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MODELING THE EFFECTS OF SOIL IMPROVEMENT ON TRAIN INDUCED RANDOM GROUND-BORNE VIBRATIONS

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ABSTRACT. Ground-borne vibrations by railway trains are generated at the rail-wheel interface due to the passage of wheels and due to irregularities of wheels and tracks. These vibrations need to be predicted and controlled during the design and service of the railway for the safety and serviceability of the railway to avoid possible vibration-induced problems such as settlement and differential settlement due to their compaction effect, liquefaction, and discomfort of people. While such railway vibrations are modeled by different techniques, only a few studies do exist to analyze them in the case of soil-improved conditions. In this study, we propose a mathematical framework to study the effects of soil improvement on the ground-borne vibrations induced by railway trains. We use an experimentally calibrated model that utilizes the evolutionary random process approach to model the time-varying transfer functions between the axles of the train and the fixed observation point. The railway is modeled as a Winkler foundation with rail pads and corresponding transfer functions are used. The target area of this study is the Eminönü-Alibeyköy Tramway Line in İstanbul, which is under construction. Due to poor soil conditions at the specific stations along the proposed tramway route, soil improvement by the application of geo-synthetics is performed at the site and taken into account in our model. The improvement in soil conditions is modeled as increased vertical soil stiffness in the Winkler foundation of the evolutionary random process model. To model the various tramway loading conditions, both the 5-axle and 6-axle tramway configurations with non-uniform axle spacing are considered. We show that by increasing the vertical soil stiffness k_{sb}, the vibration velocity and acceleration levels can be reduced significantly. By implementing the model proposed, we present the reduction of the vibration velocity and acceleration levels as the functions of soil improvement parameters and discuss our findings and the applicability of the model.

Keywords: Train Induced Vibrations, Random Vibrations, Soil Improvement.

AMS Subject Classification: 65T50, 65Z05

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1. Introduction

Railway-induced ground-borne vibrations can lead to many engineering problems such as settlement and differential settlement due to their compaction effect, they can lead to damage to historical buildings, soil liquefaction, and discomfort of people in the frequency interval of $1 - 80Hz$ [1, 2, 3]. Therefore it is crucial to analyze these vibrations. Many different analytical, numerical and experimental techniques are used to model these vibrations. The reader is referred to some of the vast literature such as modeling the elastic tunnel behavior under the influence of random axle vibrations [4, 5], modeling ground vibration generated by a harmonic and moving loads spectrally acting on a railway track on a layer soil media [6, 7, 8, 9], analytical and experimental modeling the effects of track irregularities on train-induced ground-borne vibrations [10, 11, 12, 13] and the references therein to catch a glimpse of the work done. Additionally, manuscripts such as [14, 15] are good sources to examine the comprehensive state-of-the-art literature.

In analytical methods, the elastic foundation beneath the railway is commonly modeled by elastic beam theories, such as the Euler-Bernoulli beam. The effect of vertical soil stiffness leads to the Winkler beam theory, or beam on elastic foundation, which is widely used to model railways. Some researchers calculate the harmonic response of infinite beams on simple and general elastic periodic supports [4]. Others applied a similar idea to a rail beam on periodic sleeper beam supports [4]. In empirical methods, some measurements of the ground vibration from heavy freight trains are compared to models using an infinite rail beam on discrete mass–spring sleepers on 3D layered media [4], additionally some models are validated comprising two rail beams on continuous layers for which the validation is performed against measurements of the soil dynamic response and track receptance [4]. In numerical methods used in modeling railway behavior, the most common choice is the finite element method (FEM). Several researchers have investigated the dynamics of railways using FE models [4]. These models include but are not limited to the simulation of the infinite soil under the rail with an FE mesh; and dynamic analysis of general 3D structures resting on an elastic half-space under rail [4]. Additionally, some research does exist in which 3D coupled FEM–Boundary Element Method (BEM) treatment of a railway resting on half-space [4]. Existing models for ground vibration from underground railways are summarized in [4], where the authors develop a 3D model considering the underground tunnel dynamics as well. More recently the effects of groundwater table and ground inclination on train-induced ground-borne vibrations are studied in [16]. This brief list is by no means complete but aims to give the reader a picture of the vast literature. The reader is referred to [4, 6, 15] for a more comprehensive discussion.

