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Response Spectra of Structures under Subway Induced Vibrations

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ABSTRACT

Passing underground trains induce vibrations transmitted to the ground surface and the nearby structures. Ordinarily, these vibrations do not result in structural damage but can harm nonstructural elements and disturb the occupants. These effects are more pronounced when evaluating buildings like hospitals, laboratories, museums, etc., and their assessment is an important design need. To respond to this requirement, in this paper response spectra for passing trains moving with different velocities are calculated. Using these spectra, without resorting to the time consuming and costly analysis of a tunnel-soil system under moving loads, the maximum structural responses can be calculated rapidly. To make this end, the soil-tunnel interaction is modeled using a three dimensional (3D) finite difference scheme under the standard moving train loads. The dynamic analysis of such a system results in the ground surface vibration time histories at different distances from the tunnel axis. Then the maximum values of acceleration, velocity, and displacement responses are calculated for a single degree of freedom (SDOF) dynamical system. The above calculations are accomplished for different standard trains, train velocities, tunnel depths, distances from tunnel, and soil types, and are presented as response acceleration, velocity, and displacement spectra.

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1. INTRODUCTION[1]

Railway trains have been among the main means for public transportation in the last century. When trains move over the railways, they produce waves due to this movement. The waves propagate in ground and appear as noise or vibration at the ground surface, and reach the buildings adjacent to railway. Subway trains passing through underground tunnels are among the main sources of in-ground induced vibrations. Oscillation frequencies produced by subway trains range between 1-80 Hz and the corresponding noise has a frequency of 30-200 Hz [1, 2]. Disturbance due to these vibrations occurs when amplitude of such vibrations exceed the threshold sensible by human. This threshold is usually much lower than that resulting in damage in ordinary buildings.

Different factors determine the amplitude oftrain induced vibrations including train type and velocity, ground condition, building and its foundation's type, distance between railway and building, and manyotherfactors [3]. A complete study of the mentioned factors needs using extensive models in which it is possible to calculate ground's response due to different factors.Such a study would take a great amount of time. Response of ground under a moving load is determined by specifying the relation between the load velocity and ground wave velocities. In the theory of elastodynamics the problem of a moving load is categorized to subseismic, superseismic, and transeismic problems. This categorization is performed by considering whether the load velocity is less than the ground's Rayleigh wave velocity, or larger than the velocity of longitudinal waves, or is in between [4]. For a load moving with the velocity of the Rayleigh wave, a resonance occurs in soil. Such a phenomenon was observed in Ledsgaard site due to softness of the soil and large velocity of the train [5].

In recent years many research works have been done in this regard and it has been tried to add to the accuracy of results for a simpler model. Generally, the accomplished studies can be placed in one of three

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groups. The first group include the works in which it has been tried to correctly simulate the train movement and the railway-soil interaction. For example, Krylov [6], Kaynia et al. [7], Takemiya [5], Lombaert et al. [8], Cheblia et al. [9], Gupta et al. [1], and Galvin and Dominguez [10] have worked in this regard.

The second group includes studies where various analytical, numerical, and field measurement methods have been utilized to predict vibrations due to movement of trains on the ground surface or in underground tunnels. For instance, Degrande and Schillemans [11], Hall [12], Hussein and Hunt [13], Pakbaz et al. [14], Hou et al. [15], Cik and Lercher [16], and Yao et al. [17] can be mentioned.

The third group of research works consists of different methods for control and reduction of vibrations, as those of Adam and von Estorff [18], Lombaert et al. [8], Andersen and Nielsen [19], Xu and Guo [20], and Wang et al. [21].

Between the above research works, those on the analysis of vibration in structures adjacent to subways are usually limited to a case study on a certain building and lack of extensive parametric studies is clearly observed. Also, considering the time consuming nature of the numerical study for exact prediction of vibrations in a moving train problem, a dire need exists for pre-determined graphs to make it possible to have an appropriate estimation of building response against movement of underground trains. To fulfill this need,in this research a parametric analysis of vibrations induced in SDOF systems adjacent to a subway is implemented. The results are presented as graphs of maximum response of the SDOF system depending on train velocity, soil type, and tunneldepth. By having such graphs at hand, after selecting the suitable values of the parameters, the corresponding graph is consulted and the SDOF spectral responses (displacement, velocity, and acceleration) are picked upquickly on the graphs. The practical use of these graphs is for spectral analysis of MDOF systems. The results of such an analysis can be compared with human vibration relief thresholds in the corresponding codes of practice.

