Train-induced field vibration measurements of ground and over-track buildings

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HIGHLIGHTS

\begin{itemize}
  \item Train-induced vibrations in the metro depot and over-track buildings were measured and studied.
  \item Building train-induced vibrations were amplified around the vertical natural frequency.
  \item Building train-induced vibrations over throat area can potentially exceed the FTA limits within 40 m.
  \item Traffic-induced high-frequency noise has the potential to annoy occupants on upper floors.
\end{itemize}

GRAPHICAL ABSTRACT

Abstract

Transit-oriented development, such as metro depot and over-track building complexes, has expanded rapidly over the last 5 years in China. Over-track building construction has the advantage of comprehensive utilization of land resources, ease of commuting to work, and provide funds for subway construction. But the high frequency of subway operations into and out of the depots can generate excessive vibrations that transmit into the over-track buildings, radiate noise within the buildings, hamper the operation of vibration sensitive equipment, and adversely affect the living quality of the building occupants. Field measurements of vibration during subway operations were conducted at Shenzhen, China, a city of 10.62 million people in southern China. Considering the metro depot train testing line and throat area train lines were the main vibration sources, vibration data were captured in five measurement setups. The train-induced vibrations were obtained and compared with limitations of FTA criteria. The structure-radiated noise was calculated using measured vibration levels. The vertical vibration energy directly passed through the columns on both sides of track into the platform, amplifying vibration on the platform by up to 6 dB greater than ground levels at testing line area. Vibration amplification around the natural frequency in the vertical direction of over-track building made the peak values of indoor floor vibration about 16 dB greater than outdoor platform vibration. We recommend to carefully examining design of new over-track buildings within 40 m on the platform over the throat area to avoid excessive vertical vibrations and

Keywords:
Over-track buildings
metro depot
vibration measurements
floor vibrations
radiated noise

Article history:
Received 14 June 2016
Received in revised form 3 September 2016
Accepted 27 September 2016
Available online 1 October 2016

Editor: D. Barcelo

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http://dx.doi.org/10.1016/j.scitotenv.2016.09.216
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1. Introduction

Urban Rail Transit is an efficient way to reduce highway traffic in metropolitan cities. For urban rail transit, subways have the characteristics of higher cost and less return on investment, which can limit the sustainable development of subway projects. As of the end of August 2015, 22 cities in mainland China have in-service subway lines with a total of 3140 km. However, by 2020, more than 45 Chinese cities are expected to build additional 7395 km of subway lines (CDMC, 2014). A metro depot is a railway or subway facility where trains are regularly parked for maintenance, testing, and storage and usually occupy the largest ground areas (Zou et al., 2015). Traditional metro depots with lower density buildings require large spaces that have significant impact on the space and the environment, and the lower density buildings are normally not conducive to economical use of urban land. In order to provide funds for subway projects and improve utilization efficiency of urban land and space resources, more than 15 Chinese cities began developing over-track building complexes above metro depots where people live and work. Over-track building complexes are built utilizing a new structural system, with large structural platforms. These platforms are floors built over the metro depot that are supported by the columns that are set in-between train tracks, as shown in Fig. 1. In this figure, the lower floor is the subway train station, the platform level is for car parking, and it supports high-rise buildings above. This is a form of modern transit-oriented development (Newman and Kenworthy, 1996 and Handy, 2005), and a way of comprehensive utilization of land resources with reasonable conversion of urban space with a smaller building footprint.

However, the high frequency of subway operations into and out of depots can generate excessive vibrations that transmit into the over-track buildings, with radiate noise within the buildings that hamper the performance of vibration sensitive equipment, and adversely affect the living quality of the building occupants. It is essential to determine the influence of train-induced vibration in the over-track buildings prior to construction and then develop efficient and cost-effective methods to mitigate the vibration for human comfort.

