Original Article

Latin American Journal of Solids and Structures

www.lajss.org

Effectiveness of track stiffness reduction in attenuation of metro induced vibrations received by historical buildings

Abstract

Preservation of historical buildings is a main challenge in civil engineering field. One of the main concerns in this regard is metro induced vibration received by historical structures. There is a need to evaluate effectiveness of vibration mitigation measures in preservation of monumental buildings. The most widely used method of reducing metro vibrations is changes in the structure of the vibration source (not sufficiently investigated in the literature). In response to this need, effectiveness of track stiffness reduction in mitigation of vibration was investigated in this research. Comprehensive field tests were conducted in the Iranian metro lines. The track stiffness as well as the induced vibrations were measured. It was shown that track stiffness has noticeable role in the track levels of vibration, and in turn in metro vibration reduction. The amounts of vibration reduction were derived as a function of track stiffness reduction.

Keywords

Railway track, stiffness, vibration, historical buildings

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http://dx.doi.org/10.1590/1679-78255252

Received: August 27, 2018
In Revised Form: October 28, 2018
Accepted: November 03, 2018
Available online: November 05, 2018

1 INTRODUCTION

Construction of subways have eased the transportation and caused a boom in tourism industries in ancient and historical cities (Gonzalez-Navarro and Turner 2016, Sadeghi and Esmaeili 2017). However, there are various reports indicating damages made by the metro induced vibrations to the cultural and historical structures/buildings adjacent to the metro lines (Vogiatzis 2012, Galvín, Mendoza et al. 2018). For instance, the ICHTO report (Sadeghi and Esmaeili 2017) indicates that the subway vibration levels has exceeded the allowable limits in the subway, Line 1, in Isfahan. Isfahan has several historical monuments registered by the ICHTO or UNESCO including Si-o-Se-Pol, a thirty-three arches bridge built 700 years ago, Charbagh Islamic school, a historical school built 600 years ago, and SarDar-e-Keymeghah, a building built 400 years ago (Sadeghi and Esmaeili 2017) (Figure 1).

There are several methods of reducing metro induced vibrations (Connolly, Kouroussis et al. 2015, Xu, Yan et al. 2015, Esmaeili, Naeimi et al. 2016). Vibration Reduction Methods (VRM) are categorized into three different groups. They are the VRM at source, at the propagation path, and at the receiver (Younesian and Sadri 2014, Connolly, Kouroussis et al. 2015). In the majority of the cases, the most preferable method is the VRM at the source since it is less costly and more practical compared to other methods (Cox and Wang 2003). In addition to prevent any possible rail/wheel irregularities or track roughness (which accuse extraction of vibrations), the main approach for attenuation of the vibration at the source is reduction of track stiffness (Cox and Wang 2003, Van Leuven and Vanhonacker 2008, Sadeghi and Esmaeili 2017). This is the most widely approach employed in the new and existing railway tracks. A low track stiffness can be achieved mostly by the use of Floating Slab Track (FST) or High Resilient Fastening systems (HRF) (Sadeghi and Esmaeili 2017). In FST, track stiffness can be reduced by decreasing the modulus of elasticity of elastic layer, increasing the thickness of elastic layers, or decreasing the area of the elastic layers used under the slab-track. In the HRF, the track stiffness is reduced by installing elastic elements on the bottom or in the rail web which prevents the direct connection between rail and track and cause a considerable reduction in the stiffness of the track system.

A large amount of research has been made to drive a suitable methods for reduction of track stiffness (Cox and Wang 2003, Saurenman and Phillips 2006, Van Leuven and Vanhonacker 2008, Sadeghi and Esmaeili 2017). As a result, the HRF systems have been introduced and widely used in the world. Cox and his colleagues made a research in which they have partially studied the HRF method in the laboratory and proposed a relationship between track stiffness and vibration level based on laboratory tests (Cox and Wang 2003). Wang et al. conducted some field measurements to investigate the effectiveness of a new type of HRF (whit the stiffness of 5 Mpa) recently appeared in Chinese subway lines (i.e. vanguard fasteners produced by Pandrol company) (Wang, Wei et al. 2016). Thorough field measurements, they found that this system is capable of reducing the vibration level up to 25 decibels. Van Leuven and Vanhonacker (Van Leuven and Vanhonacker 2008) developed a new HRF with the considerably low stiffness values (Less than 7 MPa) capable to reduce vibration levels up to 30 decibels. They installed this system in Brussels subway and monitored its dynamic behavior. Sadeghi and Esmaeili developed and implemented a HRF in the vicinity of monumental buildings in Isfahan subway line which decreased the vibration levels to the level below the acceptable range of allowed vibration (Sadeghi and Esmaeili 2017). In 1983, Federal Transportation Association (FTA) arranged a series of tests to investigate the effectives of a new kind of HRF system manufactured by Clouth Gummiwerke AG company in Germany (Chen 1995). This system has 13 MPa stiffness and called Cologne-egg. The results showed that it could reduce the vibration of the subway up to 8 decibels in the range of 31.5 to 63 Hz (Chen 1995). This system was further evaluated and implemented in the railways around the world including Chinese metro lines (Cui, Chen et al. 2016), Australia and Europe (Delkor-Rail 2017). Kun et al.(Kun, Lei et al. 2017) examined the effectiveness of Cologne-egg on the vibration response of bridge system compared with three other conventional fastening types. A special HRF system called Cradle fasteners with the ability to reduce the track stiffness by 2.5 MPa was developed by ABV Company in Russia (ABV-Co 2017). It has been installed on the Sokolniki line of Moscow subway under the Pushkin Museum of Fine Arts and A. M. Shilov art gallery. The evaluation of this system showed that this system is capable of reducing the vibrations up to 10 decibels at frequencies from 32 to 63 Hz (ABV-Co 2017).