2. NUMERICAL MODELING

2. 1. General In this study, calculation of subway induced vibrations at the ground surface has been implemented using FLAC3D V3.0. The software FLAC3D (abbreviation for Fast Lagrangian Analysis of Continua), makes a quick and continuous Lagrangian analysis using the central difference method. This program has been extensively used for analysis of the Ledsgaard site under high-speed trains and illustrated a good conformance between the measured and calculated response values [22].

The central difference simulation of ground vibrations due to passage of trains includes a 3-D model subjected to a moving load. The entire finite difference analyses of this study are implemented in the time domain using the explicit time integration method. The time step of analysis, Δt, is about 2.5×10^{-5} s. For slow trains, the analysis time for train approach, passage, and diminishing of vibrations is longer. The calculation time for a single problem for about 120,000 time steps is about 10 hours on an ordinary personal computer. Using the above finite difference analysis of the tunnel–soil interaction, the time histories of vertical acceleration, velocity, and displacement are calculated for different points on the ground surface at various horizontal distances perpendicular to the axis of tunnel. Then the acceleration response is used as input in Matlab 9.0 to calculate the maximum vertical responses of an SDOF system located at the same points on the ground.

2. 2. The Finite Difference Model

2. 3. Characteristics The 3D model of the system is developed in FLAC 3D. This model has a longitudinal vertical plane of symmetry, therefore only a half of it has actually been constructed to minimize the analysis time. The model is 110 m long (along the railway), 45 m wide, and 50 m deep (down to the bedrock). The dimensions have been selected such that effects of boundaries on the response at the ground surface in the middle of the model are minimal. It means that moving the boundaries farther will have almost no effect on the response at such a location. Since changing the model dimensions' case by case is not practical, the largest suitable dimensions have been selected by examining representative cases.

In this model, use is made of elastic brick elements for soil and ballast and of shell elements for the lining of the tunnel. The model's behavior is considered to be predominantly elastic because of very low amplitudes of responses due to train induced vibrations

2. 4. Optimization of Element Dimensions Because of large dimensions of the studied model, the number and dimensions of the elements should be optimized so that more accuracy is achieved in less time. For this purpose, element dimensions should be small enough to be able to pass important high frequency waves and should be large enough to minimize the analysis time. In practice, different models with element sizes gradually increasing with distance from the tunnel were tested. In each test, acceleration, velocity, and displacement time histories were calculated at three certain points at the ground surface subject to a unit load moving at different velocities. The model that was insensitive to smaller elements (and a larger number of elements) was selected as the optimum system. In such a system, the element dimensions of the ballast zone (where the loading is applied on), is 0.60 ×0.625×0.5 m, of the lining is 0.3×0.625×1.26 m, of the central zone (where the tunnel is located) is averagely 0.60×0.725×1.75 m, and in other parts is on the average 3.0×2.4×2.5 m. Commonly, use of five elements is taken to be sufficient to model accurately a wavelength λ. For the average size of the elements of the central zone, use of this criterion results in a reliable frequency up to about 100 Hz equivalent to a period of 0.01s for the average shear wave velocity of the following computations

2. 5. Boundary Conditions The model is fixed at its base (the bedrock). The symmetry condition is applied above and below the tunnel section by restricting the displacements perpendicular to the plane of longitudinal section at boundary nodes. At other three vertical planes of the model, use is made of viscous dampers at each node along each three perpendicular directions with a damping coefficient of ρc_s in tangential and ρc_p in normal directions, where ρ is the soil's mass density and c_s and c_p are the shear and longitudinal wave velocities in soil, respectively [23].

2. 6. The Loading Model The train loading has been introduced in the literature as a series of point load pairs moving at a constant speed. Each of the load pairs is transmitted from an axle (a pair of wheels) to sleepers and then to soil. In this study the load distribution proposed by Krylov [24] accompanied with the modifications suggested by Galvin and Dominguez [10] has been used. In the load distribution of Krylov, the railway is dealt with as a beam on a Winkler foundation. The shape of distribution depends on the stiffness of rails (as a pair of beams), stiffness of ballast, and the unit mass of rails and sleepers [24].

Figure 1 shows the transferred load due to a single sleeper under an AVE-Alstom train passing at a velocity of 300 km/h.

