The effect of underground cavities on design seismic ground motion

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SUMMARY:
In this paper, the amplification of seismic ground motion by underground cavities in poroelastic (fluid-saturated) layered half-space in time domain is studied using indirect boundary element method by frequency transform, and the effect of the cavity interval and spectrum of incident waves on the amplification are studied. It is shown that the effect of underground cavities on seismic ground motion is significant, and the amplification of peak ground acceleration and its peak response spectrum can be up to 38.8% and 64.7%, respectively, for the case of Metro in Tianjin, China, excited by Taft wave and El Centro wave. It is suggested that the effect of underground cavities on design seismic ground motion be considered.

Keywords: Underground cavities, design seismic ground motion, poroelastic, amplification

1. INTRODUCTION

Underground railways are extensively being built in large cities in China to relief urban traffic pressure in recent years. Underground railway cavities are usually composed by two or more parallel cavities. According to engineering wave propagation theory, underground cavities may affect the design seismic ground motion along the cavities. However, as the authors know, there is little consideration of the effect of underground cavities on the design seismic ground motion in design codes and engineering practice.

The amplification of underground cavities on seismic ground motion is nothing but the scattering and diffraction of seismic waves around the cavities. The scattering and diffraction of plane waves around single cavity or tunnel in homogeneous half-space were presented by Lee (1977), Lee and Trifunac (1979), Lee and Karl (1992; 1993) and Davis et al (2001) using wave function expansion method. The scattering and diffraction of plane waves around twin cavities in half-space were studied by Liang et al (2003; 2004; 2005, 2006) using wave function expansion method. Recently, this problem were studied numerically by finite element method combined with artificial boundaries (Chen et al, 2003; He et al, 2009; Zhu et al, 2011; Liang et al, 2011) and by indirect boundary element method (Liang and Ba, 2012). All the studies above are limited in elastic half-space. However, engineering sites are often saturated in coastal area. Liang et al (2007a; 2007b; 2007c) present analytical solutions for the case of single cavity in poroelastic half-space.

In this paper, the amplification of seismic ground motion by underground cavities in poroelastic layered half-space is studied using indirect boundary element method, and the effect of underground cavities on the design seismic ground motion is presented.

2. METHOD

The model is shown in Figure 1. Two cavities, with radius R, interval B and depth d, are located in

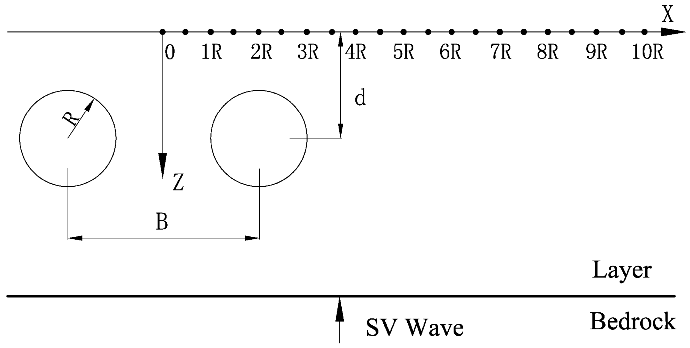

Figure 1. The model

poroelastic layered half-space, with the soil layers above water level being elastic and dry, with the soil layers under water level being poroelastic and saturated, and with the bedrock being elastic and dry. Seismic (SV) wave is incident vertically at the bedrock.

We use indirect boundary element method to determine the amplification of incident seismic waves by the cavities. First, the free-field responses in frequency domain are calculated to determine the dynamics response at the surface of the half-space and the cavities, and fictitious uniformly distributed loads are then applied at the surface of the cavities in the free field to calculate the Green's functions for dynamics response. The amplitudes of the fictitious distributed loads are determined from the zero stress boundary condition, and the dynamic response arising from the waves in the free field and from the fictitious distributed loads are summed to obtain the response in frequency domain. Then, the response in time domain is calculated by frequency transform. More detail about the methodology can be found in Liang et al (2006).

The exact dynamic stiffness matrix (Liang and You, 2004) of poroelastic soil layer and half-space based on Biot's theory, and the dynamic Green's function (Liang and You, 2005) for uniformly distributed load on an inclined line in a poroelastic layered half-space are used in the above analysis by indirect boundary element method.

3. NUMERICAL EXAMPLES AND DISCUSSIONS

The poroelastic layered half-space with typical soil parameters in Tianjin district are shown in Table 1. Two cavities are of radius 5m and depth 10m. Two acceleration time histories (Figure 2) with peak 0.1g, modified from Taft wave and El Centro wave, are used for incident seismic waves.

