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# Train-Induced Indoor Secondary Vibration Study and Control Over-Track Buildings in a Subway Transfer Station

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## Abstract

Using Transit-oriented development over-track buildings have been rapidly expanding on Chinese subways due to its convenience, however the excessive indoor vibration and noise within over-track buildings has been a cause of concern for some time. A prediction method considering soil-pile-structure dynamic interaction based on the three-step approach is proposed to study train-induced vibration of over-track buildings. A case study is carried out of over-track buildings on a subway transfer station in Chengdu, China. The simulation results indicate that, the highest indoor vibration of a superstructure is 84.0dB without vibration reduction measures, which seriously exceeded the criterion limit; train-induced vertical and longitudinal building foundation vibrations are quite large and relatively the same; lateral vibration is at a minimum. Six combined comprehensive vibration reduction measures are analyzed by numerical simulation; field measurements show that ground and local building vibration in a Line 3 transfer station are not exceeded.

**Keywords:** subway transfer station, over-track buildings, vibration prediction, propagation law, controlling methods, field experiment.

## 1 Introduction

Transit-oriented development (TOD) over-track buildings have been rapidly expanding on Chinese subways, which can make full use of both the above ground space in addition to the underground space, further increasing land utilization. However, the vibration and noise caused by the operation of urban railways has become an unavoidable problem, thus posing enormous challenges to the realization of green rail transit [1].

To deepen the understanding of the factors affecting the train-induced vibration, several environmental vibration prediction models have been proposed in the previous studies [2-4]. However, they were mainly aimed at near field ground vibration induced by the operation of rail transit, in addition to the response to the transmission and decay of vibration on far field buildings [5-6]. However, secondary vibration propagation law of over-track buildings on the subway is different from that of normal buildings around rail transit [7]. A monolithic track bed is usually utilized in between stations, with most of its vibration energy being transmitted to over-track buildings directly along the track bed, column and others without decaying through the soil; thus, causing the vibration of structures and other components. The impact of vibration on buildings is remarkably obvious. Furthermore, subway over-track buildings have a short history, insufficient engineering implementation and a severe lack of relevant research, in addition to differing greatly on a case-by-case basis [8].

This study developed a numerical model that can effectively predict train-induced indoor secondary vibration of over-track buildings in a subway station while exploring a practical controlling method. Chengdu over-track buildings on the subway transfer station will then be studied, combining comprehensive vibration reduction measures from the top-down in route of the vibration transmission. And the results show the method of vibration reduction design can in theory provide a consultative basis for practical engineering.

## 2 Methods

### 2.1 General architecture of the wheel wear prediction model

Vibration generation, vibration propagation, and vibration reception are three key contents in a numerical prediction model on environmental vibration.

In this study, the numerical prediction model that can effectively predict train-induced indoor secondary vibration of over-track buildings in a subway station while exploring a practical controlling method is developed. This objective is achieved by firstly establishing the numerical prediction model based on a three-step approach, the vehicle-track-tunnel rigid-flexible coupling subsystem (“vibration generation”) , the track-tunnel-soil three-dimensional finite element (3D FEM) subsystem (“vibration propagation”) and the transfer station and over-track buildings 3D FEM subsystem (“vibration reception”) respectively. The first two steps are coupled through wheel-rail force to predict the vibration source and the vibration induced by trains. The second and third steps are coupled through the acceleration at column base of station to predict vibration propagation, as well as the buildings’ vibration response. A schematic representation of the numerical simulation procedure is shown in Fig.1.