Numerous studies have been conducted on the propagation characteristics and levels of vibration near trains, railways, and subways. The effect of vehicle characteristics on ground and track borne vibrations from railways has been previously summarized (Thompson, 2009, Galvin and Dominguez, 2009, Kouroussis et al., 2011a, 2013, 2015, Connolly et al., 2014, 2015 and Zhai et al., 2015). Anderson (1994) performed vibration measurements in two buildings subject to railway vibration input at the foundations and found that perceptible vibration with dominant frequencies between 5 Hz and 50 Hz can propagate through the ground to nearby buildings. Xia et al. (2009) studied impact of train speed and distances from the track on floor vibrations of a 6-story masonry building near Beijing-Guangzhou railway. Sanaye et al. (2013, 2014) studied ground-borne vibration induced by trains and subways at different sites in the Boston area. Vibration transmissions from bottom floor up into a 4-story building were also reported to provide the basis that would allow the designers to estimate the vibration levels in sensitive locations within buildings.

Potential locations for vibration mitigation methods can be used at the vibration source, in the propagation path, and at the structure's base (Bahrekazemi, 2004, Vogiatzis and Vanhonacker, 2015a). Vibration mitigation at the source includes floating slab tracks (Tayabji and Bilow, 2001, Lombaert et al., 2006, and Ding et al., 2010, Vogiatzis, 2012, Vogiatzis and Kouroussis, 2015b), rail pads (Kaewunruen and REMENNIKOV, 2006), fasteners (Zou et al., 2011), or resilient wheels (Kouroussis et al., 2011b). As passive isolation, wave barriers in the propagation path include open trenches, in-filled trenches, sheet-pile walls, and rows of solid or hollow concrete or steel piles that can reflect incident waves in the propagation path (Woods, 1968, Beskos et al., 1986, Andersen and Nielsen, 2005, Connolly et al., 2013, and Coulier et al., 2013). Vibration isolation of buildings is often achieved by introducing base isolation systems at the foundation-building interface (Coelho and Koopman, 2012). Ju (2007) investigated three common types of foundation isolation, which include the extension of retaining walls, pile foundation, and soil improvements around the building. He found that soil improvement by using hard soil around the building is the best way to reduce the building vibration both in horizontal and vertical directions.

The trains usually run on one side of buildings and subways operate in tunnels underneath of adjacent buildings with vibration transmission from source to building foundation through soil. This is not the case with metro depots, where the subway usually operate on ground under the platforms and over-track buildings, where the vibration energy directly transmits to the building through the ground, vibration energy indirectly transmits through vertical support structures on both sides of tracks, such as columns and walls, to the platform, and then to the upper floors, as shown in Fig. 2.

The vibration sources can be divided into three groups based on the characteristics of the rails (Zou et al., 2015), including (1) throat area, (2) testing line, and (3) storage tracks and repair tracks. Wu et al. (2015) measured floor vibrations in a building over train storage tracks and repair tracks. The maximum vertical acceleration level was 61.8 dB,
which was lower than the limit of 65 dB by Chinese standard (Ministry of Environmental Protection of the People’s Republic of China, 1988; Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2009). The vibrations induced by trains running on the storage and the repair tracks, while below Chinese recommended levels, can still be detectable by a portion of the population in the busy train operations hours. Zou et al. (2015) also investigated vibrations on the ground and inside a 3-story building due to the subway trains in a metro depot at Guangzhou, China. Train operations in the testing line and throat area were the main vibration sources in the metro depot. The results suggested that the mitigated measures should be taken into account to reduce vibrations in the metro depot. Moreover, whether the performance of existing isolation methods can be effectively applied in the metro depot and over-track buildings need to be further verified.

This study focuses on the influence of subway train-induced vibrations on the ground and inside over-track buildings in a typical metro depot in order to characterize the vibration transmission in the metro depot and over-track buildings. Considering the metro depot train testing line and throat area train lines were the main vibration sources, vibration data were captured in five measurement setups. The train-induced vibrations were obtained and compared with limitation of FTA vibration criteria. The structure-radiated noise was calculated using measured vibration levels. The findings are useful information for designing vibration mitigation systems in metro depots to minimize vibration levels in the over-track buildings subjected to the governing codes and standards.