Table 1. Soil parameters of poroelastic layered half-space

soil layers	h_i (m)	V_{dry} (m/s)	ρ_{dry} (kg/m^3)	ξ_i	ρ_w (kg/m^3)	α	M (N/m^2)	m (kg/m^3)	b (Ns/m^4)
1	5	150	1750	0.05	—	—	—	—	—
2	5	150	1750	0.05	1000	0.8287	6506.9 E5	7222.2	1.0E6
3	10	175	1775	0.05	1000	0.8287	8661.5 E5	7222.2	1.0E6
4	10	200	1800	0.05	1000	0.8287	11027.5 E5	7222.2	1.0E6
5	10	250	1850	0.05	1000	0.8287	16095.8 E5	7222.2	1.0E6
6	10	300	1900	0.05	1000	0.8287	21341.6 E5	7222.2	1.0E6
7	10	350	1950	0.05	1000	0.8287	26451.6 E5	7222.2	1.0E6
8	10	400	2000	0.05	1000	0.8287	31232.1 E5	7222.2	1.0E6
9	10	450	2050	0.05	1000	0.8287	35563.6 E5	7222.2	1.0E6
Bedrock	∞	500	2100	0.02	—	—	—	—	—

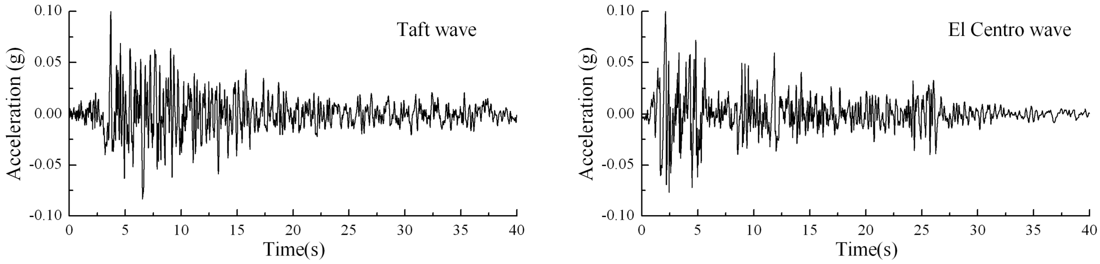

Figure 2. Incident seismic waves

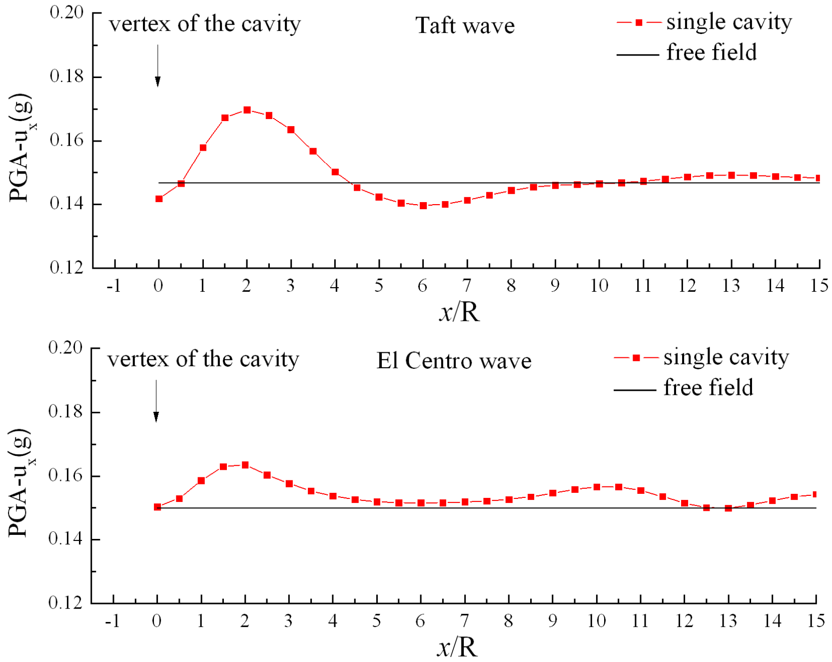

Figure 3. Envelope of horizontal PGAs at surface of half-space with single cavity