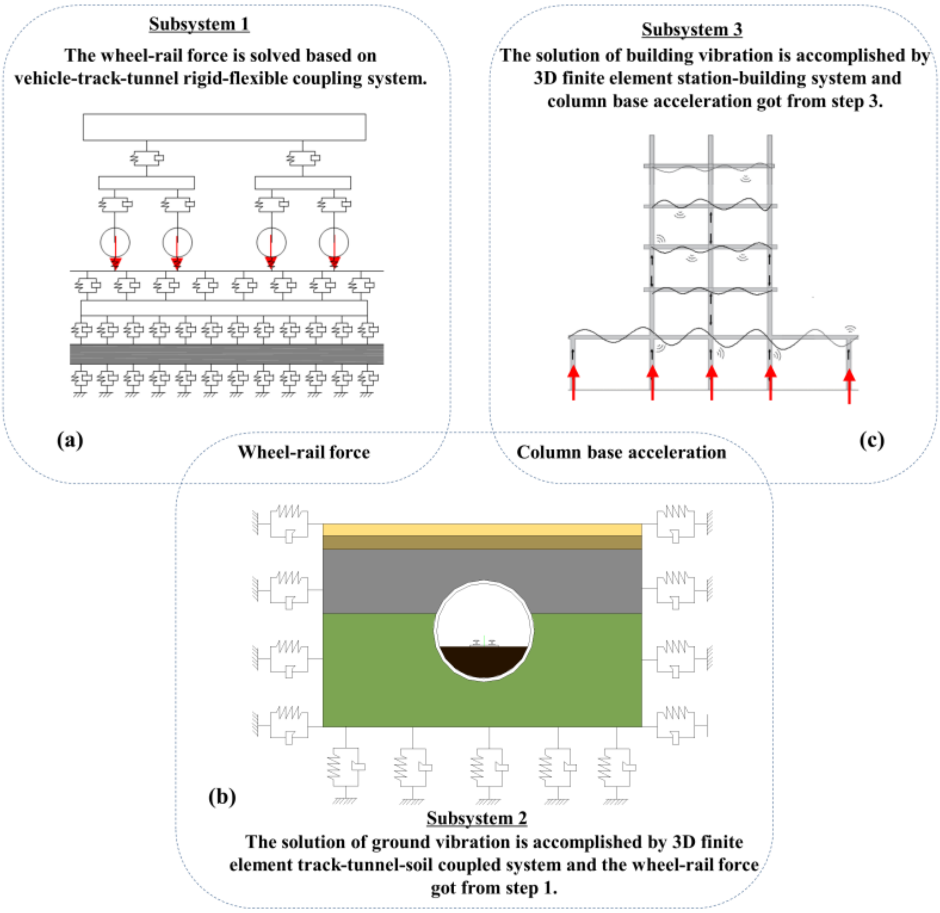


Figure 1: Schematic representation of numerical simulation procedure. (a) subsystem 1 for "vibration generation", (b) subsystem 2 for "vibration propagation" and (c) subsystem 3 for "vibration reception".

Based on multi-body system dynamics and the finite element method, the vehicle-track-tunnel coupling system is established. The vehicle system is simplified into a rigid multi-body with 42 degrees of mobility, a car body, two bogie frames and four wheelsets, totaling seven space rigid body parts. The fixed track will be studied and the flexible track-tunnel model established, taking rail flexibility, fastener elasticity, deformation of the track slab and tunnel and elastic supports into consideration. The rail standard used is the Timoshenko beam model, with an interval of 0.6m; track slab and tunnel are solid element; fasteners are linear spring-damper element; the elastic soil support is simplified as uniformly distributed viscoelastic element with a support stiffness of 60MPa/m.

Track-tunnel-soil 3D finite element subsystem is established, which includes rail, fasteners, track slabs, tunnel and soil. The model extends 80m along the line vertically, the width perpendicular to the central line of the line is 100 m, the depth of soil layer is 60 m, the beam element grid of the rail is 0.1m and the solid element grid of track slab and tunnel is 0.5m. The soil's solid element is divided into three regions, with the grid size of the middle region being 0.5m, being perpendicular to two sides along the 0.8m line and a bottom region of 1.0m. The finite element model has a total of 1260560 elements and 1341516 nodes.

