Study on the influence of vibration induced by subway train on huge ground structures

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Abstract: The huge structure (huge platform with storied buildings on it) of Bawangfen vehicle depot of Beijing subway and its soil-foundation system are studied in this article. Based on interpretation of relevant geotechnical data, a 2D numerical model is built with FLAC. With the input of a vibration acceleration history of subway train, a full dynamic analysis of soil-pile-structure is carried out. The vibration responses of the huge platform and storied buildings are analyzed. The conclusions can provide references for vibration evaluation and control of huge ground structures around the subway line such as vehicle depots of subway system.

Résumé: La structure énorme (la plateforme énorme avec storied des bâtiments là-dessus) du dépôt de véhicule de Bawangfen du souterrain de Pékin et son système de sol-base sont étudiés en cet article. Basé sur l'interprétation des données géotechniques appropriées, un 2D modèle numérique est établi avec FLAC. Avec l'entrée d'une histoire d'accélération de vibration de métro, une analyse dynamique complète de sol-pile-structure est effectuée. Les réponses de vibration de la plateforme énorme et storied des bâtiments sont analysées. Les conclusions peuvent fournir des références pour l'évaluation de vibration et la commande des structures au sol énormes autour de la ligne de souterrain telle que des dépôts de véhicule de système de souterrain.

Key words: subway, vibration, modeling, evaluation

INTRODUCTION

Subway transporting system, one of main city traffic methods, has many obvious advantages. In resent years, subway transportation systems have been developed rapidly in China. However, with the development of subway construction, some negative effects appear at the same time. One of the serious problems is the impact of vibration induced by subway train to environment. The buried depth of subway tunnel is generally shallow, and the vibration caused by the running subway train will be transmitted to the lining through the track structure, and then to the ground through the rock/soil mass outside the lining structure, causing the ground to vibrate. The vibration is more intense in some areas where subway train is running on the ground. This kind of vibration will influence earthbound building as well as ground environment. Owing to that subway circuit in a city generally passes through downtown area, the vibration effects of the subway to the buildings and circumstance around can not be neglected.

Vehicle depots of subway system are always built on ground with platforms which are huge multi-story structure commonly. Some of them are developed as residential area or for commercial purpose, such as Kowloon Bay vehicle depot of Hong Kong subway, Bawangfen vehicle depot of Beijing subway and etc. Thus the influence of vibration induced by subway train on the huge structures and the buildings on them can not be ignored. The huge structure (huge platform with storied buildings on it) of Bawangfen vehicle depot of Beijing subway and its soil-foundation system are studied in this article with numerical simulation, and responses of the huge platform and storied buildings on it under action of subway train running on ground are gained and studied.

GENERAL SITUATION OF ENGINEERING

The engineering of Bawangfen vehicle depot is a crucial component of Fuxingmen-Bawangfen subway line of Beijing. The engineering is composed of huge platform of vehicle depot and storied buildings on it. The length of the huge platform (east-west) is 1290m, the width of it (south-north) is 226m, and the height (top of the platform to ground) is 11.6m. The subway line and repairing warehouse are under the huge platform whereas residential area Tonghuijiayuan, which is one of the first economical housing projects, is on the top of it, with 600,000m2 exploitation area and 4,800 tenements. The general situation of the engineering is shown in figure 1.

