Influence of rubber pads on vibration levels and structural behavior of subway tunnels

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Abstract
The principal aim of this paper is to analyze the impact of rubber pad systems on levels of vibrations and values of stresses and deformations induced in the subway tunnel segments. Thus, the 3D model has been selected to be isotropically simulated in the ANSYS program to conduct a finite element analysis. Therefore, the proposed track system in the tunnel of line 4 of the Greater Cairo Metro has been selected as an analytical and simulation case study. The impact of using eight different values for the stiffness of the rubber pad system in the case of a single tunnel has been analyzed. The results showed that levels of vibrations are significantly affected and are in logarithmic correlation with the stiffness. Also, the impact of the stiffness on the deformations and stresses are determined as well as mathematical models connecting the different parameters have been introduced.

Keywords
subway tunnel, rubber pad system, vibrations, finite element method, stresses and deformations

Introduction
The increase in transportation demand in megacities results in bustling surface roads, especially in urban areas. Therefore nowadays, many designers of transportation planning tend to pass the transportation modes, e.g. light rails and heavy transit rails in tunnels. Induced vibrations inside and outside these tunnels are caused due to the interaction between moving trains of different axles’ loads and intervals and the railway tracks. Many other sources of vibrations in tunnels such as the rolling motion of the train wheels, rail and wheel irregularities, unsteady friction forces in sharply curved tracks, and stiffness of track components were classified, studied, and analyzed. Three important modeling methods for investigating the induced vibrations due to train movements are developed. This, mathematical models for the wavelengths of rail surface irregularity, wave speed, and frequencies were determined. It is found that the corresponding amplitudes range about 50 μm at long wavelengths to <1 μm for short wavelengths. These methods are categorized into empirical, numerical such as finite element method (FEM), and analytical methods. TCRP described that most standards are based on either a weighted or un-weighted vibration velocity in absolute units or decibels. The most common unit is the maximum root-mean-square (RMS) vibration level obtained using a one-second time constant (commonly known as a slow RMS detector).
Various excitation mechanisms of ground vibrations were investigated and validated, where the semi-analytical model of Train à Grande Vitesse, “high-speed train” has been validated by an extensive measurement campaign.\(^7\) The study, which was carried along at grade-ballasted tracks, found good agreement between the records of the carried out measurements and the predicted vibration levels due to train movements. In addition to those agreements, the study concluded that rail pads, ballast mats that were laid under ballast, and soffit pads cause an increase in the induced ground vibrations in the range of vibrations of 20–40 Hz at 10 m from the track. However, it was found that the attenuation of vibrations occurs above about 50 Hz. The effect of sleepers was also estimated; hence the results show that it had less effect on the ground response than the roughness of rail surface.\(^7\)

It was presented\(^8\) that capturing the hidden effects that are not obtained by 2D models due to variations in the geometric and material properties of the soil–structure system; a full 3D finite element modeling may still be necessary.\(^8\) Yang and Hung\(^9\) represented the soil–tunnel interaction system to study the impact of soil layers, assuming the material and geometry properties of the soil–tunnel system to be uniform along the load-moving direction. Also, they analyzed the case of a tunnel embedded in a uniform viscoelastic half-space, with or without bedrock, subjected to an underground moving train with a speed of 108 km/h. They concluded that the velocity levels of the induced ground vibrations increase as the number of train carriages increases as well as increasing the ground surface velocity with the increase in train speed. Another significant result from their research is the impact of the tunnel wall thickness on tunnel invert, where they found that a decrease accompanies the increase in wall thickness in the invert response.\(^10\)

In a study carried out under the EU FP7 project,\(^11\) it has been focused on anti-vibrating under sleeper pads in railway curves and turnouts. It was found that attenuation of up to 14 dB recorded when the turnout was provided with a soft under sleeper pads (0.095 N/mm\(^3\)). A model for train track/tunnel interaction was developed to calculate the generated vibration in a railway tunnel\(^12\); hence the results were compared with on-site measurements. In this research, a numerical calculation for the ground-born vibration was carried out using the 2D finite element model. The train wheels were modeled as moving mass, whereas the rails were modeled as continuous beams. The anti-vibrating rubber pads were represented in the model by springs and dashpots. The accelerations of vibrations inside the tunnel at a location near the track were measured and calculated in one-third octave bands. A previous Japanese mathematical model was used in that research to predict the vibration levels on the ground surface. This prediction model based on the records carried out in 14 locations on the subway network in Tokyo, Japan.\(^11,13\) The main conclusions of the study were that high-frequency components gradually attenuate in the ground, and absolute peaks were observed at 50 Hz on the ground surface, and a slight difference of 0.7–3.6 dB between the measured and the calculated values of the vibration acceleration levels were recorded.

