Experimental study of train-induced vibration in over-track buildings in a metro depot

Ziyu Tao\textsuperscript{a}, Yimin Wang\textsuperscript{a}, Masoud Sanayei\textsuperscript{c}, James A. Moore\textsuperscript{d}, Chao Zou\textsuperscript{b}

\textsuperscript{a} School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, Guangdong 510641, China
\textsuperscript{b} School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, China
\textsuperscript{c} Department of Civil and Environmental Engineering, Tufts University, Medford, MA 02155, USA
\textsuperscript{d} Acoustic & Vibrations, Acentech Inc., Cambridge, MA 02138, USA

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ABSTRACT

Over-track buildings in Chinese metro depots have recently been designed to accommodate the rapid urbanization and massive construction of urban rail transit systems. However, train-induced vibration and noise impacts in over-track buildings need to be carefully assessed to provide comfortable working or living environments for the building's occupants. Vibration and noise measurements were carried out in a typical 28-story load-bearing wall supported residence and a 4-story steel-framed office building during train pass-by events in the Qianhai metro depot in Shenzhen, China. Measured points were set at ground level adjacent to the building support structures as well as on upper floors.

Train induced noise levels were within both FTA and Chinese limits. Floor vibration levels in the low-rise building were within FTA limit but not the more stringent Chinese limit. Ground-borne vibration signals in the throat area contained high level, short duration impacts generated as cars passed over discontinuities in rails at a switch. Ground vibration levels near the columns under the low-rise building were significantly greater than at the load bearing walls of the high-rise building by 20 dB or more. Levels within the buildings near columns or walls were only 5 dB higher in the low-rise building. The low-rise building transfer structure apparently significantly reduced transmission into the building above the platform. Vertically aligned load bearing walls in the high-rise building more effectively transmitted vibration. The measured vibration reduction from floor to floor was meaningfully less than recommendations in FTA guidelines.

This research enriches the database of train-induced vibration and noise in over-track buildings, provides insights into the vibration transmission process into and within over-track buildings and is of value for the design and construction for similar over-track buildings in future train depots.

1. Introduction

Increase of urbanization and development of urban rail transit are interdependent. Some inevitable issues arise with urbanization such as road traffic congestion, air pollution and land scarcity etc. However, urban rail transit, which encompasses metros, light rail, monorail, trams and maglev, is an effective solution to road traffic congestion and air pollution problems. Many cities in China have experienced rapid urbanization with population growth and economic development since the recent social reforms [33]. The urbanization level in China is expected to reach 66% by 2050 [29]. By the end of 2018, a total of 35 cities in mainland China have constructed urban rail transit systems and put them into service with a total length of 5766.6 km, containing 4511.3 km for metros [2]. Metro depot, which is used for subway train storage, cleaning, maintenance and performance test, is a basic ancillary facility of a metro system and usually covers a large land area [19]. With the massive construction and development of metro systems, traditional metro depots of lower building density but large land occupation aren’t an economical use of urban land. To relieve the issue of urban land scarcity and also offer financial support to the operation of metros, over-track buildings built above metro depots or stations are increasing. More than 27 cities in mainland China have built or have begun construction of over-track buildings recently.

Newer metro depot incorporates a large-scale reinforced concrete platform over the tracks that covers the full extent of the depot. The platform is supported from the ground by columns and load bearing...
walls that are located in-between tracks. The platform is segmented horizontally by construction joints to accommodate thermal expansion and to create modular seismic-resistant structures. Over-track buildings in metro depots normally form an entire community including residences, offices, schools, clinics, stores, restaurants, etc., and accommodate thousands of citizens.

However, along with the increased urbanization and growth of rail infrastructure [27], the distance between urban area and railway corridors is decreasing, which results in growing concerns about railway-induced vibrations [5]. Although the speed of the trains in the metro depots is low, the train-induced vibration can transmit from the tracks through the columns and walls into the platform and over-track buildings where it can impact the buildings’ occupants [36].

Train-induced vibration may cause discomfort and annoyance to people living or working in over-track buildings in terms of feelable vibration and noise [20,7]. It can also adversely affect the operation of vibration sensitive equipment such as those found in medical laboratories and hi-tech manufacturing. Additionally, side effects due to excessive vibration and noise exposure include the price depreciation of over-track real estate property. As a result, it is important to understand, predict and assess the impact of train-induced vibration on occupants of the over-track buildings to develop mitigation measures if needed.