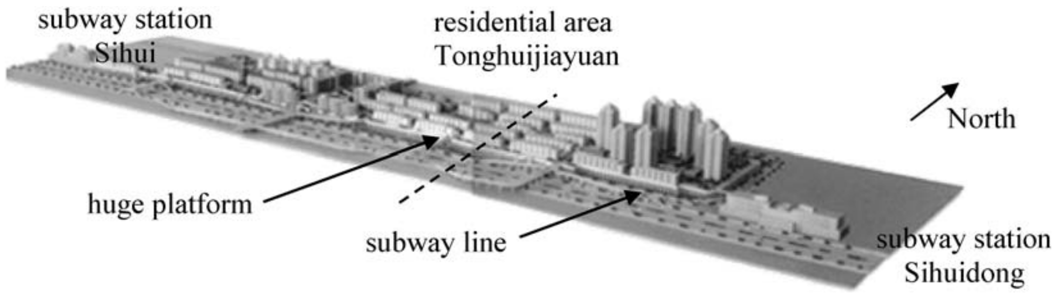


Figure 1. Bawangfen Vehicle Depot & Tonghuijiayuan

The foundation of the huge platform of Bawangfen vehicle depot is independent pillar-pile system with big-diameter (1000mm or 800mm) bored piles, one supporter for one pillar. Component of the whole structure above ground is frame structure including a two-storied platform with 7.5m height of first story (low) which is used as subway vehicle depot and 4.1m height of second story (high) where the residential area is built on. The subway line in this site is running on the ground through the south side under the huge platform.

The studied area has a flat topography. The stratums disclosed by reconnaissance include (from up to down):

artificial soils:

① 1 miscellaneous fill
② clayey silt

quaternary period alluviums:

② 1 silty clay
② clayey/sandy silt
③ 1 silty clay
③ 2 heavy silty clay
③ clayey/sandy silt
④ fine sand

Among the stratums above, layer ①, ②, ③ and ④ exist in whole engineering field whereas layer ①1,②1, ③1 and ③2 distribute as lens and exist in limited places.

As a whole, the geological condition of studied area is fairly good, where no undesired geological phenomena and special soil geological phenomena exist. Moreover, under water has little impact to the engineering since subway train is running on the ground.

NUMERICAL SIMULATION

Numerical simulation of influence of vibration induced by subway train on huge ground structures is performed with FLAC in this article. FLAC dynamic module (Dynamic Optional) can be applied to analyze the full dynamic activity of two dimension plane strain or axial symmetry case, and in the program the system kinetic equation is solved with explicit finite difference method. The equation can be solved coupled with structure element so as to solve problem of soil-structure dynamic interaction. The dynamic module is an add-in option of FLAC, and can be used in fields such as earthquake engineering, vibration and blasting engineering.

Since numerical method always uses a finite region to simulate an infinite or half-infinite one, how to deal with the boundary condition becomes to the crux of calculation. In static analysis, this problem can be solved approvingly by set displacement boundary to a certain distance away from the position interested. But in dynamic analysis, such boundary condition will make the wave propagating to boundary reflect from boundary to model inversely (Kyum Kim Moon, et al., 2000, pp.670-680), which is not identical to the reality that vibration wave always propagates beyond. This will make the calculation result uncertain. Building a sizeable model is one viable way to solve this problem, which can make vibration be exhausted after a long way propagating and before reaching boundary. However, this will result in a sharp extend of calculation scale. Fortunately, this matter can be settled skillfully by "quiet boundary" technique adopted in dynamic calculation of FLAC, which can absorb the vibration propagating to the boundary.

Calculation Model

Strictly speaking, the analysis of influence of vibration induced by subway train is a three dimensional issue. But the calculation time on a PC for a three dimensional issue will cost a quite long time. In view of the calculation time, the structure of vehicle depot has such a long length along subway line, and the dynamic load subway train acting on track also has such a long length along subway line, the three dimensional issue can be simplified to a two dimensional one. Thus, the calculation time can be cut down greatly. At the same time, the precision of calculation result can be satisfied. (Wang Jiexian, 2001. p.236; Pan Changshi, et al., 1995. pp.63-124)

The location of cross section for a two dimensional calculation is show in figure 1 marked by dashed line. The cross section is shown in figure 2.

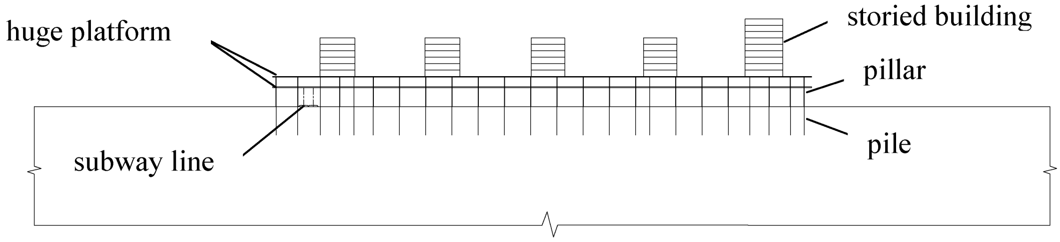


Figure 2. Cross Section for Computing

Calculation Parameters

Stratums parameters

In terms with the real condition of stratums, the stratums (from ground surface to underground) involved in calculation are:

