Research Paper

A comparative investigation on different measures to mitigate metro trains induced vibrations from the aspects of Resource, Propagation path, and Receiver

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ARTICLE INFO	ABSTRACT
	Preservation of historic buildings is a main challenge in the civil engineering field. One of the main concerns about this subject is to be sure of environmental effects like noise and vibration on monuments. To overcome these problems, a wide range of noise and vibration mitigation measures could be applied. To reach a proper evaluation, in this paper, a detailed assessment is made on the efficiency of various vibration mitigation measures by a series of field tests and sensitivity analysis in Isfahan metro lines close to some vibration-sensitive cultural structures. The sensitivity analysis was performed in possible ranges of vertical stiffness of track superstructure materials. Results showed that vertical track stiffness equal to 5 kn/mm would lead to a 5 db reduction with regarding 4 millimeters limit of rail deflection.

1. Introduction

Nowadays, great expansion of megacities around the world, demands an efficient, safe and environmentally compatible urban transportation system. To this end, it is proved that various modes of urban railway transportation system say, LRT, LRV and metro is the best option. Despite of these all benefits, there are some environmental problems resulting from the construction and operation of subway lines near sensitive buildings, Residential Complexes, laboratories and hospitals. The cities could be moving faster than ever but there are great benefits to preserving historical sites and keeping things as they were many years ago. That big cities are facing with Among the possible environmental problems, ground-borne noise and vibration created by metro is one of the major environmental problems faced by rail transit systems. Intermittent sounds

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and vibrations in the environment may endanger people's mental health and can lead to long-term depression and fatigue. This issue also can cause abnormal noises and annoying vibrations in buildings and be heard in the interior spaces of buildings. Subway noise problems are not as serious as vibration, since it can be controlled by using noise isolation with the vehicle and the track structure, but the metro induced vibration usually has a complicated effect and commonly complex strategies are used for its control. Ground-borne vibrations radiated in the surrounding Non-homogeneous media in form of pressure waves, shear waves and surface waves. In this journey, various phenomena affects vibration, some amplify, some reflect and some phenomena attenuate it. Thus, Choosing vibration reduction technology depends on several factors despite of cost-effective and feasibility of implementation. The first step in vibration evaluation that is of great importance in related guidelines is to develop an accurate model for vibration prediction. A consummate method for subway vibration prediction should accurately simulate vibration source, propagation path and receiver. During the last decades, although there have been considerable developments in control and prediction of ground-borne vibration, but it is evident that further research is required. Track vibration isolation performance has often been evaluated based on a simple lumped mass spring argument. Using this approach, Zach and Rutishauser (1998) claim that a 25 dB reduction in transmitted vibration at 50 Hz can be achieved by using a floating slab track with an 8–9 Hz natural frequency (A. Zach, 1989). Wettschureck and Kurze (1985) use a one-dimensional impedance model for ballast mats in underground railways, assuming that the ballast mat is a simple spring and the tunnel is rigid. With this method and by a set of measurements, they claim a 20 dB reduction of tunnel wall vibration (R. Wettschureck, 1985). Similarly large reductions are predicted by Wettschureck (1995 and 1997) for ballast mats in railway tracks above ground and on bridges (Wettschureck, 1995) (Wettschureck, 1997). Wilson et al. (1983) predict high reductions above 20 Hz for a floating slab track designed for a 14–16 Hz natural frequency; their measurements on the surface above the railway tunnel indicated a modest reduction of 7 dB above 31.5 Hz (Wilson, Saurenman, & Nelson, 1983).

In this paper, factors affecting ground borne vibration is investigated, vibration effects on human, sensitive equipments and structures are discussed, the appropriate methods for reducing metro vibration from the aspects of source, propagation path and receiver has been investigated, and the effectiveness and feasibility of these methods is compared. Finally, as a case study, the efficiency of three types of floating slab tracks for reduction of ground borne vibration and noise are discussed in Isfahan metro lines.

