is shown in Equation 1:

$$[C] = \alpha[M] + \beta[K] \tag{1}$$

Here α and β are the Rayleigh coefficients, and [M] and [K] are the mass and stiffness matrix, respectively. The damping ratio coefficients α and β have a relation with fundamental frequency and damping ratio. The fundamental frequency is determined by solving the free vibration equation of the system. The calculated α and β are 2.159 and 0.00115, respectively.

3.1 Verification of the FE Model

In the present section, the response to a train moving at a speed of 32 km/h is predicted with 3D FE model, and compared to the experimental results. Figure 4 shows the comparison of measurement and calculation results, in time history and frequency content on the slab.



(a) (b)

Figure 4

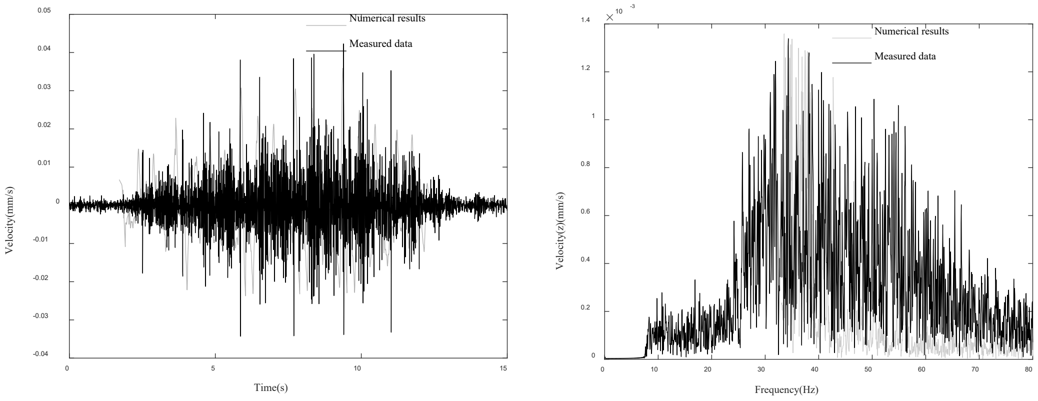
The experimental and numerical: (a) time history and (b) frequency content of the station 1 response

The general agreement between both results is acceptable. However, some discrepancy are existence, which this could be due to the underestimation of the dynamic forces and the influence of the train suspensions, which has been disregarded in the FE model.

Vibration measurements have also been performed in above the Tabriz line tunnels on the surface as well as at the slab in tunnel. Figure 5 compares the experimental and computed ground surface vibration at the distance between the two tunnels. Both the experimental and numerical results show a relatively good agreement at the observation point. The difference between the predicted and experimental results could probably be due to background noise, soil layers damping or inhomogeneities in the soil layers.

4 Effect of Separation Distance of Two Tunnels

In this section, the influence of separation distance of the two tunnels on the responses at the ground surface is investigated. The single tunnel model and the present model under different separation twin tunnels distances have been compared. The goal is to determine the distance, which the induced vibration from the two tunnels does not affect each other. The cross sections of the two models, and the observation point at the ground surface are presented in Figure 6.



(a) (b)

Figure 5
The experimental and numerical: (a) time history and (b) frequency content of the station 2 response

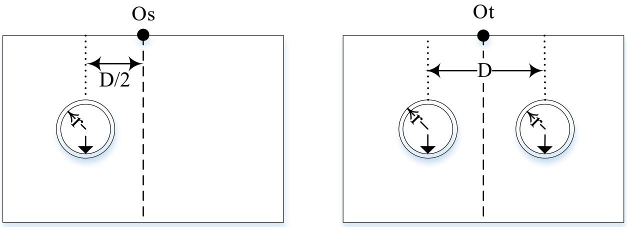


Figure 6
Cross sections of single tunnel and twin tunnel and observation point location

For a complete study, a homogeneous single layer with 3 different elastic modulus, 60, 150 and 400 MPa are considered. The comparison of the results between the single and twin tunnels is shown in Figure 7 for layer elastic modulus 150 MPa.

As shown in Figure 7, the responses at the ground surface above the twin tunnels are greater than those of the single tunnel. This is because the values obtained above the twin tunnels are the sum of the vibrations from the active tunnel and reflected waves from the adjacent tunnel lining. However, the dynamic responses at point O_s are only from the active tunnel. Also, the tunnels separation increases, the differences of the responses at observation points (O_t, O_s) decrease. Figure 7 shows that, when the distance between the two tunnels is more than 9r, the vibrations on the ground surface are equal to those of the single tunnel.