2. Metro depot and over-track buildings description and measurement program

The metro depot used in this study is located in Shenzhen, China. The total land use area is about 235,132 m² and the total building area is approximately 690,000 m². The over-track buildings include
residential, offices, hotels, schools, and a shopping center. The south side of metro depot also is a railway and a highway. An avenue and the metro station are at the north side of the metro depot, as shown in Fig. 3. All the buildings are directly accessible by escalators, stairs, bridges, air corridors, and connecting metro station.

Fig. 3 shows the typical train tracks plan of the metro depot. The throat area, where trains fan out into individual parking berths that consists of 150 m curved rails, turnout, and rail joints. The testing line, which runs along the south side of the depot, is used for high speed testing and for performance evaluation of trains to ensure safe operations.

Fig. 3 shows the typical train tracks plan of the metro depot. The throat area, where trains fan out into individual parking berths that consists of 150 m curved rails, turnout, and rail joints. The testing line, which runs along the south side of the depot, is used for high speed testing and for performance evaluation of trains to ensure safe operations.

Fig. 4 shows the typical train tracks plan of the metro depot. The throat area, where trains fan out into individual parking berths that consists of 150 m curved rails, turnout, and rail joints. The testing line, which runs along the south side of the depot, is used for high speed testing and for performance evaluation of trains to ensure safe operations.

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FFT analysis was carried out averaging contiguous 1-second long periods during the train pass-by.

3. Ground, platform, and 14-story building vibration at testing line area

Three setups were selected include (1) setup A, on the ground near train tracks; (2) setup B, on the platform away from buildings; and (3) setup C, in the building, as shown in Fig. 6. All setups were measured in one-hour intervals from 1 to 4 pm, beginning with setup A and ending with setup C. The vertical and horizontal accelerometers were set perpendicular to the track on the ground and platform with different distances from the testing line and at the centers of the selected floors in the 14-story building. The vertical accelerometers, which were 28 m away from the testing line and have the same elevation, were set on the platform and on the 1st floor in the building to compare the indoor and outdoor platform vibrations. An open trench, which was used to store cables, was located 2 m from the closest track, and was 1.7 m deep by 2.1 m wide. It ran the full length of the testing line.

3.1. Vibration response on the ground at testing line area

Fig. 7 shows how 1/3 octave spectra of typical ambient and train-induced vertical and horizontal vibrations on the ground change with

![Fig. 5. Instrumentation used in the measurement.](image)

![Fig. 6. Accelerometer setups at testing line area.](image)

![Fig. 7. Ground vibrations vary with distance from testing line.](image)
distance from the testing line. The reference velocity is $1 \times 10^{-6}$ in./s according to FTA (2006), which is $2.54 \times 10^{-8}$ m/s. It is observed that the vibrations induced by trains were about 5–10 dB greater compared to the typical ambient vibrations at all distances from the testing line. Vertical vibrations were greater than horizontal ones within 14 m from the track. However, from 14 m to 28 m, vibration levels in both directions were comparable.

The change in peak vertical vibration levels in the 1/3 octave band at 16 Hz for different train pass-by events is plotted as a function of distance from the track, as shown in Fig. 8. The first measurement on the ground was at 7 m from the track centerline. There was an average attenuation of about 0.6 dB/m within 7 to 28 m further away from the track.

3.2. Vibration response on platform at testing line area

There are two different paths of vibration transmission from vibration source to building, which contribute to the total vibration response of platform and building. The one path is from the vibration source at the track transmission up through columns into the platform and across the platform to the building. The other path is the vibration across the ground from the track and up the columns under the building (Fig. 2).

Fig. 9 shows the vibration levels in vertical and horizontal directions at 0 m, 14 m, and 28 m away from the testing line. The vibrations induced by the trains were about 5–10 dB greater than typical ambient vibrations for both directions. The vertical vibration levels were 5–10 dB greater than levels in horizontal direction within 14 m. However, the peak levels were close in both directions at 28 m from the testing line. For horizontal vibration, the velocity levels were comparable below 20 Hz and amplified zones were observed above 20 Hz at 28 m. It is difficult to explain the amplification and the similar results also reported by Xia et al. (2005). It is also possible that a measurement error at 28 m from the testing line in horizontal direction is responsible for the higher vibration levels above 20 Hz up to 63 Hz where the levels fall off rapidly.