2. Vibration induced by trains and its effects on environment

2.1. Generation of vibrations induced by metro factors affecting it

Noticeable vibrations in buildings near the underground railway are attributed to moving vehicles. Metro induced vibrations in dense urban environments can cause irritation to residents of nearby buildings. One of the main difficulties in accurately estimating ground borne vibration is very large number of factors affecting vibration receiver. To select the best solution for reducing vibration, the first step is to define factors affecting ground-borne vibration and then possible solutions to reduce vibration will be offered (Bonin, Cantisani, M, Loprencipe, & A, 2007). A study by Kurzweil (1979) identifies a number of factors that influence the magnitude and frequency of the ground-borne vibration produced by underground railways. These include: train speed; axle load; car body primary suspension system; the presence of resilient wheels; the unsprung mass; wheel and rail conditions; the presence of resilient rail fasteners (including resiliently supported sleepers); the presence of floating slab track; ballast depth; the presence of ballast mats; and the tunnel construction (Kurzweil, 1979).

2.2. Influence of vibrations induced by metro

Numerous studies have been conducted into the response of humans to vibration and re-radiated noise. A study by Knall (1996) shows that noise from road traffic, aircraft, industry and neighbors may cause more annoyance and disturbance to residents than railway noise (Knall, 1996). The main concern of residents experiencing vibration and re-radiated noise from railways is the possibility of damage caused to the building (Degrande et al., 2006) (Gupta, Liu, Degrande, Lombaert, & Liu, 2008). However, there are two orders of magnitude separating the threshold of human perception of vibration and the onset of building damage (HILLER, HOPE, BS, & TRL, 1998). The most common, annoying aspects of railway noise and vibration are interruption of concentration, disturbance of sleep, and, in particular, interference with speech and communication (Okumura, Takewaki, Shimizu, & Fukutake, 1992). The response of residents to vibration and re-radiated noise has been shown to depend not only on the level of the noise, but also on non-acoustic factors such as people's attitude towards the railway, the neighborhood environment and their sensitivity to noise (Knall, 1996). Some researchers conducted studies into the effects of railway noise and vibration on humans (Howarth & Griffin, 1988) (Vadillo, Herreros, & Walker, 1996) (Hood, Greer, Breslin, & Williams, 1996) (Okumura et al., 1992) (Knall, 1996) (Aasvang, Engdahl, & Rothschild, 2007). Two experiments by Howarth & Griffin (1988) show that human annoyance to railway vibration induced on building depends on both the frequency of train passes, and the magnitude of the vibration produced by the trains. The results suggest that neither the age nor the gender of subjects is a significant parameter (Howarth & Griffin, 1988). A field study is conducted by Vadillo et al. (1996) with the aim of determining an acceptable level of low frequency, re-radiated noise within a residence. Residents exposed to maximum (1 second) levels below 32dB, do not complain about the presence of the train, even though, they could sometimes feel vibration from the passing train. All residents exposed to maximum levels above 42dB complain strongly about noise and vibration levels, with the vibration being the most annoying effect of the passing train. Varied responses are obtained when residents were exposed to maximum levels between 32-42dB (Vadillo et al., 1996).

The response of buildings to dynamic excitation depends on both the response characteristics of the buildings and foundations (natural frequencies, mode shapes, damping) and the spectral content of the excitation. The existence of cracks in a building in the vicinity of a vibration source does not imply that this structural damage has resulted from the vibration source: cracking may be due to any number of factors, including settlement, material creep, natural ageing and occupational loads. The response of the building is also influenced by the geology of the area, the type and depth of the foundation of the building, the design and construction of the building, and even the arrangement of furniture within the building (British Standards, 1990). Generally, vibration with high peak particle velocity acting on a building sited on hard ground induces the same magnitude of strain levels in the building as vibration of a lower peak particle velocity acting on a building sited on softer ground. Dawn and Stanworth (1979) observed that the amplitude and attenuation with distance of ground-borne, vehicle-induced vibration depends critically on the soil composition. In particular, it is the shear modulus of the soil layers that determines the magnitude of the vibration produced: a low shear modulus (soft soil) produces relatively large responses, whereas a high shear modulus produces little vibration. Watts & Krylov proposed that soil layering would increase the magnitude of ground borne vibration levels, as reflections from the layer interfaces would lead to lower rates of attenuation (Dawn & Stanworth, 1979). Environmental vibrations have serious influences on the operations of precise instruments, such as laser devices, electronic microscopes, electronic scales, the surgical operations, the manufacture of semiconductor integrated cores, etc. which may result in inaccurate readings, decrease the precisions of the instruments, shorten their service life, or even interrupt their work (Xia, Cao, De Guido, & Geert, 2007) (Xiaojing Sun, 2008).