In the station-building 3D FEM subsystem, the geometrical dimensions of the beams, columns, doors, windows and other components, as well as the spatial arrangement of structures, are established depending on situation. The beam, structural column and pile foundation of the structures, such as the metro stations and the over-track buildings, are made of three-dimensional elastic beam, unit beam 4, which can withstand tension, compression, bending and torsion. The unit will not consider the influence of shear deformation. It is assumed that the normal of the center line maintains the straight normal line perpendicular to the mid-surface after deformation, thus better facilitating stress hardening and large deformation calculation. The walls, floors and raft foundation of the structure are a four-node elastic shell unit, shell63. Each node has 6 degrees of mobility in this unit. Considering the stress stiffening and large amount deformability, each node has the function of analyzing the bending of the shell and the mechanical behavior of the thin film and is suitable for analysis of shell structures of medium thickness. In addition, metro stations and over-track buildings are all part of the structures of buildings.

### 2.2 Case study


Figure 2: Schematic representation of the over-track buildings and transfer station.

"Station" refers to the transfer station of Metro Line 3 and Line 5. The station of Line 3 is a 12m island platform at the second floor basement which is roughly arranged in the east-west direction. Located in the block of over-track buildings, the station of Line 5 is a 13m island platform at the third-floor basement with the main body arranged in a north-south direction. The relative position of the station and the building is shown in Fig.2. The plan is to construct buildings above the transfer subway station. The over-track buildings include Building No.1 (20th floor, 74.8m high, frame structure), Building No.2 (5th floor, 24.0m high, frame-shear structure) and Building No.3 (5th floor, 23.8m high, frame-shear structure). Specifically, Building No.2 is more than 40m away from the station of Line 5, while Building No.1 and Building No.3 are surrounded by the stations of Line 3 and Line 5. The floor of Building No.1 is relatively high and is greatly affected by environmental vibration. Building No.3 is the closest to the two metro stations, and part of it is directly above the stations. In light of this, this paper takes Building No.1 and Building No.3 as the object of study to predict vibration and constructs a 3D finite element model for transfer station and over-track buildings to conduct numerical analysis.

# 3 Results

Based on the prediction model in this paper, the vibration response of the building foundation in three directions is calculated respectively when the trains for Metro Line 3 and Line 5 separately enter the station at a constant speed (specifically, the vertical direction means perpendicular; the longitudinal direction is along the direction of the line; the horizontal direction refers to in the plane of the section of track, perpendicular to the direction of the line). Because Building No.3 is closest to the two metro stations and is constructed directly above the station, the column bases of the first row of columns adjacent to Building No.3 are selected to calculate the vibration response of the building foundation. The induced vibration response of the building foundation when the train of Line 3 and Line 5 enters the station given in Figs.3~4, respectively. Based on the response of building foundation, we have selected the middle point of the floorboard of the larger room on each floor of the building, and calculated the floorboard vibration response of each floor of Building No.1 and Building No.3 in Figs.5~6.