For vertical vibrations, Fig. 10 shows the peak velocity levels on the platform at 16 Hz of individual train pass-by events at various distances from the testing line. The peak velocity levels decreased with a rate of about 0.2 dB/m on the platform, which was not as strongly attenuated across it to the building in comparison with transmission across the ground that decreases more rapidly toward the building. This may be due to the platform was not a heavily damped structure. In addition, the two different paths of vibration transmission may also cause this difference due to the open trench was only set at one side of the track and it has little impact on vibration transmission at the other side. It resulted an amplification of vibration on the platform by 6 dB or greater compared to the ground vibration levels at 28 m from testing line.

3.3. Vibration response in the 14-story over-track building at testing line area

Fig. 11 shows the vibration spectra on different floors in the 14-story over-track building in the testing line area. Overall, the ambient vibration levels are well below train-induced vibrations, especially for peak

Fig. 8. Peak vertical velocity levels at 16 Hz on the ground at testing line area.

Fig. 10. Peak vertical velocity levels at 16 Hz on the platform at testing line area.

Fig. 9. Platform vibrations vary with distance from testing line.
levels in frequency. The vibration levels in vertical direction were 5 dB or greater than in the horizontal direction. For the horizontal direction, the velocity levels were comparable below 31.5 Hz and attenuated rapidly above 63 Hz. The peak levels of all floors were below 50 dB. For the vertical direction, the average peak levels occurred in the 50 Hz with values between 53 and 64 dB. Fig. 12 shows the peak levels of all the train pass-by events. The differences of velocity levels caused by different events were in 3–7 dB. The peak levels increased slightly from 1st floor to 4th floor, and then decreased from 4th floor to 10th floor and finally amplified on the top floor.

4. Platform and 25-story building vibration at throat area

Fig. 13 shows the measurement setups at throat area. The measurement position selected at the entrance of throat area over 3 parallel tracks, where the 3 parallel tracks branched out to 27 curved tracks from the entrance to parking garage with a total length of 230 m, as shown in Fig. 3. All the trains must go through three tracks at throat area and can go through any one of those tracks with the same probability. For these 3 tracks, the centerline spacing of adjacent tracks is 5 m, which means the distances of the nearest accelerometer to the tracks are 5 m, 10 m and 15 m, respectively. The train’s speeds were between 10 and 20 km/h in this area. An array of accelerometers were installed in the vertical and horizontal directions on the platform at 10 m, 30 m, 40 m and 55 m perpendicular to the middle track (setup D). In addition, accelerometers were installed near the column on the 1st floor and near the load-bearing walls on selected upper floors in the 25-story building (setup E). Vibration measurements were taken on the platform and 1st floor in the over-track building during the late night when trains return to parking garage and on the upper floors of over-track building in the early morning during the time the trains leave the depot with no interference of people’s activities.

The vertical accelerometers were set 55 m from the middle track on the platform and on the 1st floor (the platform) inside the building to compare the indoor with the outdoor platform vibrations.

4.1. Vibration response on the platform at throat area

Fig. 14 shows 10 measured trains’ pass-by through these three tracks induced vibrations at 10 m from the middle track on the platform. The average ambient vibrations were well below levels on the platform during train events. The train induced vertical vibration levels were 6 dB or greater than levels in the horizontal direction. For different train pass-by events, the velocity levels were consistent in the range from 20 to 63 Hz where most of the energy lied.

There were two lines of columns that contribute to the vibration transmission into the platform on either side of the 3 tracks, as shown in Fig. 13. Therefore, which track the train was on has little influence on platform vibrations, whether close to one or the other of the columns or in the middle where contributions from both columns may be important contributors to platform vibration. In addition, the train speeds are not constant and with the speed of 10–20 km/h. Due to the platform vibrations induced by trains have something to do with the train’s speed and distance, it is hard to say that the nearest track can cause the biggest vibration. For these reasons, the trains running on any one of three tracks caused the comparable vibrations on the platform.