Several research works have been made on the use of the FST in the design of low-stiffness track systems. Xin and Gao modeled a Train-FST-Bridge system using a combination of Finite Element and Multi Body Dynamics technique to investigate the effects of track stiffness on wheel-rail forces, slab and bridge responses (Xin and Gao 2011). They concluded that a change in the stiffness of floating slab track (FST) does not noticeably affect the wheel-rail force and bridge response, but they have considerable effect on the response of the rails and slab track. They offered the optimum stiffness for a pad under a slab in the range of 20 to 40 MN/m^3 . Zhu et al. developed a FST system which provides the possibility of mitigating vibrations at low frequencies of 9 to 16 Hz (Zhu, Wang et al. 2017). They evaluated the effectiveness of their proposed FST in urban rail transit system. Toll et al (Töll, Achs et al. 2018) verified the performance of a FST System after 20 Years of Service. Similar works on FST systems were conducted by Ma et al. (Ma, Jiang et al. 2017) and Zhao et al. (Zhao and Ping 2018). A summary of stiffness variations of FST systems used in European countries was done by International Union of Railways (UIC 2008).

Fig. 1. *Isfahan Metro Line 1 and historical monuments in the vicinity of this Line.*

As discussed above, the review of the available literature indicates that investigations on the effectiveness of the track stiffness reduction are limited to theoretical evaluations, some laboratory tests and very limited field works on the on attenuation levels of track induced vibrations. In other words, the full scale evaluation of the effectiveness of stiffness reduction methods (i.e. HRF and FST approach) has not been sufficiently investigated.

Addressing the limitations of the available literature, the effectiveness of the FST and the HRF on reducing metro induced vibrations has been investigated in this research. This was made by comprehensive experimental investigations. Seven track fields, with various track structures which cover different arrangements of FST and HRF were selected. The track stiffness was measured in each track field and track induced vibrations were recorded at various train speeds. The filed results obtained were used to derive a relationship between track vibration reduction and track stiffness and as a result, a new mathematical expression was proposed by which the vibration reduction level for various track stiffness values can be derived.

2 Field measurements procedure

Field measurements were made in seven separate sites spread in the Iranian subway network (Figure 2). The Sites were selected and used in this investigation in a way to cover various possible track structures (i.e., Direct Fixation Track (DFT), Floating Slab Track (FST) and High Resilient Fastener (HRF)). A schematic view of various track structures used in the tests is presented in Figure 3. Sites 1 to 3 are in the Tehran metro network (in the Iranian capital city) in which the track structure is DFT type (Figure 3-a). Site 4 is in Tabriz (a city in the north-west of Iran) with FST system. Sites 5 and 6 are in the Isfahan metro first line (in the central part of Iran). The track structure in these sites includes two types namely FST and HRF (Figure 3-b and c). Site 7 is in Shiraz (a city in the south-center of Iran). The track structure in this site is FST type with high stiffness elastic layer. Details of the track structure and train parameters at the measurement sites are presented in Table 1. The track and rolling stock parameters conditions (provided in Table 1) were either measured in the sites or provided by the metro authorities. More details of the test sites are presented in (Sadeghi, Liravi et al. 2017).