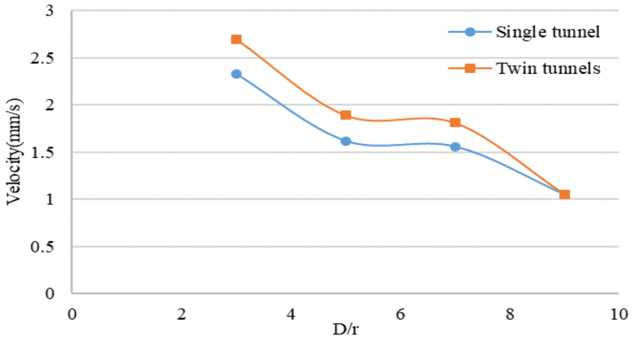


Figure 7
The effect of the separation distance of twin tunnels on the induced vibration and comparison with a single tunnel (Esoil=150 MPa)

The comparison between the single and twin tunnels models is shown in Figure 8 under different layer elastic modulus. The difference between the results is represented as a percentage, which is determined from the following equation (Equation 2).

$$DV(\frac{D}{r}) = \frac{Velocity(Ot)\text{-Velocity(Os)}}{\text{Velocity(Os)}} \times 100 \tag{3}$$

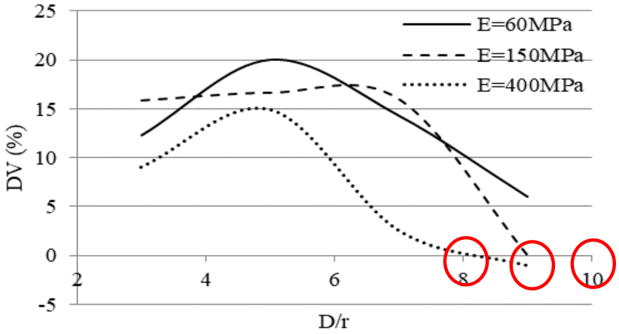


Figure 8
Comparison between the single tunnel and the twin tunnels model for different tunnels spacing and soil layer elastic modulus

As can be seen, the differences increase first, because of second tunnel effect, and then decrease to zero by the increase of the D/r ratio. From the results Figure 8 it can be concluded that The effect of the second tunnel for the soil layer with Young's modulus 60, 150, and 400 MPa disappears at a D/r ratio of 8, 9, and 10, respectively. In other words, as the soil layer becomes softer, the second tunnel affects the response at the ground surface at a larger distance.

5 Effect of Twin Active Tunnels on Surface Vibrations

During field measurements in twin tunnels, one of the trains usually passes through a tunnel. This is because as the second tunnel is not finished to the operation, or during measurement, two trains do not pass simultaneously. Therefore, if the measurement results are used to design the structure at ground surface above the tunnels, it is not completely correct. Because it is possible that during the structure lifespan, both trains pass each other through the tunnels at several times while daytime. To the author's knowledge, this correction factor has not reported in any published work. This section aims to present the effect of second active tunnel on the free field response for soil layer with different elastic modulus 60, 150 and 400 MPa. In additional this parameter is investigated to different twin tunnel separation distance (Figure 9). Insertion Gain (IG) concept (Equation 3) is used to assess determined results [4]:

$$IG = 20\log\left(\frac{x_2}{x_1}\right) \tag{3}$$

where x_1 is the reference case results (twin tunnel with one active tunnel), and x_2 is result after changes (twin tunnel with two active tunnels). IG represents the changes in the vibration response and expresses in decibel (dB).

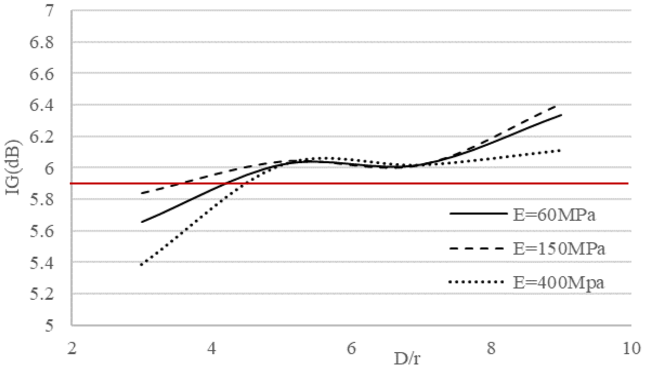


Figure 9

IG due to the existence of the load in the second tunnel compared to the passive tunnel model

As can be seen, in all cases, the IG is positive, which means that the existence of the load in the second tunnel causes an increase the vibration at the ground surface. Figure 9 shows that as the distance between the tunnels increases, the effect of the load in the second tunnel on the induced vibrations increases. But this effect is small and can be ignored. Also, the influence of the stiffness of the soil beneath the tunnels on the response is small. therefore, the improvement factor +6 dB (on average) have been suitable for the measurement of the field vibrations.

