Acta Geologica Sinica (English Edition), 2020, 94(1): 152–161

Preliminary Investigation on the Causes of Odd Vibration of Buildings in Guilin City—a Study on the Resonance between Buildings and the Underlying Soil Layer

ZHANG Fawang, GAN Fuping, LUAN Song*, MENG Yan, ZHENG Zhijie and LI Weixuan

Institute of Karst Geology, Chinese Academy of Geological Sciences, Guilin 541004, China

Abstract: A residential building in Guilin City, China, underwent an up-and-down vibration with an amplitude of 2 cm. By eliminating several causes such as earthquake, wind and construction, in combination with the unique karst geological conditions of Guilin, it was inferred that the effect of turbulent karst water is the main contributor to the occurrence of this vibration. Therefore, a geophysical survey was undertaken on the vibration zone and its surroundings. The resutls suggest that the soil in the upper part of the karst grooves shows conspicuous traces of disturbance and the water content has low resistance. A comprehensive analysis indicates that there is a karst strong runoff zone beneath the area. According to the water level and water temperature data collected automatically by the instrument, it can be concluded that the groundwater level had changed significantly twice during this period, so it was determined that the denudation of groundwater strong runoff causes the overlying soil layer to collapse, forming a soil-water soft-flow material with mixed phase. Since the building in this area was supported by friction piles, the groundwater-soil soft-flow material with mixed phase has intense plasticity, and the up-and-down vibration resulted in the change of the friction piles, which caused the up-and-down vibration of the building structure.

Key words: karst, building vibration, groundwater, strong runoff

Citation: Zhang et al., 2020. Preliminary Investigation on the Causes of Odd Vibration of Buildings in Guilin City—a Study on the Resonance between Buildings and the Underlying Soil Layer. Acta Geologica Sinica (English Edition), 94(1): 152–161. DOI: 10.1111/1755-6724.14494

1 Introduction

The 34th Research Institute of China Electronics Technology Group Corporation (CETC for short), located in Qixing District of Guilin City, is a typical karst area in Guilin. At 17:00 of July 27, 2018, the No. 8 and No. 10 buildings of the Institute experienced an up-and-down vibration (Fig. 1), with an amplitude of 0.5–2 cm, the intense vibration lasted for about 2 hours, and the (electric) power lines around the buildings were obviously shaking. At noon of the next day, the recognizability of the buildings' shaking tremendously reduced, but that of the surrounding lines were still very visible. According to the data of Guilin Seismological Bureau, there were no earthquake in Guilin from July 27 to July 30, 2018.

Similar incidents occurred in other countries, too. In July 1940, the Tacoma Narrows Bridge was completed and put into use, but only a few weeks later, the deck began to swing at an amplitude of up to 2 meters. Engineers placed huge cement piers on both sides of the bridge to connect the tie rope with the bridge structure, in an attempt to mitigate the vibration. But soon the rope was broken off by the bridge deck and disintegrated like a toy building block on November 7, 1940 (Gu and Tsien, 1991; Ding et al., 2014). At the evening of May 19, 2010, the Volga River Bridge in Russia experienced violent oscillation, with the vertical vibration amplitude of up to 400 mm. The reinforced concrete bridge was undulating and swaying in a wave shape (Huang, 2002). Based on the analysis of the bridge vibration causes, experiments were

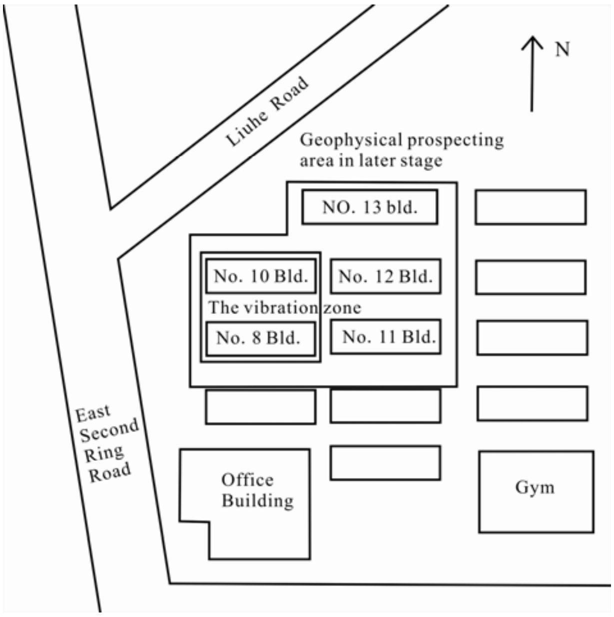

Fig. 1. The location of the vibration zone of the CETC buildings.

* Corresponding author. E-mail: luansong@karst.ac.cn

http://www.geojournals.cn/dzxbcn/ch/index.aspx; https://onlinelibrary.wiley.com/journal/17556724

conducted on the vibration zone of the CETC buildings, with the vibration causes predicted and analyzed in an open way (Liu and Liu, 2007; Tsuno et al., 2010).

2 The Regional Physiographic Conditions

Guilin is a typical karst area, with carbonate rocks extensively distributed (Chen et al., 2019). The central and southern part of the city are mainly the karst valleys, and the karst erosion plains, peak cluster depressions and peak forest plains are developed as well. This region has a subtropical monsoon climate, with an average annual temperature between 17°C and 20°C, and an average annual rainfall of 1850 mm. The rainy season begins in March and ends in August. The Lijiang River runs through Guilin from north to south, with an average flow of 4.03 billion cubic meters per year. The CETC vibration zone is 2.4 km west of the main channel of the Lijiang River. The main stratum of the vibrating zone is:

The genetic type of middle pleistocene series (Q_2) is debris flow accumulation and alluvial-diluvial, and the clay intercalated with gravel. The clay is mainly composed of quartz sand, and the gravel of purple-red sandstone, siltstone and quartzite.

Carbonate rocks facies (D_3r): The main lithology is gray -white-grey micrite, biosparry micrite, micrite, containing dolomite limestone, fine medium-crystal, fine-crystalline dolomite. According to the regional geological data, the average value of dolomite content is 24.82%, the CaO content is 48.61%, the CaO/MgO ratio is 55.32, and the average porosity is 2.13% (Yang and Hung, 2009; Huang et al., 2011).