Although railway-induced ground-borne vibrations are well studied, the effect of soil and subgrade stiffening on these vibrations are not well studied and only very few studies exist in the literature such as [17, 18]. In [17], the authors carried out a parametric study using a 2.5D coupled FE-BEM numerical methodology where they examined the effects of subgrade stiffening and stiff inclusions [4]. In [17], the authors reviewed some vibration mitigation methods such as open trenches, soft or stiff buried barriers, and subgrade stiffening techniques. However, to our best knowledge, there is no research on examining the direct effects of increasing the bearing capacity of the subgrade soil and therefore aims to contribute to this problem.

In this study, following [4, 16, 19], the railway is modeled as a Winkler foundation with rail pads, and corresponding transfer functions are used. The target area of this study is the Eminönü-Alibeyköy Tramway Line in İstanbul, which is under construction. Along the planned route, many historical buildings do exist and some of them were constructed by Architect Sinan [20]. Few of these historical buildings are damaged by past earthquakes and soil amplification is considered as one of the key reasons that caused some buildings to collapse in this region. Due to poor soil conditions soil improvement and stiffening of the subgrade were deemed necessary at this site. Soil improvement is being and will be performed at the site using geo-textiles and geogrids. Although the effect of the application of geotextiles on the bearing capacity and other parameters of the soil is studied, their effect on railway-induced ground-borne vibrations is not studied. This work aims to address this open problem.

2. Methodology

In this section, we give a brief review of a random vibration model of a simple slab beam which is modeled as a Winkler foundation. We refer the reader to the [4, 5] for a more comprehensive discussion of this part.

2.1. Review of the Random Vibration Model for a Simple Slab Beam.

Time harmonic displacement response of a simple slab beam, $Y(x)$, can be modeled computed by the spatial convolution

$$y(x) = \int_{-\infty}^{\infty} H(x-\chi)Q(\chi)d\chi \tag{1}$$

where $Q(\chi)$ is the force per unit length acting along the rail and $H(x)$ is the frequency response function for $Y(x)$ at the application location of the point load, that is $x = 0$ [4, 5]. It is well known that convolution operations are computationally costly and critical vibration levels presented in some standards such as ISO 2631, DIN 4250-3 are spectral. Therefore it is easier to formulate the analysis spectrally in the Fourier domain. Some applications, uses and advantages of the spectral analysis can be seen in [21, 22, **?**, 24]. Taking the Fourier transform of Eq.1, one can obtain

$$\tilde{Y}(\xi) = \tilde{H}(\xi)\tilde{Q}(\xi) \tag{2}$$

where $\tilde{H}(\xi)$ is the frequency response function in the Fourier domain. The dynamics of the slab beam can be modeled using the Euler-Bernoulli beam if small displacements are considered. Adding the force due to vertical soil stiffness, the governing equation becomes the Winkler model for elastic foundation. Winkler foundation can be modeled using

$$m\frac{\partial^2 y(x,t)}{\partial t^2} + EI\frac{\partial^4 y(x,t)}{\partial x^4} + k_w y(x,t) = f(x,t) \tag{3}$$