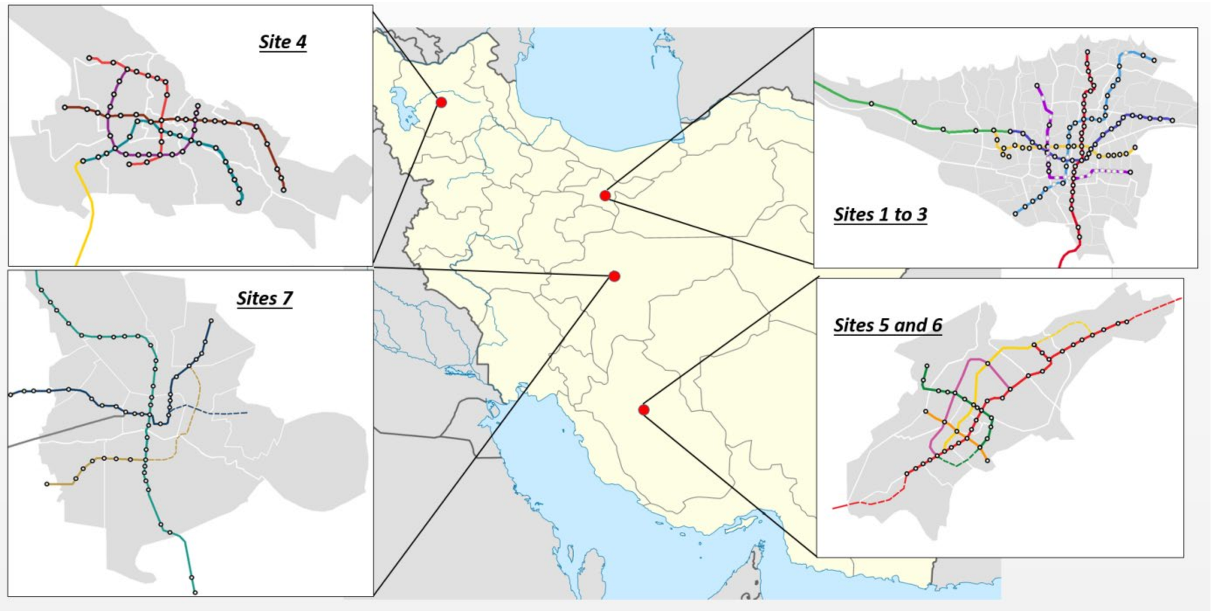
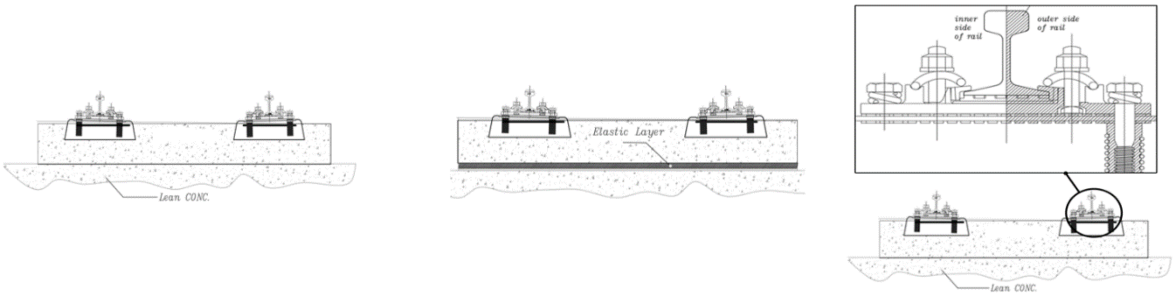


Fig. 2. *Seven separate sites used in field tests*



(a) (b) (c)

Fig. 3. *Various types of track structures used in the measurements (a) Direct Fixation Track (DFT), (b) Floating Slab Track (FST), (c) High Resilient Fastener (HRF)*

Two types of sensors were used for the measurement. They are Linear Variable Differential Transformer (LVDTs) for the track stiffness measurements and accelerometers for the track vibration measurements. LVDTs were selected with the consideration of the possible ranges of the train loads and accelerometers, taking into consideration the amplitude and frequency ranges of track vibrations.

The stiffness of the tracks was computed using the Talbot-Wasiutynski method(Ali Zakeri and Abbasi 2012, Heydari-Noghabi, Varandas et al. 2017, Sadeghi, Liravi et al. 2017). For this purpose, the vertical deflections of the rail relative to the tunnel invert were measured for two different axle loads. Schematic view of the Talbot-Wasiutynski method is presented in Figure 4. Instrumentations and testing procedure were precisely designed considering the Talbot-Wasiutynski method detailed in the literature (Kerr 2000, Sadeghi, Liravi et al. 2017). In each site, 3 meters of the tracks were instrumented (i.e., LVDTs were set on 5 consecutive rail seats) to obtain the pattern of the rail deflections at the rail seats positions (Figure 5-a). Japanese data logger series TML7200 was used to record the data.