clayey silt, thickness: 1.5m;
clayey/sandy silt, thickness: 5.0m;
silty clay, thickness: 2.0m;
clayey/sandy silt, thickness: 1.5m;
fine sand, extend to the bottom of the model.
The physical and mechanical parameters are shown in table 1.

Table 1. Physical & Mechanical Parameters of Each Stratum

No.	Stratum	Thickness (m)	Es (×106Pa)	ρ (Kg/m3)	μ	c (×103Pa)	φ
1	clayey silt	1.5	6.1	1890	0.46	16	17°
2	clayey/sandy silt	5.0	12.8	2010	0.40	21	34°
3	silty clay	2.0	8.7	1960	0.46	20.5	16°
4	clayey/sandy silt	1.5	11.1	2020	0.40	24	29°
5	fine sand	--	25	2050	0.40	5	35°

Concrete parameters

All concrete structures are made of concrete C30. Its physical and mechanical parameters are:

E = 3×104 MPa

μ = 0.2

ρ = 2400 Kg/m3

The Mohr-Coulomb model is adopted as construct model of stratum soils and elastic model for concrete structure including piles, huge platform and storied buildings.

Calculation Project

By performing whole process numerical simulation according to the procedure of forming gravity field-constructing-working, not only the vibration results of the model in phase of subway working, but the change of stress and strain in phase of constructing can be gained, which is one of the merits of whole process numerical simulation.

Based on principle mentioned above, the calculation project can be devised as follow:

- The first stage
  In this stage, a model containing stratums only is built and load is gravity only. The initial gravity stress field can be formed in whole model when equilibrium is reached, which is the base of the next stage.
- The second stage
  In this stage, the piles and ground structures (huge platform and storied building on it) are added in the model. When the calculation cycle is finished, the stress and strain field in the model is got.

The first stage and the second stage are both static calculation with displacement boundary condition.

- The third stage
  In this stage, an acceleration history is exerted at the location of track to simulate the vibration induced by

subway train, and a dynamic analysis is performed. Then, the influence of vibration induced by subway train on ground structures is obtained.

In order to eliminate the boundary effect of dynamic calculation, the boundary condition in this stage is substituted for quiet boundary.

The dynamic load adopted in calculation is shown in figure 3, which is taken as the dynamic force at rails.

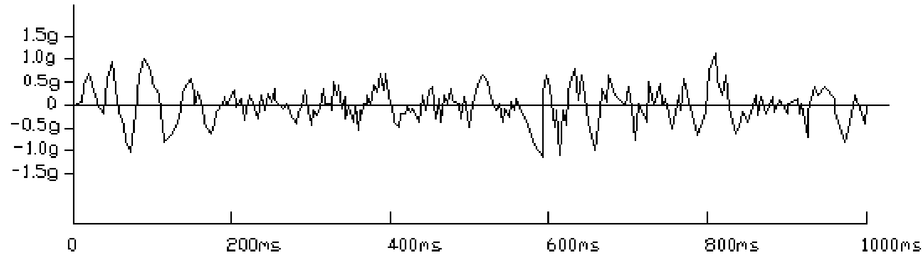


Figure 3 . Acceleration History of Vibration Induced by Subway Train

For subway line has two lines and in most disadvantageous instance that there are two trains running on both lines, the dynamic load is added at four rails of both lines. The position of the dynamic load is shown in figure 4.