Using serially connected spring analogy, the stiffness of the Winkler foundation can be calculated using

$$\frac{1}{k_w} = \frac{1}{k_{sb}} + \frac{1}{k_r} \tag{4}$$

where k_r shows the stiffness of the rail pad and is taken as $k_r = 30 * 10^6 N/m/m$ and k_{sb} is the soil-ballast stiffness measured at the site using geotechnical instrumentation. Typical values at the target area of this research are as low as $4125kN/m/m$. To take the effects of dissipation into account a constant loss factor of $\eta = 0.09$, which commensurate with experiments [4, 5], is considered, and thus k_w is multiplied with a factor of $(1 + i\eta)$ [4, 5]. The Winkler frequency response $Y(x,\omega)$ can be obtained by applying Eq.3 to an infinite beam on an elastic foundation [4, 5], which leads to

$$Y(x,\omega) = \frac{1}{4\alpha^3 EI}(e^{\alpha|x|} + ie^{i\alpha|x|}) \tag{5}$$

where

$$\alpha^4 = \frac{m\omega^2 - k_w}{EI} \tag{6}$$

The root *alpha* in Eq.5 is selected in the second quadrant so that both exponentials decay as $|x| \to \infty$ [4, 5]. So that the Winkler frequency response at $x = 0$ becomes

$$\tilde{Y}(x=0,\omega) = \frac{1}{4\alpha^3 EI}(1+i) = \tilde{H}(\omega) \tag{7}$$

Assuming that all wheels of the train are smooth and all irregularities are in the rail surface, the axle inputs can be assumed to differ by a time delay [4, 5]. The time delay between two axles is $T = L_{pq}/v$ where L_{pq} is the nonuniform axle spacing and v is the velocity of the train. Under these assumptions, using random vibration theory the output spectrum of the vertical rail displacement can be written as [24]

$$S(\omega) = \sum_{p=1}^{N}\sum_{q=1}^{N} H_p^*(\omega)H_q(\omega)S_o(\omega)e^{-i\omega L_{pq}/v} \tag{8}$$

where p and q are axle indices, $H_p(\omega)$ and $H_q(\omega)$ are the frequency response functions of axle loadings of p and q respectively. 5 and 6 axle spacings, used in the calculation of the L_{pq}, are shown in Fig.1. Here, $S_o(\omega)$ is the two-sided rail roughness spectrum which

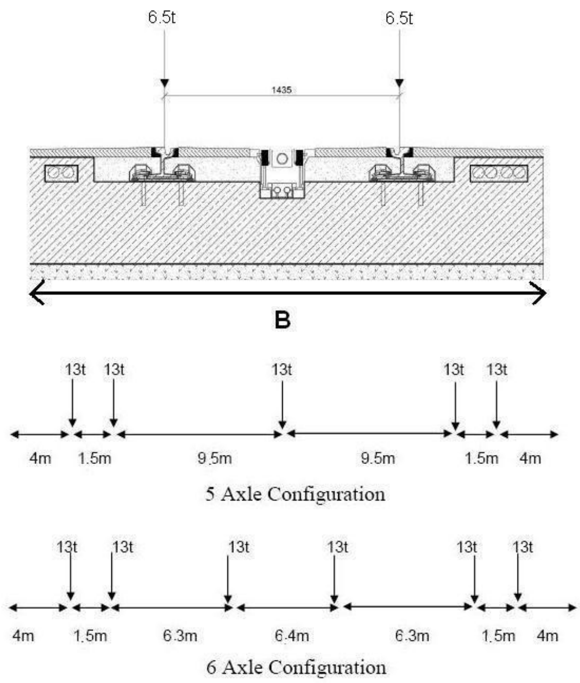

FIGURE 1. 5 axle and 6 axle configurations.

can be calculated from the one-sided rail roughness spectrum by $S_o(f) = 4\pi S_o(\omega)$ where $\omega = 2\pi f$. One of the most commonly used one-sided rail roughness spectrum is proposed in [25] and given as

$$S_o(f) = \frac{1}{v}\frac{a}{(b+f/v)^3} \tag{9}$$

where the parameters a and b are tabulated below for different rail conditions.

Table 1. Rail roughness parameters for different rail conditions.