Past studies have focused on the characterization, assessment and prediction of vibration in the nearby environment and buildings due to high-speed railway trains [11,8,14,4,32], high-speed Maglev [31,16], underground subway trains [17,18], and elevated railway trains [12,15], etc.

Prediction of train-induced vibration propagation through buildings, have included empirical formulae [28], numerical modeling [6] and theoretical analysis [35]. All of these prediction models need to be verified by field measured data. There are also a number of field measurements carried out on train-induced vibration [26,13,3]. Xia et al. [30] conducted an experimental study of train induced vibration on a low-rise masonry building near the Beijing-Guangzhou railway track. The dependence of vibration levels on train speed, type, and at different floor elevations and locations within the building were measured. Sanayei et al. [22,23] measured vibration levels induced by surface trains and underground subway trains respectively, both in open fields and on the foundation slabs inside nearby buildings, with the intent of quantifying the difference between ground vibration levels in an open field and in a building foundation at the same distance from the tracks. The measurement of ground vibration before construction of a building can then be adjusted to account for the effect of the foundation on vibration levels in the foundation after construction. Train-induced vibrations in a full-scale four-story building were also measured for comparison with predictions of a modeling procedure being developed.

Recent studies have measured the impact of vibration due to surface and subway trains on the surrounding environment and over-track buildings of metro depots. Xie et al. [34] evaluated vibration serviceability of an 11-story over-track building with frame structure built over the parking area through finite element modeling, finding the serviceability of the over-track building could not meet relative standard requirements and two vibration mitigation measures were proposed. Cao et al. [1] conducted field measurements in a 7-story over-track building with concrete frame structure, which was built over an elevated metro depot. The trains were running on the 2nd or 3rd floor of the elevated metro depot at speeds below 5 km/h. Guo et al. [9,10] proposed and verified numerical and theoretical models based on Cao’s research.

Our research team have also conducted comprehensive researches related with vibration and noise problems [25] of modern metro depot with over-track platform structure since 2015. According to functional partition of a metro depot, the throat area and test line are usually considered to be the most serious vibration and noise sources [37]. Zou et al. [36] measured train-induced vibration transmission in two over-track buildings of a metro depot, one of 14 floors and another of 25 floors, and suggested that vertical vibrations and noise impacts be carefully examined during the design of over-track buildings within 40 m on the platform above the throat area. An impedance model for efficiently predicting train-induced vibration in over-track buildings has been proposed and verified through data of field measurements [35].

Over-track buildings in metro depots typically have different structural configurations, including concrete and steel-columns, concrete load-bearing walls as well as transfer structures between the primary ground columns and those in the over-track building. Reliable in-situ measurements in over-track buildings with different construction during train pass-bys in the metro depot below are needed to assess the impact of the rapid development and massive construction of metro systems in China.

The primary objective of this research is to assess the impact of train-induced vibration and noise on occupants in over-track buildings at Qianhai metro depot in Shenzhen, China. A 4-story steel-framed building with a transfer structure and a 28-story load-bearing wall supported building were chosen for the measurements, which are compared with both US and Chinese standards for feelable vibration and noise. Insights into how vibration transmits from the ground into the different building constructions were also developed.

2. Description of Qianhai metro depot

Shenzhen has developed to one of the biggest modern cities in China with a population of about 12 million people and serves as the headquarters to many high-tech companies. Its subway system is currently extensive and growing. Plans are for the urban railway system in Shenzhen to grow to include 16 lines from the current 11 lines with a total length of 596.9 km (371 miles) by the year of 2020 [21].

Qianhai metro depot of Shenzhen Metro is where subway trains are parked, prepared, repaired, and tested with a total land use area of about 489,700 m², a total over-track building area of 350,000 m² and a total overall floorage of 1,410,000 m².

The over-track buildings in the Qianhai metro depot (Fig. 1) include more than 25 high-rise buildings of 18–35 floors in which people live and over 30 low-rise buildings of 4–6 floors where people work. It is estimated the community hosts more than 16,000 residents.

The elevation view of Qianhai metro depot with typical over-track buildings is shown in Fig. 2. The train tracks are on the ground level, the platform level (9 m above the ground) is a mixed-function zone with restaurants and stores where people can gather, socialize or shop and it also acts as the car garage level for over-track buildings, and the plaza level (16 m above the ground) is used as a green space for over-track buildings. The platform covers the whole metro depot with width of 387 m and length of 1521 m.