Song et al.\(^14\) and Bian et al.\(^15\) presented that in recent decades, the unballasted slab track has been widely used in newly built railways in tunnels, where the slab track uses concrete slabs with high levels of rigidity to support the rails. Sleepers are embedded in the track slab as part of the whole structure, instead of lying on the ballast layer individually as in a conventional ballasted track. The apparent differences in track structure cause the dynamic performance of the unballasted railway to be quite different from that of a ballasted railway, including transient dynamic responses and long-term irreversible deformation.\(^16\) Thus, the unballasted tracks, especially in tunnels, need components of more vibration attenuation (rubber pad and rubber boot systems) to reduce the effect of rigidity on the railway system and the levels of vibrations either inside tunnels or on the ground surface above the tunnel.

The objective of this paper is establishing a calculation model for different stiffnesses of the under sleeper rubber pads to get the corresponding vibration levels that affects the tunnel structural behavior. Besides, the influences of the vibrations on the induced deformations and stresses in the tunnel structure near the track have been estimated and analyzed using a 3D numerical method (FEM). Thus, modeling the impact of the pad stiffness on the maximum values of vibrations, deformations, and stresses have been conducted. To validate the results of the modeling, comprehensive comparisons with previous studies have also been made in this paper.

**Material and data**

**Track cross-section**

The given cross-section of the shield tunnel in Figure 1 has been simulated in ANSYS-Dynamic software using the rubber pad system (RPS) that is installed under the railway sleepers. A photo for Japanese RPS is shown in Figure 2.
Tunnel cross-section

The route of the Greater Cairo Metro, line 4, is passing under roads in very populated residential areas and under some part of dwelling houses. So, the Tunnel Boring Machine is selected to be applied for the whole tunneling route. The single-track double tunnel system has been used to pass in the available narrow spaces to avoid many obstacles such as deep foundations of flyovers and existing underpass at road intersections. Figure 3 illustrates a cross-section for tunnel cross-section.

Train load and interaction with the track system

To calculate the vibration generated in the tunnel, the train/track/tunnel interaction model has been investigated and developed, as shown in Figure 4. The cars, tracks, tunnel, and the soil around the tunnel have been modeled in three-dimension, and load from running train of line 4 has been considered in the model. The train wheel has been simulated as a moving mass. The situation where a train is running on the track with an average running speed of 65 km/h has been simulated and analyzed by utilizing the time history response analysis method; hence the time acceleration amplitude measured on the wheel–rail contact point is simulated as given values in Figure 5. Figure 6 illustrates the magnitude–frequency curve of the forced vibration for the train wheels that has been obtained after Fast Fourier Transformation (FFT).

The vibration level at some distance from a railway track or a tunnel is highly impacted by the vehicle and track system force density levels (FDL). These forces are generated due to wheel and rail roughness, heterogeneities of distribution of track sleepers, and unbalancing of the rotating components in the train bogies. FDLs should be measured for the vehicle and track interaction in order to be used in the numerical analysis and simulation.
The interaction between the train wheels and the railway track varies depending on the type of track components. The input FDL that is used for simulation in this paper has been recorded by Kinkisharyo (the supplier company of the trains and it is illustrated in Table 1.