Rail Condition	$a(mm^2.(1/m)^2)$	$b(1/m)$
Worst	9.39×10^{-1}	6.89×10^{-2}
Average	1.31×10^{-2}	2.94×10^{-2}
Best	1.90×10^{-4}	9.71×10^{-3}

Throughout this study, the worst rail conditions are considered and calculations are carried out accordingly. Using the output spectrum, $S_y(\omega)$, the mean square value of the vertical rail displacement can be calculated using

$$E[y^2] = \int_{-\infty}^{\infty} S_y(\omega) d\omega \tag{10}$$

which eventually leads to rms vertical displacement values, y_{rms}, that can be calculated by taking the square root of $E[y^2]$. Using random vibration theory, the output spectra for vertical rail vibration velocity and vertical rail vibration acceleration can be found using [24]

$$S_v(\omega) = \omega^2 S_y(\omega) \tag{11}$$

and

$$S_a(\omega) = \omega^2 S_v(\omega) = \omega^4 S_y(\omega) \tag{12}$$

Finally, the RMS values for the vibration velocity and vibration acceleration, v_{rms} and a_{rms}, can be calculated using the square root of $E[v^2]$, which is given as

$$E[v^2] = \int_{-\infty}^{\infty} S_v(\omega) d\omega \tag{13}$$

and the square root of the $E[a^2]$ given by

$$E[a^2] = \int_{-\infty}^{\infty} S_a(\omega) d\omega \tag{14}$$

Typically, the vibration parameters are given spectrally. Therefore the frequency axis is divided into octave bands and averaging is performed within each octave band.

2.2. **Modeling the effect of soil improvement on the level of ground-borne vibrations.** High levels of railway-induced ground vibrations are often associated with sites' poor ground conditions. Therefore stiffening the subgrade under the railway track is considered as the first possible remedy to reduce the vibration level at such sites. However, the mechanisms behind this reduction are not well studied and there are only very few studies in the literature such as [17, 18] which discuss the effects of soil improvement on the ground-borne vibration levels induced by the railways. In [17], the authors carried out a parametric study using a 2.5D numerical coupled FEM/BEM methodology. They examined the effects of (a) 'subgrade stiffening, where the soil directly under the track is stiffened' and (b) 'stiff inclusions introduced at some depth under the track, also known as 'wave impeding blocks". They also considered the effects of a new and thin soil layer and jet grouting. In [17], the authors gave a performance review of the vibration mitigation methods such as open trenches, buried barriers, and subgrade stiffening techniques. However, to our best knowledge, there is no research on examining the direct effects of increasing the bearing capacity of the subgrade soil on the ground-borne railway-induced vibrations. For example, in the case of applications of geosynthetics such as geogrids and geotextiles which are usually made up of polymer materials such as polyester, polyethylene, or polypropylene; this analysis would be very important. In this study, we propose an easily applicable procedure to include such effects. Various studies relate the increase of the bearing capacity of the foundations when geotextiles are used as stiffeners [26, 27]. Using the formula

$$k_{sb} = 40 \text{ x } SF \text{ x } q_a \tag{15}$$

it is obvious that bearing capacity and vertical soil stiffness are linearly proportional [28]. Here SF is the safety factor and q_a is the bearing capacity of the subgrade. The target area discussed in this paper is the Eminönü-Alibeyköy tramway line, where geogrids are planned to be used due to poor site conditions reaching typical stiffness value as low as $4125kN/m/m$. Application of geogrids provides an increased bearing capacity which can be related to the vertical stiffness using Eq.15. In the coming section, we discuss our findings about the effect of enhanced bearing capacity, thus stiffness, on the ground-borne vibrations induced by the railway due to the passage of trains.

3. Results and Discussion

3.1. **Results for 5 axle configuration.** The results obtained by implementing the methodology summarized above are displayed in Fig.2 for the 5-axle train configuration. The k_0 stiffness value for this simulation is taken as $4125kN/m/m$ from data readings at the site. The horizontal axis in these figures is the relative stiffness that is enhanced normalized stiffness, that is k divided by k_0. The RMS ground-borne vibration velocities are depicted in Fig.2 as a function of relative soil stiffness for three different train speeds.