Fig. 3 shows the plan view of tracks within Qianhai metro depot. Throat area is a sector area with curve tracks and switches, linking the entrance/exit lines and the parking or maintenance area, where tracks split one into two and trains fan out into parking slips. Although trains pass through the throat area at relatively low speeds of between 10 and 20 km/h, the curved lines and switches can cause undesirable impacts resulting in higher vibration and noise in the over-track buildings. The test line is a straight track along the edge of the metro depot which is used for testing performance of trains where they are operated over a range of speeds from 20 to 80 km/h.

3. Description of over-track buildings

There are typically two types of supporting method of over-track buildings. The structures of buildings in the throat areas of metro depots are generally supported by irregularly spaced ground columns that are located between the densely spaced tracks. The ground columns that support the platform cannot be conveniently aligned with the
building columns that are arranged on a regular and rectangular grid. Thus, it is necessary to design transfer girders that span between the ground columns to support the building columns at locations along their spans. This is a key reason why only low-rise over-track buildings are built over throat areas on top of platforms with transfer girders, which would not be feasible to support a heavy high-rise over-track building. High-rise buildings, located in areas with less dense tracks, are supported by deep foundation and load bearing wall segments extending from the ground contiguously through the platform all the way up into the building.

In Qianhai metro depot, the low-rise over-track buildings are steel-framed structures with reinforced concrete floor slabs for office use. They are constructed just above the throat area and supported by concrete platform columns of circular cross section (diameter of 1.2-1.4 m) through transfer girders (Fig. 2a). Generally, under the ground a rectangular cushion cap and several piles of diameter of 1 m are connected with each concrete platform column base. A low-rise 4-story building (Building #36, Fig. 4) was chosen as a typical office building for carrying out measurements because it is located just over the switches and curve track segments which are typical of the throat area track.

The high-rise over-track buildings are reinforced concrete load-bearing walls supported structures for residential use. Among all the high-rise over-track buildings, a 28-story high-rise building (Building #20, Fig. 5) was selected as the typical residential building for the measurements because it is located between the throat area tracks and the intermediate section of the test line track with the highest train speed. The instrumented load-bearing walls include two cross-sections,
one with a rectangular cross-section (S wall) and the other with an L-shaped cross-section (L wall). The former is designated as Straight/S wall shown in Fig. 6a and the latter is designated as L-shape/L wall in Fig. 6b. Deep foundations are used under the load-bearing walls of the high-rise building.

4. Measurement program

The test train in this research is A-type metro train with 6 cars. Each car has a length of 22 m and a weight of 48,800 kg. The test line track is composed of 60 kg/m seamless rail, a concrete sleeper, with two-layer ballast and resilient non-separated rail fasteners. The throat area track consists of 50 kg/m seam rail, a wood sleeper, single-layer ballast and resilient separated rail fasteners.

4.1. Test plan

For the low-rise building, vibration measurement locations are given in Table 1, and include ground locations adjacent to the concrete platform columns, locations adjacent to steel columns within the buildings at different floors, locations on the open floors at different elevations and microphone locations for measuring noise levels in a room on the 2nd floor.

Measurements of vibration at track level adjacent to three concrete platform columns G1-G3 are shown in Fig. 7. These three columns are under or near the footprint of the test room of the low-rise building. Train induced vibration propagates across the ground into the bases of columns G1-G3, and up through the columns into the low-rise building through the transfer structure and building columns. A question in mounting accelerometers on the ground adjacent to building columns or walls is whether the measured vibration is the same as the axial vibration within the column/wall, or whether the ground motion is potentially partially coupled with the column/wall in some frequency ranges depending on soil properties and foundation type/dimensions. This issue is of interest to the authors for future investigation.

Measurement locations on the 2nd floor room of the low-rise building are shown in Fig. 7 and include floor vibration levels at different locations including on the balcony, adjacent to the room columns B1-B4, and four locations in the middle of the room floor. Vibration measurements were also made on the open floor, adjacent to room column B3 and staircase column S1 on different floors.

Several sets of measurements were made with the wireless units that contained two accelerometers, one measuring vibration in the vertical direction and the second one in horizontal direction (set perpendicular to the track). Vibration measurements on open flooring were made only in the vertical direction for bending deformation of the floor.