3 The Preliminary Analysis of the Vibration Causes

Any object, once vibrating, thanks to its physical characteristics such as composition, size, shape, etc., initially vibrates at a variety of frequencies, and then vibrates at a certain fixed frequency (Hu et al., 2017). This frequency is called the "natural frequency" of the object, because it is related to the physical properties of the object (Phien-wej et al., 1998, 2006). When another vibration (called a “motion”) is added to the object, and if the frequency of the motion is exactly the same as the natural frequency of the object, the vibration amplitude of the object reaches the maximum, and this phenomenon is called “resonance” (Chen et al., 2007; Zhu et al., 2013). Any building has its own basic vibration frequency. The building is given considerations to the excellent period of seismic structure and foundation under construction, so as to avoid damages to the building caused by resonance. However, during the use of the building, the following three conditions, to some extent, can temporarily or permanently change the natural vibration frequency of the building (APABroch,1980; Ferronato et al., 2006).

The first is environmental change, such as those caused by the piling, blasting, the passing of heavy vehicles, and changes in wind power that occurs within a certain proximity to the area (François et al., 2007).

The second is building changes. Seismic reinforcement and height addition as additional functions change the internal or external structure of the building (Degrande and Lombaert, 2011).

The third is the changes in building functions. Such as the relocation and migration of heavy equipment inside the building as well as a remarkable change in population flow (Xia et al., 2005).

According to the information released by Guilin Meteorological Service, on July 27, 2018, Guilin city was cloudy, with a temperature range of 27°C–34°C, southeast wind level 1, and light wind. Also, it was known through a visit, that there were no activities such as piling or blasting in the past 10 days, so there was no change in the environment; the CETC No. 8 and No. 10 buildings were built in the 1990s, with 5 floors above ground and no basement. Since establishment, they’ve been being provided to staff, and there are no changes in themselves or their functions. From July 30 to October 2018, there was no vibration phenomenon any more in the buildings. It’s inferred that the vibration of the building structure was not caused by the change of natural frequency, but by the resonance of the building caused by the vibration of any other object. What’s more, a small-scale karst collapse once occurred in the area before, so it’s inferred that this incident was caused by the unique geological environment of the karst area, and the vibration source was the turbulent groundwater in the karst strong runoff.

4 Samples and Methods

4.1 Methods

In this work, the geophysical survey was carried out on the vibration zone with the transient electromagnetic method and the micro-vibration surface wave method. With the electromagnetic method, the difference characteristics of the conductivity of the underground medium was obtained to detect the underground geological structure and tectonics, so as to determine the underground karst characteristics of the underground karst cave, the underground river, the karst fracture zone, etc.; (Breuer et al., 2002; Gu et al., 2008) with the natural vibration, the surface wave velocity variation with respect to the depths was acquired, and the surface wave velocity was used to ascertain the “softness” and “hardness” characteristics of the subsurface soil layer. The two methods were used to comprehensively analyze the underlying stratigraphic changes and spatial structures. By setting measuring lines in areas where small karst collapses occurred in the past, the comparison with other areas can be easily acquired (Wang and Zhang, 2014).

PROTEM47, manufactured by the Canadian-based Geonics, was used in the transient electromagnetic method. The turn-off time is one of the important technical indicators of the CUGTEM-GK. If the turn-off time is long, the shallow signal will be lost, and the secondary field strength will be weakened, directly affecting the detection effect. The turn-off time of this instrument can be as short as 0.5μv, with high resolution and extensive dynamic range. The signal resolution of PROTEM is 24 bits, the system resolution is 29 bits, and the dynamic range is 175dB. What’s more, the instrument also has the advantages of flexible installation, excellent stability, and wide operating temperature, which satisfy the site’s requirement, so this instrument was selected for geophysical analysis of the area (Men et al.,1998).

The German-manufactured DMT Summit X One 3D Seismograph was adopted in the 3D seismic method, because it features high responsiveness in addition to being lightweight, not to mention that the 2D and 3D observation systems could be arranged under complex terrain and geographical conditions. More importantly, the equipment can continuously record and monitor seismic activity and vibration detection (Adam and Estorff, 2005). The vibration in this area is also continuous, so this instrument has excellent performance on this type of vibration detection.

4.2 The geophysical analysis of the vibration zone

From July 28 to 30, 2018, geophysical survey were carried out on the study area while slight vibration was still proceeding in the vibration zone. At the same time, geological drilling is carried out in the vibration area to check the correctness of geophysical analysis.

Seven lines, 265 transient physical points, and 189 surface wave physical points were tested at a point-to-point distance of 2 m.

In 2015, a small area of karst collapse occurred in this area. See Figure 2 for the specific location. At that time, the pavement was leveled after grouting in a small area of the collapsed area. In this geophysical exploration work, there is a survey line V2 passing through the area. The 85–95 m of H2 survey line is the karst collapse in 2015. The surface layer has been simply grouted with relatively high resistance, so the geological structure of other areas can be inferred based on the characteristics of the collapse area. It is inferred that the resistivity of 220–320 Ω m and wave velocity of 260–290 m/s are the surface of loose soil or bedrock with very low water content. If the resistivity is less than 220 Ω m and the wave velocity is less than 260 m/s, it is the loose soil layer or soil cave with high water content. The resistivity more than 320 Ω m and wave velocity more than 290m/s are bedrock (Figs. 3 and 4) .

At the same time, on the second day of vibration, geological drilling was carried out in the vibration area, which is located at 75m of V2 survey line, in order to understand the underlying strata and check the accuracy of geophysical exploration. The drilling histogram is shown in Figure 5.

Through drilling inspection, it is found that the formation and lithologic structure are basically consistent with the geophysical speculation, so the geophysical analysis takes the V2 line resistance value and wave velocity as the benchmark value to analyze the other six lines.

Taking H3 survey line as an example, obvious low resistance area and low speed area can be seen at 50–90 m. According to V2 standard value, it is speculated to be water filled cohesive soil. This area should be solution tank, distributed in north-south direction. There are low resistance area and low speed area at 105 m, which is speculated to be soil cave. Finally, the comprehensive geophysical interpretation result map of vibration area is drawn.

5 Results

From the test results (Fig. 8), it can be undoubtedly known that a resistivity anomaly zone exists at the 60–85 m of line H2, the shear wave velocity is lower than the normal value, and the lower part is the bedrock, where

