Study on Characteristics of Ground Motion in Karst Area Based on Viscoelastic Artificial Boundary

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Abstract. Karst is a common geological condition in engineering construction. In order to study the influence of karst cave and boundary condition on the analysis of free field ground motion in karst area, viscoelastic artificial boundary was studied in free field ground motion analysis of karst region, a three-dimensional finite element model whose dimension is 1000 m × 1000 m × 500 m was set up, characteristics of ground motion in karst region were studied on the basis of viscoelastic artificial boundary, as well as the influence of karst cave on displacement, velocity and acceleration were considered. The results show that, natural frequencies of free field were decreased at different degrees after viscoelastic artificial boundary was adopted. Compared with the response of free field without karst cave, the variation trend of maximum displacement, maximum velocity and maximum acceleration were all spread around the karst cave, the biggest change of maximum displacement, maximum velocity and maximum acceleration appeared on the top of karst cave. Compared with spectrum curve of free field without karst cave, the amplitude difference of free field with karst cave was significant in low order frequency, and was opposite in high order frequency, the influence of karst cave on vertical direction is bigger than horizontal direction, which can provide reference for construction of karst region.

Keywords: Karst area · Vibration analysis · Karst cave
Viscoelastic artificial boundary

1 Introduction

The karst areas in the south of China are mainly composed of soluble carbonate rocks. Under the action of dissolution, weathered, denuded and red soil, the karst area is formed with various terrain. The representative soil layers or strata in karst areas are: carbonate rock layer, calcareous mud stone layer and red clay layer, the geological structure of karst area determines the activity and its nature of earthquake [1, 2], for some small magnitude

D. Zhang and X. Huang (Eds.): GSIC 2018, *Proceedings of GeoShanghai 2018 International Conference: Tunnelling and Underground Construction*, pp. 207–214, 2018.
https://doi.org/10.1007/978-981-13-0017-2_20

earthquake can cause considerable damage in karst area, As a result, free vibration analysis is really essential in karst area. So far, among the study on the influence of karst cave in karst area, boundary is often simplified as a fixed end constraint, viscoelastic artificial boundary was seldom used. In order to study the influence of karst cave and boundary condition on free field vibration analysis in karst area, a three-dimensional karst area finite element model of 1000 m × 1000 m × 500 m was established by ANSYS finite element software, and the effects of fixed end constraint and artificial boundary constraint on natural vibration frequency of karst free field were studied, the influence of karst cave on the displacement, velocity and acceleration of free field, as well as the influence of karst cave on spectral curve of center node on surface of free field was researched, which can provide reference for engineering construction in karst area.

2 Artificial Boundary of Karst Foundation

The purpose of artificial boundary is to convert an infinite model into a finite model which is easy for implementation [3]. At present, the widely used artificial boundary in engineering mainly includes viscous boundary, transmission boundary and viscoelastic boundary [4, 5]. The earliest adhesion boundary aims to set up the damper on the artificial boundary to absorb the external wave whose concept is simple and easy to implement. However, it ignores the resilience of elastic boundaries. The transmission boundary proposed by the academician Liao Zhenpeng is the process of using artificial boundary to simulate the boundary crossing, and it establishes the inner point to simulate the displacement of the boundary node at the edge of the boundary at the same time, however, when the input time is long and the waveform is highly irregular, the seismic wave will cause instability [6].

The viscoelastic boundary is the spring unit which is set up in parallel with the damping element on the viscous boundary, which possesses a good stability [7]. It is a local artificial boundary to use the viscoelastic boundary for the boundary effect of the distance simulation of karst foundation. It overcomes the low frequency drift caused by the viscous boundary, as well as it can simulate the elastic recovery performance of the outer half of the artificial boundary and can be excellently combined with the finite element software to meet engineering requirements [8]. The viscoelastic boundary is the stress boundary, and the elastic boundary element parameter is on the principle of dissipating energy by using viscous dampers, i.e. the vibration energy is dissipated by the viscous damping force produced by the damper which is set up at the boundary. In this paper, we adopt the concentrated viscoelastic artificial boundary. The specific parameters are as follows:

$$\text{The normal elastic stiffness is: } K_N = \alpha_N \frac{G}{R} \sum_{i=1}^{n} A_i \tag{1}$$

$$\text{The tangential elastic stiffness is: } K_T = \alpha_T \frac{G}{R} \sum_{i=1}^{n} A_i \tag{2}$$

$$\text{The normal damping coefficient is: } C_N = \rho c_p \sum_{i=1}^{n} A_i \tag{3}$$

$$\text{The tangential damping coefficient is: } C_T = \rho c_s \sum_{i=1}^{n} A_i \tag{4}$$