3. Ground borne Vibrations Reduction Methods

There are several methods for reducing vibration: such as source isolation, the impairment of vibration isolation and receivers. To select an appropriate vibration reduction approach, beside cost and feasibility of implementation a variety number of technical factors should be considered. Therefore, improving the accuracy of vibration prediction is a foremost factor in development of vibration control guidelines. To this end, the vibration reduction methods are divided into three different categories say, source, propagation path and receiver vibration reduction methods (Kuo, 2011) (Bahrekazemi, 2004).

Floating slab tracks are designed to control ground borne noise and vibration by reducing the fundamental natural frequency of the track system. They can be effective at controlling perceptible ground borne vibration. The floating slab track is by far the most effective method available for reduction of ground borne noise and vibration. Nevertheless, unfortunately, it is so expensive. In order to reduce amplitudes of vibrations on the track, grinding of rails has been used for several years on railway networks. This method is usually used in tracks, which has rail with distortion. Reductions of 40 – 90% for normally worn rails, or 90–98% for corrugated rails, can be achieved (Schillemans, 2003). Resilient direct fixation fasteners are used in surface or underground railways. They are used to reduce vibrations and noise at frequencies above 30 Hz. Design of vehicle primary suspension system is not part of the track design, but has a direct effect on the amplitude of ground-borne vibration along the track. To select vibration isolation depends on the type of vehicle used. vehicles with low stiffness primary suspension systems can cause lower vibration levels in comparison with high stiffness primary suspension systems. Using low stiffness primary suspension systems vibration attenuation in the frequency range 10 -31.5 Hz could be achieved so that there is no need to use other types of vibration isolations (Yang & Hung, 2009). Elastic elements in a wide variety of tracks are used to increase the elastic properties. The pads play an important role in enhancing the elasticity. Solutions to reduce noise and vibration and increasing the elasticity of non-conventional tracks are the usage of elastic supports under the concrete slab, using elastic fastenings on non-conventional tracks and pads under the base plate. Ballast mats can provide attenuation as high as 10 to 15 dB at frequencies above 25 to 30 Hz. Ballast mats are the most convenient vibration reduction methods for current tracks with high vibration problem (Wettschureck, 1995).

Some common vibration countermeasures that involve disruption of the transmission path include the construction of open trenches, in-filled trenches; wave-impeding blocks (WIBs) and pile rows. Use of trenches for control of ground borne vibrations is similar to control of noise through the sound barrier. These methods have been investigated in experimental and numerical studies. A study on the effectiveness of open trenches, in-filled trenches and a WIB in reducing ground borne vibration is conducted by Hung et al. using a 2.5D finite/infinite-element approach, Their findings showed that open trenches are the most effective method of isolating the vibrations induced by the static and dynamic moving loads produced by trains. The WIB is seen to be effective only in isolating vibrations with wavelengths comparable to the dimensions of the WIB itself. Yang and Hung determine the optimal parameter values for these three barriers in isolating the train-induced vibrations (Kuo, 2011) (Alabi, 1992). There are also a number of methods that can be employed to reduce the vibration levels in buildings. Some of these methods can be used to mitigate vibration problems that arise post-construction. Damping treatments (such as free-layer damping and constrained layer damping) can be applied to resonant floors or walls, and tuned vibration absorbers can be installed to attenuate specific resonant frequencies. Localized stiffening or mass addition can be used to move structural resonances away from the excitation frequency. Furniture designs can be selected so that they do not resonate at the excitation frequencies and sensitive equipments can be moved near to the walls, where the vibration levels are likely to be lower than at the centre of the floor (Wilson et al., 1983). Buildings by elastic foundation isolation systems. The track should be built as far as possible away from sensitive structures. A

small displacement as 3 meters (10 feet) of a vibration sensitive structure can cause a good vibration reduction (Wettschureck, 1997).