Unlike the low-rise building with the transfer structure the S wall and L wall segments between floors are aligned from ground at the
track level throughout the full height of the building. Measurement locations of the high-rise building are listed in Table 2 and shown in Fig. 8. Wireless units set near the wall base collect both vertical and horizontal vibration levels. An accelerometer was epoxied to the wall as shown in Fig. 8 in order to measure out-of-plane bending vibration in the wall. Vibration measurements were made only near the load-bearing walls outside the residences because the building was occupied and there was no access to measure floor vibration within the residences. A total of 13 train pass-bys on track 1 in the throat area and on the test line track were measured for the high-rise building. For pass-bys on the test line track with train speeds of 20 km/h and 60 km/h were measured.

4.2. Instrumentations and signal processing

The instrumentation used in testing is shown in Table 3. It consists of 941B ultra-low frequency accelerometers (Fig. 9a), microphones (Fig. 9b), 4-channel digital data recorders (Fig. 9c), wireless units with 2 built-in magnetoelectric accelerometers (one for vertical direction, a second for horizontal direction), and a JM3873 Data Acquisition System (Fig. 9d). Each wireless unit has a time synchronizer with accuracy of 1 ms and a gigabyte storage card. The wireless units also have an input connector for a third external accelerometer signal that is sampled at the same sampling rate as the other two accelerometers and which is also stored within the unit.

Prior to the field measurements, all wireless units were time-synchronized side-by-side using a laptop with the DAQ software through a wireless gateway. The wireless units were then left running to maintain the synchronization among units and mounted in place at their measurement locations. Potential concerns with interference/blockage issue were avoided during testing as the internally sampled/stored time signals were not transmitted during the measurements. The one gigabyte storage memory was sufficient to store the data at the 512 Hz sampling frequency for up to about 12 h. After completion of the measurements the time-synchronized data was downloaded from each wireless unit.

The sampling frequency was set to 512 Hz for each wireless unit which provides spectral information to the Nyquist frequency at 256 Hz. The dominant frequency range for train-induced floor vibration in the two buildings in this study was below 80 Hz. The Chinese code used in this research for train-induced vibration and secondary-radiated noise assessment stipulates a frequency range up to 200 Hz, thus the 512 Hz sampling rate chosen was adequate for these measurements.

For the 4-channel RION digital data recorders the sampling frequency was set to 12,800 Hz to provide spectra of the microphone noise signals in the 2nd floor room to 5 kHz. The low rise building in which the noise measurements were made was unfurnished, unoccupied, and very quiet. Above 80–100 Hz, ambient noise levels in between train pass-bys were comparable to the train-induced noise levels. Below 80–100 Hz the train-induced noise levels exceeded ambient levels by up to 10 dB for a particularly robust pass-by (see Section 5.4).

Digitized acceleration time signals were downloaded from both the wireless units and the Rion data recorder and read by a Matlab script to compute frequency spectra. The Matlab script computes average power spectra over the relatively steady period of the acceleration time signals during train pass-bys. Narrowband spectra in 1 Hz bands were computed and 1/3 band levels were synthesized from the narrowband spectra. All spectra are shown in 1/3 octave bands.

5. Measurements in a low-rise building supported by columns through a transfer structure

The next sections present and discuss results for the vibration measurements in the low-rise building. All vibration measurements in following sections refer to the vertical direction, unless otherwise stated.

Fig. 5. Elevation view of typical high-rise residential building.

Fig. 6. Typical load-bearing walls in the high-rise building.
5.1. Train-induced time signals and spectra

Among the 29 train pass-bys measured in the low-rise building, one, pass-by #4, had distinct, large amplitude, short duration spikes in the measured acceleration time history at ground column G1, as shown in Fig. 10. By comparison, measured time signals at ground column G3 and at the base of columns B3 and B4, and on the open floor in the 2nd floor room were of lesser amplitude with a more varied array of spikes.

As seen in Fig. 7 ground location G1 is near a switch on track 1, which is the track that pass-by #4 was on. It is suspected that the spikes are generated as each truck set passes through the switch. For a six-car train there are 12 trucks with 12 spikes at G1 as shown in Fig. 10a. However, individual spikes aren't as obvious in the measurements on the 2nd floor room were of lesser amplitude with a more varied array of spikes.