R: distance from source to artificial boundary, c_p and c_s: wave velocity of P wave and S wave, G: shear modulus of the foundation, ρ: mass density of foundation, α_N and α_T: correction coefficients of spring stiffness for normal and tangential in viscoelastic artificial boundary, based on parameter robustness and a large number of literatures [9–11], correction factor can be set as 1.33 and 0.67, formulas of wave velocity were shown as follows:

$$c_p = \sqrt{\frac{\lambda + 2G}{\rho}} = \sqrt{\frac{(1-\upsilon)E}{(1+\upsilon)(1-2\upsilon)\rho}} \tag{5}$$

$$c_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\upsilon)\rho}} \tag{6}$$

$$m = \rho r,\ c = \rho c_p,\ k = \frac{4G}{r} \tag{7}$$

The viscoelastic boundary is a stress boundary, which is the actual state of infinite domain, it is a function associated with the acceleration, velocity and displacement of boundary nodes. The force on the artificial boundary node is applied to the free space according to the equilibrium of the boundary node force:

Normal node force: $R_N = K_N \cdot w_N + C \cdot \dot{w}_N + f_N$

Tangential force: $R_T = K_T \cdot w_T + C \cdot \dot{w}_T + f_T$

These parameters are obtained by an infinite domain linear elastic medium:

$$f_N = -A\sigma = A\rho c_p \dot{w}_N \tag{8}$$

$$f_T = -A\tau = A\rho c_s \dot{w}_T \tag{9}$$

3 Overview of Karst Free Field Finite Model

In order to analyze the vibration of free field in karst area, a three-dimensional finite element model of free site in karst area was established by ANSYS finite element software. The model size is 1000 m × 1000 m × 500 m, the field length direction was set as X axis direction, the width direction was set as Y axis direction, and the vertical direction was set as Z axis direction. Solid 45 element was used to simulate soil, element grid size is 25 m × 25 m × 25 m, whose precision meets engineering requirements, viscoelastic artificial boundary condition was simulated by Combin14 unit. For the shape of actual cave is complicated and various, it was simplified as a cube of 50 m × 50 m × 25 m, which was located at 37.5 m below the surface of free ground in karst area. Sketch map of cave position with a red mark is shown in Fig. 1. Sketch map of viscoelastic artificial boundary condition is shown in Fig. 2.

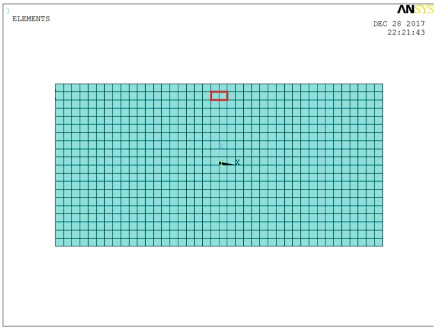

Fig. 1. Sketch map of karst cave position

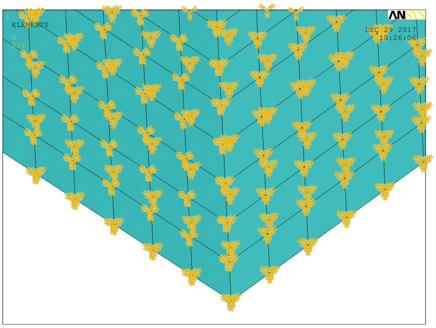

Fig. 2. Sketch map of viscoelastic artificial boundary condition

Material characteristics were as follows, elasticity modulus: 8000 MPa, deformation modulus: 4000 MPa, density: 2680 kg/m^3, Poisson's ratio: 0.25, damping ratio: 0.05, Longitudinal wave velocity: 0.60 m/s, Shear wavevelocity: 11937500 m/s.

4 The Influence of Boundary Condition on Natural Vibration Characteristics of Free Field

In order to study the influence of boundary condition on natural vibration characteristics of free field in karst area, the boundary condition of finite model was divided into three kinds: the first kind of boundary condition refers to only applying fixed end constraint at the bottom of finite element model, the second kind of boundary condition refers to applying fixed end constraint at the bottom and four sides of finite element model, the third boundary condition refers to the application of viscoelastic artificial boundary condition at the bottom and four sides of finite element model. Finite element model of the three boundary conditions was analyzed respectively, the results were shown in Table 1.