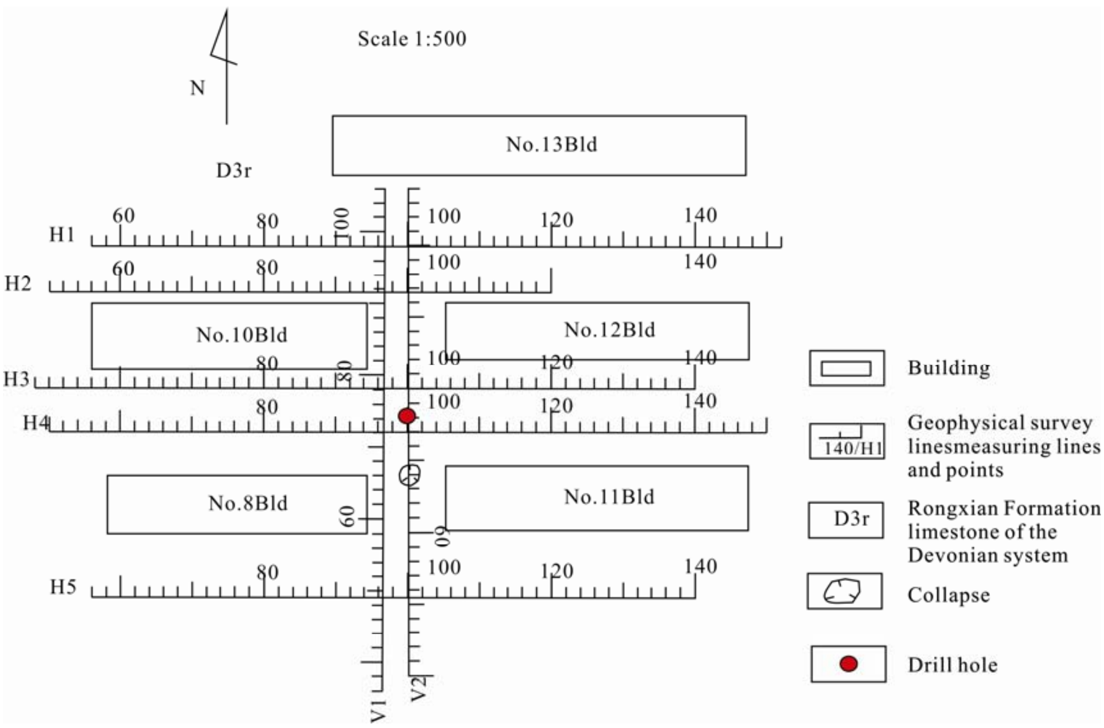

Fig. 2. The actual work materials for geophysical survey.

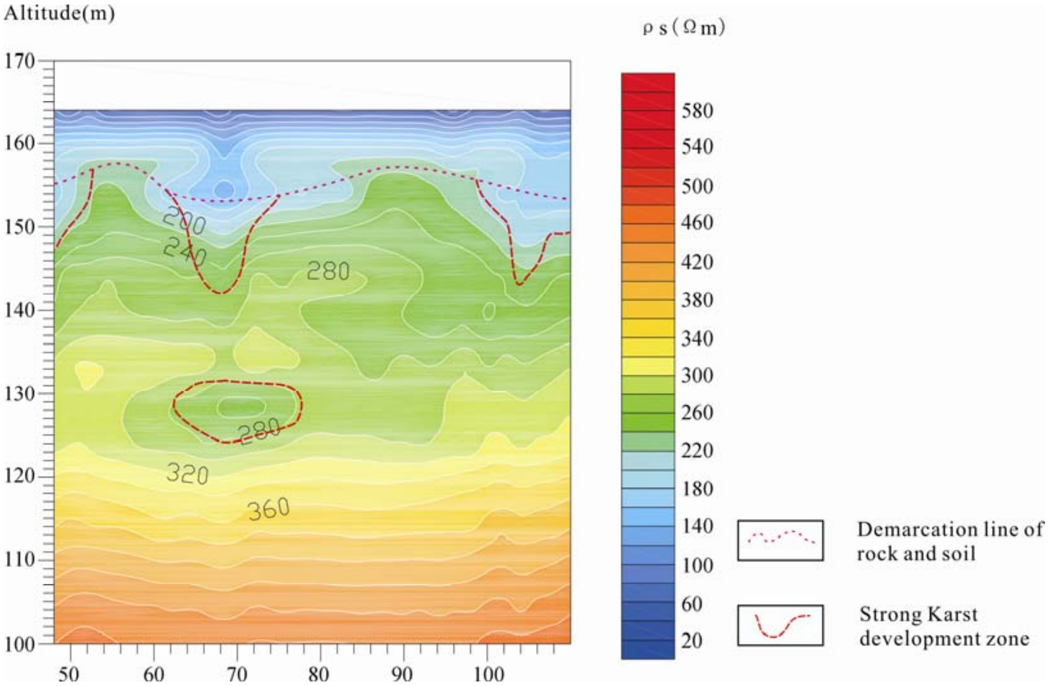

Fig. 3. Line V2 resistivity profile.

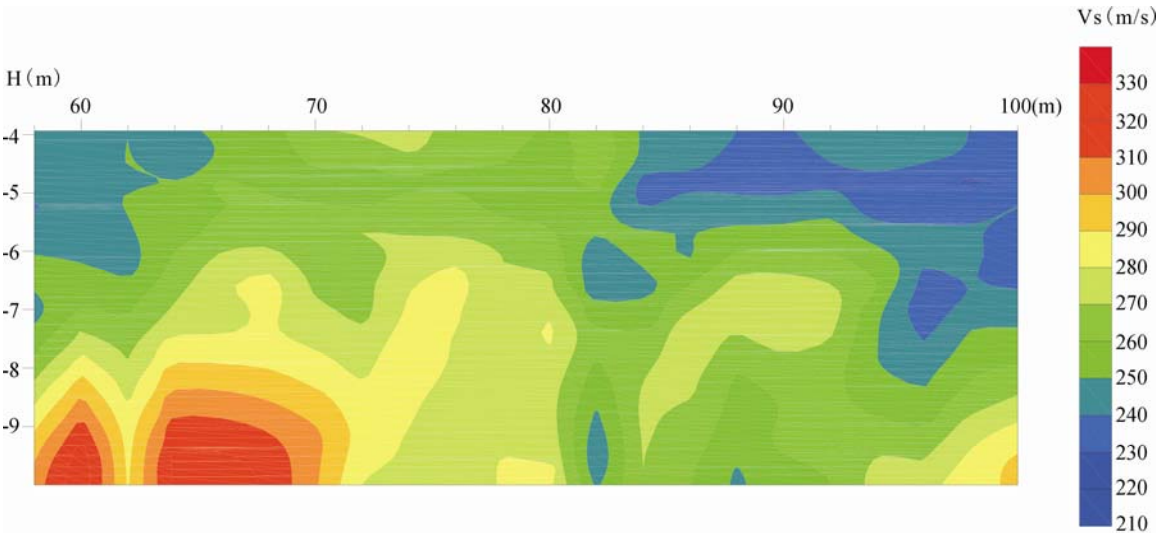

Fig. 4. The shear wave velocity profile of line V2.

karst grooves have developed. It is conjectured that the overlying soil layer is disturbed, with water content of low resistance and low wave speed.