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5.2. Vibration levels for different pass-bys through the throat area in the low-rise building

The next four sections show comparisons of overall vibration levels and 1/3 octave band spectra for trains on different tracks. The overall
Table 3
Instrumentation.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Model</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vibration sensors</td>
<td>941B ultra-low frequency sensor</td>
<td>1. Select velocity or acceleration time signals for output</td>
</tr>
<tr>
<td></td>
<td>Wireless magnetoelectric accelerometer</td>
<td></td>
<td>1. Vertical and horizontal measurement directions</td>
</tr>
<tr>
<td>2</td>
<td>Data recorders</td>
<td>Rion DA-20, 4-channel digital data recorder</td>
<td>1. Capable of recording acoustic and vibration time signals</td>
</tr>
<tr>
<td></td>
<td>JM3873 Data Acquisition System (including the wireless unit)</td>
<td></td>
<td>2. Recorded signals saved in waveform format on CF cards</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Wireless unit and data acquisition system exchange information through wireless communication</td>
</tr>
<tr>
<td></td>
<td>Microphones</td>
<td>1. B&amp;K 4189 ½&quot; Type I mic cartridge</td>
<td>2. Vibration time signals are stored in the wireless units for subsequent download to the data acquisition system</td>
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<tr>
<td></td>
<td></td>
<td>2. PCB 426EO1 Preamp</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3. PCB 480EO9 signal conditioner, ICP power supply</td>
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</tbody>
</table>
levels are computed by summing the spectral energies in 1/3 octave bands.

5.2.1. Overall vibration level comparison of ground level measurements

There are three main throat area tracks (Tracks 1–3) under the low-rise building. Track 1 is adjacent to columns G1 and Track 2 is next to G3, both in-between G1 and G3. Track 3 is beyond column G3. Overall vibration levels adjacent to columns G1 and G3 indicate which track the train was running on for each pass-by. The overall vibration levels at ground locations adjacent to columns G1 and G3 for Tracks 1, 2, or 3 are shown in Fig. 13(a)–(c), respectively. The closer the measured location is to the track which the pass-by was on, the higher will be the overall vibration level. Overall vibration levels at both G1 and G3 are lower for pass-bys on Track 3 due to the greater separation between it and Tracks 1 and 2 as shown in Fig. 7.

5.2.2. Vertical vibration transmission along the height of the low-rise building

Figs. 14 and 15 show overall vibration level comparisons for pass-bys on different tracks and at different locations within the low-rise building. Of note is that differences in overall levels are not particularly great regardless of which track the pass-bys were on, including the

![Figure 9. Sensors and data acquisition system.](image)

![Figure 10. Vertical acceleration time signals during pass-by 4.](image)
more distant Track 3. Levels within the building, as opposed to on the ground, are due to contributions from all ground columns that support the platform and all transmit vibration into the transfer structure under the low-rise building. For instance, pass-bys on Track 3 would transmit higher vibration levels into ground columns near Track 3, which while not measured, would likely transmit equally well into the platform and transfer structure and the low-rise building as from columns near Tracks 1 or 2 for pass-bys on either of these tracks.

As seen in Fig. 14(a) and (b), overall vibration levels at staircase column S1 were higher than at room column B3 for elevations above the platform and plaza. It is likely that the heavier column/wall structures near the staircase and elevator transmit vibration across the plaza floor to and through the upper floors more effectively than occurred through the lighter building columns, such as B3. The transmission through column B3 to upper floors was more effectively attenuated by the intervening floors.

Overall vibration levels in open areas on the 2nd room floor, shown in Fig. 15, are generally higher than that at the 2nd floor building columns which transmit vibration to the floor. This is attributed to amplification due to resonances within the floor, which is discussed further on in the paper.

Fig. 16 shows vibration transmission along staircase column S1 and room column B3 of the low-rise building during pass-by 4. In the frequency range of 10–25 Hz, the acceleration levels in the building measured at different floors are comparable to levels at the ground columns. Above 25 Hz the acceleration levels in the building drop off rapidly compared to those at the ground. It is likely that this is related to the reduction in transmission through the transfer structure at the platform level to the floors above the platform.