4. Comparison of Different Vibration Reduction methods

In Table 1, there have been a number of methods developed for the control of ground borne noise and vibration and their efficiency are compared (Wilson et al., 1983).

Table 1- Comparison of ground borne noise and vibration reduction methods

Reduction Methods	Efficiency
Floating Slab tracks	Very effective at reducing ground-borne vibration and noise at frequencies above the vertical resonance frequency of the floating slab system
Ballast mats	Ballast mats can be effective at frequencies above 30-40 Hz
Trenches	Although trenches do not appear practical for subway applications there are indications that they would be effective along at-grade track ways
Rail grinding and wheel truing	Rough wheels and rails, particularly wheel flats and rail corrugations, can increase ground-borne noise and vibration by 10-15 dB
Low stiffness primary suspension systems Resilient direct fixation fasteners	Usually in vibration frequency 20 to 53 Hz with reduced overall vehicle suspension system of about 70%, 1 to 5 dB reductions in ground motion is obtained.
Reduce resonance and unsprung mass of bogie	At vibration frequency of 30 Hz, vibration reduction Between 9 to 12 dB is achieved.
Distance	Up to 10-15 dB reduction in levels of ground-borne
	A small distance as 3 meters (10 feet) of a vibration sensitive structure can cause a good vibration reduction.
Resilient supported sleepers	By making use of rubber pads between the sleepers and the foundation, it is possible to reduce the vibration by at least 10 dB.
Proper maintenance of wheels and track	a proper track maintenance can decrease the ground borne vibration as much as 10 dB.

According to Table 1, vibration reduction methods on railway transport system are not considered as a fixed variable. Sometimes in two similar urban railway systems, due to differences in the content of the vibration frequency (for example, due to the characteristics of the selected structural geology or system), different reduction methods are needed. Methods for reducing vibrations caused by trains and urban railway transport systems should be chosen according to the content of the vibration frequency. Reduction methods in source are the most effective methods in vibration attenuation. The floating slab tracks have been found to be a very effective vibration and noise reduction mechanism for underground railways (Wilson et al., 1983).

5. Application of Vibration Reduction methods in Isfahan metro (line 1)

One of the most important issues in the construction and operation of urban railways is the possibility of damages made by subway to neighboring structures, in particular monumental buildings. Construction of Isfahan Metro has been commenced since 2001. It goes through "Charbagh Boulevard" in which there are several historical monuments including: Si-o-Se-Pol (a thirty-three arches bridge built in 600 years ago), Charbagh Islamic school (a historical school built 500 years ago) and SarDar-e-Keymeghah (a building built 400 years ago) (Figure 1).

The priority line for city recommended as a result of feasibility studies is north-south line from Kaveh intercity bus terminal to the Soffeh intercity bus terminal (Figure 2). The line generally follows the alignment of the wide Boulevard of Chahar-Bagh which is in driven tunnel in most of its length. This line gives the best economic return of all networks studies.