**Calculation model**

**Simulated models in ANSYS.** The simulated model of the unballasted track inside the tunnel has been established and processed in the program software according to the data mentioned above. To study the influence of running trains, horizontal single tunnel configuration was modeled. 3D finite element model for tunnel and track, including soil, is shown in Figure 7. The width, length, and thickness of the 3D model are 30 m, 30 m, and 0.60 m, respectively. And the inner and the outer diameter of the tunnel are 5.80 m and 6.40 m, respectively. A solid65 element was used to simulate the soil and concrete. Solid180 was used to simulate the metal and rubber members like the rails, connections, and anti-vibration systems. The media of the single tunnel was taken by dimensions 30 m in wide and 30 in height, where the depth of the model is 0.6 m as the distance between the two sleepers. The mesh of the numerical model was meshed as the tetrahedral elements and refined at the rail systems to be the
smallest size than the border of the model. The boundary conditions were done in the numerical model; the bottom of the model was restrained for the vertical motion, the two vertical sides at the border of the models were restrained for the horizontal motion, and the front and back elevations of the model were restrained to orthogonal motion.

**Material characteristics.** The characteristics of the materials of the RPS that have been used in the modeling have been simulated as orthotropic material, and the simulation process are shown in Table 2.20 Also, the physical characteristics of materials of the tunnel, soil, and track components are simulated as linear materials and shown in Table 3.21 The vertical stiffness (Ky) of the RPSs had been made constant value by 8.2 MN/m. On the other hand, the horizontal stiffness’s (Kx and Kz) had been changed in every model. The RPSs were simulated as an

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**Table 1. Force density levels for similar Japanese train.**

| Octave band center frequency | 4  | 8  | 16 | 31.5 | 63  | 125 | 170 |
|-----------------------------|----|----|----|------|-----|-----|-----|
| 1/3 Octave force density    | 8  | 80 | 17 | 42   | 122 | 73  | 66  |
| 1/3 Octave force density level—(dB) | 18 | 37 | 23 | 32   | 41  | 36  | 35  |

*Source: reproduced with permission from JRTS, 2012.*

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**Figure 5.** Time–acceleration amplitude.

*Source: reproduced with permission from JRTS, 2012.*

**Figure 6.** Frequency–magnitude (FFT).
orthotropic material, where the other members were simulated as isotropic material. Besides, all materials in the different models were simulated as the linear material for the resulted problems of nonlinear material within the dynamic analysis.

Results and discussion

Numerical model validation

The validation was applied to the finite element parameters of this study by verifying against numerical results from the previous literature. He and Cui\(^{22}\) conducted the numerical simulation of thawing soil, as shown in Figure 8.

| Properties                          | Units | Horizontal stiffness |
|------------------------------------|-------|----------------------|
|                                    |       | 10  | 15  | 18  | 20  | 22  | 25  | 30  |
| A (bearing area)                   | m\(^2\) | 0.1913 | 0.1913 | 0.1913 | 0.1913 | 0.1913 | 0.1913 |
| d (thickness)                      | mm    | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 | 0.018 |
| Kx (spring coefficient)            | MN/m  | 10  | 15  | 18  | 20  | 22  | 25  | 30  |
| Ky                                 | MN/m  | 8.2  | 8.2  | 8.2  | 8.2  | 8.2  | 8.2  | 8.2  |
| Kz                                 | MN/m  | 10  | 15  | 18  | 20  | 22  | 25  | 30  |
| Ex (modulus of elasticity)         | Mpa   | 0.9410 | 1.4115 | 1.6938 | 1.8820 | 2.0702 | 2.3525 | 2.8230 |
| Ey                                 | Mpa   | 0.7716 | 0.7716 | 0.7716 | 0.7716 | 0.7716 | 0.7716 | 0.7716 |
| Ez                                 | Mpa   | 0.9410 | 1.4115 | 1.6938 | 1.8820 | 2.0702 | 2.3525 | 2.8230 |
| Vxy (Poisson’s ratio)              |       | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.42 |
| Vyz                                |       | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.42 |
| Vxz                                |       | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 |
| Gxy (shear modulus)                | Mpa   | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2727 |
| Gyz                                | Mpa   | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2679 | 0.2727 |
| Gxz                                | Mpa   | 0.3313 | 0.4970 | 0.5964 | 0.6627 | 0.7289 | 0.8283 | 0.9940 |

Source: reproduced with permission from JICA Study Team, 2011.\(^{20}\)
The verification model characteristics are listed in Table 3. The tunnel and soil media were modeled using the same parameters proposed in this study, as shown in Figure 8. The frequency–displacement resulted from the numerical model by using FFT at point A (at the right of the contact between the tunnel and soil) were compared with the He and Cui results, as shown in Figure 9. The results are in good agreement and pattern of the curve. These results indicate that the analysis method proposed in this study imitates the behavior of the actual structures accurately. Thus, the study of the various design parameters can be carried using the proposed analysis method.