Table 1. *General specifications of the train and tracks in the fields*

Site No	Location	Rail Type	Fastening Spacing (mm)	Axle load* (Tone)	Train speed (Km/h)	Track support system	
						Type	Description
1	Line 3 Tehran-Southern part	UIC 54	450-600	16	78	DFT-RP2	Direct Fixation Track-Medium Stiffness
2	Line 3 Tehran-Central part	UIC 54	650-750	14	76	DFT-RP2	Direct Fixation Track - Medium Stiffness
3	Line 3 Tehran-Northern part	UIC 54	600	15	78	DFT-RP2	Direct Fixation Track - Medium Stiffness
4	Line 1 Tabriz	S49	600	14	76	FST-RP1	Floating Slab Track - Low Stiffness
5	Line 1 Isfahan-Northern part	S49	600	15	80	FST-RP2	Floating Slab Track - Low Stiffness
6	Line 1 Isfahan- Central part	S49	600	16	75	HRF	High Resilient Fastener mounted on Floating Slab Track
7	Line 1 Shiraz	S49	600	14	77	FST-RP1	Floating Slab Track - Low Stiffness

* P_2 in equation 1

The track stiffness was calculated by dividing the amount of the differences in the wheel loads by the area under the load-deflection curve (Ali Zakeri and Abbasi 2012) as indicated in Eq.1 .

$$k = (\sum p_2 - \sum p_1)/A_r \tag{1}$$

where K and Ar are track stiffness (MPa) and the area between the load-deflection curves for the first and second axle loads (kN), respectively. P1 and P2 are the first and the second wheel loads.

Vibration measurements were made on the rail, on the top of the slab (Figure 5-b) and at the tunnel base (Figure 5-c). Vibration measurements were made using Tokyo-Sokki accelerometers (Table 2). These accelerometers are piezoelectric. The accuracy of this type of sensors in the vibration measurement has been previously shown in the literature (Chang, Kim et al. 2014). The accelerometers used on the rail had a peak input level of 50 g (Type ARF-500A) and the others had a peak input level of 10 g (Type ARF-100A) with the natural frequency of 870 and 300 Hz, respectively . The vibration measurements were repeated in various train passes with different train speeds (Figure 5-d). Data including accelerations and deflection were recorded by a Data logger (Figure 5-d), and downloaded into a computer for the analysis. The test procedure was the same in all of the tests (sites).