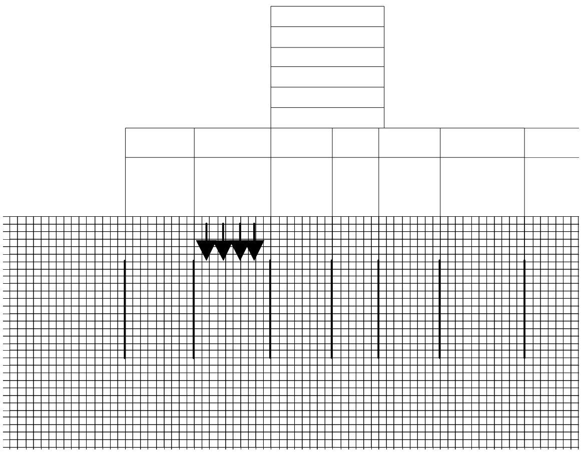


Figure 4 . Imported Location of Dynamic Load

The calculation time is 5 seconds, thus both the responses of ground structures in the time when dynamic load acts on (the first one second) and the responses in the time when the action disappears can be obtained.

In order to seeing about the vibrations of the two ends of the huge platform, four reference points are set in calculation: PS1 (south end and the first story of the huge platform), PS2 (south end and the second story of the huge platform), PN1 (north end and the first story of the huge platform) and PN2 (north end and the second story of the huge platform). Similarly, for observing the vibrations of storied buildings on the huge platform, there are 48 reference points are set in calculation: AS0~AS6 (girder-pillar nodes at south side of building A), AN0~AN6 (girder-pillar nodes at north side of building A), CS0~CS6 (girder-pillar nodes at south side of building C), CN0~CN6 (girder-pillar nodes at north side of building C), ES0~ES9 (girder-pillar nodes at south side of building E) and EN0~EN9 (girder-pillar nodes at north side of building E). The locations of reference points are shown in figure 5.

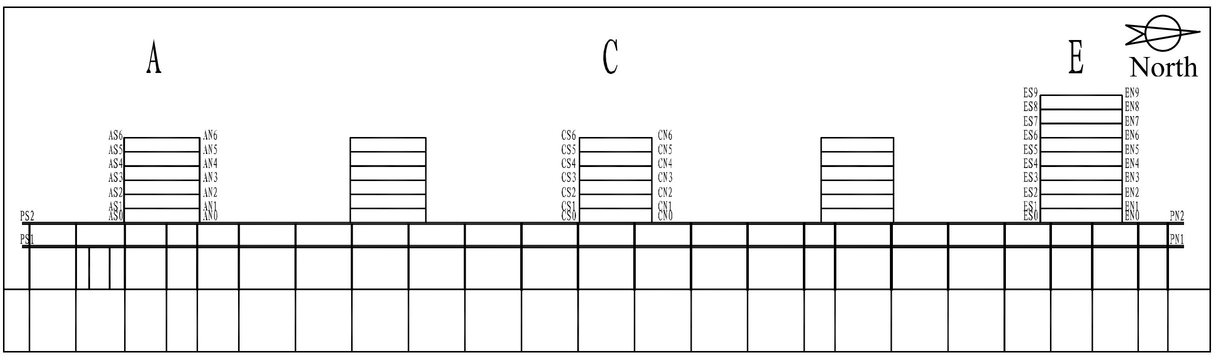


Figure 5. Locations of Reference Points at Storied Buildings

In order to compare vibration intensities of structures, the compared object should be appointed in advance. In respect that virtual value of acceleration indicates the intensity of vibration directly (Sun Jiaqi, 2002. p. 2), virtual value of acceleration is used as compared object. Virtual value of acceleration is defined as:

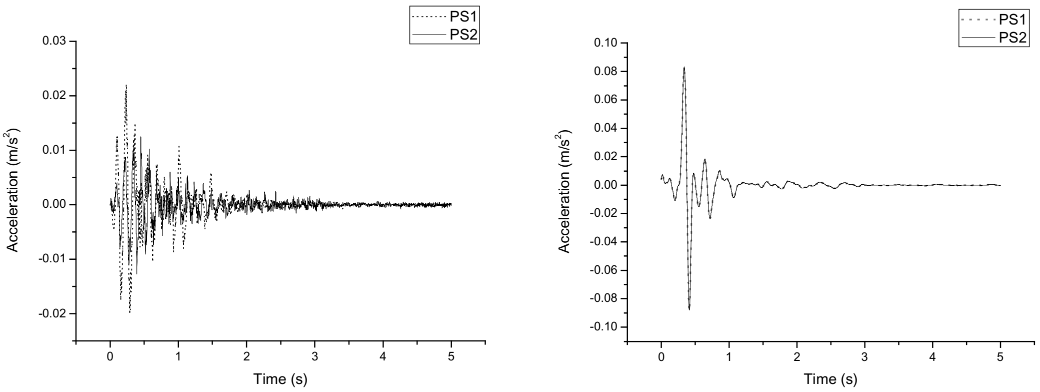
$$a_{rms} = \sqrt{a^2(t)} = \sqrt{\frac{\int_0^T a^2(t)\mathrm{d}t}{T}}$$

arms —— virtual value of acceleration
a(t) —— acceleration history
T —— duration of acceleration history

RESULT ANALYSIS

Analysis of Result of the Huge Platform

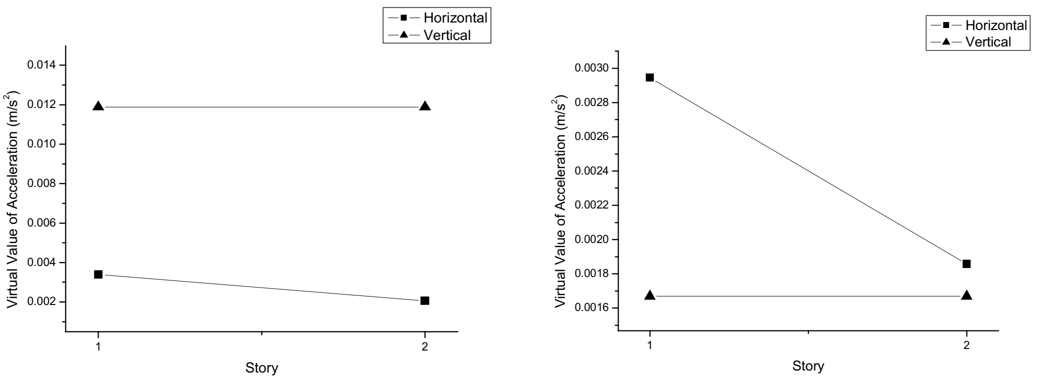
After 5 second calculation, the velocity history and acceleration history can be obtained. The horizontal acceleration and vertical acceleration are shown in figure 6.



a) horizontal b) vertical

Figure 6. Horizontal and Vertical Accelerations at Point PS1 and PS2

Comparisons of horizontal acceleration and vertical acceleration at reference points of the huge platform are shown in figure 7.



a) PS1, 2 b) PN1, 2

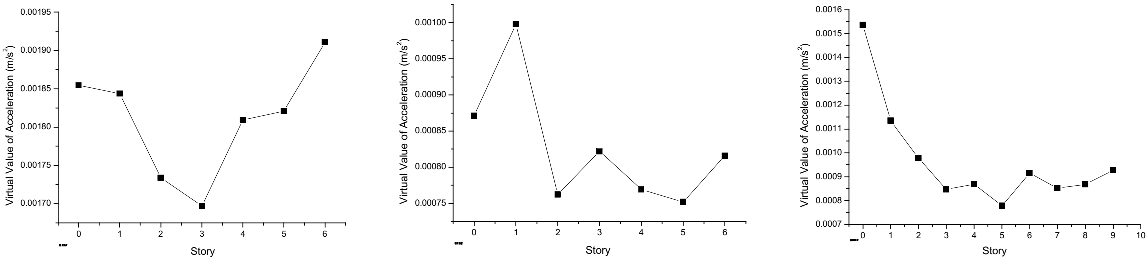
Figure 7. Horizontal and Vertical Virtual Values of Accelerations at Point PS1, PS2, PN1 and PN2

It can be descried in figure 6 that horizontal acceleration and vertical acceleration at point PS1 and PS2 decrease with time, which reflects the attenuation of vibration with time. At the same time, acceleration of end points of the first story of the huge platform is greater than that of the second story. The same result can be seen in a) and b) in figure 7.