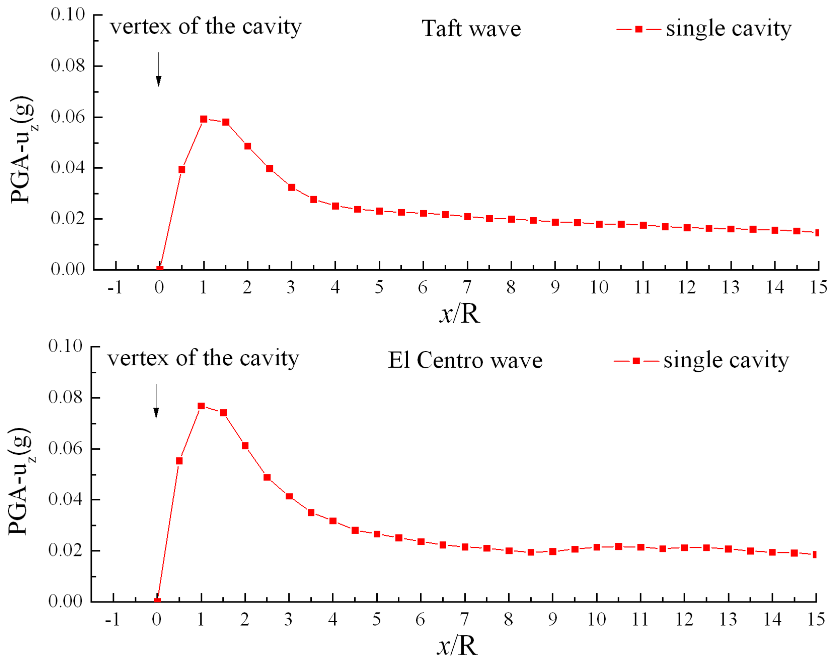

Figure 4. Envelope of vertical PGAs at surface of half-space with single cavity

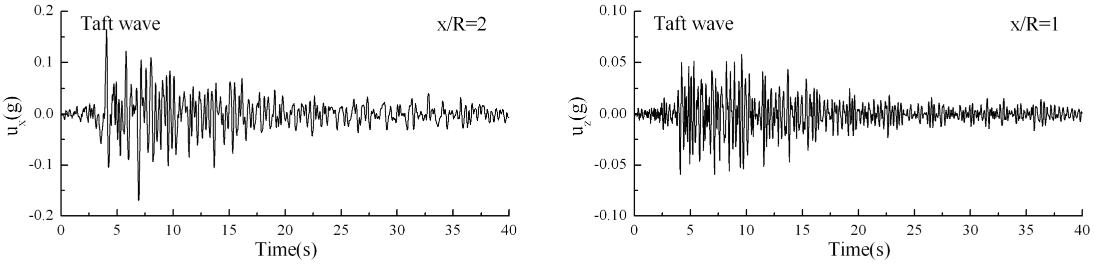

Figure 5. Surface acceleration time histories with single cavity for incident Taft wave

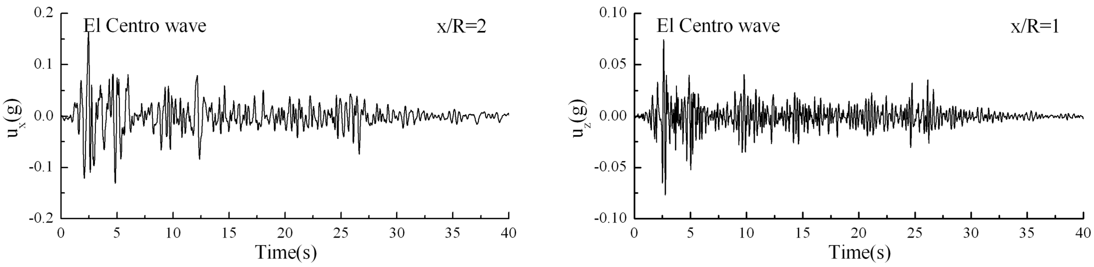

Figure 6. Surface acceleration time histories with single cavity for incident El Centro wave