Through the on-site geophysical survey, the preliminary conclusions are drawn as follows:

(1) When the covering layer has a thickness of several meters and more than 10 meters, the thickness changes sharply within or near the strong karst development zone;

(2) Through the resistivity profile, the karst development depth is less than 50m, and as the measuring lines unveil, the karst is mostly developed within 30m. The covering layer and the bedrock surface are uneven, which can be reflected in significant changes in the sparse and dense contours, which also appear in similarly uneven shapes;

(3) Through a comparison of the collapsed line V2 and drilling verification, the anomalous characteristics are evidently manifested as follows: the upper soil layer is disturbed and developed in the karst groove, with caves emerging in the development of the deeper layers, causing soil loss to form ground collapse;

(4) The typical karst anomalies revealed are mainly presented as follows:

Karst groove: The upper soil is disturbed. Since the water content has a low-resistance, large porosity, low wave velocity, and took the form of a gourd-like shape, karst caves usually develop in the lower part;

Karst cave: The resistivity is relatively high, the local

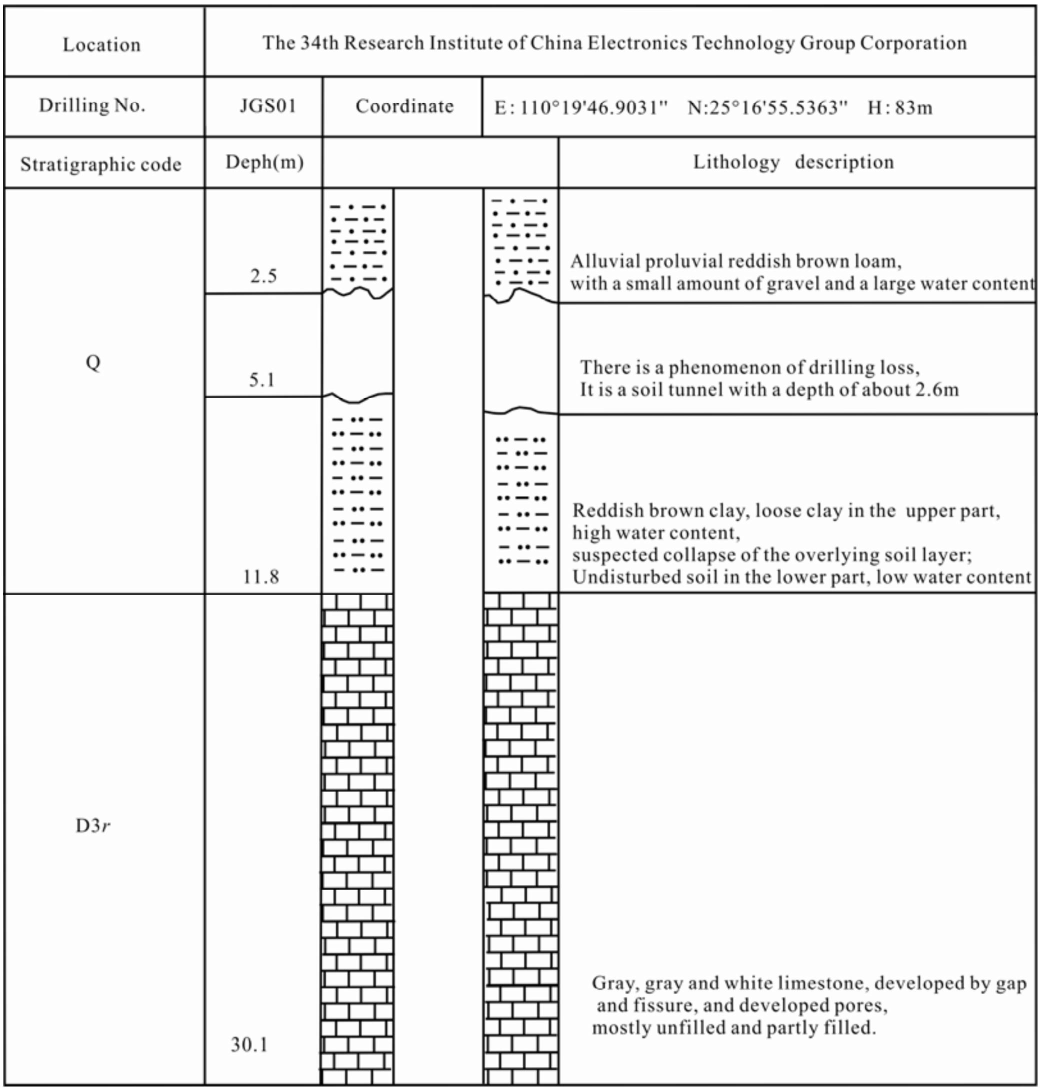

Fig.5. The drilling histogram of vibration area.

0–2.5 m is alluvial proluvial reddish brown loam with a small amount of gravel and a large water content; 2.5–5.1 m is a soil hole with a depth of about 2.6m; 5.1–11.8m is reddish brown clay, the upper clay is loose, with large water content, which is suspected to be collapse of the overlying soil layer; the lower part is undisturbed soil with low water content; 11.8–30.1 m, the upper Devonian Rongxian formation (D_3r) is composed of gray and gray micrite limestone, with developed dissolution gap and fissure, developed dissolution pores, mostly unfilled and half filled.

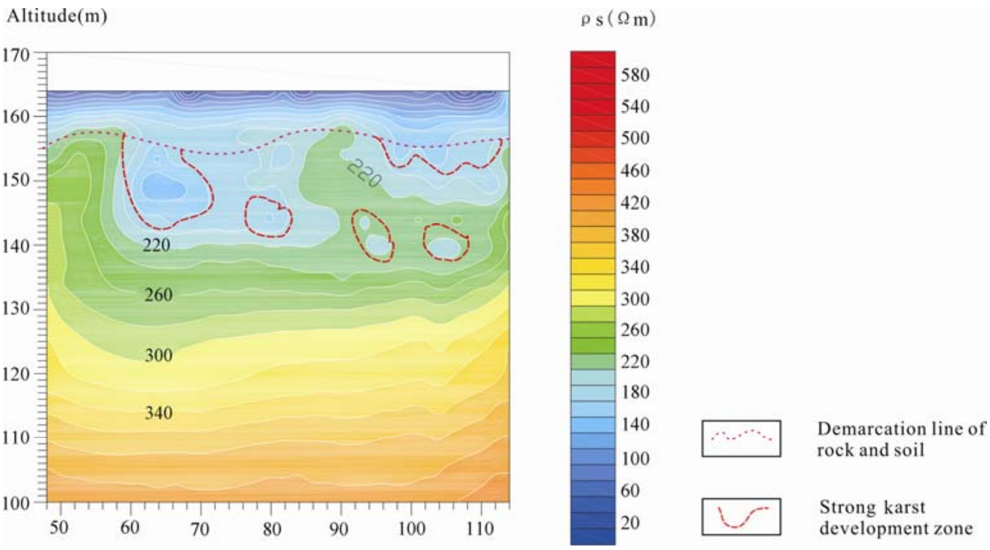

Fig. 6. Line H3 resistivity profile.