Compared to testing line area (Fig. 10), the platform vibrations at the throat area were 10 dB or greater, even though train speeds of 10–20 km/h in throat area were slower. This is because throat area has small-radius curved rails, turnouts, and rail joints causing train wheel-rail contact releasing high-amplitude vibrations. Wheel squeal occurs from wheels sticking and slipping laterally on the rails.

Fig. 15 shows the average vibration levels at 10 m, 30 m, 40 m and 55 m from the track on the platform in the rails throat area. Vibrations in both directions decreased with distance from the track, especially at high frequency. Fig. 16 shows the peak velocity levels at 40 Hz on the platform of individual train pass-by events at various distances from the testing line. Due to different train speed and unknown operated tracks, the peak velocity levels showed wide range and decreased 0.6 dB/m in the vertical direction.
4.2. Vibration response in 25-story over-track building at throat area

Fig. 17 shows the ambient vibrations in the 25-story over-track building at throat area. For horizontal vibration, the ambient vibrations have minimal influence on train induced floor vibrations. Ambient vertical vibrations are also well below levels due to trains on the 1st floor by at least 10 dB below 80 Hz. However, ambient vertical vibration levels on the upper floors were greater than levels during train pass-by between 63 and 100 Hz, for unknown reasons.

Fig. 18 shows vibration levels on the 6th floor for 10 trains’ pass-by events. The velocity levels were closely comparable below 50 Hz, but wide variations were observed at higher frequencies between 63 and 100 Hz. There was a lot of truck traffic into the downtown area on the highway near the metro depot during the time of the measurements on the upper floors, which may explain the greater levels at higher frequencies that are the result of airborne transmission of the exhaust noise from the trucks. However, ambient levels are still up to 15 dB lower than train-induced floor vibrations around dominant frequencies around 31.5 Hz.

Fig. 17 also shows the vibration transmission in 25-story over-track building. The vibrations in vertical direction were around 15 dB greater than horizontal ones. For vertical direction, the average peak values were between 54 and 61 dB and observed at 31.5 Hz. Fig. 19 shows the peak vertical velocity levels of all train pass-by events in the 25-story building. The differences of velocity levels caused by different events were in 3–8 dB. The peak levels were slightly increased between 1st to 6th floors, and then attenuated between 6th to 16th floors and amplified at the top floor.

5. Discussion of measured vibration levels

The findings of this research are useful for designing effective vibration mitigation measures in metro depots, and for developing predictive models of building vibrations. Overall, both at the testing line area and throat area, the vertical vibrations always decreased with distance from the track; however, horizontal vibrations did not show a universal
decrease. For vibrations on ground surface, the data was only collected at the testing area due to the inability to access the trains’ operating area at the throat area. In the field of this area, the train-induced vertical vibrations were greater than the horizontal ones. The open trench were beneficial in reducing vibration transmissions from the source to the ground and ground to the building foundation.

Two different paths of vibration transmission from vibration source to building contribute to the total platform vibration response. For the testing line area, the platform vibrations were around 10 dB or lower than the vibrations at throat area, even though the speed of trains at the testing line area was faster. This difference might be caused by the interactions between the wheels and rail joints or turnout. For the throat area, the vibration of the whole throat area need to be more concerned rather than the individual track, and the measured responses indicated that the trains running on any one of tracks in the throat area caused the comparable vibrations on the platform.

For vibrations transmitted into the over-track buildings, vertical vibrations were dominant. According to the FTA (2006), vibration generally reduces in level as it propagates through a building, and a 1 to 2 dB attenuation per floor is usually assumed. However, in this paper, the results are inconsistent with the FTA guidelines. The vertical vibrations generally slightly increased on the lower floors, then decreased on the middle floors, and increased again on the top floor because there was no structure above the top floor to absorb the vibrational energy, as shown in Fig. 12 and Fig. 19. The FTA guideline did not consider the vibration amplification at the top floor. For the 14-story building at testing area, the average attenuation rate of vibration was about 1 dB per floor from 1st floor to 10th floor. For the 25-story building at throat area, the average attenuation rate of vibration was about 0.2 dB per floor from 1st floor to 16th floor.