### Table 3. Physical characteristics of materials of tunnel, soil, and track components.

| Properties        | Units | Rail   | Pad    | Fasten. | Sleeper | Bed    | Invert concrete | Tunnel | Soil |
|-------------------|-------|--------|--------|---------|---------|--------|-----------------|--------|------|
| \( \gamma \), Density | N/mm\(^3\) | 7.83E-05 | 9.0E-06 | 7.83E-05 | 2.55E-05 | 2.55E-05 | 2.55E-05          | 2.55E-05 | 1.94E-05 |
| E, Modulus of elasticity | MPa    | 210000  | 2      | 210000  | 26192   | 26192  | 26192           | 26192  | 1000 |
| \( \nu \), Poisson’s ratio |       | 0.30    | 0.49   | 0.30    | 0.20    | 0.20   | 0.20            | 0.20   | 0.33 |

Source: reproduced with permission from JICA Study Team, 2011.\(^2\)

**Figure 8.** Numerical model of the tested specimen.

**Figure 9.** Numerical model verification results.

The verification model characteristics are listed in Table 3. The tunnel and soil media were modeled using the same parameters proposed in this study, as shown in Figure 8. The frequency–displacement resulted from the numerical model by using FFT at point A (at the right of the contact between the tunnel and soil) were compared with the He and Cui results, as shown in Figure 9. The results are in good agreement and pattern of the curve. These results indicate that the analysis method proposed in this study imitates the behavior of the actual structures accurately. Thus, the study of the various design parameters can be carried using the proposed analysis method.

### Results of simulation

The forces coming from the wheels of the track were applied at convergence the wheel with track on the top of the rail by accelerations vs time. The values of accelerations have been simulated orthotopically at vertical stiffness 8.2
MN/m and seven different values of the rubber lateral stiffness: 10 MN/m, 15 MN/m, 18 MN/m, 20 MN/m, 22 MN/m, 25 MN/m, and 30 MN/m. The type of analysis processes for the different models was done by transient analysis method from zero time to one second at the end of the load step, where the time step size is 0.002 s. The overall values of vibration acceleration obtained from the simulation output are calculated on the edge of the concrete bed beside the track in the tunnel segment. As well as, modal analysis was conducted for the numerical model, and 200 modes were extracted. The frequencies of the first eight modes are shown in Table 5. The resulted natural frequency of the tunnel was 7.4113 Hz from the modal analysis. On the other hand, the natural frequency of the metro vibration was 122.42 Hz. Consequently, tunnel response due to vibration of the metro is feeble and the resonance will not occur due to the large gap between the frequencies of the tunnel and the metro vibration.

The generated acceleration amplitudes beside the track in the tunnel segment for the seven cases of the rubber pad stiffness are illustrated in Figure 11(a) for values 10, 18, 22, and 30 MN/m and Figure 11(b) for the rubber lateral stiffness, 15, 20, and 25 MN/m.

### Calculations of vibration levels

According to different specifications in the field of vibrations, the following model is used to convert the vibration acceleration to $L_{va}$ in decibels:\(^{3,13}\)

$$L_{va} = 20 \log \frac{a}{a_0}$$

where $a$ is the RMS of the vibration acceleration, and $a_0$ is the reference vibration acceleration, which is taken as $10^{-6} \text{ m/s}^2$. So, the maximum vibration levels ($L_{va}$) for RMS of accelerations are calculated and are given in Table

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**Table 4. Parameters of the tunnel and soil of the model of He and Cui.**

| Properties                  | Soil  | Tunnel |
|-----------------------------|-------|--------|
| $\gamma$, Density (N/mm²)   | 2.1E-05 | 2.5E-05 |
| $E$, Modulus of elasticity (Mpa) | 250 | 35000  |
| $\nu$, Poisson’s ratio      | 0.46  | 0.25   |

Source: reproduced with permission from He and Cui, 2015.\(^{22}\)
Calculation of deformations and stresses of the tunnel segments