Figure 1. Historical monuments in the vicinity of Isfahan metro line (Sadeghi.Javad, 2011)
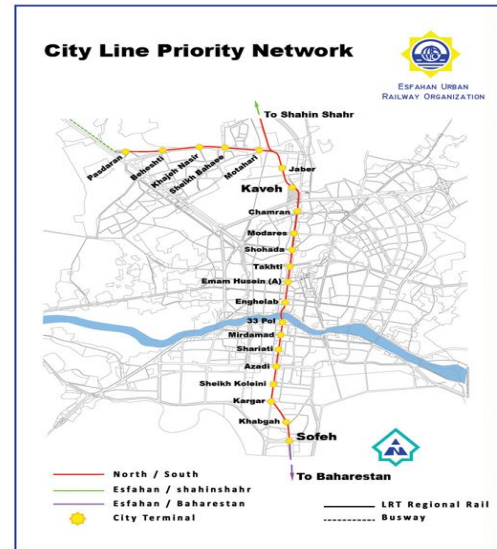

Figure 2. Isfahan Metro- Line 1 (P. C. Eng, 1998)

This part of the paper mainly discusses the problem of ground borne vibrations due to Isfahan metro line 1, which passes close to monumental buildings. Due to their unique design as well as international and national concerns about the effect of metro vibration on these heritages, both structural and architectural damages should be avoided with great degree of safety. It is therefore necessary to study metro vibration induced on adjacent monumental buildings within exact experimental vibration measurement techniques. To this end a set of site tests was conducted in order to predict vibration level in metro operation phase as well as proposing an efficient solution in vibration reduction.

5.1 Test Set up and instrumentation

Two kinds of slab tracks, say floating and direct fixation slab track has been constructed in Kaveh station in the northern part of the Isfahan metro line (Figure 3). To reduce vibration level, there is a full-face polyurethane layer under floating slab. The slab segments are 12 meters length, which are connected by expansion joints. The slab track has 150 to 200 meters length outside the tunnel and 600 m inside. Since metro rolling stock has not been bought yet, a car wagon was designed in order to evaluate the slab performance in vibration reduction. It has 3.5 (5 tons is accessible too) tons axle load with 2.6 axle distance (Figure 4).

Floating slab track   Direct fixation slab track
Figure 3. two kinds of slab track in Isfahan metro line

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The car wagon was run over the slab track in two different conditions: with and without damping layer (PU). The car-wagon was run with the speeds of 10, 15, 25, 30, and 35 km/h and the accelerations were recorded in several locations as indicated in Figure 5 and 6. The accelerometers were installed at 10 different positions called A1 to A10.

A1 was set on the ground beside the PU layer, A2 on the rail web, A3 on the sleeper, A4 and A5 adjacent to the vertical PU layer, A6 on the slab, and A7 to A10 on the line perpendicular to the track centerline. A7 to A10 have an equal distance from track centerline. The same procedure was made for the slab without PU layer.

Figure 4. Car Wagon used for loading (outside the tunnel)
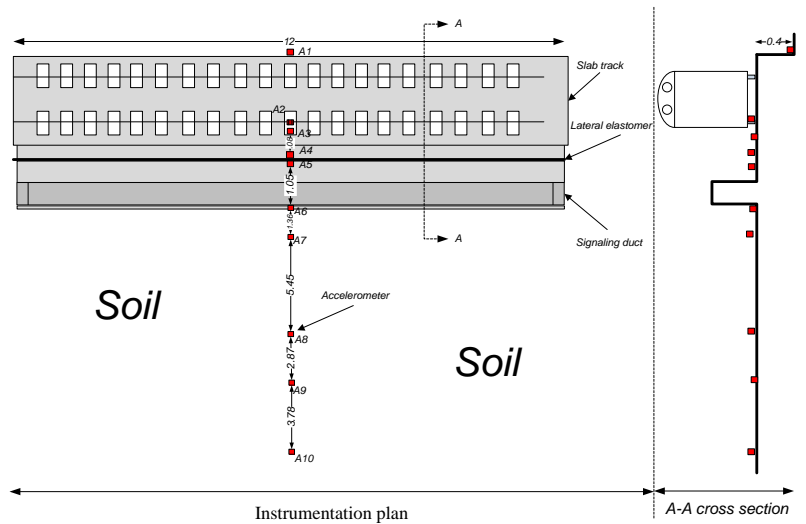
Figure 5. Instrumentation plan and profile in train passing test at Kaveh station