5.1. Comparison of indoor and outdoor vibrations

To compare indoor and outdoor vertical vibration levels, the outdoor vibration on the platform at 28 m away from the track and the
corresponding indoor vibration on the 1st floor within the 14-story building at testing line area were measured and shown in Fig. 20(a). Note that accelerations measurements for the platform and the 1st floor were at the same elevation. To compare between test sites, we measured the outdoor vibration on the platform at 55 m away from the track and the corresponding indoor vibration on the 1st floor within the 25-story building at throat area shown in Fig. 20(b). All the accelerometers were mounted near the column. The indoor vibrations were comparable with the outdoor ones at low frequencies, but the indoor vibrations increased significantly by about 16 dB near and above 50 Hz in the 14-story building, which is 51.4 m tall, and near and above 31.5 Hz in the 25-story building, which is 83.3 m tall.

This amplification is perhaps related to resonance behavior of vertical vibrations within the building. Taller buildings would have lower vertical natural frequencies compared to shorter buildings (François et al., 2007). However, the soil–structure interaction can influence on the vertical dynamic response of the building. Lopes et al. (2014) used a finite element model of a two-story building to simulate the resonance response of the building–ground system subjected to excitation at ground-level. The coupling of the building to the ground through footing of the building was established by taking into account the soil–structure interaction. They found that there was a trend for the attenuation of building resonance effects with increases in soil flexibility.

5.2. Vibration for human comfort

The platform serves as an outdoor living space for people’s relaxation and entertainment and the buildings are used for people’s living and office space. However, excessive vibration on the platform and in the buildings can affect the living quality of the building occupants. The factors affecting human comfort are amplitude and frequency of vibrations. According to ISO2631-1 (International Organization for Standardization, 1997), the main frequencies of vibration impact on humans is within 1–80 Hz. The vibration impact criteria of FTA (2006) gave a limit value of 75 dB due to train induced vibration for institutional land uses with primarily daytime use and established vibration criteria with a limit of 72 dB for residences and buildings where people normally sleep.

Fig. 21 compares the average velocity levels of individual train pass-by events on the platform with FTA limits. Platform’s average vibration velocity levels in the testing line area and the throat area that are less than the FTA limit of 75 dB for institutional land uses with primarily daytime use. However, the average velocity levels at mid-frequencies within 10 m from the tracks at throat area are close to the FTA limit value of 72 dB for residences, and velocity levels for train pass–by events exceeded the FTA limit by 1–2 dB (Fig. 16), which would affect human comfort. In addition, the FTA limit for residential buildings is 72 dB for the platform over throat area and testing line area where buildings can be potentially constructed. If the buildings are developed on the
platform over the throat area within 40 m from the tracks, the vibrations potentially can exceed the FTA limit due to vibration amplification, which is perhaps related to resonance behavior of vertical vibrations within the building. It is recommended to carefully study other over-track building constructions and possibly avoid building within 40 m on platform over rails throat areas.

Fig. 22 shows the comparison of average velocity levels of individual train pass-by events in the buildings, as opposed to on the platform relative to the FTA limiting value of 72 dB for residences. Vibration levels in the 14-story building at testing line area were less than the limit value by 10 to 20 dB at and around 50 Hz. Vibration levels in the 25-story building at throat area were less than the limit value by 11 to 17 dB around 31.5 Hz. These frequencies for the two buildings are related to the suspected resonances of the building systems, including the building-foundation-soil interactions.