2. 7. Verification Analysis In order to verify the meshing, boundary condition assumptions, and loading

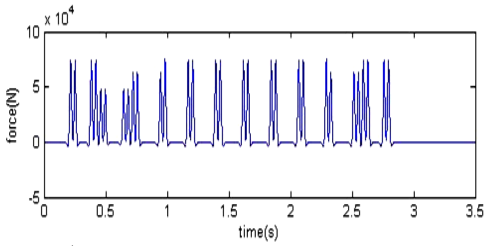

Figure 1. The load transferred by a single sleeper under an AVE-Alstomtrain moving at V=300 km/h

of the system, an example on measurement of response using real data in actual sites is selected.

The example corresponds to Degrande and Schillemans [11] in which several in-situ measurements were performed in the vicinity of Paris-Brussels railway at various distances. The passing trains were of Thalys type with a total length of about 200m moving at velocities between 200-300 km/h. The site consisted of two surface layers, being 1.5 and 2m thick, resting on a halfspace. The upper layer was 1.4 m thick with a shear wave velocity of 80 m/s. The corresponding values for the lower layer were 1.9 m and 133 m/s, respectively. The shear wave velocity of the halfspace was 226 m/s. The analysis is conducted for the vertical component of ground velocity at the surface at different distances from railway axis. A good consistency was observed between the analyzed responses and the measured values [25]. The average relative difference between the two sets of responses is about 20%. Moreover, the induced motion is of high frequency type as expected.

2. 8. Train and Soil Characteristics In this study three soil types A, B and C with their shear wave velocities being 750, 550, and 250 m/s, respectively, are considered. The soil is uniform down to the bedrock. This is not a limitation of the model since what is decisive for the soil response at the surface is its average shear wave velocity not its layering (except for layers with much different properties). Because of very low amplitudes of soil response against underground trains, the soil is modeled as a visco-elastic medium with a damping ratio of 2%.

The thickness of the tunnel's concrete lining is 30 cm and the tunnel's outer diameter is 6 m. In the space between the sleepers and the bottom of tunnel, a concrete layer 65 cm thick is used. The compressive strength of the concrete is 28 MPa. Using the theory of elasticity, the soil's reaction factor k_s has been derived as a function of the modulus of elasticity, E and the Poisson's ratio ν. However, it has been recommended to be taken equal to 1.2 times the allowable bearing stress because of soil's inelasticity especially under passing waves [26]. To study the effect of tunnel depth on the response values, three different depths of 10, 15 and 20 m are considered.

The rails are of UIC 60, with a mass per unit lengthof 60 kg⁄m, and a moment of inertia of I= 0.3038×10^{-4} m^4 attached to concrete sleepers each one 2.5 m long, 0.235 m wide, and 0.205 m thick spaced at 0.60 m and weighing 300 kg.

The AVE-Alstom, AVE-Talgo, and X-2000, are the standard trains used in this study, having the total lengths of 109.5 m, 222 m, and 279.3 m, respectively. The figures and characteristics of the trains can be found elsewhere [25].

3. THE ANALYSIS RESULTS

The induced oscillations do not produce serious structural damages perhaps except of in decayed historical buildings. Therefore, the acceptable level of vibration is limited to the values defined by the relief of building's occupants [27]. The undesirable values of the peak vertical acceleration and velocity begin from 550 mm/s^2 and 7 mm/s, respectively [25].

In this study, response spectra of SDOF systems having various damping ratios located on the ground surface in the middle of the system are calculated. By referring to these spectra, maximum responses of fixed-base SDOF systems having a certain damping ratio and natural period can be extracted. The characteristics of the SDOF system can be looked upon as the equivalent n-th mode properties of an MDOF system.

Each spectrum corresponds to the specific assumptions for the train type, train velocity, tunnel depth, distance from tunnel, and the soil type. It is seen in Figure 2 that if h=H+2.4 m, then the tunnel depth is characterized by H, and distances from the tunnel axis at the points P1, P2, and P3 are 0, h, and 2h, respectively. The points are located at the middle of the system.

