Field measurement, analysis and protection for the vibration response of granary ruins caused by train load

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Abstract. In this paper, the vibration effect of Longhai Railway on a granary ruins is taken as the research object. Firstly, the vibration response of the granary ruins is obtained by field test. Then, using FLAC3D finite element analysis software to establish an overall calculation model, and the shock absorption effect of vibration isolation barrier is analyzed and predicted. The conclusions are as follows: the horizontal vibration of granary ruins is stronger than the vertical vibration; because of the special structure of the granary ruins, when the vibration propagates to the interface of the cellar wall, it will produce horizontal vibration amplification phenomenon, and the vibration intensity of the granary ruins away from the vibration source will decrease faster; discontinuous concrete isolation piles are used to protect granary ruins. Under the premise of considering more economical, double-row piles with staggered layout have the best vibration isolation effect.

1. Introduction
The vibration produced in the process of railway traffic operation will seriously affect the safety of buildings on both sides of the railway, especially the ancient buildings that are very sensitive to vibration, which will be more strongly affected. Many scholars on the vibration source, propagation path and vibration isolation from several aspects such as research, have made some achievements. P.Fiala [1], deals with the numerical computation of the structural and acoustic response of a building to an incoming wave field generated by high-speed surface railway traffic. The isolation performance of three different vibration countermeasures: a floating-floor, a room-in-room, and base-isolation, is examined; in order to avoid the deterioration of urban environment caused by ground noise and vibration during subway operation, K. V. Ogiatzis [2] et al., through numerical prediction of ground noise and vibration level, compared the calculated results with the ground noise and vibration level standard, and determined the necessary mitigation measures; in the research of Javad Sadeghi [3] et al. new classifications of the CHSs and the track sub-structure form the aspect of metro-induced vibrations were developed. Through parametric analyses of the model, the SD was developed for the first time as a function of metro characteristics, geo-mechanical properties of the media between the metro and the CHS, and the type of CHS. The effectiveness and practicability of the SD in construction of new subway lines were illustrated; also, some investigations on isolation trench which is used to reducing the vibration induced by train have been done. For example, Kuma et al. [4] have studied the damping effect of isolation trench which is filled with water; Kawamura et al. [5] have proposed a new type of vibration isolation measures which
is combined with ground groove and dynamic damper; and other scholars have studied the reduction of railway-induced vibration for different isolation trench [6-9].

As an important part of the ancient ruin, granary ruins has outstanding historical and scientific value. In order to ensure the structural safety of granary ruins, it is very necessary to evaluate the impact of vibration caused by train operation on granary ruins and to predict its protection measures. At the same time, because the structural characteristics of granary ruins are different from those of other above-ground ancient sites, the study on the vibration law of granary ruins under train load has reference significance for the protection of underground ancient sites with the same structure.

2. Field measurement

2.1. Project summary
The test object was a granary ruins in Luoyang. The site is located in the north of Laocheng city, Luoyang City, Henan Province, close to the Longhai Railway.

The granary ruins is shaped like a round cylinder with a large mouth and a small bottom. The diameter of the pit is 11.1 meters, and the total depth of the pit is 6.2 meters, as shown in Figure 1. At present, the soil on the surface of granary ruins is loose, and because the north side of the site is close to the Longhai railway, it can cause the vibration of granary ruins under the train load, resulting in cracking and shedding of soil on the surface of the pit wall.

![Figure 1: Present situation of granary ruins](image)

2.2. Test instruments and test methods
This test uses INV9832 three-way acceleration sensor, INV3062C-C1(L) data acquisition instrument, etc. Four measuring points (No. CD1～CD4) are arranged at the mouth of the pit. The measuring points are located in the four directions of the south, east, north, and west of the mouth of the pit. Each measuring point is synchronized with two acceleration sensors. Since the accelerometer should be placed in a flat position to ensure its effective vibration pickup, and the southern half of the bottom of the pit is curved, and the northern half of the bottom of the pit is relatively flat, so two measuring points are arranged in the northern half of the bottom of the pit (No. CD5～CD6), which corresponds vertically to the two measuring points west and north of the pit mouth. The site layout and location of the measuring points are shown in Figure 2 and Figure 3. The X direction is set to be parallel to the main railway line, the Y direction is perpendicular to the main railway line, and the Z direction is the vertical direction.
In order to remove the influence of interfering signals on the test results, this paper performs DC removal, de-trend item, smoothing data and signal de-noising processing on the collected accelerogram data.