5.3. Structure-radiated noise

Train induced structure-radiated noise with an audio range of 16–250 Hz is produced by vibration of floors and walls exciting the
surrounding air in the room (Lim, 2000). It can be derived from ground-borne vibrations and can be verified using sound measurements by microphones. At present, several analytical methods are available for assessing the structure-radiated noise. Federal Swiss Rail (SBB) developed a regression model based on a large amount of measured data to predict structure-radiated noise impact (Kuppelwieser and Ziegler, 1996). The Austrian Standard Institute (2008) proposed an equation, which linked structure-radiated noise level to vibration velocity level on the floor, volume, surface area, and reverberation time (echo properties) of the space used. Generally, A-weighted level of structure-radiated noise can be expressed as (FTA, 2006):

\[ \text{LA} = \text{LV} + A + R \]

(1)

where \( \text{LV} \) is velocity level (dB, re 2.54 × 10^-8 m/s^2), \( A \) is a parameter that accounts for the room volume and surface area, as well as air density and wave speed; and \( R \) is adjustment of A-weighting factor at the 1/3 octave band center frequency.

For a room with typical acoustical absorption and size, the sound pressure level is approximately equal to the average vibration velocity levels on the floors, hence, \( A \) can be ignored (FTA, 2006). The \( R \) values for each 1/3 octave band center frequency can be found in FTA (2006). For example, the corresponding adjustment \( R \) values for vibration spectrum peaks that appeared at 3.15 Hz for the 25-story building and at 50 Hz for the 14-story building are \(-39.5\) dBA and \(-30.3\) dBA, respectively.

Measured A-weighted structure-radiated noise levels within these two buildings are shown in Fig. 23. Compared to the criterion level of \(35\) dB for residences and buildings where people normally sleep (FTA, 2006), the structure-radiated noise in both buildings were inaudible and acceptable for sleeping areas. However, the structure-radiated noise levels at 50 Hz on the 1st floor, 4th floor and 14th floor in the 14-story building were close to the limit value. As it is known, the velocity levels increase with the increasing train speeds (Connolly et al., 2014, Xia et al., 2009). Increasing test speed of trains in the future can potentially lead to exceeding the FTA sound limits creating annoying sound levels. Additionally, the traffic-induced high-frequency noise has the potential to annoy occupants on the 24th floor in the 25-story building.

6. Conclusions

Vibration measurements were carried out at a typical metro depot in Shenzhen, China in order to characterize the vibration transmission in the metro depot and over-track buildings. These findings are related to these two buildings studied in this research. These findings can provide useful insight for designing vibration mitigation systems in new metro depots with over-track buildings.

(1) The vibration energy directly passing through the column at both sides of track into the platform resulted an amplification of vibration on the platform by \(6\) dB or greater compared to the ground vibration levels at testing line area.

(2) The soil-pile-structure interaction affected the vertical dynamic response of the two buildings studied. The increased vibration levels around natural frequencies within the building were about \(16\) dB greater than outside the building on the platform.

(3) Vibration levels in the 14-story building at testing line area and in the 25-story building at throat area were less than the FTA limit value of \(72\) dB. However, the traffic-induced high-frequency noise has the potential to annoy occupants on the 24th floor in the 25-story building.

(4) For new buildings, the sound and vibrations levels can potentially exceed the FTA criteria due to vibration amplification near the tracks over throat area. We recommend to carefully examining design of new over-track buildings within \(40\) m on the platform over the rails throat areas to avoid excessive vertical vibrations and noise.

7. Future work

The continuation of this research will include the following:

(1) Better understanding of the reasons for different corresponding frequencies of peak values for over-track buildings.

(2) Use impedance modeling for predicting train-induced building vibrations.

(3) Verification of a numerical model with measured data for predicting train-induced building vibration in a metro depot.

(4) Development of design guidelines for the prediction and mitigation of building vibrations.

Acknowledgements

The first author wishes to thank the support by China Scholarship Council and innovation fund of South China University of Technology leading to an excellent Ph.D. dissertation. The assistance of Hao Sun and Peng Wang at South China University of Technology and Emily Pitcairn at Tufts University is also acknowledged. This research was supported by Guangzhou Metro (GZMTR) projects (J11Z2090008). The measurements were made in China though the South China University of Technology and analysis was conducted in the US at Tufts University in collaborations with Acentech Incorporated.

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