Table 1. Influence of boundary conditions on natural vibration characteristics of free field.

Order number	1	2	3	4
The 1st boundary condition (Hz)	0.4594	0.5128	0.7533	0.8166
The 2nd boundary condition (Hz)	1.1044	1.1662	1.3248	1.3605
The 3rd boundary condition (Hz)	0.3279	0.3287	0.3358	0.3362

Table 1 shows that, for free field model, compared with the 1st and the 2nd boundary condition, after viscoelastic artificial boundary condition was applied in finite element model, natural frequencies of free field model in karst area were reduced at different degrees, and vibration modes were also changed, which is more consistent with actual situation.

5 The Influence of Karst Cave on Displacement, Velocity and Acceleration of Karst Free Field

In order to study the influence of karst cave on the displacement, velocity and acceleration of karst free field. Viscoelastic artificial boundary condition was adopted in the finite element, EI Centro seismic wave was applied in the finite element, finite element model with karst cave and without karst cave were both analyzed. The maximum displacement, maximum speed and maximum acceleration of each node between free field with karst cave and free filed without karst cave were subtracted. The difference contour line of maximum displacement, maximum velocity maximum acceleration on each node was shown in Figs. 3, 4 and 5 respectively.

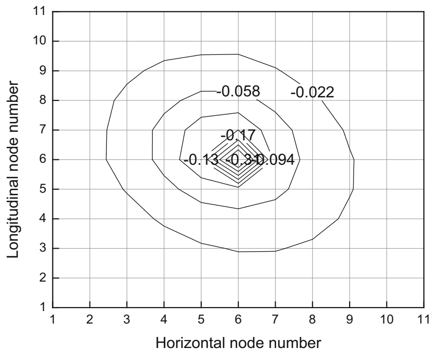

Fig. 3. Difference contour line between the maximum displacement of each node (m)

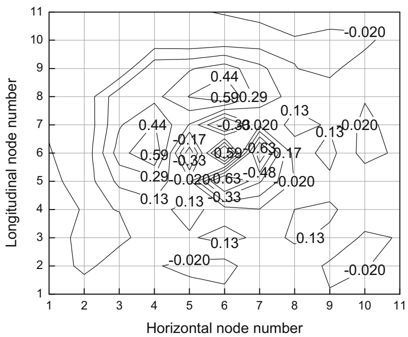

Fig. 4. Difference contour line between the maximum speed of each node (m/s)

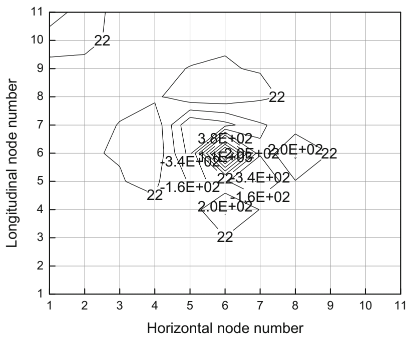

Fig. 5. Difference contour line between the maximum acceleration of each node (m/s^2)

Based on Figs. 3, 4 and 5, after viscoelastic artificial boundary was adopted in finite element and EI Centro earthquake wave was applied in finite element, the response of the maximum displacement, the maximum velocity and the maximum acceleration in the free field with karst cave in karst area compared with them of free filed without karst cave were spread around the karst cave, and the significant change of the maximum value of the displacement, velocity and the acceleration appeared at the top of karst cave.

6 Influence of Karst Cave on Spectrum Curve for Surface Center of Free Field

In order to study the influence of karst cave on the spectral curve of the center surface in free field, free field finite element model was divided into two working conditions: free field with karst cave and free field without karst cave, at the same time viscoelastic artificial boundary conditions and EI Centro seismic wave were applied in the finite element. Then the acceleration epoch curve was extracted from the center of earth surface in free field finite element model, and Fourier transform was carried out. In karst area, the variation trend of spectrum curve for the center node of earth surface was consistent, peak frequency were mainly located between 0 Hz and 5 Hz. In order to study the influence of karst cave on karst field better, the spectral curve values for center node of earth surface in free field with karst cave were subtracted by them without karst cave, the results were shown in Fig. 6.