Figure 6. instrumentation of slabtrack

5.2 Results of Field investigation

The results obtained were filtered and analyzed based on the method described above. The results include accelerations and speeds of the transmitted vibrations, as well as displacements in all assigned points where the responses were taken. For instance, the acceleration, speed wave and displacement recorded at the position of A2 in Kaveh station is presented in Figure 7.
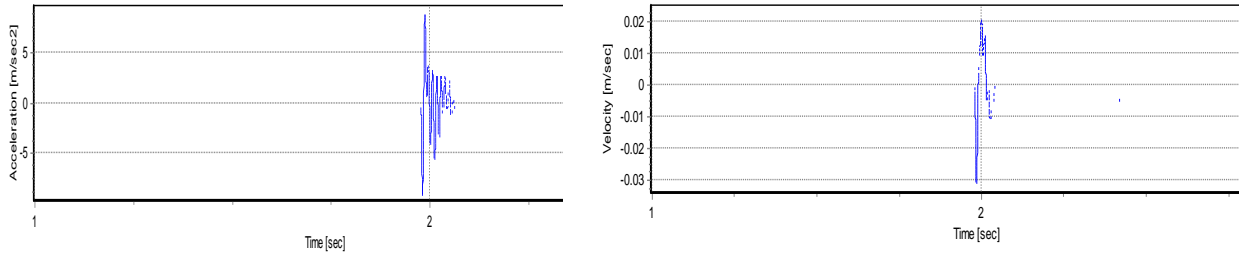
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Figure 7. Acceleration and velocity spectrums measured in track test with PU layer

Using the Fourier transform and the time history of the recorded accelerations from the accelerometers, one can obtain results in frequency domain. From results obtained in frequency domain, the frequencies, at which the largest amount of energy was produced, can be recognized. It means that the larger amounts of damages to the structure can be made at these frequencies. Moreover, from results in frequency domain natural frequencies as well as velocities of the waves received by the references (accelerometers) can be evaluated.

5.3 sensitivity analysis

To evaluate the vibration reduction performance of slab with various properties, a finite element model was built, calibrated with test results and used as a method for sensitivity analyses. Considering a floating slab track model in Fig 8. , the system model comprises of rail, slab track, PU damping layer, and the surrounding soil. The properties of the element used in the model are presented in Table 2. Models properties were obtained from several filed tests results provided by the metro superstructure consultant companies (Z. C. Eng, 2009) (Z. C. Eng, 2001-2005) (I. C. Eng, 2006). The finite element mesh used is presented in Figure 9.
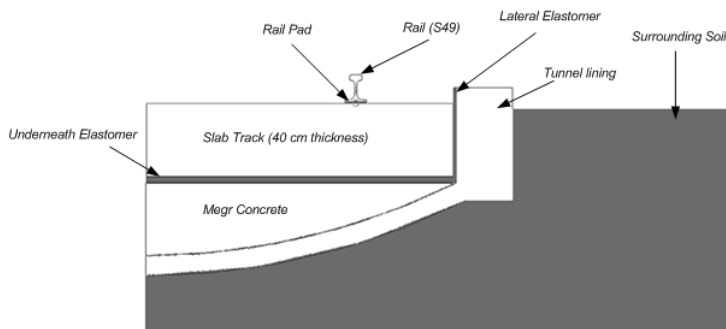

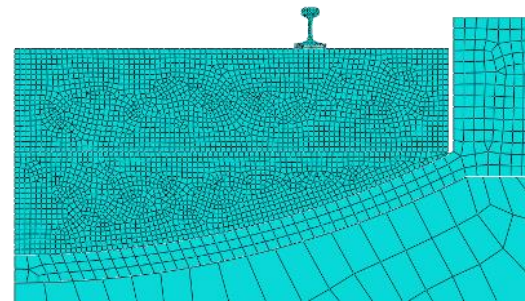**Figure 8. Metro superstructure components**