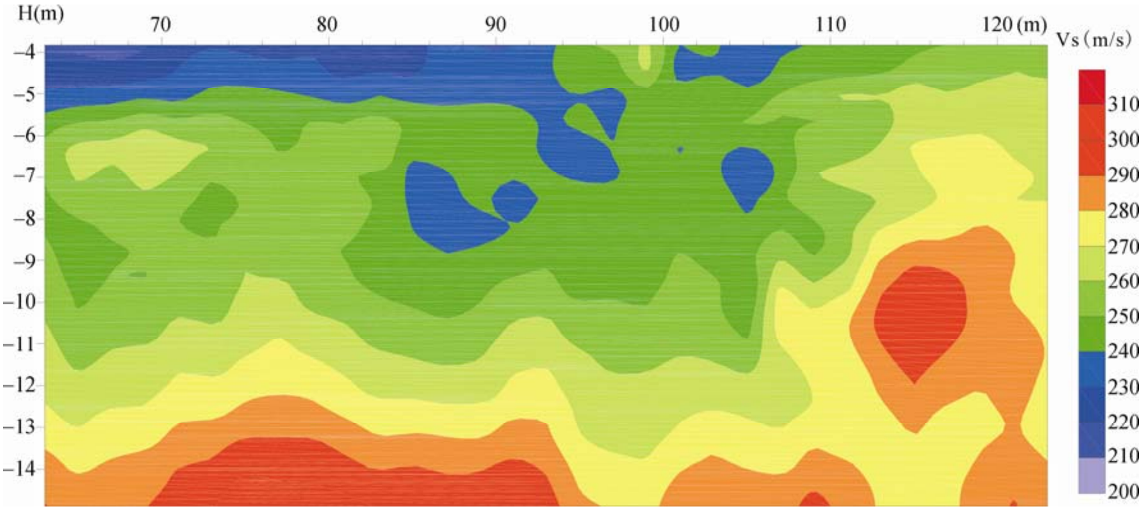

Fig. 7. The shear wave velocity profile of line H3.

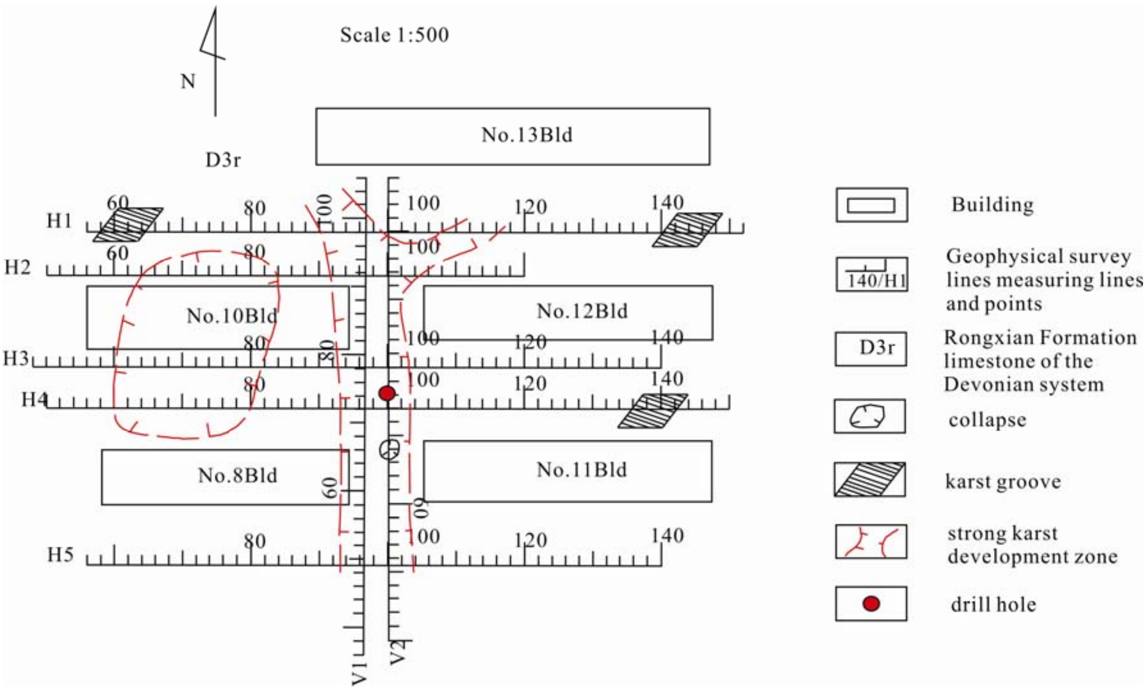

Fig. 8. Result interpretation of the comprehensive geophysical survey of the vibration zone.

contour takes the shape of an enclosed entrapment; or the contour is partially concave;

Fracture: It is mainly developed near the bedrock surface, the resistivity is a median, and the contour changes slowly. Despite being quite different from the karst cave, it is hardly identifiable unless it forms into a dense fracture zone, which is reflected as an obvious abnormal zone.

Two strong karst development zones: The resistivity variation in this area is complex, and the bedrock surface is sharply undulating, with developed karst grooves, karst caves, and fractures. The other prominent feature is that the area is large and has a certain extension direction, which can be interpreted as a strong runoff belt.

6 Discussions

There is a groundwater monitoring hole at 800 m on the southeast side of the CETC vibration zone. The Solinst groundwater automatic monitor was adopted to obtain one data every other hour (see Table 1). It can be seen that the groundwater level in this area had two evident fluctuations, with an amplitude of 3 m (Fig. 9), while the water temperature fluctuated slightly, showing little variations of no more than 0.1°C (Fig. 10).

There are more than 10 villagers residing at an area located 100 m to the east of CETC. According to the local villagers, the domestic water is mainly from the urban tap water. From July 26th through 28th, the tap water supply was suspended for pipeline maintenance (Fujikake, 1986).