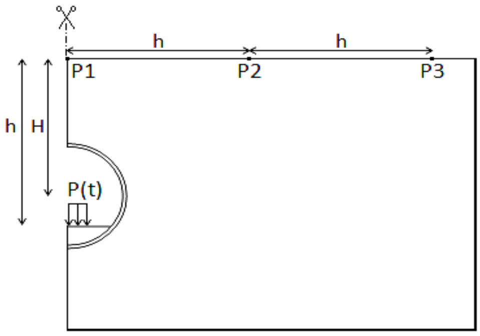

Figure 2. Cross section of the tunnel

The spectra are calculated for an SDOF system with damping ratios ξ= 0, 2 and 5% to make a linear interpolation possible for intermediate values. Totally, 756 groups of spectra each one composed of one spectrum for each response component (displacement, velocity, and acceleration) were calculated. Here only a few of the graphs are presented with the rest gathered in Nikbakht [25]. In the figures, T_n and ζ are the natural period and damping ratio of the SDOF system.

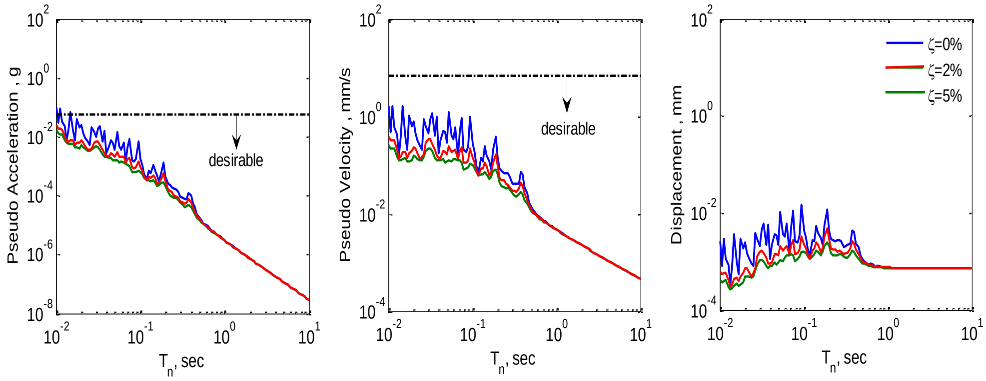

Figure 3. The response spectra under the AVE-Alstom train. V=180 km/h, H=10 m, soil type A, point P2

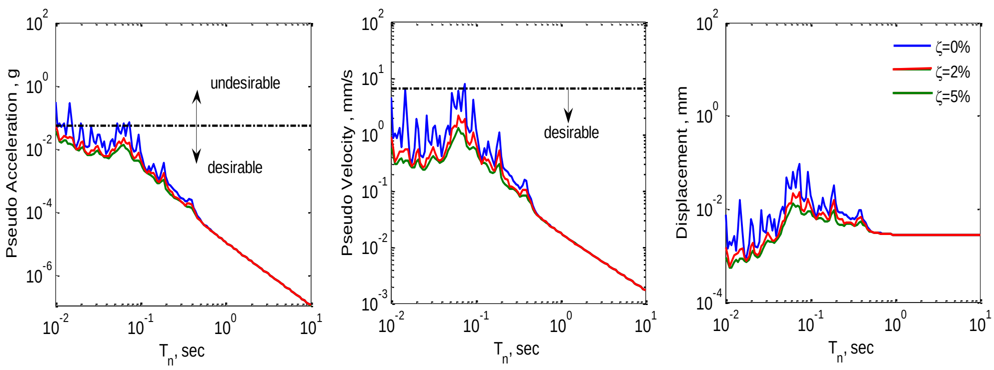

Figure 4. The response spectra under the AVE-Alstom train. V=180 km/h, H=10 m, soil type B, point P2

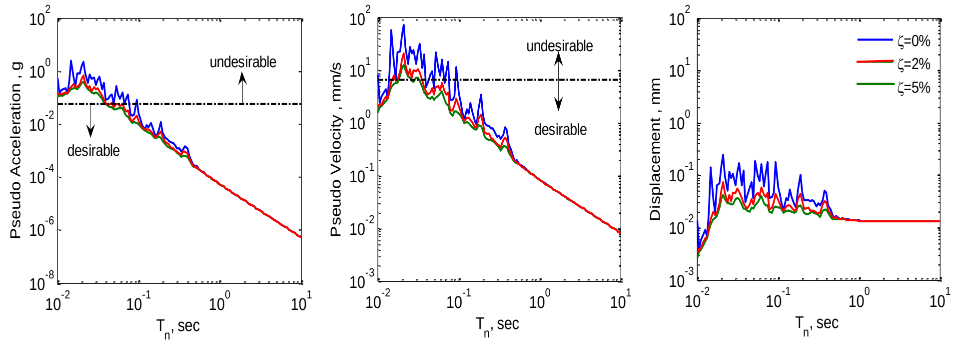

Figure 5. The response spectra under the AVE-Alstom train, V=180 km/h, H=10 m, soil type C, point P2