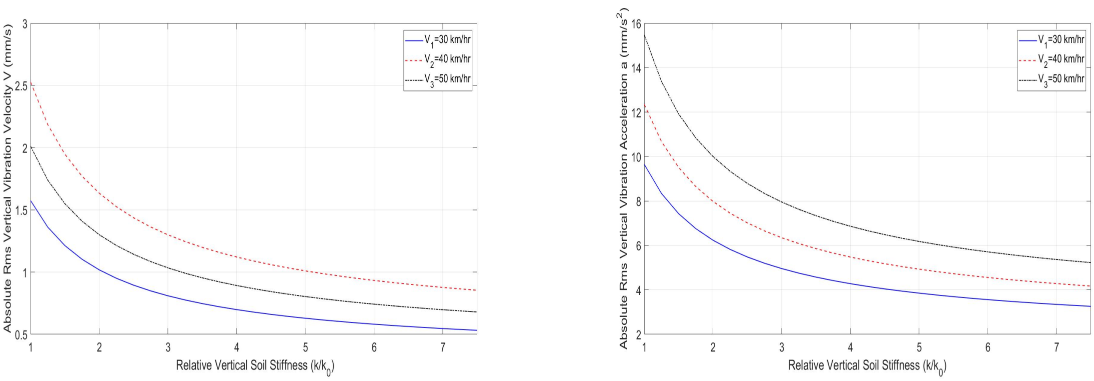

Figure 2. Ground-borne vibration a) velocities b) accelerations as a function of normalized stiffness, 5-axle configuration.

Since Eq.13 gives the RMS vibration velocity as a function of spectral octave bands, the peak of this spectral RMS vibration velocity is selected for each simulation and its decay as a function of relative soil stiffness is presented in Fig.2. Similarly, the results for the RMS ground-borne vibrations acceleration obtained by Eq.14 are depicted in Fig.2 for three different train speeds. Checking Fig.2, it is possible to conclude that the decay rate of the ground-borne vibration and acceleration due to enhanced soil ballast stiffness are almost identical.

To better illustrate the similar tendency of these vibration parameters the reductions in the relative vertical vibration RMS velocity and the relative vertical vibration RMS acceleration are given as functions of relative stiffness, k/k_0, for the 5-axle tram configuration in Fig. 3 and Fig. 4. The horizontal axis is again the normalized enhanced stiffness, that is k/k_0.

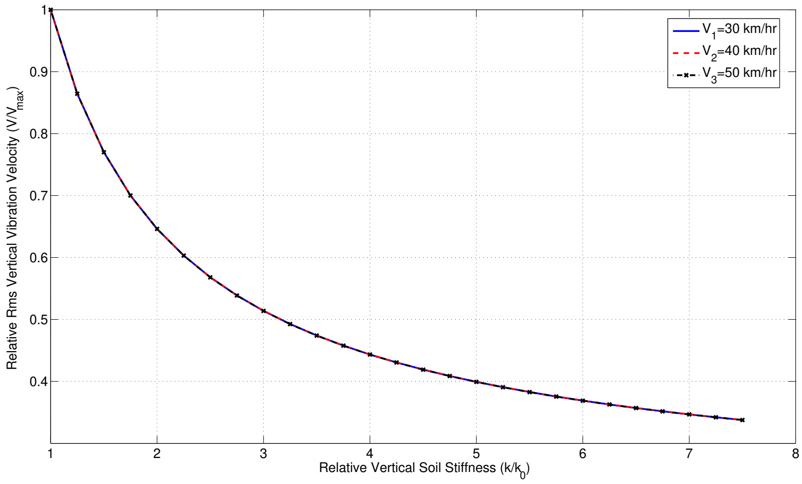

FIGURE 3. Reduction of relative vibration velocity as a function of relative foundation stiffness for 5-axle configuration.