Table 1 Automatic groundwater monitoring data (excerpts)

Date	Time	Depth of water level: (m)	Water temperature (°C)
2018/7/26	14:22:49	33.9164	24.028
2018/7/26	15:22:49	33.9221	24.029
2018/7/26	16:22:49	33.9252	24.032
2018/7/26	17:22:49	33.9104	24.033
2018/7/26	18:22:49	33.9076	24.036
2018/7/26	19:22:49	36.8911	24.021
2018/7/26	20:22:49	37.0707	24.002
2018/7/26	21:22:49	37.1197	23.988
2018/7/26	22:22:49	37.1553	23.98
2018/7/26	23:22:49	37.185	23.974
2018/7/27	0:22:49	37.1995	23.97
2018/7/27	1:22:49	37.2101	23.966
2018/7/27	2:22:49	37.2155	23.964
2018/7/27	3:22:49	37.2162	23.962
2018/7/27	4:22:49	37.2198	23.961
2018/7/27	5:22:49	37.2212	23.96
2018/7/27	6:22:49	37.2221	23.958
2018/7/27	7:22:49	37.2218	23.956
2018/7/27	8:22:49	37.2182	23.956
2018/7/27	9:22:49	37.2142	23.956
2018/7/27	10:22:49	34.356	24.012
2018/7/27	11:22:49	34.1042	24.011
2018/7/27	12:22:49	34.0119	24.017
2018/7/27	13:22:49	33.9708	24.022
2018/7/27	14:22:49	33.9604	24.024
2018/7/27	15:22:49	33.9351	24.028
2018/7/27	16:22:49	33.9481	24.031
2018/7/27	17:22:49	33.9077	24.036
2018/7/27	18:22:49	33.8912	24.04
2018/7/27	19:22:49	33.899	24.039
2018/7/27	20:22:49	36.699	24.008
2018/7/27	21:22:49	37.013	23.998
2018/7/27	22:22:49	37.0796	23.986
2018/7/27	23:22:49	37.1085	23.978
2018/7/28	0:22:49	37.1226	23.973
2018/7/28	1:22:49	37.131	23.971
2018/7/28	2:22:49	37.1347	23.967
2018/7/28	3:22:49	37.1364	23.964
2018/7/28	4:22:49	37.1341	23.962
2018/7/28	5:22:49	37.1297	23.961
2018/7/28	6:22:49	37.183	24.022
2018/7/28	7:22:49	36.997	23.972
2018/7/28	8:22:49	37.071	23.968
2018/7/28	9:22:49	35.6087	23.974
2018/7/28	10:22:49	34.1686	24.023
2018/7/28	11:22:49	33.9759	24.023
2018/7/28	12:22:49	33.9027	24.026
2018/7/28	13:22:49	33.8218	24.029
2018/7/28	14:22:49	33.8306	24.029
2018/7/28	15:22:49	33.8235	24.032
2018/7/28	16:22:49	33.8883	24.009
2018/7/28	17:22:49	34.3293	24.031
2018/7/28	18:22:49	33.9727	24.041
2018/7/28	19:22:49	33.8921	24.038
2018/7/28	20:22:49	33.8597	24.038
2018/7/28	21:22:49	33.8237	24.042
2018/7/28	22:22:49	33.4766	23.987
2018/7/28	23:22:49	33.8982	23.998
2018/7/29	0:22:49	33.511	24.019
2018/7/29	1:22:49	33.9723	24.041
2018/7/29	2:22:49	33.8727	24.038
2018/7/29	3:22:49	33.8028	24
2018/7/29	4:22:49	33.9405	23.991

The villagers had to get their water from a motor-pumped well in the village and stored the water in a small reservoir. The well was 43 m in depth, and has a 110 mm wellhead diameter, which causes a drastic change in the

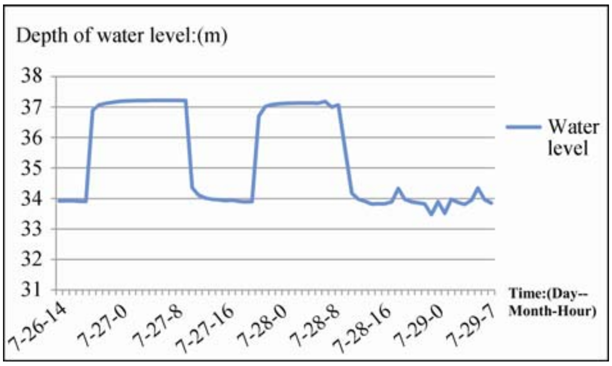

Fig. 9. The burial depth change of groundwater level at the monitoring point.

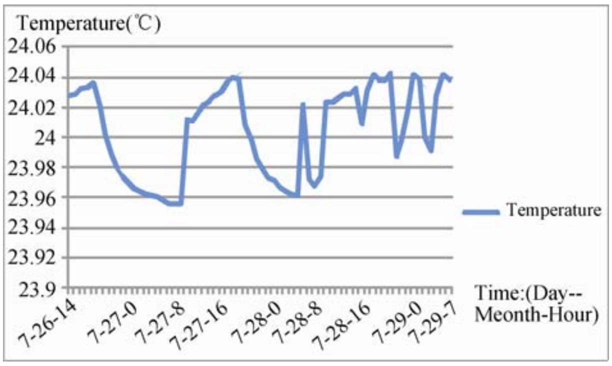

Fig. 10. The groundwater temperature variation at the monitoring point.

instantaneous water level (Hao and Ang, 1998; Massimiliano, 2006). Combined with the above status quo, the causes for this phenomenon are analyzed to be as follows:

(1) Initial state

The building in this area were built in the early 1990s. The pile foundation of the buildings are friction piles, that is, the pile bottom is located in a soft soil layer, and the load is supported by the friction resistance of the pile sides and the reaction force of the pile bottom soil. According to the geophysical analysis, it was found that the soil layer in this area has a thickness of about 30 m, the strong karst runoff zones are developed under the building, and the bedrock is buried deeply (Fig. 11), the groundwater level is mainly located near the contact surface between the soil and the bedrock, and the building stress is mainly gravity and friction, i.e. G=f.

(2) The vibration state (Meng et al., 2007)

Since the well had not been used for a long time, the groundwater level in this area had been relatively stable. From the geophysical data, it can be seen that the soil above the karst groove is disturbed, with large soil pores and water content of low resistance, which is inferred to be due to the collapse of the soil cave in the overlying soil layer caused by the sudden pumping of the motor-pumped well. This area is a strong karst runoff zone, where the karst water flow is large, and this layer of clay can easily turn into soft soil with a plastic flow behavior when it comes into contact with water. The soft soil layer has

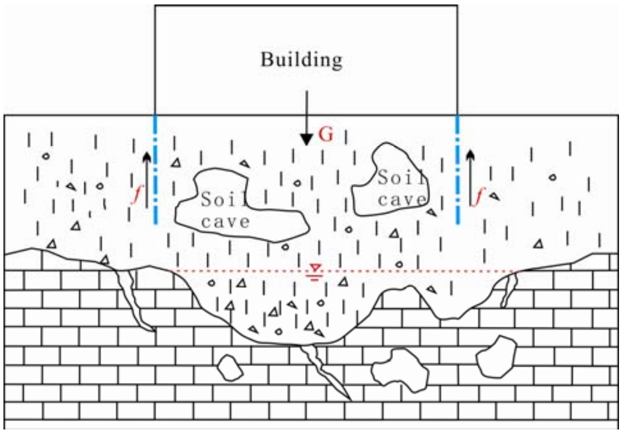

Fig. 11. The initial state of the vibration zone.