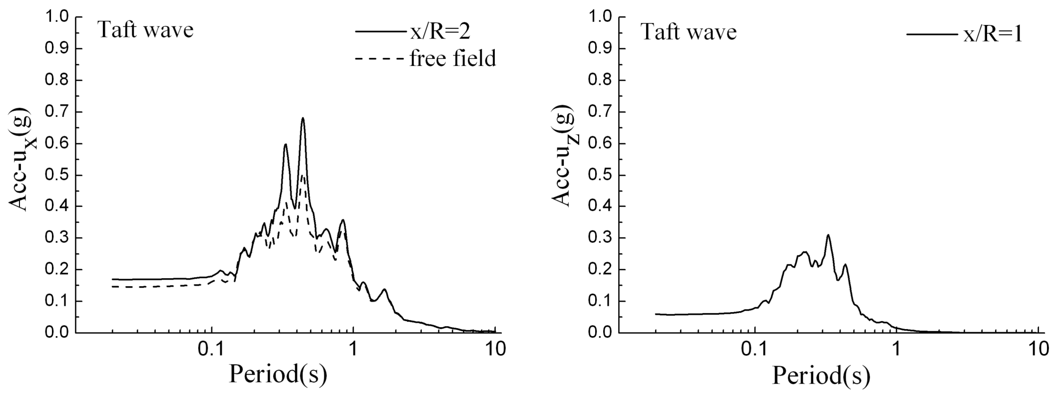

Figure 7. Acceleration response spectrum with single cavity for incident Taft wave

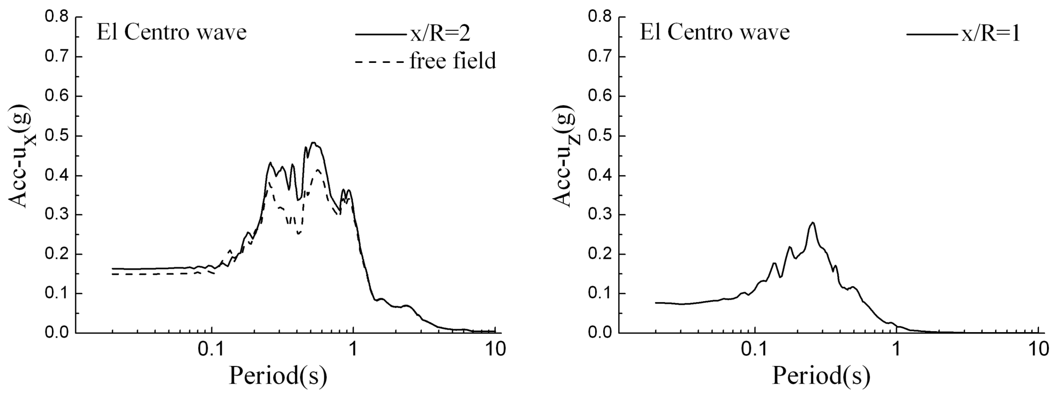

Figure 8. Acceleration response spectrum with single cavity for incident El Centro wave

We study the case of single cavity first. Figures 3 and 4 illustrate the envelope of horizontal and vertical PGAs (peak ground acceleration) at the surface of half-space versus different observation positions x/R, for incident Taft wave and El Centro wave. Figures 5 and 6 show the acceleration time histories at x/R=2 and x/R=1 on the surface of half-space, for incident Taft wave and El Centro wave. Figures 7 and 8 illustrate the response spectra of those acceleration time histories in Figures 5 and 6, compared with response spectra of the free-field response.

It can be found from these figures that, the maximal PGA is 0.170g at x/R=2 for incident Taft wave, and the amplification can be 15.6%, compared with the PGA 0.147g of the free field; the maximal PGA is 0.164g at x/R=2 for incident El Centro wave, with the amplification of 9.3%, compared with the PGA 0.150g of the free field.

For the response spectrum, the peak is 0.68g for incident Taft wave, and the amplification is 33.3%, compared with the peak 0.51g of the free field; the peak is 0.48g for incident El Centro wave, and the amplification is 14.3%, compared with the peak 0.42g of the free field.