Six measurement points are set up on site. Since the weight, model, passing time and speed of the train cannot be controlled, multiple sets of sample data are collected at each measurement point (at least two sets are collected), and the measured raw data is preprocessed. After that, a set of data with the largest vibration acceleration amplitude at each measuring point is selected for comparison and analysis. Because the measured data is very large, this article selects the data in a certain period of time including the maximum acceleration for processing.

Table 1  Vibration acceleration value of each measuring point during train operation

| Test point number | Peak mm/s² | Effective value mm/s² |
|-------------------|------------|-----------------------|
|                   | X          | Y                     | Z                      | X    | Y    | Z    |
| CD1               | 9.17       | 36.64                 | 13.31                  | 2.04 | 4.29 | 3.02 |
| CD2               | 5.61       | 6.5                   | 9.87                   | 1.03 | 1.59 | 1.95 |
| CD3               | 2.12       | 5.82                  | 3.14                   | 0.41 | 0.88 | 0.60 |
| CD4               | 8.66       | 8.37                  | 8.72                   | 1.38 | 1.31 | 1.34 |
| CD5               | 5.11       | 8.7                   | 4.01                   | 0.86 | 1.66 | 1.06 |
| CD6               | 5.01       | 6.19                  | 3.36                   | 1.03 | 1.22 | 0.86 |

2.3. Test result analysis

The results of the vibration acceleration value of each measurement point under the train load are summarized in Table 1 and the acceleration amplitude change of each measurement point is shown in Figure 4. The following conclusions can be drawn from the figure:

- The vibration of the granary ruins has obvious directionality. It can be clearly seen from the acceleration peak that the vibration of the railway horizontal direction (Y) is the largest, and the vibration of the side points of the pit bottom along the railway horizontal direction (X) is greater than the vertical direction (Z), indicating that the horizontal vibration at each location of the warehouse site is stronger than the vertical vibration;
Comparing the respective horizontal acceleration peaks of CD1~CD4, the Y-direction acceleration peaks of CD1 and CD3 are larger than the X-direction acceleration peaks. The Y-direction acceleration peaks of CD2 and CD4 are similar to the X-direction acceleration peaks, namely CD1, CD3 Y-direction vibration intensity is more prominent. This is because the vibration generated by train operation propagates from the main railway line to both sides, and when it spreads to the interface of the cellar wall, the soil on the interface will move to the side of the space due to the impact of the vibration, causing a level on the interface vibration amplification phenomenon.

The z-direction peak acceleration of CD2 and CD4 is less than 35% lower than that of CD1, while the z-direction peak acceleration of CD3 and CD2 and 4 is more than 60% lower than that of CD4, indicating that the attenuation rate of vibration strength of the north cellar wall is less than that of the south cellar wall. This is related to the circular cylinder structure of the granary ruins. Granary ruins is equivalent to a circular vibration isolation ditch. When the vibration is transmitted to the north side of the granary ruins, due to the vacancy of the side of the granary wall, the vibration lacks the media for forward propagation, which hindering the propagation of the vibration to the south side of the granary wall. Therefore, the attenuation rate of the vibration strength of the cellar wall at the side far from the source is faster.

Comparing the acceleration peaks of CD1~3, the vibration intensity decreases continuously from the location close to the vibration source along the pit wall and away from the vibration source; comparing CD1 and CD5, CD2 and CD6 with the same distance from the vibration source, the vibration intensity of the granary ruins decrease as the depth increases. Therefore, the pit opening on the north side of the granary ruins has the highest vibration intensity under the action of train load, and it is most prone to diseases such as soil falling and collapse, and should be treated.

3. Finite element analysis and results
According to the field measurement situation, the train vibration has a greater impact on the granary ruins, and the granary ruins needs to be protected against vibration. In this paper, the finite element analysis software FLAC3D is used to build the overall calculation model, and analyze the vibration
isolation effect caused by the arrangement of concrete rows of piles to provide a basis for actual engineering design.