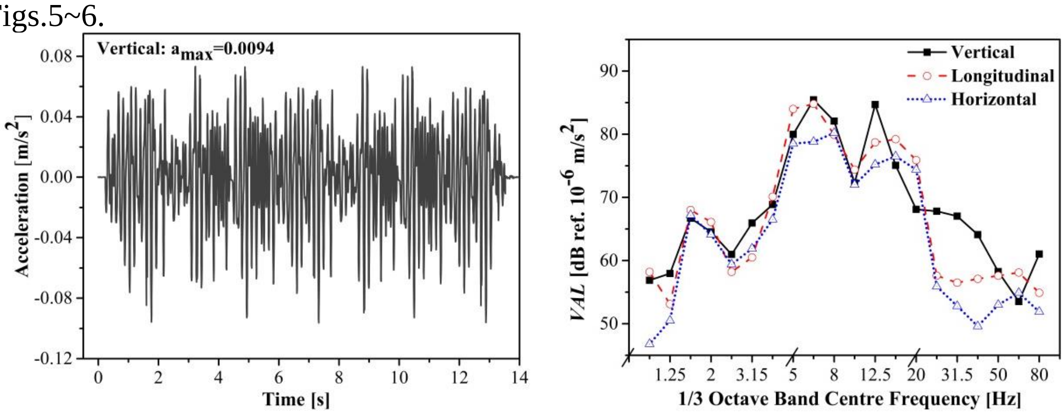


Figure 3: Building No.3 response when Line 3 train enters station in (a) time domain and (b) frequency domain.

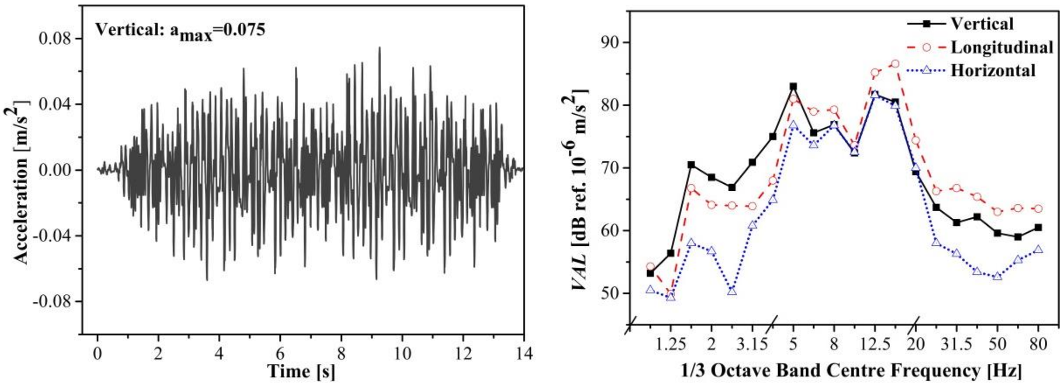


Figure 4: Building No.3 response when Line 5 train enters station in (a) time domain and (b) frequency domain.

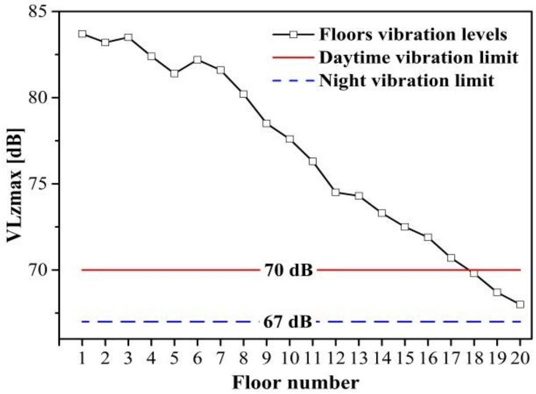


Figure 5: Maximum Z-weighted vibration level of each floor of Building No.1.

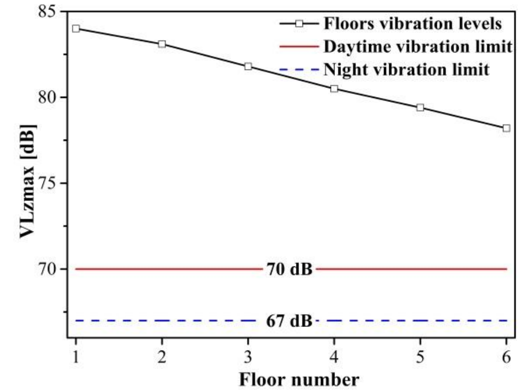


Figure 6: Maximum Z-weighted vibration level of each floor of Building No.3.