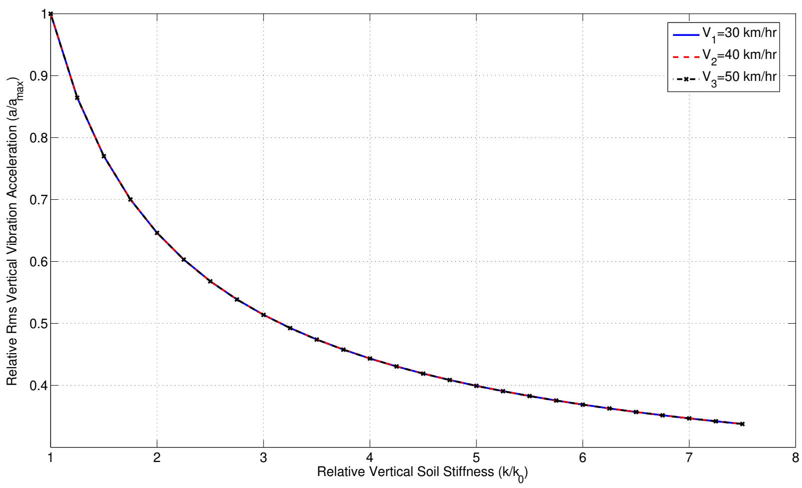

FIGURE 4. Reduction of relative vibration acceleration as a function of relative foundation stiffness for 5-axle configuration.

Checking these figures it can be concluded that increasing the vertical stiffness of the foundation by application of geosynthetics can effectively decrease the vibration levels, as expected. When the stiffness of the foundation is doubled, a reduction of 25% both in the RMS velocity and the RMS acceleration levels is expected. If an increase in the stiffness by a factor of 5 is accomplished, then this results in a 60% reduction in the same vibration parameters for the 5-axle configuration for all three tram velocities considered. The maximum RMS vibration velocity value for this simulation is on the order of $2.0m/s$ for $V = 50km/hr$ and the maximum RMS vibration acceleration value for this simulation is on the order of $16mm/s^2$ for $V = 50km/hr$.

3.2. **Results for 6 axle configuration.** In Fig.5, the RMS ground-borne vibration velocities and accelerations are depicted respectively for the 6-axle train configuration for the three different train speeds. As before, the tendency of decay in the vibration levels due to increasing stiffness is almost identical for the velocities and the accelerations, as well as they are very similar to their analogs for the case of the 5-axle configuration.

Checking Fig. 6 and Fig. 7 given for the 6-axle configuration, it is possible to conclude that the results are almost identical to the 5-axle configuration case.

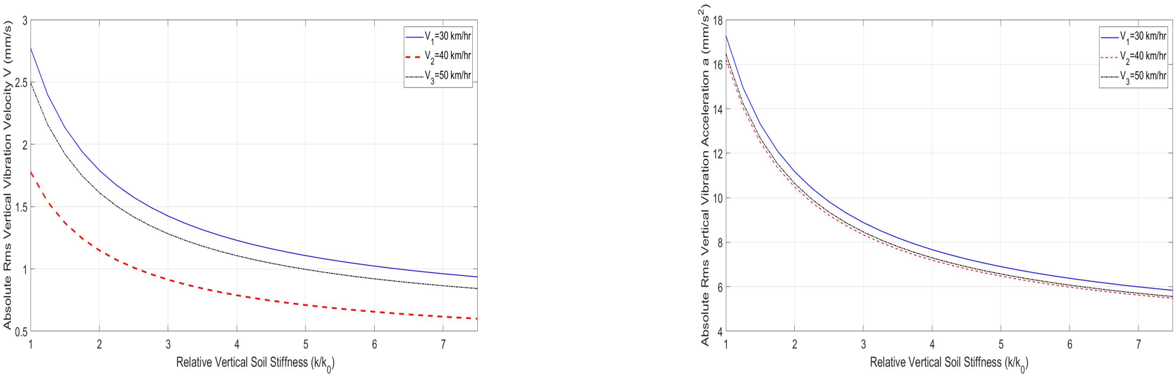

FIGURE 5. Ground-borne vibration a) velocities b) accelerations as a function of normalized stiffness, 6-axle configuration.