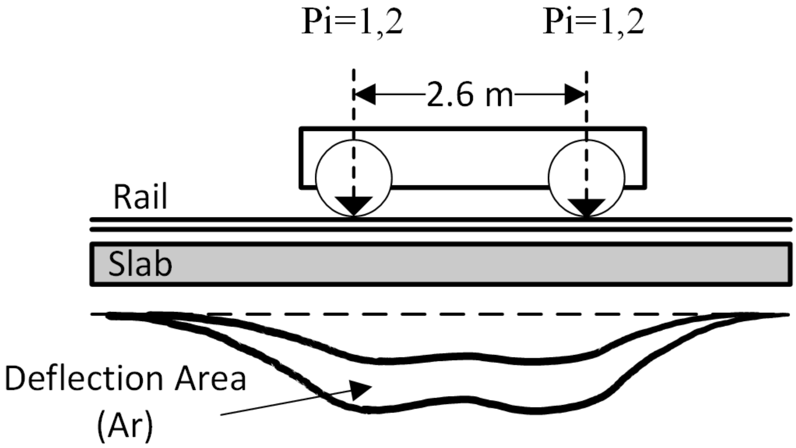
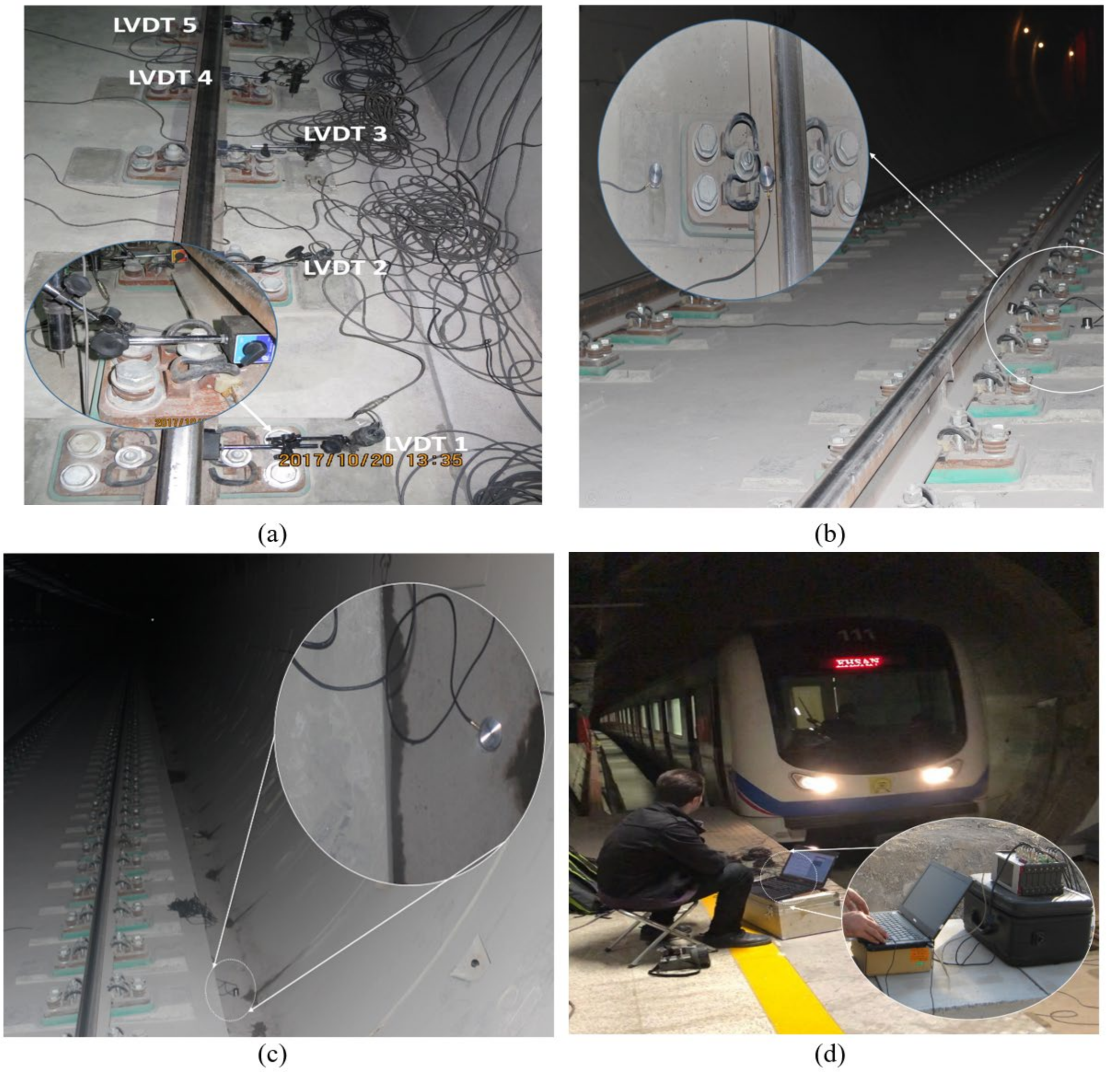


Fig. 4. *Schematic view of the Talbot-Wasiutynski method used to derive rail support modulus (Track stiffness)*



(a)
(b)
(c)
(d)