marked plasticity, which causes it to change easily with the fluctuation of the water level. The stress of the building is as shown in Fig. 12. The groundwater level fluctuations give the soil force f1. After the soil layer is stressed, the stress of friction piles changes, and the force is f2, the building gravity G is affected by f1, and f2≠G, resulting in an uneven force on the upper and lower floors, so the frivolous vibration is generated, and when the vibration frequency of the building body is consistent with the natural vibration frequency of the building body, resonance emerged.(Crispino and Apuzzo, 2001)

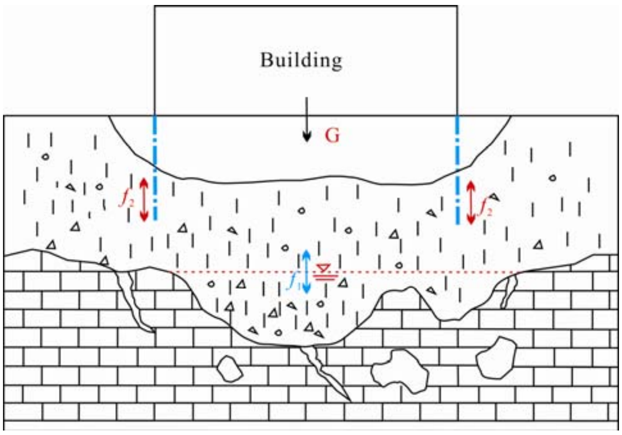

Fig. 12. The vibration state of the vibration zone.

In general, the sudden pumping of the well was both the external cause and the triggering factor of this phenomenon (Fig. 13); the internal cause was that the strong karst runoff zone existed underneath the area, the karst was developed and the soil layer was dominated by quartz sand, rendering strong plasticity; the sudden water pumping caused the soil layer to collapse and in turn gave it a plastic flow property once it came into contact with the karst water in the strong runoff zone. Impacted by the fluctuation of groundwater, the water-soil mixture also vibrated up and down, changing the stress of the friction piles of the building. As the vibration frequency of groundwater approaches the natural vibration frequency of the building, resonance is generated, causing the building to vibrate up and down.

7 Conclusions

This paper raised questions based on the on-site observations of the building vibration. The changes of the natural vibration frequency of the building was firstly excluded, and it was inferred that the external force must be the only cause, after which other external force factors were also excluded. Then a geophysical survey was conducted on the underground space, and it was found that the underlying soil showed obvious signs of disturbance. Combined with the water-use investigation of the villagers, it was ascertained that the water pumping caused the variation of the geological environment that triggered the acting force. When the underlying water-soil mixed phase vibration frequency becomes consistent with the natural vibration frequency, the building structure began to vibrate up and down. This is the major process of the building vibration inference. The following conclusions are also drawn:

(1) When the groundwater in the karst area remains relatively stable for a long time, the instantaneous groundwater pumping may easily causes the instability and collapse of the overlying soil layer.

(2) When the water content of the plastic soil increases, a water-soil binary plastic flow phase is likely to form with a high plasticity. In the strong runoff zone of the karst zone, it can provide water for the soil layer, and more attention should be paid to the impact of the

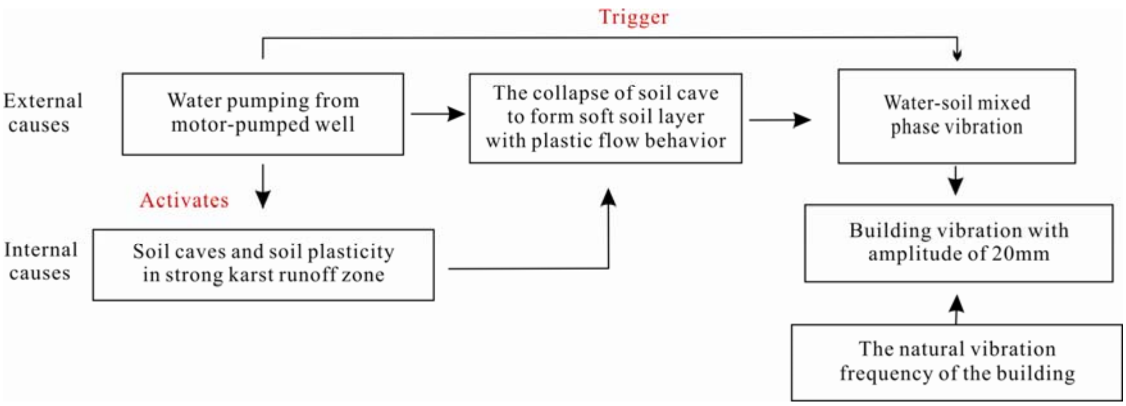

Fig. 13. The analysis on major factors of building vibration.

situation on the building foundation.

(3) Groundwater level fluctuations can hardly cause vibrations to the overlying buildings. However, when the water-soil coupled vibration emerges, the vibration frequency and the vibration mode change; once the vibration frequency gets close enough to the natural vibration frequency of the building, resonance with a large amplitude will be caused, significantly weakening the building's service life and safety. This has a great impact on the building safety, and this problem should be fully avoided during the construction process.

(4) This paper only made a preliminary speculation and analysis of this phenomenon, and made no comparison or discussion on the natural vibration frequency of the building and the vibration frequency of the groundwater vibration source. Since there was no monitoring condition for building vibration, the vibration frequency could not be measured. Water-soil vibration does not cause the building to vibrate sharply, so it's inferred that the vibration was caused by resonance.

(5) For the CETC site, it is suggested to conduct deformation observation and drilling on the soil. According to the comprehensive analysis of drilling data and deformation observation, grouting treatment, if necessary, should be carried out. The bearing stratum of the foundation layer is compacted tightly, and the natural vibration period of the foundation and buildings can be changed to reduce the possibility of resonance.

Acknowledgements

A special gratitude is reserved to the Research and Application Center of Karst Geology Detection Technology of the Institute of Karst Geology of China Geological Survey for the geophysical prospecting survey and to Guangxi Geological Environment Monitoring Station for the monitoring data of groundwater level. This work is a Guangxi research and development project: Guangxi Science and Technology AB17195036, China; Guangxi Science and Technology AB18126062, China; Guilin Innovation-driven Programme: 20170214, China; project support.