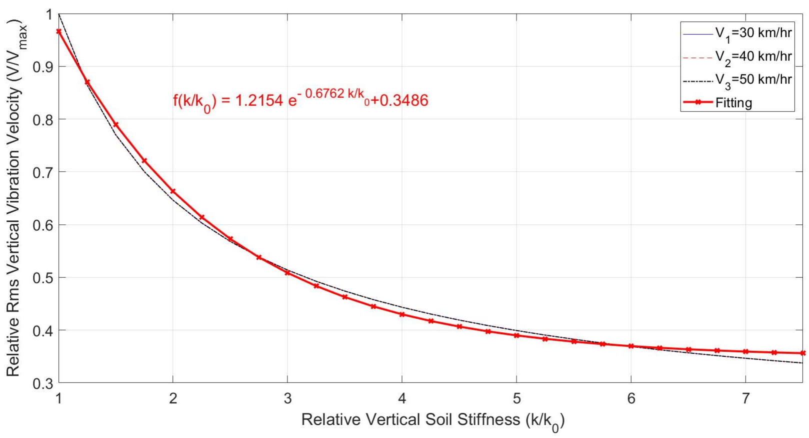

FIGURE 6. Reduction of relative vibration velocity as a function of relative foundation stiffness for 6-axle configuration.

The non-dimensional maximum RMS vibration velocity value for this simulation is on the order of $2.5m/s$ for $V = 50km/hr$ and the maximum RMS vibration acceleration value for this simulation is on the order of $17mm/s^2$ for $V = 50km/hr$. Similar to the 5-axle case, it is possible to conclude that a reduction of the same order of magnitude in the vibration levels can be accomplished by increasing the stiffness with the above-mentioned factors, for the 6-axle configuration.

It is also possible to propose different functions that fit the curves displayed in Figs. 3-7. Approximating the curve obtained using the model and depicted in Fig. 6 with an

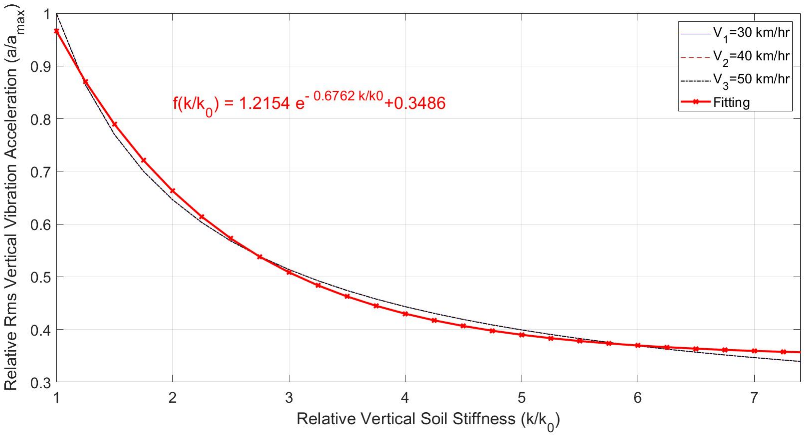

FIGURE 7. Reduction of relative vibration acceleration as a function of relative foundation stiffness for 6-axle configuration.