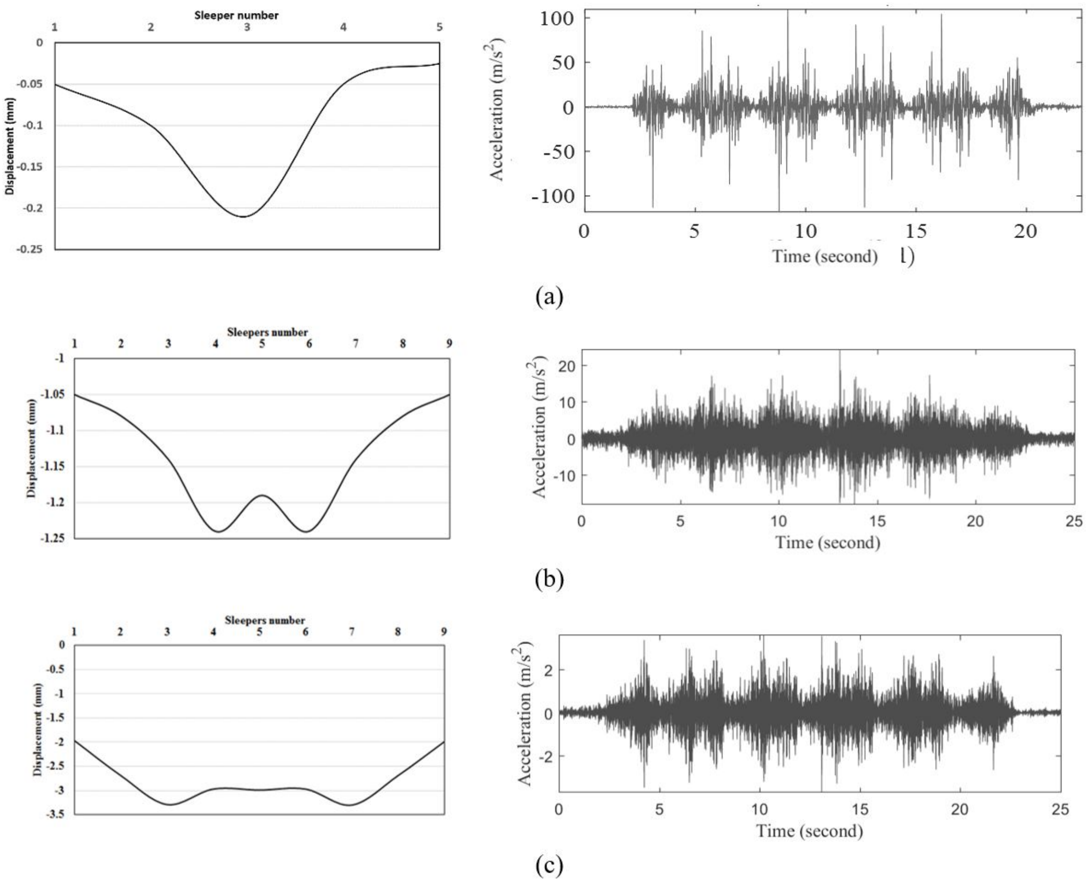
Fig. 5. *Field measurement (a) LVDTs installed for track stiffness measurement, (b) Installation of vibration sensors (accelerometers) on the slab, (c) Installation of vibration sensors (accelerometers) on the tunnel base, (d) Data logger and laptop computer used for the measurement at each train pass*

Table 2. *General specifications of the accelerometers used in measurements*

-	**Model**	Tokyo-Sokki ARF100A	Tokyo-Sokki ARF500A
1	**Sensitivity (m/s²)**	1	5
2	**Capacity (m/s²)**	100	500
3	**Frequency range (Hz)**	1-240	1-690
4	**Sensing element**	Piezoelectric	Piezoelectric
5	**Natural frequency (Hz)**	300	870
6	**Temperature range (°C)**	-10 to +50	

3 Experimental results and discussions

As explained in the test procedure, the vertical deflections of the rail along 3 meters of the rail were recorded and consequently, the track stiffness were computed based on the Talbot-Wasiutynski method. Moreover, the accelerations of the rail heel and slab at the fastener position, and the accelerations of the tunnel base were recorded. Samples of results in DFT, FST, and HRF track structure types, measured in Sites 2, 7 and 6 are presented in Figure 6-a to c, respectively (track deflection at left and acceleration at right). As indicated, the track deflection and acceleration values change considerably depending on the track structure type. The deflections values was reduced up to 15 times from that of the stiff (i.e. DFT) to soft (i.e. HRF) track structure type, while the corresponding acceleration values were increased up to 25 times. These considerable difference is due to the considerable variations in the stiffness of the track in the test sites.



(a)

(b)

(c)

Fig. 6. *Samples of track deflection (Left) and acceleration (Right), measured in various track structure types (a) DFT (measured in Site 2), (b) FST (measured in Site 7) (c) HRF (measured in Site 6), Accelerations and deflections were measured on top of the slab and at the rail heel, respectively*

Using omega arithmetic method (Mercer 2006) the corresponding velocity for each measurement was computed and presented in decibels form. A summary of the results obtained is presented in Table 3. Based on this table, although the track stiffness does not have much influences on the rail vibration level, the tunnel base and slab vibration level decreases considerably as the track stiffness decreases.

Table 3. *Summary of the results obtained (track stiffness and vibration levels)*

Site	Deflection* (mm)	Track stiffness (MPa)	Vibration velocity level (dB reference 25.4×10-6 mm per second)		
			Rail	Slab	Tunnel base
1	0.6	81	100	92	89
2	0.21	83	105	97	95
3	0.24	87	107	103	99
4	1.35	60	97	91	82
5	2.87	43	90	83	65
6	3.25**	9	93	75	64
6	2.13	53	92	84	71
6	3.15	15	93	81	69
7	1.24	54	96	93	79

*Measured at fastener location.