3.1. Project summary

According to site conditions and railway design requirements, the corresponding three-dimensional numerical calculation model is established. The upper bottom radius of the granary ruins site is 6m, the lower bottom radius is 5m, and the depth is 6m. According to the actual survey, the rammed soil layer on the pit wall has fallen off, so the parameters of the pit wall soil layer and the surrounding soil layer parameters are set to be consistent. The subgrade is simulated by solid elements with a maximum grid size of 1m. The track bed is a ballast bed with a thickness of 0.7m and a slope ratio of 1:1.75. The model is 60m long, 40m high, and 40m wide, which meets the calculation accuracy requirements. Set the free field boundary around the model, and at the same time impose a static boundary at the bottom of the model. The model grid is shown in Figure 5. The various parameters of the model soil are obtained through on-site survey. The selected calculation parameters of this model are shown in Table 2.

| Table 2 Calculation parameters of soil layer and subgrade |
|--------------------------------------------------------|
| name         | thickness | Natural density $\text{kg/m}^3$ | Elastic Modulus $\text{MPa}$ | Poisson's ratio |
| Track bed    | 0.7       | 2500                           | 350                        | 0.3            |
| Roadbed      | 4         | 2000                           | 110                        | 0.25           |
| Soil layer 1 | 10        | 1700                           | 25                         | 0.3            |
| Soil layer 2 | 30        | 1860                           | 50                         | 0.3            |

3.2. Train load input

3.2.1. Simplification of train load

In the numerical simulation, Liang Bo et al. [10] simplified the vertical load generated by the train running on the track into the excitation force function to simulate. The excitation force function expression is shown in equations (1), (2) and (3).

$$ F(t) = P_0 + \sum_{i=1}^{3} P_i \sin \omega_i t $$  \hspace{1cm} (1)

$$ P_i = M_0 \alpha_i \omega_i^2 $$  \hspace{1cm} (2)

$$ \omega_i = \frac{2\pi\nu}{l} $$  \hspace{1cm} (3)

In the formula: $P_0$ is the static load of the train; $P_i$ is the load amplitude, ($i = 1,2,3$); $\alpha_i$ is the positive loss, ($i = 1,2,3$); $\omega_i$ is the vibration circle frequency, ($i = 1,2,3$); $\nu$ is vehicle speed; $l$ is vibration wavelength.

See Table 3 below for the wavelength of irregularity vibration and typical deflection values under China's railway operating standards.

| Table 3 Value of irregularity wavelength and height loss |
|--------------------------------------------------------|
| Control condition | wavelength $l$ /m | Vector $\alpha$ /mm |
| According to the driving comfort | 10.00 | 3.5 |
| According to the additional dynamic load acting on the line | 2.00 | 0.4 |
| Waveform wear | 0.50 | 0.08 |

According to the research of Wu Yubin, Qiu Yanjun and others [11], the higher the speed of the train, the greater the vertical dynamic displacement of the track bed and surrounding soil. The design speed of Longhai Railway $\geq 160$km / h, this paper selects the most unfavorable. The working conditions are
studied. According to formula (1) and table 2, the vibration load time-histories function of the railway passenger car is obtained, see formula (4).

\[ F(t) = 110 + 2.04 \sin 27.91t + 5.84 \sin 139.54t + 18.69 \sin 558.17t \]  

(4)

According to formula (4), the train load time history curve with speed \( v = 160 \text{km/h} \) is obtained, as shown in Figure 6 below.

![Grid diagram of whole model](image1)

![Train load time history curve](image2)

3.2.2. How the load is applied

In this paper, the train load is simplified as the uniform distribution load along the track direction with time [13], that is, the line load along the single track direction is:

\[ P(t) = \frac{n k F(t)}{L} \]  

(5)

In the formula: \( n = 4 \), is the number of wheels on one side of each car; \( k = 1 \) is the correction coefficient; \( L = 25 \) is the length of each car.

3.3. Analysis of shock absorption effect of vibration isolation barrier

Vibration reduction and isolation measures for vibration induced by existing railway operations usually use vibration isolation barriers. According to their structural form, vibration isolation barriers are divided into two categories: continuous vibration reduction and isolation barriers (empty trenches, filled trenches, reinforced concrete walls, etc.) and discontinuous vibration reduction and isolation barriers (empty wells, rows of piles, honeycomb wave blocks, etc.). After research [14], the empty trench must reach a certain depth in order to achieve the ideal vibration isolation effect. However, due to the narrowness of the site and it cannot have a strong impact on the cultural relics, it does not have the conditions for digging deep empty trenches, so it is proposed to adopt discontinuous vibration isolation barrier, concrete vibration isolation piles are set by manual digging.