Based on the numerical model for the vibration prediction of over-track buildings above the metro station, we have compared and analyzed a number of control methods. With reference to the actual situation of the subway line, we have set up a total of six types of vibration mitigation conditions, as shown in Tab.1. Specifically, the static stiffness of the vanguard fastener is 4.2kN/mm. Isolation trenches of different widths are filled by coarse sand and arranged around the cushion caps under the columns of stations, with a thickness of 400mm, a density of 1979kg/m$^3$, an elastic modulus of

202.2MPa, the Poisson's ratio of 0.38, and the damping ratio of 0.034. The calculation parameters of the ladder-type track and the steel spring floating slab track are shown in Ref. [9].

Table 1: Design of vibration reduction.

| Metro | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|---|
| Line 3 | Vanguard fasteners + Isolation trench 60mm wide | Vanguard fasteners + Isolation trench 80mm wide | Vanguard fasteners + Isolation trench 100mm wide | Vanguard fasteners + Isolation trench 100mm wide | Isolation trench 350mm wide | Isolation trench 700mm wide |
| Line 5 | Ladder track | Ladder track | Ladder track | Steel-spring | Ladder track | Ladder track |

Fig.7 illustrates the vibration response of each floor of the over-track buildings under different vibration mitigation conditions. Case 4 and Case 6 are applied to Line 3 and Line 5 to mitigate vibration. In other words, the vibration-damping fasteners of Line 3 are replaced with the less rigid Vanguard fasteners; a 100mm wide Isolation trench is installed between Line 3 and over-track buildings; Steel spring floating slabs are adopted for Metro Line 5. Alternatively, a 700mm wide Isolation trench is set between Line 3 and the over-track buildings, and Steel spring floating slabs are used for Line 5. This way, the indoor secondary vibration of the buildings is well-controlled.

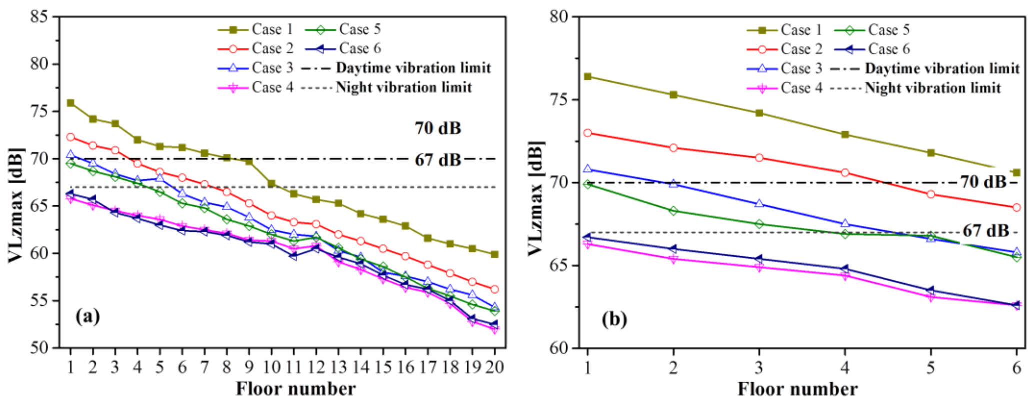


Figure 7: Vibration response of each floor in different vibration reduction cases of (a) Building No.1 and (b) Building No.3.

## 4 Conclusions and Contributions

A numerical prediction model for the train-induced indoor secondary vibration level of over-track buildings in a subway transfer station based on the three-step approach is developed. Based on this, different vibration reduction measures are assembled and analyzed. The numerical prediction method is an effective tool for over-track buildings before and during construction. Results of a case study show that ground vibration is mainly at the low frequency of between 4Hz and 20Hz, the indoor vibration of the buildings will gradually weaken with the increase in floor number. Designing top-down vibration mitigation measures in the route of the vibration transmission is a better way to adopt practical controlling methods, which could provide a certain reference and guidance for practical engineering. In the future, we will continue to deepen the study of train-induced vibrations and noises, verify the accuracy of numerical method by more field measured data.

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