Manuscript received Sept. 4, 2019
accepted Dec. 19, 2019
associate EIC FEI Hongcai
edited by FEI Hongcai

References

Adam, M., and Estorff, O.V., 2005. Reduction of train-induced building vibrations by using open and filled trenches. Computers & Structures, 83(1): 11–24 .

Breuer, P., Chmielewski, T., Górski, P., and Konopka, E., 2002. Application of GPS technology to measurements of displacements of high-rise structures due to weak winds. Journal of Wind Engineering & Industrial Aerodynamics, 90 (3): 223–230.

Chen, Y. J., Ju, S.H., Ni, S.H., and Shen, Y.J. 2007. Prediction methodology for ground vibration induced by passing trains on bridge structures. Journal of Sound & Vibration, 302(4): 806–820.

Chen, W.H., Zhang, Y.H., and Qin, H.R., 2019. The karst geomorphologic regionalization in China. Acta Geologica Sinica (English Edition), 2019, 93(supp.2): 462–463.

Crispino, M., and D"Apuzzo, M., 2001. Measurement and prediction of traffic-induced vibrations in a heritage building. Journal of Sound & Vibration, 246(2): 319–335.

Ding, D.M., Ma, F.S., Zhang, Y.M., Wang, J., and Guo, J., 2011. Characteristics of land subsidence due to both high-rise building and exploitation of groundwater in urban area. Journal of Engineering Geology 19(03): 433–439 (in Chinese with English abstract).

Ferronato, M., Gambolati, G., Teatini, P., and Domenico, B., 2006. Stochastic poromechanical modeling of anthropogenic land subsidence. International Journal of Solids and Structures, 43(11–12): 3324–3336.

Fujikake, T., 1986. A prediction method for the propagation of ground vibration from railway trains on level tracks with welded rails. Journal of Sound & Vibration, 128(3): 524–527.

François, S., Pyl, L., Masoumi, H.R., and Degrande, G., 2007. The influence of dynamic soil–structure interaction on traffic induced vibrations in buildings. Soil Dynamics & Earthquake Engineering, 27(7): 655–674.

Gu, C., Wang, L.H., and Wan, J., 2008. Multi-frequency component analysis of building vibration measured with RTK-GPS. Journal of Geodesy and Geodynamics, 2: 120–122 (in Chinese with English abstract).

Gu, X.Y., and Tsien, S.I., 1991. Analysis of Shanghai land subsidence. Land Subsidence (Proceedings of III International Symposium on Land Subsidence). IAHS Publ.no.200.

Hao, H., and Ang, T.C., 1998. Analytical modeling of traffic-induced ground vibrations. Journal of Engineering Mechanics, 124(8): 921–928.

Hu, Y., Zhang, Z., and Guo, J., 2017. Discussing on monitoring and evaluation of building indoor ground-borne vibration induced by subway. Environmental Science and Technology, 30(01): 53–57 (in Chinese with English abstract).

Huang, Z.L., 2002. Analysis of ground water's uplift pressure on underground construction. Geotechnical Engineering Technique, 5: 273–274+283 (in Chinese with English abstract).

Huang, X.X., Xu, M., and Zhou, Y., 2011. Research on environmental geology problems of urban underground engineering in karst areas. Yangtze River, 42(10): 13–16+24 (in Chinese with English abstract).

Lak, M.A. , Degrande, G., and Lombaert, G., 2011. The effect of road unevenness on the dynamic vehicle response and ground-borne vibrations due to road traffic. Soil Dynamics & Earthquake Engineering, 31(10): 1357–1377.

Li, Q.S., Yang, K., Wong, C.K., and Jeary, A.P., 2003. The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building. , 91(9), 1175-1198.

Liu, J.G., and Liu, B., 2007. Anti-floating design and engineering technology of buildings. Industrial Construction, 4: 1–5. (in Chinese with English abstract).

Men, F.L., Chen, W.H., Cui, J., and Yuan, C.D., 1998. Moisture transfer in subsoils and its hazardous effect on buildings. Journal of Natural of Natural Disasters (?), 4: 88–97 (in Chinese with English abstract).

Meng, X., Dodson, A.H., and Roberts, G.W., 2007. Detecting bridge dynamics with gps and triaxial accelerometers. Engineering Structures, 29(11): 3178–3184.

O'Brien, J., and Rizos, D.C., 2005. A 3D bem-fem methodology for simulation of high speed train induced vibrations. Soil Dynamics & Earthquake Engineering, 25(4): 289–301.

Phien-wej, N., Giao, P.H., and Nutalaya, P., 2006. Land subsidence in Bangkok Thailand. Engineering Geology, 82: 187–201.

Phien-Wej, N., Giao, P.H., and Nutalaya, P., 1998. Field experiment of artificial recharge through a well with reference to land subsidence control. Engineering Geology, 50: 187–201.

Trampe Broch, J., 1980. Mechanical vibration and shock measurements. Place name (?): Bruel & Kjaer.

Tsuno, K., Furuta, M., and Abe, K., 2010. Numerical calculation method for prediction of ground-borne vibration near subway tunnel. Journal of Mechanical Systems for Transportation & Logistics, 3(1): 53–62.

Wang, G.Y., and Zhang, Y., 2014. Discussion on building resonance effect detection and solution. Water Resources

Planning and Design, 2: 51–53+57 (in Chinese with English abstract).
Xia, H., Zhang, N., and Cao, Y.M., 2005. Experimental study of train-induced vibrations of environments and buildings. Journal of Sound & Vibration, 280(3): 1017–1029.
Yang, X., 2018. Detection and treatment of resonance phenomenon of small high-rise buildings. Value Engineering, 37(03): 63–65 (in Chinese with English abstract).
Yang, Y. B., and Hung, H.H., 2009. Wave propagation for train-induced vibrations. World Scientific.America.
Zhu, Z.H.,Yu, Z.W., Zhu,Y.L., and Gao, M.M., 2013. Analysis on environment and building vibration induced by passing trains on bridge structures. Journal of the China Railway Society 35 (04): 102–109 (in Chinese with English abstract).

About the first author

ZHANG Fawang, male, born in 1965 in Hengshui City, Hebei Province; researcher; graduated from China University of Geosciences (Beijing); Secretary, Institute of Karst Geology, Chinese Academy of Geological Sciences. The research direction is hydrogeology and environmental geology. Email: zhangfawang@karst. ac.cn; phone: 18707737886.

About the corresponding author

LUAN Song, male, born in 1989 in Jixi City, Heilongjiang Province; Engineer; graduated from Guilin University of Technology; research assistant of Institute of Karst Geology, Chinese Academy of Geological Sciences. Research direction: Hydrogeology and Karst geology. Email: luansong@karst.ac.cn; phone: 18778382121.