In this paper, the main judgment is based on the decline in acceleration peaks at the pit opening and the bottom of the pit at the bottom of the pit as the main judgement. It mainly studies the influence of the number of concrete pile rows and the arrangement method on the vibration isolation effect of the pit and the bottom, and determines its optimal vibration isolation. The plan provides a design basis for the actual project.

It can be seen from Figure 3 that the model is symmetrical as a whole, and the simulated calculation values of monitoring points 2 and 4 are basically the same. In order to analyze the vibration isolation of various parts of the granary ruins more intuitively, the calculation point 1~6 is set on one side of the granary ruins. The location of each calculation point is shown in Figure 7.
In order to analyze the influence of the arrangement of multiple rows of piles on the vibration isolation effect, the pile section of the proposed row of piles is circular, the pile length is 8m, the pile diameter is 0.8m, the pile spacing is 2m, the row pile width is 20m, and the row spacing is 1m. Now calculate the acceleration value of each calculation point when the double-row piles and three-row piles are arranged in the following two situations (see Figure 8～11) and compare and analyze the peak acceleration of each calculation point. It can be seen from Figure 12 and Table 4:

- The use of discontinuous concrete row pile barriers can effectively reduce the vibration of the warehouse ruins under train load;
- The arrangement of multiple rows of piles has a greater influence on the vibration isolation effect, and the vibration isolation effect is better when the rows of piles are arranged in a staggered manner;
- The vibration isolation effect of the staggered layout of the double-row piles is similar to that of the side-by-side layout of the three-row piles, both reaching 53%, but the vibration isolation effect of the staggered layout of the three-row piles is only 5% higher than that of the double-row piles.

Therefore, considering the engineering economy, it is recommended to choose staggered double-row piles.

### Table 4: Vibration isolation effect of different arrangement forms of row piles

| Row pile arrangement form | Open ground simulation | Double-rows piles form I | Double-rows piles form II | Three-rows of piles form I | Three-rows of piles form II |
|--------------------------|-----------------------|--------------------------|---------------------------|---------------------------|-----------------------------|

Figure.7 Schematic diagram of position of calculation point

Figure.8 Double-rows piles form I

Figure.9 Double-rows piles form II

Figure.10 Three-rows of piles form I

Figure.11 Three-rows of piles form II
| Acceleration peak (mm/s²) | 28.82 | 16.68 | 13.53 | 13.69 | 11.91 |
|---------------------------|-------|-------|-------|-------|-------|
| Vibration isolation effect | -     | 42.12%| 53.05%| 52.50%| 58.67%|

Figure 12 Curve diagram of relationship between pile arrangement and accelerations

4. Conclusion

- The vibration of the granary ruins has obvious directionality, and the horizontal vibration at each position of the granary ruins is stronger than the vertical vibration;
- Due to the special cylindrical structure of the granary ruins, when it spreads to the empty interface of the pit wall, the soil on the empty interface will move to the empty side under the influence of vibration, causing horizontal vibration amplification on the empty interface, and the cylinder-shaped structure is equivalent to a vibration isolation ditch, so that the vibration lacks a forward propagation medium, which hinders the propagation of vibration, resulting in a faster attenuation rate of the vibration intensity of the pit wall on the side of the granary ruins far from the vibration source;
- The vibration intensity of the granary ruins decreases with the increase of the distance between the measuring point and the main railway line, and decreases with the increase of the soil depth. Therefore, the vibration intensity of the pit opening on the north side of the granary ruins under train load is the largest. Soil falling off, collapse and other diseases are most likely to occur, which should be treated;
- The use of a discontinuous concrete row pile barrier can effectively reduce the vibration of the warehouse site under train load; the arrangement of multiple rows of piles has a greater impact on the vibration isolation effect, and the vibration isolation effect is better when the rows of piles are arranged in a staggered manner. And considering the effect of vibration isolation, it is recommended to use double-row piles staggered arrangement to realize the protection of the granary ruins.
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