FTA guidelines for floor to floor changes in vibration level are about 2 dB per floor for lower floors. As shown in Figs. 15 and 16, overall vibration levels of the low-rise building at columns and on the floor in the primary bands from 20 to 50 Hz drop off at a lesser rate than suggested by the FTA guidelines. As described in a subsequent section, this was also the case for the high-rise building showing an even smaller...
Fig. 14. Overall vibration levels of columns S1 and B3.

Fig. 15. Overall vibration levels at open floor locations.

Fig. 16. Column vibration levels during pass-by 4 at different floors in the low-rise building.

Fig. 17. Spectra of vertical vibration at G1 and G3 during pass-bys on different tracks.
5.2.3. Spectra of ground measurements at columns G1 & G3 for pass-bys on different tracks

Fig. 17 shows the differences of frequency spectra at different ground columns and tracks. Pass-bys 29, 27 and 15 were selected as being typical pass-bys on tracks 1, 2 and 3, respectively. The distances of G1 and G3 to the track center line are 4.2 m and 8.8 m, while for Track 2, the distances to G1 and G3 to the track center line are 9.2 m and 3.8 m, respectively. Vibration levels at G1 and G3 at frequencies below 40 Hz were comparable while above 40 Hz levels 8–21 dB discrepancies show up. It is inferred that along the direction perpendicular to the track line in a distance of 4–9 m, vertical vibration components above 40 Hz reduce significantly, while low-frequency vibrations barely reduce in this range.

5.2.4. Frequency spectra comparison between ground measurements at G1 and building measurements at B3

Fig. 18 compares frequency spectra between ground and building measurements. For pass-bys on each track, the spectra are close to each other with some variation due to differences in the trains, speeds, and direction of travel. It was also shown that track location is a more sensitive factor for vibration levels at ground in comparison to that within the building.

5.3. Transfer functions from column to floor of the test room on the 2nd floor

Fig. 19 shows transfer functions from average vibration levels at four room columns to average vibration levels at two open floor locations for individual pass-bys. The floor measurement locations were near the middle of the floor. Vibration levels for each pass-by at the two open floor locations were of comparable amplitudes, as was the case for the four columns (B1-B4). Peaks levels on the floor are significantly higher than at the columns. The amplification at the peaks is due to low order floor resonances whose mode shapes have high response amplitudes near the middle of the floor. The pronounced dips suggest that the locations in the middle of the floor may be at nodes or low modal response locations on the mode shapes of other resonances in the frequency region of the dips. A more representative transfer function including resonances that have high modal response at locations away from the middle of the floor may vary smoothly between the peaks shown.

![Fig. 18. Frequency spectra comparison of measurements at column G1 and B3 for different pass-bys.](image)

![Fig. 19. Column to floor transfer function on the 2nd floor of the low-rise building.](image)

![Fig. 20. Relationship between room noise level and floor velocity level in the 2nd floor room.](image)
5.4. Noise levels induced by floor vibration velocity

Fig. 20 shows the average noise level between two microphone locations in the 2nd floor room during the robust pass-by # 4 which had the greatest potential to excite noise levels relative to ambient levels. Vibration induced radiated noise is proportional to the average vibration velocity of the floor. The noise levels within a room depend on the vibration induced radiated sound power as well as the noise absorption within the room, for a given radiated sound power in a room with greater absorption, i.e., an acoustically deader space, the resulting noise levels would be less. The 2nd floor room during the measurements had bare concrete surfaces including the floor, walls, and ceiling, and no furnishings. The proportional relationship then involves what are, in general, frequency dependent factors related to vibration induced noise radiation and sound absorption within the room. The intent was to determine if there might be a noise issue relative to Chinese or FTA noise standards, where the measurements indicated that there was not a concern. Noise levels with the room when fully outfitted and occupied would likely be lower than what we measured.

6. Measurements in the high-rise building supported by load-bearing walls

The following three sections discuss results for the high-rise building. For measurements with the trains on the test line track there was little variation in time signals and spectra between different pass-bys. The trains were operated at steady speeds of 20 and 60 km/h in both directions, with no variation for travel in opposite directions. Overall levels at 20 km/h were about 10 dB less than at 60 km/h. Therefore, only the higher speed data are reported. Data was also recorded for all measurement locations during train pass-bys on Track 1 in the throat area.