**High resilient fastener mounted on FST.

Using the Fourier transform, the time histories of the recorded accelerations were converted into the frequency domain. That is, each record was analyzed using a uniform filtering process and Fast Fourier Transform function to drive the frequency domain responses. The level in 1/3 octave bands was derived. From the results obtained in the frequency domain, the frequencies at which the largest amount of energy was produced can be distinguished. The greatest vibration levels to the structure can be made at these frequencies. Moreover, natural frequencies as well as velocities of the waves received by the accelerometers were evaluated from the results in the frequency domain. The vibration spectra measured on the tunnel invert in Site 4, 1 and 6 with the three tested track structures (i.e. HRF, DFT and FST) is presented in Figure 7. The general form (pattern) of the spectra obtained from other sites is similar. As illustrated, the peak level of vibrations measured on the tunnel base is mainly between 40 and 80 Hz.

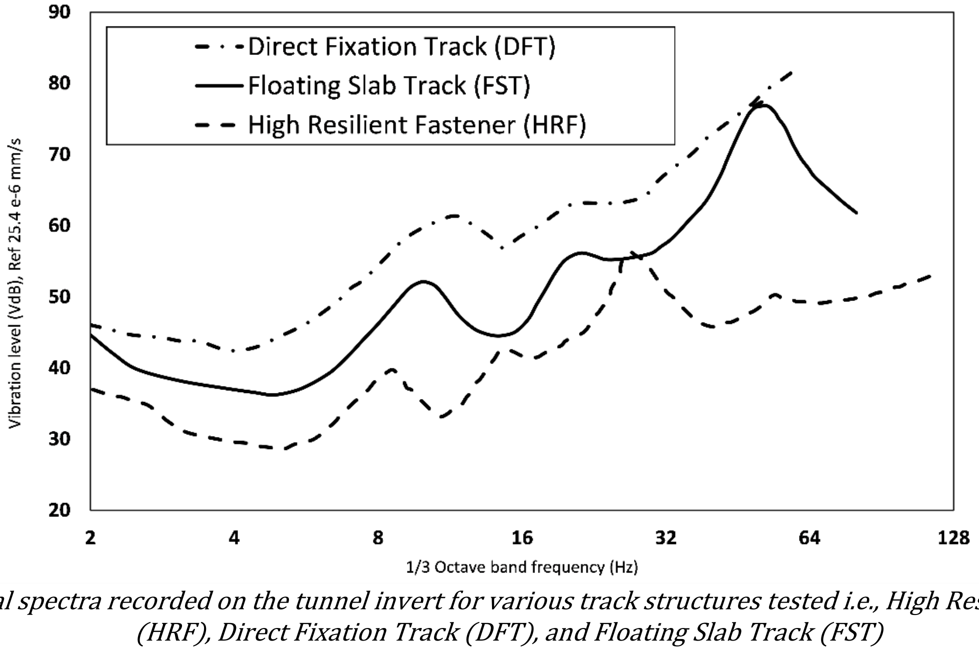


Fig. 7. *Typical spectra recorded on the tunnel invert for various track structures tested i.e., High Resilient Fasteners (HRF), Direct Fixation Track (DFT), and Floating Slab Track (FST)*

Based on the results obtained (Table 3), the effectiveness of track stiffness in the reduction of track vibrations (velocity levels) is illustrated in the logarithmic scale in Figure 8. The results indicate a linear logarithmic relationship between the track stiffness and the vibrations attenuation (the difference between velocities recoded at the tunnel invert and rail). As illustrated, the vibration attenuation between the rail and the tunnel base increases with decreases in the track stiffness. For instance, 10 times reduction in the track stiffness causes 19 dB reductions in the vibration level.

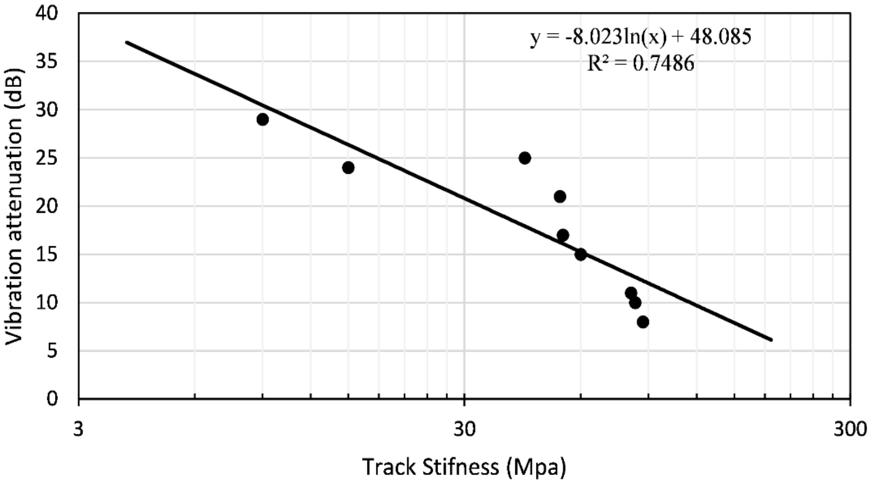


Fig. 8. *Effectiveness of track stiffness reduction on reducing track vibrations*