exponential-trigonometric fit in the least squares sense, one can come up with a fit-type equation in the form of

$$V_{k/k_0}(k/k_0) \approx V \times f(k/k_0) \approx V \times (1.2154e^{-0.6762k/k_0} + 0.3486) \tag{16}$$

where k/k_0 is the normalized subsoil stiffness. Here, V denotes the peak or the RMS vertical vibration velocity when the stiffness at the lowest level of $k = k_0$. Using the result depicted in Fig.7 and carrying out a similar analysis for the acceleration levels, one can come up with the same basic fit type formula as

$$a_{k/k_0}(k/k_0) \approx a \times f(k/k_0) \approx a \times (1.2154e^{-0.6762k/k_0} + 0.3486) \tag{17}$$

where a shows the peak or the RMS vertical ground-borne vibration acceleration for the stiffness of $k = k_0$. Thus a_{k/k_0} becomes the corresponding peak or RMS vertical vibration acceleration as a function of normalized soil stiffness of k/k_0. Although these results are obtained for the 6-axle configuration, the same results also hold for the 5-axle configuration.

This paper aimed to investigate the effects of subsoil improvement on train-induced ground-borne vibrations. In our future work, we aim to investigate the effects of combined soil improvement and soil amplification on these vibrations. We aim to follow a spectral approach by introducing a spectral representation of these effects. With this motivation, one can rewrite Eq.8 as

$$S(\omega) = \sum_{p=1}^{N}\sum_{q=1}^{N} H_p^*(\omega)H_q(\omega)S_{amp}(\omega)S_o(\omega)e^{-i\omega L_{pq}/v} \tag{18}$$

where $S_{amp}(\omega)$ is the amplification spectra which may include the sole or the combined effects of spectral soil amplification and spectral response of vibrations to soil improvement. While it is possible to argue that amplification spectra of the train-induced ground-borne vibrations are similar to the earthquake amplification spectra, there is no experimental evidence to support this argument yet. We aim to address this open problem in the future. Additionally, it is also possible to investigate the effects of different soil improvement techniques such as jet grouting or the usage of other types of geo-synthetics and geo-textiles on these types of vibrations and soil dynamics in general. Furthermore, it is also possible to investigate the possible usage of smart sensing and signal processing tools such as the compressive sensing [29, 30, 31, 32], phase retrieval techniques, artificial intelligence, and machine learning in analyzing ground-borne vibrations. One can also investigate the possibility of extension and development of the structural health monitoring systems that rely on these types of algorithms (i.e. see [33, 34, 35]) for monitoring the health and safety of the railways and their subsoil conditions. Another possible research direction is to model the nonlinear rail dynamics. The envelope of the elastic rail that can be obtained via Hilbert transformation of the rail displacement curve is modeled in terms of the Schrödinger equation [36, 37] similar to the water waves and elastic plates. Thus, the nonlinear dynamics of the track vibrations not necessarily limited to the small displacement theory will be a pioneering field of research for railway dynamics.

4. Conclusion and Future Work

In this work, we have examined the effects of soil improvement on the ground-borne vibration levels induced by moving trains. More specifically we have applied a random vibration analysis to a Winkler foundation which can be considered as a model of elastic rail resting on soil. Among different soil improvement techniques, the application of geotextiles is considered. Installation of these geo-synthetics generally increases the bearing capacity of the foundation. The increase in the bearing capacity of the foundation can be directly related to the increase in vertical stiffness of the foundation, which is used in the Winkler foundation model. Using 5-axle and 6-axle train configurations which operate at different velocities of 30 km/hr, 40 km/hr, and 50 km/hr the effect of increasing the stiffness of the foundation on ground-borne vibration velocity and accelerations are discussed. Typical soil stiffness values are acquired by geotechnical in-situ tests from the Eminönü-Alibeyköy Tramway Line site in İstanbul. It is shown that increasing the vertical stiffness of the foundation by the application of geosynthetics can effectively decrease the vibration levels. Doubling the stiffness of the rail subgrade by applications of such soil improvement techniques, results in 25% reduction in RMS velocity and RMS acceleration levels, while an increase in the stiffness by a factor of 5 results in 60% reduction in the same parameters for both of the 5-axle and 6-axle configurations.

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