The 3D finite element analysis was used to predict both the deformation and the stress values of the tunnel segment at the different values of horizontal stiffness for the RPS under the effect of the vertical acceleration load. The parametric study concentrated on the under-tunnel segment with the different values of horizontal stiffness for the RPS, i.e. the horizontal stiffness (10, 15, 18, 22, 25, and 30 MN/m). Figures 13 and 14 show the total deformation results for the tunnel segments in models with horizontal stiffnesses 10 and 30 MN/m, respectively. The maximum value of the deformation is noticed in the model with 30 MN/m, while the minimum value of deformation was noticed in the model with 10 MN/m. The additional deformation due to the vibration load from the train decreases with the decrease in the horizontal stiffness for the RPS. The effect of the horizontal stiffness

### Table 5. The frequencies of the numerical model with different modes.

| Mod | Frequency (Hz) |
|-----|----------------|
| 1   | 7.4113         |
| 2   | 13.892         |
| 3   | 18.362         |
| 4   | 22.074         |
| 5   | 23.483         |
| 6   | 27.624         |
| 7   | 28.225         |
| 8   | 30.148         |

Figure 11. Acceleration amplitude beside the track in the tunnel segment. (a) The rubber lateral stiffness, 10, 18, 22, and 30 MN/m. (b) The rubber lateral stiffness, 15, 20, and 25 MN/m.
Table 6. Maximum generated accelerations and levels of vibrations.

| H. Stiffness of rubber pad | $K_h = 10$ MN/m | $K_h = 15$ MN/m | $K_h = 18$ MN/m | $K_h = 20$ MN/m | $K_h = 22$ MN/m | $K_h = 25$ MN/m | $K_h = 30$ MN/m |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Maximum RMS value of Acc. (a) (m/s²) | 0.000229775 | 0.000308676 | 0.000332118 | 0.000420919 | 0.000493534 | 0.001032927 | 0.001110322 |
| Vibration levels ($L_{va}$) dB | 47.22 | 49.79 | 50.42 | 52.48 | 53.86 | 60.28 | 60.91 |

Figure 12. Effect of the horizontal stiffness of rubber pad on vibrations levels on tunnel segment.

Figure 13. Deformation values in tunnel segment at the case of 10 MN/m stiffness.
of the rubber pad on the deformation of the tunnel segment beside the track has been illustrated in Figure 15. Thus, the different tendencies of deformation of the tunnel wall with the horizontal stiffness are logarithmically fitted based on the calculated values. The obtained model is also shown in Figure 15.

Figures 16 and 17 show the von Mises stresses distribution of the tunnel segments in models with horizontal stiffnesses 10 and 30 MN/m, respectively. The maximum value of von Mises stresses is noticed in the model with 30 MN/m, while the minimum value of von Mises stresses is noticed in the model with 10 MN/m. The additional stress due to the vibration load from the train decreases with the decrease in the horizontal stiffness for the anti-vibration system. The effect of the horizontal stiffness of rubber pad on von Mises stresses in the tunnel segment beside the track has been illustrated in Figure 18. Thus, the different tendencies of von Mises stresses of tunnel wall with the horizontal stiffness of the rubber pad are logarithmically fitted based on the calculated values. The obtained model is also shown in Figure 18.

**Discussion**

Analyzing the calculated vibration levels, which are recorded in Table 4 and illustrated in Figure 8 for the given stiffness values of the rubber pad stiffness, it is noticed that the different tendencies give the following logarithmic
The model shows a good coefficient of determination ($R^2 = 0.9183$). The model demonstrates that vibration values increase with increasing the stiffness values of the rubber pad stiffness. Also, the influences of the stiffness values of the rubber pad on the tunnel wall deformation and induced stresses that respectively are shown in Figures 14 and 20 have been fitted with the following logarithmic models given in Table 7. The variables in those models are correlated with good coefficients of determination ($R^2 = 0.9218$ and $0.9129$, respectively). The models demonstrate that both deformation and stresses values of the tunnel wall increase with increasing the stiffness values of the rubber pad.

Comparing the results with field tests
Field tests were conducted in China on Beijing Subway Line 15 to analyze the dynamic characteristics of monoblock concrete sleepers supported on rubber pads and boot system, 23 which are similar in their engineering.