6.1. Vertical vibration levels adjacent to the L and S walls

As seen from comparisons between levels in Fig. 21a and b, vertical vibration levels at the ground adjacent to the S and L walls were comparable. The distance from the Track 1 in the throat area and from the test line track to the base of the walls is 19.3 and 28.1 m respectively (Fig. 8). For train pass-bys on Track 1 in the throat area, the measured vibration levels peak at lower frequencies in the 31.5–50 Hz bands compared with peak levels on the test line in higher frequency bands above 63 Hz. The test line has seamless or welded rails without any switches, so there are no spikes related to impacts within switches.

6.2. Vertical vibration levels at different floors in the high-rise building

Fig. 22 shows vertical vibration levels adjacent to the L wall at different elevations in the high-rise building. Vibration levels at different floors extending to near the top on the 22nd floor of the high-rise building were comparable to levels at the ground up to 80–100 Hz, above which the levels in the building drop off compared to those at the ground. This is in contrast to the results for the low-rise building where building levels drop off from ground levels at 25 Hz and above. This is likely due to the transfer structure in the low-rise building where the S and L walls in the high-rise building are aligned continuously from the ground up.

As was observed for the high-rise building the floor to floor reduction in levels is significantly less than suggested by the FTA guidelines for overall vibration levels which indicate a 1 dB drop per floor above the 5th floor and on the order of 2 dB per floor at lower elevations. The FTA guidelines suggest a total decrease of nearly 30 dB at the 22nd floor which is considerably more than measured as seen in Fig. 22.

6.3. Power transmission comparison between longitudinal and bending waves

Fig. 23a shows measured vertical vibration adjacent to the wall on the floor and out-of-plane bending vibration on the wall. These are for different types of motion within the wall so a direct comparison isn’t meaningful. If the measured levels characterized the amplitudes of waves within the wall in one direction, a meaningful comparison would be between the power transmission for longitudinal and bending waves based on the measured vibration levels and the appropriate elastic parameters for each motion type. The actual vibration measurements involve waves propagating in both upward and downward directions for each type, with different amplitudes.

Shown in Fig. 23b, the power transmission by vertical (axial) vibration is much higher than that carried by out-of-plane bending vibration. This crudely suggests that axial wave transmission through supporting wall segments is the more important mode of transmission within the building.

7. Vibration transmission reduction due to the transfer girders/floor

Fig. 24 shows comparison of transfer functions from ground to platform of the low- and high-rise building induced by throat area pass-bys (Track 1 and Track 2) and test line pass-bys with speed of 60 km/h,
respectively. The low-rise building is supported by the transfer floor at the platform level, unlike the high-rise building that is supported directly at the ground level. For the low-rise building, vibration level at the ground is comparable to that at the platform level for frequencies below 31.5 Hz. However, vibration levels at frequencies above 40 Hz drop off significantly. For the high-rise building, vibration reduction from ground to the platform drops off for higher frequencies above 63 Hz. The transfer floor effectively reduces vibration levels at higher frequencies within the low-rise building above the platform relative to transmission in the high-rise building. This is due the fact that for the low-rise building (1) there is no direct contiguous vertical path from the ground columns into the building columns for axial wave transmission, and (2) the transmission reduction due to the conversion of axial waves in ground columns into bending waves in transfer floor and also the conversion to axial waves in building columns from bending in the transfer girders/floor.

8. Vibration and noise impact assessment

The US standard [7] and Chinese standard (JGJ/T 170-2009) are chosen to assess the impact of train-induced vibration and noise levels on human comfort of occupants in the low- and high-rise buildings. The US code uses an overall rms velocity level while the Chinese code uses frequency-weighted maximum acceleration level ($V_{L_{max}}$) in 1/3 octave bands. The US standard has different limits corresponding to different frequency of events per day. Based on the frequency of train operation events in Qianhai metro depot, the velocity level limit of 75 dB for
30–70 events per day is appropriate. The Chinese standard sets different day-time and night-time limits based on the different functions of the building. For vibration and noise sensitive buildings such as research institutes, hospitals, residential buildings, etc., the limit is more stringent. Considering that the over-track buildings are multi-functional, including office buildings, residential buildings and commercial buildings, etc., a day-time acceleration level limit of 70 dB for the low-rise office building and a night-time acceleration level limit of 67 dB for the high-rise residential building are chosen for assessment.

For residences both the US and Chinese standards use an A-weighted noise limit of 35 dBA.