Figure 9. Finite element mesh for superstructure and surrounding soil model

Table 2. Specifications of materials used in numerical model

Elements	Behavioral model	Modulus of elasticity (N/mm2)	Damping coefficient	Poisson ratio	Density (ton/mm3)	Cohesiveness coefficient	Friction Angle (degree)
rail	elastic	210000	-	0.3	7850e -12	-	-
Soil	Mohr-Coulomb (elastoplastic)	100	-	0.35	2000e-12	0.03	25
Slab concrete	elastic	26000	-	0.15	2400e -12	-	-
Megr concrete	elastic	21000	-	0.15	2400e -12	-	-
Lining concrete	elastic	26000	-	0.15	2400e -12	-	-

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pad	elastic	37/5	-	0.12	500e -12	-	-
Polyureth ane layer	elastic	0.55	0.105	0.3	200e-12	-	-

An efficient aproach to attain vibration reduction goal is to reduce vertical stiffness of systems resiliant elements, say rail pad, baseplate pad and etc by replacing them with softer materials. A question who arises here is to determine appropriate stiffness for the elements. It should be mentioned that a system with less stiffness means more deflection. since exessive deflection is not allowed in railway track, an equilibrium should be made between stiffness and displacement of the track.

To investigate optimized stiffness, a sensitivity analysis on the calibrated model was performed with various amounts of railpad, baseplate pad and under slab pad stiffness. To avoid exessive displacement, in each situation rail deflection was controlled. Allowble displacement criteria was derived from national codes equal to 4 milimeters (Transportation Research Board-National Academies of Sciences, 2010).

Fiqures 10 and 11 show the results of various baseplate pad stiffnesses on the vibration reduction and track displacement in comparison with current Direct fixsation slab, respectively. As can be seen, the best vibration reduction is 6 db at 2 kn/mm stiffness, but with this stifness the track diflection would be 5 mm and is not acceptable. the 5 Kn/mm stifness produces 4 mm displacement, and 5 db vibration reduction, therefore it could be concluded that with changing the rail and baseplate pad propertis the best vibration reduction is 5 db at 5 kn/mm stifness.
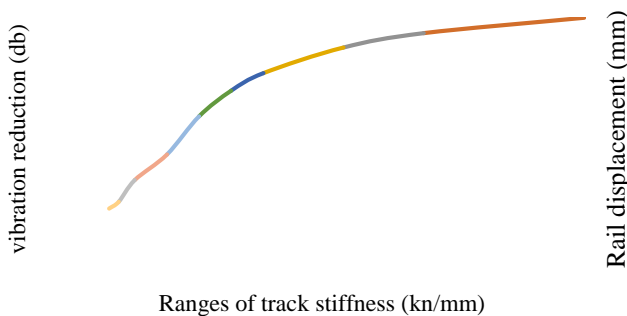

Fig 10- Track vibration reduction in different amounts of rail and baseplate pad stiffness in comparison with current rail and baseplate pad system
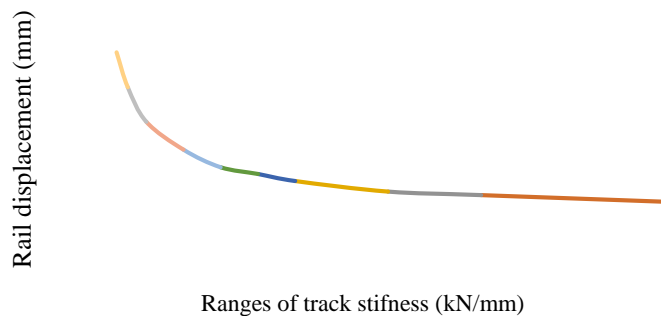
Fig 11- Track displacement in various amount of rail and baseplate pad stiffnesses

One of the vibration reduction methods in source is the usage of floating slab track as introduced in previous sections. Generally, there are three main types of floating slab tracks, say Full surface support, Linear support and point like (discrete) support (Figure 12). The results of sensitivity analysis showed that Point like support floating slab track has the best performance in vibration reduction. With this type of FST the vertical stiffness equal to 3.5 kn/mm and 10 db vibration reduction in comparison with DFT could be achieved.