Conclusions

In this paper, a 3D twin-tunnel model is presented to evaluate the vibrations induced by trains. In continuation, a 3D FE model is validated with filed measurement data. Then the effects of two tunnels separation distance and existence of second tunnel on the vibration response are investigated. The present work includes field measurements of twin tunnels, which do not exist in previous studies. Field measured data can be used for future works as a reference. With the increase of the separation distance of two tunnels, the response of the active tunnel on the ground surface decreases. In addition, the elastic modulus of the soil layer influences the obtained results. The response on the ground surface increases with the decrease of the Yang's modulus of the soil layer. In other words, the distance between the tunnels, which the effect of the active tunnel disappears, for the soil layer with an elastic modulus of 60, 150, and 400 MPa, is equal to 8, 9, and 10 times the tunnel radius, respectively. In the field measurements of twin tunnels, if measured data do not include the vibrations induced from the two trains that pass each other simultaneously, according to the results of this paper, +6 dB should be added to the obtained values. In addition, this value does not depend on the distance between the tunnels and the elastic modulus of the soil layer.

References

[1] Forrest, J. A., & Hunt, H. E. M. (2006) Ground vibration generated by trains in underground tunnels. Journal of Sound and Vibration, 294(4-5), 706-736

[2] Yuan, Z., Boström, A., Cai, Y., & Cao, Z. (2019) Analytical solution for calculating vibrations from twin circular tunnels. Soil Dynamics and Earthquake Engineering, 117, 312-327

[3] Andersen, L., & Jones, C. J. C. (2006) "Coupled boundary and finite element analysis of vibration from railway tunnels—a comparison of two- and three-dimensional models". Journal of sound and vibration, 293(3-5), 611-625

[4] Gupta, S., Degrande, G., & Lombaert, G. (2009) "Experimental validation of a numerical model for subway induced vibrations". Journal of sound and vibration, 321(3-5), 786-812

[5] Gupta, S., Stanus, Y., Lombaert, G., & Degrande, G. (2009) "Influence of tunnel and soil parameters on vibrations from underground railways". Journal of Sound and Vibration, 327(1-2), 70-91

[6] Real, T., Zamorano, C., Ribes, F., & Real, J. I. (2015) "Train-induced vibration prediction in tunnels using 2D and 3D FEM models in time domain". Tunneling and Underground Space Technology, 49, 376-383

[7] Ruiz, J. F., & Rodríguez, L. M. (2015) "Application of an advanced soil constitutive model to the study of railway vibrations in tunnels through 2D

numerical models: a real case in Madrid (Spain)". Revista de la Construcción. Journal of Construction, 14(3), 53-61

[8] Németh, A., & Fischer, S. (2018) Investigation of glued insulated rail joints with special fiber-glass reinforced synthetic fishplates using in continuously welded tracks. Pollack Periodica, 13(2), 77-86

[9] Fischer, S. (2021) Investigation of effect of water content on railway granular supplementary layers. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2021(3), 64-68

[10] Kuo, K. A., Hunt, H. E. M., & Hussein, M. F. M. (2011) The effect of a twin tunnel on the propagation of ground-borne vibration from an underground railway. Journal of Sound and Vibration, 330(25), 6203-6222

[11] Hamad, W. I., Hunt, H. E., Talbot, J. P., Hussein, M. F., & Thompson, D. J. (2015) "The dynamic interaction of twin tunnels embedded in a homogeneous half-space". COMPDYN 2015, Greece. 13 pp.

[12] He, C., Zhou, S., Guo, P., Di, H., Zhang, X., & Yu, F. (2019) Theoretical modelling of the dynamic interaction between twin tunnels in a multi-layered half-space. Journal of Sound and Vibration, 456, 65-85

[13] Yuan, Z., Boström, A., Cai, Y., & Cao, Z. (2019) Analytical solution for calculating vibrations from twin circular tunnels. Soil Dynamics and Earthquake Engineering, 117, 312-327

[14] Yuan, Z., Boström, A., & Cai, Y. (2019) An analytical model for calculating vibrations from twin tunnels in a saturated poroelastic half-space. Soil Dynamics and Earthquake Engineering, 120, 23-27

[15] Heidary, R., Esmaeili, M., & Gharouni Nik, M. (2021) Effects of train operational parameters on ground-borne vibrations induced by twin metro tunnels. International Journal of Rail Transportation, 9(2), 144-156

[16] Heidary, R., Esmaeili, M., & Gharouni Nik, M. (2021) Evaluation of the soil layering and soil lens effect on the ground-borne vibrations induced by twin metro tunnels. European Journal of Environmental and Civil Engineering, 1-20

[17] El Kacimi, A., Woodward, P. K., Laghrouche, O., & Medero, G. (2013) Time domain 3D finite element modelling of train-induced vibration at high speed. Computers & Structures, 118, 66-73

[18] Real Herráiz, J. I., Zamorano, C., Hernández, C., Comendador, R., & Real, T. (2014) Computational considerations of 3-D finite element method models of railway vibration prediction in ballasted tracks. Journal of vibroengineering, 16(4), 1709-1722

[19] Wu, T. X., & Thompson, D. J. (2001) Vibration analysis of railway track with multiple wheels on the rail. Journal of Sound and Vibration, 239(1), 69-97