8.1. Vibration and noise impact assessment for the low-rise building

A-weighted noise levels in the 2nd floor room during the high amplitude, pass-by 4 measured at Loc A and Loc B were 34.8 dB (A) and 34.0 dB (A), respectively and satisfy limits of both the US and Chinese standards. Less robust pass-by events would exhibit lower noise levels and the levels would also be somewhat lower if the room had been fully outfitted with carpets, acoustical ceiling tiles, and furniture.

Fig. 25 shows measured 1/3 octave band spectra of floor and column vibration velocity levels for comparison with the FTA limit of 75 dB overall for occasional pass-by and vibration acceleration levels for comparison with the day-time Chinese limit of 70 dB, both during the most unfavorable pass-by 4 with high amplitude. Although the overall floor velocity levels are within the limit of the FTA limit, the floor acceleration levels exceed the Chinese limit by around 10 dB. The lower column levels without amplification due to floor resonance are comfortably below both limits.

The standard deviation of overall open floor vibration levels within the low-rise building for all measured 11 pass-bys was about 2.91 dB. Fig. 26 shows the average floor acceleration level along with levels at ± two standard deviations about the average level in 1/3 octave bands. Two standard deviations about the average statistically includes about 95% of pass-bys which has a maximum acceleration level of 67–78 dB. It is seen from Fig. 26 that the average open floor acceleration level is about 2 dB higher than the limit.

8.2. Vibration impact assessment for the high-rise building

Vertical floor vibration levels at measured locations adjacent to walls in the high-rise building were well below the Chinese limit, by at least 12 dB or more (Fig. 27). Without any measurements on the flooring within the residences of the high-rise building it is not possible to estimate whether the FTA or Chinese limits are exceeded at open floor locations. It would not be appropriate to apply the transfer function from column vibration to open floor vibration for the low-rise building because there are significant differences in the building support structures between the two buildings, i.e. load bearing concrete walls in the high-rise building and steel columns in the low-rise buildings, and with different spacings.

9. Conclusions

This paper presents train-induced vibration and noise levels in over-track buildings at Qianhai metro depot in Shenzhen, China. The measured levels were compared with Chinese and US FTA standards for potential impact on the buildings’ occupants in terms of annoyance in terms of feelable vertical floor vibration and radiated noise. Response to wind and earthquake excitation occurs at considerably lower frequencies than are of concern for train induced vibration. Useful insights have been developed in understanding vibration transmission into and within low-rise over-track buildings with steel-frame columns and high-rise buildings with concrete load-bearing walls. The findings presented provide useful vibration level estimates prior to construction in designing similar buildings in metro depots in the future.

(1) For the Qianhai metro depot in Shenzhen recorded noise levels
were within both FTA and Chinese limits. In the low-rise building floor vibration levels were within the FTA limit but exceeded the more stringent limit in the Chinese code.

(2) For the low-rise buildings in the throat area recorded impacts caused by switches in the tracks significantly contributed to the generation of ground-borne vibration that transmits into the buildings. It is speculated that higher impacts are generated as wheels pass onto the transition rail of the switch when it is positioned so that the train changes direction through the switch.

(3) Vibration levels at the ground columns that support the low-rise building due to train pass-bys in the throat area are significantly greater, by more than 20 dB, than levels at the ground adjacent to load bearing wall support structures of the high-rise building for trains on the test line at high speed (60 km/h). However, levels adjacent to the building columns within the low-rise building are only somewhat greater by about 5 dB than at floors within the high-rise building.

(4) While vibration levels at a ground column in the throat area can vary considerably by more than 10 dB depending on its proximity to the track with the pass-by, levels within the low-rise building above the transfer structure do not vary much for pass-bys on different tracks. Transmission into the building includes contributions from several ground columns that are equally effective in transmitting vibration into the building. The tracks in the throat area are all near a ground column(s) that contribute to transmission into the building.

(5) The transfer structure is apparently responsible for significantly reducing vibration levels within the low-rise building above the platform. The building columns are supported by the transfer girders and are not aligned with the ground columns that support the platform from the ground. Conversely, in the high-rise building the load bearing walls are vertically aligned throughout the full height from the ground to the roof resulting in higher vibration transmission.

(6) Vibration attenuation in vibration levels from floor to floor within both buildings are less than FTA guidelines. As a result, the FTA guidelines significantly overpredict the vibration transmission loss from the platform to the top of each building compared to the measured change in each level.

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Appendix A. Supplementary material

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