- Variation of the Tunnel Depth:

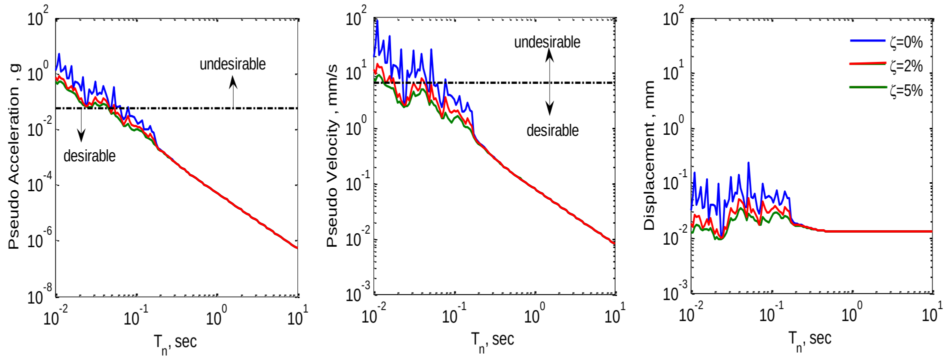

Figure 6. The response spectra under the AVE-Talgo train.V=300 km/h, H=10 m, soil type B, point P1

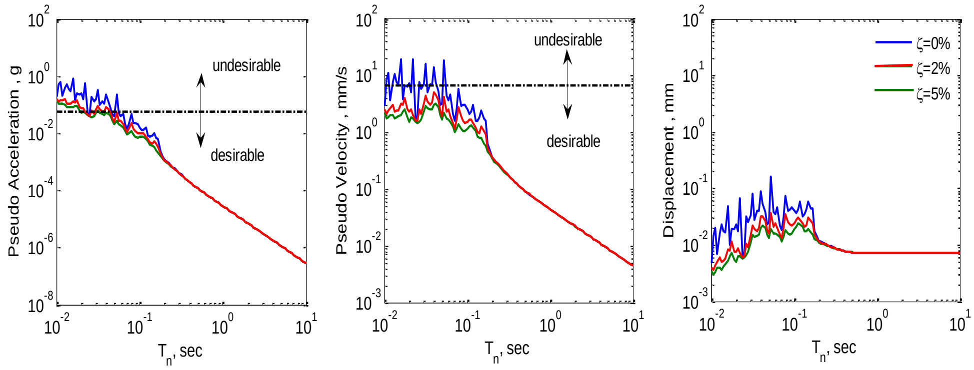

Figure 7. The response spectra under the AVE-Talgo train.V=300 km/h, H=15 m, soil type B, point P1

- Variation of the Train Velocity:

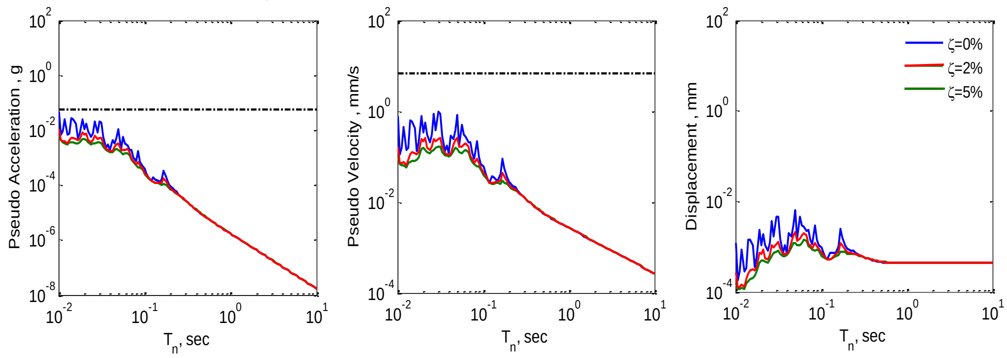

Figure 8. The response spectra under the X-2000 train.V=180 km/h, H=15 m, soil type A, point P3