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A: Point like support floating slab track   B: Full surface support floating slab track   C:Linear support floating slab track

Natural frequency : 5 to 12 HZ   Natural frequency : 14 to 25 HZ   Natural frequency : 8 to15 HZ

Figure 12. Various types of floating slab track with different natural frequencies

To investigate exact frequencies that make some problems for monumental buildings, results in time domain was converted to the frequency domain by FFT transform. As can be seen in Figure 13 for descrete support floating slab track the resonance frequency is less than the others. Besides this type has more performance in vibration reduction.
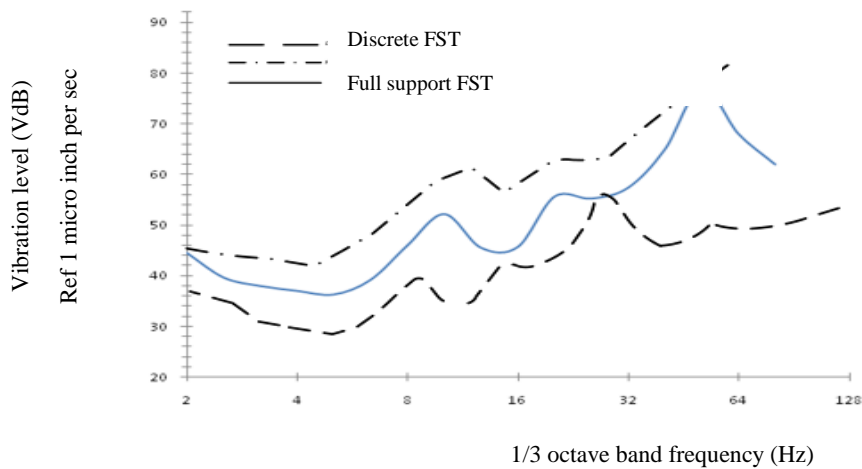

Figure 13. Comparing the performance of three common types of floating slab track in frequency domain

6. conclusions

Ground-borne noise and vibration induced from underground railways continues to be a significant concern among subway designers, operators and nearby residents. Nevertheless, vibration barely could led to structural damage, but contains some issues for occupants as interferes with speech and communication, interrupts concentration, and disturbs sleep. Modifications to the vibration source, transmission path, and building design can reduce the level of vibration in the receivers. Due to the high complexity of issue, effective and proven means for ground-borne noise and vibration attenuation in the form of source reduction methods, propagation path methods and receiver reduction methods highly differs case by case. The effectiveness of various vibration reduction approaches is strongly dependent on frequency content of the source, which has been investigated in this paper. The main results are summarized as follows:

Vibration reduction strategies on railway transport systems are not easily applicable from one case to another. In other words, even in two similar urban railway systems due to differences in new situation (for example, geology, frequency content, maintenance circumstances), different strategies are needed. Strategies for reducing vibrations caused by trains and urban railway transport system should be chosen according to the nature and behavior of the vibration. Reduction methods in source are the most effective methods of reducing vibration. Reducing the stiffness of the primary suspension, and hence reducing the primary suspension resonance frequency, will reduce the levels of ground-borne noise and vibration. The trenches have significant attenuating effects on low-frequency vibrations for propagating waves. The floating slab track has been found to be a very effective vibration and noise reduction mechanism. This method provides the largest

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amount of vibration reduction in the receivers and it yields a vibration reduction at the source, which is advantageous to all the structures around the metro line. The use of advanced prediction models prospers a better understanding in the generation and propagation mechanism of ground-borne noise and vibration and allows for studying the effect of structural changes on the source as well as the receiver side. The effectiveness of various types of floating slab tracks was evaluated through a field test in Isfahan metro line. The results showed that discrete support floating slab tracks have the best vibration isolation performance. The results of sensitivity analysis showed that vertical track stiffness equal to 5 kn/mm would lead to 5 db reduction with regarding 4 millimeters limit of rail deflection.

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Conflicts of Interest

The author declares no conflict of interest related tothis publication.

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