Based on the analysis of the measurements (Figure 8), a mathematical expression for vibration attenuation levels were developed which consider the effect of track structural properties (track stiffness) on the vibration attenuation. As a result, the best regression expression was derived as:

$$V_{AL} = 8.023\, ln(K) - 48.085 \quad (2)$$

where K is the track stiffness in MPa and V_{AL} (Vibration Attenuation Level) is the level of attenuation in dB reference 25.4×10-6 mm per second.

The Federal Transportation Association (FTA) is the most widely vibration assessment manual used in the planning phase of railway design (Hanson, Towers et al. 2006, Thalheimer and Poling 2013, Zou, Wang et al. 2017). In this model, the FTA considers reduction of vibration for various track structures in a form of a table in which all of the reductions are given as single numbers to be subtracted from the base vibrations level.

Using the experimental results obtained in this research (Equation 2), the amounts of reductions of vibrations as a function of track stiffness were derived. The results obtained here and those proposed in the FTA model are summarized in Table 4. In order to make the results comparable with those of FTA, 11 dB was subtracted from the attenuations derived from Equation 2 because the FTA considers the DFT track structure as a base (with no attenuation). In this Table, the track stiffness of 100 MPa was taken as the reference value and stiffness reduction was considered from this base. As indicated in this Table, the reduction/attenuation of railways induced vibrations are more precisely indicated in the results obtained in this research when compared with those of the FTA. For instance, the FTA proposes attention levels of -15 dB for the track with the structural types of HRF regardless of the track level of stiffness, while depending of the track stiffness value, a wide range from -13 to -25 dB reductions could be expected from HRF systems. In other words, if the track stiffness varies in each type of the track, the attenuation level proposed by the FTA does not change. That is, implementation of Level of attenuation (dB) obtained and proposed here provides a more precise amount of vibrations reduction when compared with the conventional methods (those used in the current practice).

Table 4. *Vibration attenuation levels due to track stiffness reduction obtained in this research for various track structures compared with those of FTA*

Track Stiffness (stiffness reduction), (MPa)	Level of vibration attenuation/reduction (dB) proposed here	Track structure type						Level of attenuation (dB) by FTA
		HRF mounted on FST	HRF	FST	Ballast Mats	Resiliently Supported ties	DFT	
5 (95 MPa)	-24	■						-15
10(90 MPa)	-19	■	■					
15(85 MPa)	-15	■	■	■				
20(80 MPa	-13	■	■	■				
30(70 MPa)	-10		■	■	■			-10
40(60 MPa)	-7			■	■	■		-10
50(50 MPa)	-6			■	■	■		
60(40 MPa)	-4				■	■		
70(30 MPa)	-3				■	■		
80(20 MPa)	-2				■	■		
90(10 MPa)	-1				■	■		-5
100*(0 MPa)	0						■	

*Reference value

4 Conclusions

The metro induced vibration is one of the main concerns in historical cities where metro lines are close to the monumental buildings. Although considerable number of researches have been conducted on the effect of track and train parameters on ground-borne vibration level, the effect of track stiffness reduction has not been sufficiently studied. This is addressed in this research. A number of vibration measurements have been made in different Metro systems, each with different track structure. The measurements covered a wide range of track stiffness (rail support modulus). The influences of the track stiffness on the ground borne vibration attenuation were investigated by analyses of the field measurements.

The results showed that there is a clear trend towards lower levels of vibration on the invert of the tunnel where track support stiffness is reduced. The changes in the vibration levels in various conditions of track structure were discussed and consequently correlations between the track stiffness reductions and track level of vibrations attenuation were developed. It was shown that, the vibration level decreases by approximately 19 dB for each 10-fold decrease in the track support stiffness.

Based on the results obtained, the amount of railway induced vibrations attenuation/reductions as a function of track stiffness were derived in this research. The results were compared with attenuation values for each track structure type proposed in the FTA manual (as the most widely railway vibration assessment manual used in the world). It was shown that the proposed attenuation expression developed here (which provides the vibration attenuation level as a function of track stiffens) is more precise and more comprehensive in evaluation of various track structures when compared with the conventional/current methods.

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