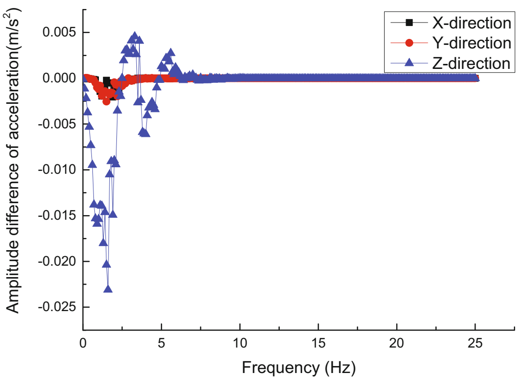

Fig. 6. Amplitude difference of acceleration for free field with and without karst cave

It can be seen from Fig. 6 that, for the surface center node of karst free field, the amplitude difference of acceleration between free field with karst and free field without karst is significant in low order frequency, while it is the opposite in high order frequency, and the influence of karst cave on vertical direction is bigger than horizontal direction.

7 Conclusions

In this paper, a three-dimensional finite element model of free field in karst area was established, and the influence of boundary condition and karst cave on the analysis of free field vibration in karst area was studied respectively. Main results and conclusions are as follows:

(1) For the free field finite element model in karst area, compared with the fixed boundary condition, the natural frequency of karst free field model was reduced to a certain extent by using viscoelastic artificial boundary condition.
(2) After artificial boundary was used in the free field finite element model in karst areas and EI Centro earthquake wave was applied in free field finite element, compared with the response of free field without karst cave, the change trend of maximum displacement, maximum velocity and maximum acceleration were spread around the karst cave, and the change of maximum displacement, maximum velocity and maximum acceleration is the biggest on the top of karst cave.
(3) After artificial boundary was used in free field finite element model in karst areas and EI Centro earthquake wave was applied in free field finite element, compared with spectrum curve of free field without karst cave, the amplitude difference between free field with karst and free field without karst is significant in low order frequency, while it is the opposite in high order frequency, and the influence of karst cave on vertical direction is bigger than horizontal direction, which can provide reference for construction of karst region.

Acknowledgement. This work was supported by National Natural Science Foundation of China (Grant No. 51068001 and 51368005), the Systematic Project of Guangxi Key Laboratory of Disaster Prevention and Structural Safety (2012ZDX04), and the Scientific Research Foundation of Guangxi University (Grant No. XBZ100762).

References

1. Yang, S., He, S., Meng, L., et al.: Research on earthquake-induced geological disasters in the karst area in Guangxi and methods for engineering-site preparation. China Earthq. Eng. J. **36** (04), 790–796 (2014)
2. Yang, S., Meng, L., Wang, Y.: Research of acceleration change in karst area by earthquake. World Earthq. Eng. **31**(03), 85–92 (2015)
3. Liu, J., Wang, Z.: 3D finite element analysis of large dynamic machine foundation considering soil-structure interaction. Eng. Mech. **19**(3), 34–38 (2002)
4. Zhang, X., Li, X., Chen, G., et al.: An improved method of the calculation of equivalent nodal forces in viscous-elastic artificial boundary. Chin. J. Theor. Appl. Mech. **05**, 1126–1135 (2016)
5. Du, X., Zhao, M., Wang, J.: A stress artificial boundary in fea for near-field wave problem. Chin. J. Theor. Appl. Mech. **38**(1), 49–56 (2006)
6. Liao, Z., Liu, J.: Finite element simulation of wave motion-basic problems and conceptual aspects. Earthq. Eng. Eng. Vib. **9**(4), 1–14 (1989)

7. Liu, J., Huan, Y., Li, J.: Application of artificial boundary and seismic input in general finite element software. Chin. J. Undergr. Space Eng. **7**(2), 1774–1779 (2011)
8. Liu, J., Lu, Y.: A direct method for analysis of dynamic soil-structure interaction. China Civil Eng. J. **31**(3), 55–64 (1998)
9. Gu, Y., Liu, J., Du, Y.: 3D consistent viscous-spring artificial boundary and viscous-spring boundary element. Eng. Mech. **24**(12), 31–37 (2007)
10. Liu, J., Wang, Z., Du, X., et al.: Three-dimensional visco-elastic artificial boundaries in time domain for wave motion problems. Eng. Mech. **22**(06), 46–51 (2005)
11. Zhao, R., Zhang, J., Liu, Z., et al.: Analysis of seismic wave problem based on visco-elastic artificial boundary under the ladder terrain. World Earthq. Eng. **31**(03), 220–227 (2015)