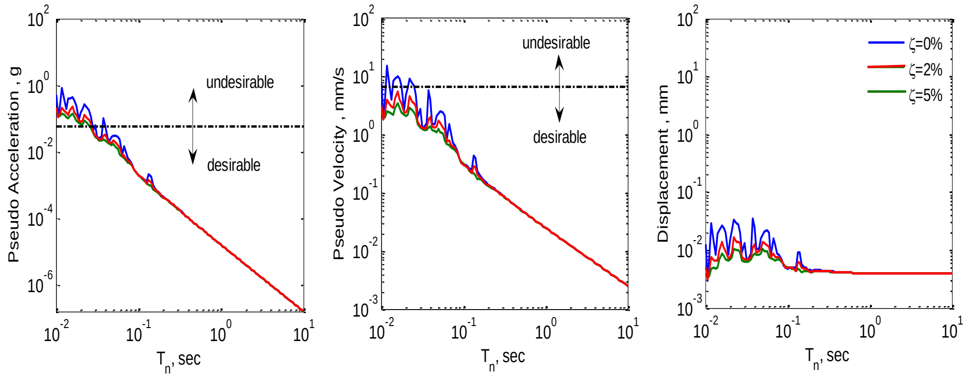

Figure 9. The response spectra under the X-2000 train.V=220 km/h, H=15 m, soil type A, point P3

4. CONCLUSIONS

A total of 756 displacements, velocity, and acceleration response spectra were calculated for SDOF systems on the ground surface subjected to the vibrations induced by passing underground trains. Effects of different factors including the damping ratio of the SDOF system, soil type, tunnel depth, train type and velocity, and distance from tunnel's axis were taken into account.

Based on the spectra presented, it can be concluded that the SDOF response to the passing trains is not much sensitive to the horizontal distances and tunnel depths studied. Instead, it exhibits sensitivity to the train type, train velocity, and the soil type. The spectra presented can be conveniently used for spectral modal analysis of MDOF systems to check for their suitability against occupants' relief subjected to underground trains.

The calculated spectra show an amplitude decay due to distance and a small shift in the governing frequency. These two important phenomena have been recognized in the past in constructing a spatial variation model. At the same time, these are the main ingredients for correcting the input motion at different points of the spread foundations using well known methods. For the first time, in this paper the variation has been recognized for train induced vibrations. As shown, the results of this paper will have wide applications in designing buildings having foundations with various sizes for train induced vibrations. Of course, since in the range of distances studied the variation is not overwhelming, in a simple approach, use of an averaged-over-distance spectrum will suffice.

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چکیده

در اثر عبور قطارهای زیر زمینی ارتعاشاتی در سطح زمین ایجاد و به سازه های مجاور آن انتقال می یابد. این ارتعاشات باعث خرابی سازه ای نمی شود اما گاهی می تواند اثرات مخرب غیر سازه ای و اذیت و آزار ساکنین این ساختمان ها را به خصوص در سازه هایی نظیر بیمارستانها، آزمایشگاه ها، موزه ها و غیره به همراه داشته باشد. با توجه به نیاز مهندسین به ارزیابی سریع ارتعاشات سطحی ایجاد شده ناشی از حرکت قطارهای زیر زمینی و تحلیل عملکرد سازه، در این کار به تهیه طیف های طراحی در اثر حرکت قطارهایی با سرعت های مختلف پرداخته شده است. با استفاده از این نمودارها بدون صرف زمان زیاد برای تحلیل یک مدل پیچیده خاک-تونل-سازه تحت بار متحرک می توان به حداکثر پاسخ سازه پی برد. برای این کار مدلسازی اندر کنش تونل و خاک، با استفاده از روش عددی تفاضل های محدود به صورت سه بعدی انجام شده و بارگذاری آن به صورت متحرک برای قطارهای استاندارد انجام می گیرد. از تحلیل دینامیکی تاریخچه زمانی این سیستم ارتعاشات سطح زمین در فواصل مختلف از محور تونل به دست می آید. با بهره گیری از تاریخچه این ارتعاشات سطحی، واکنش دینامیکی و طیف های طراحی سازه یک درجه آزادی محاسبه می گردد. این کار برای انواع قطارهای استاندارد، سرعت قطار، عمق تونل، فاصله از تونل و جنس خاک انجام شده و به صورت طیف های طراحی تغییرمکان، سرعت و شتاب ارائه می گردد.

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