It is indicated in figure 6 b) that the acceleration of end points of the first story is identical with that of the second story in vertical direction. The same result can be seen from the two horizontal lines in a) and b) of figure 7. The reason for the result is that the stiffness of the pillars connecting the first story and the second story of the huge platform is huge in vertical direction, which makes that the axial (vertical) deformations of the pillars induced by subway train are very little, thus, the vibrations at PS1 and that at PS2 are nominal identical. However, in horizontal direction, those pillars bear the moment mostly with limited stiffness, which results in that the deformations aroused by the change of moments can not be ignored.

Analysis of Result of Storied Buildings

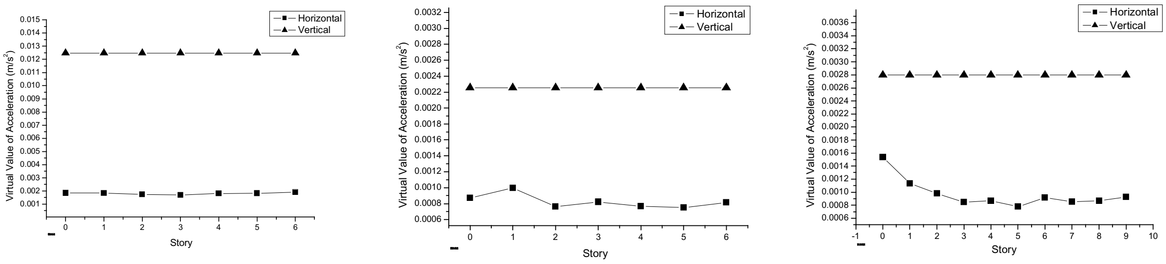
Comparisons of vibration intensity of building A, C and E in horizontal direction are shown in figure 8.



a) Building A b) Building C c) Building E

Figure 8. Horizontal Vibration Intensity (Virtual Value of Acceleration) of Building A, C and E

Comparisons of vibration intensity of building A, C and E in horizontal direction and in vertical direction are shown in figure 9.



a) Building A b) Building C c) Building E

Figure 9. Horizontal and Vertical Vibration Intensity (Virtual Value of Acceleration) of Building A, C and E

It is indicated in figure 8 that with the increase of distance to the vibration source, the situation that the vibration intensity of each storied-building in horizontal direction is maximum at highest and lowest story while minimum at the middle story changed gradually to decreasing with the height of building. Moreover, it can be seen from the three horizontal lines in a), b) and c) of figure 9 that in vertical direction, the vibration intensity of each story of a building is the nominal identical. The reason for the result is the same as that of the huge platform, which is that the stiffness of storied buildings in vertical direction is much greater than that in horizontal direction.

It is also can be seen in a), b) and c) of figure 9 that the vibration intensity in vertical direction of storied-building is larger than that in horizontal direction. Thus it can be seen that, as far as evaluation for the vibration of storied building is concerned, the vibration in vertical direction should be considered primarily.

CONCLUSIONS

Some conclusions can be drawn from the analysis mentioned above:

- For the first layer (nether) and the second layer (upper) of the huge platform, the former's vibration intensity in horizontal direction is larger whereas identical to the latter in vertical direction;
- With the increase of the distance to the vibration source, the situation that the vibration intensity of each storied-building in horizontal direction is maximum at highest and lowest story while minimum at the middle story changed gradually to decreasing with the height of building;
- In vertical direction, the vibration intensity of each story of a building is the nominal identical, which indicates that the vertical vibration of the building is unanimous;
- The vibration intensity in vertical direction of storied-building is larger than that in horizontal direction.

The study in this article provides a method of whole process numerical simulation including static stage and dynamic stage for dynamic analysis of soil-structure interaction, which accords with the real state change of actual engineering, and can be used to perform detailed simulation for the engineering studied.

The conclusions about huge ground structures can supplement field test of engineering to be studied in tested position and tested content, can provide references for vibration evaluation and control of huge ground structures around the subway line such as vehicle depots of subway system.

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