![Figure 16. Stress values in tunnel segment at the case of 10 MN/m stiffness.](image1)

![Figure 17. Stress values in tunnel segment at the case of 30 MN/m stiffness.](image2)

| Type          | Tunnel wall vibration | Tunnel wall deformation | Tunnel wall stress |
|---------------|-----------------------|-------------------------|-------------------|
| Model         | $y = 41.392 \times 0.0129x$ | $y = 0.0037 \times 0.0942x$ | $y = 0.006 \times 0.0967x$ |
| Coefficient of determination ($R^2$) | 0.9183 | 0.9218 | 0.9129 |

![Figure 18. Effect of the horizontal stiffness of rubber pad on von Mises stresses in the tunnel segment.](image3)

![Figure 19. Relationship for the frequency (Hz) and measured vibration Levels (Beijing Subway Line 15).](image4)

Source: reproduced with permission from Cai et al., 2018.23

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model shown in Table 7 with a good coefficient of determination ($R^2 = 0.9183$). The model demonstrates that vibration values increase with increasing the stiffness values of the rubber pad stiffness. Also, the influences of the stiffness values of the rubber pad on the tunnel wall deformation and induced stresses that respectively are shown in Figures 14 and 20 have been fitted with the following logarithmic models given in Table 7. The variables in those models are correlated with good coefficients of determination ($R^2 = 0.9218$ and 0.9129, respectively). The models demonstrate that both deformation and stresses values of the tunnel wall increase with increasing the stiffness values of the rubber pad.

**Comparing the results with field tests**

Field tests were conducted in China on Beijing Subway Line 15 to analyze the dynamic characteristics of monoblock concrete sleepers supported on rubber pads and boot system, which are similar in their engineering
characteristics to the user system for testing in this paper. A relationship between the frequencies and values of generated vibrations on the sidewall of the tunnel for the same system and the common ballastless track was illustrated in Figure 19. It was observed that the measured value in the tunnel of Beijing Subway Line 15 was 59.56 dB. Also, Japan Railway Technical Service\(^{19}\) conducted experimental works to evaluate the effect of the rubber pad and the boot system (with the stiffness of 25 MPa), which will be used in Greater Cairo Metro Line 4, on the vibration levels beside the track, and the results for two types of the used pads are summarized and illustrated in Figure 20. The maximum value of the vibration level (at 63 Hz) was recorded as 57.5 dB.

To verify the accuracy of the obtained model in this paper, as it was demonstrated in Table 4 and illustrated in Figure 12, it is substituted in the model at a frequency of 63 Hz which is commonly used for vibration measuring and stiffness of 25 MN/m. Thus, the calculated value of the vibration level is 58.93 dB. Comparing the calculated value with the field measured values, the error in the deduced model in this paper equals 1.06% and 2.48%, respectively.

**Conclusions and recommendation**

In this paper, the movement of trains in the Greater Cairo Metro tunnel with a single track has been simulated in the ANSYS program using FEM. The railway track in the tunnel was unballasted and was provided with a RPS of 8.2 MN/m vertical stiffness. Assessing, analyzing, and modeling the vibration levels, deformations and stresses values in tunnel wall generated as a result of the train movement have been conducted for seven different values of the horizontal stiffness of the proposed RPS. Besides, three different models determine the influence of the horizontal stiffness of the proposed RPS on the tunnel wall vibration level, deformation and stress have been obtained and compared with similar field test measurements. The models indicated logarithmic correlations between the stiffness and the three parameters, where their values increase with increasing the stiffness of the proposed RPS. Based on the obtained results, the following recommendation can be summarized as follows:

1. In case of using unballasted tracks inside tunnels, RPSs of appropriate stiffness values should be laid under the sleepers to minimize the vibration levels, deformations, and stresses that are affecting the tunnel segments.
2. According to Japanese and German standards, the maximum allowable values of vibration levels inside tunnels should be <60 dB\(^{18}\) thus the appropriate rubber pad horizontal stiffness should be within the range of 15–25 MN/m to avoid any negative impacts on the structure behavior of the subway tunnels.
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Ahmed A Khalil, Kamal G Metwally and Nasser Z Ahmed: content planning, literature search and review, simulation, modeling, statistical analysis, and manuscript writing.

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