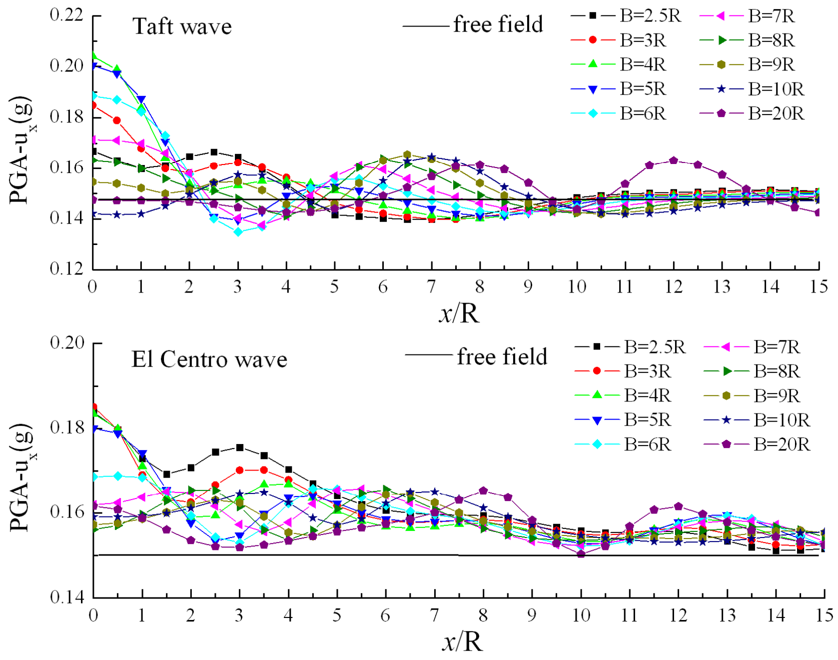

Figure 9. Envelope of horizontal PGAs at surface of half-space with twin cavities

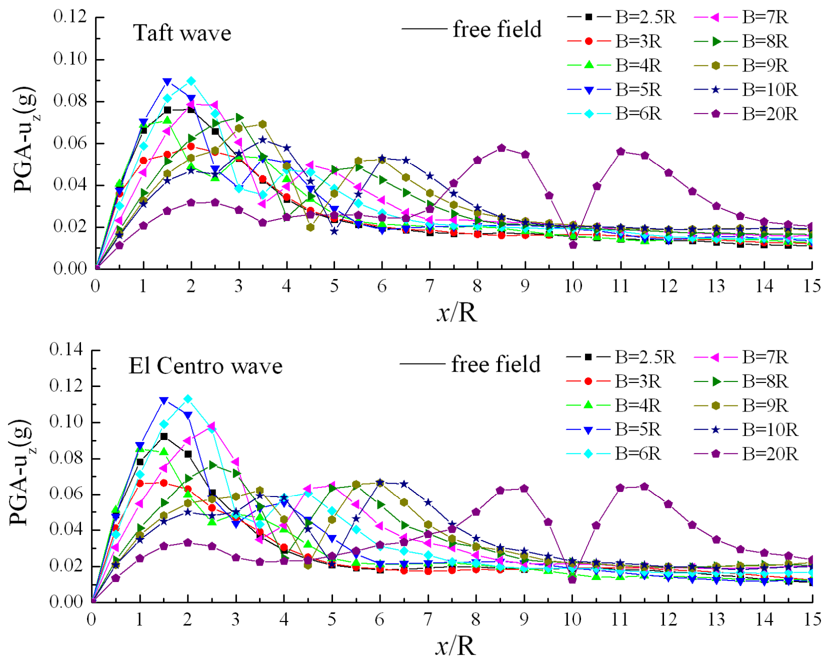

Figure 10. Envelope of vertical PGAs at surface of half-space with twin cavities

Figures 9 and 10 show the envelope of horizontal and vertical PGAs at the surface of half-space versus different observation positions x/R, for incident Taft wave and El Centro wave. Figures 11 through 14 illustrate the acceleration time histories at different observation positions on the surface of half-space, for incident Taft wave and El Centro wave. Figures 15 through 18 show the response spectra of those acceleration time histories in Figures 11 through 14, compared with the response spectra of the free field.

It can be seen from these figures that, the maximal PGA is 0.204g when B=4R for incident Taft wave, and the amplification can be 38.8%, compared with the PGA 0.147g of the free field; the maximal PGA is 0.185g when B=3R for incident El Centro wave, with the amplification of 23.3%, compared with the PGA 0.150g of the free field.

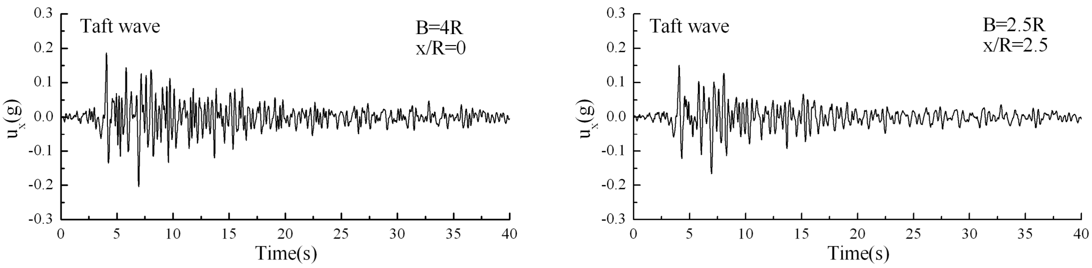

Figure 11. Horizontal acceleration time histories with twin cavities for incident Taft wave

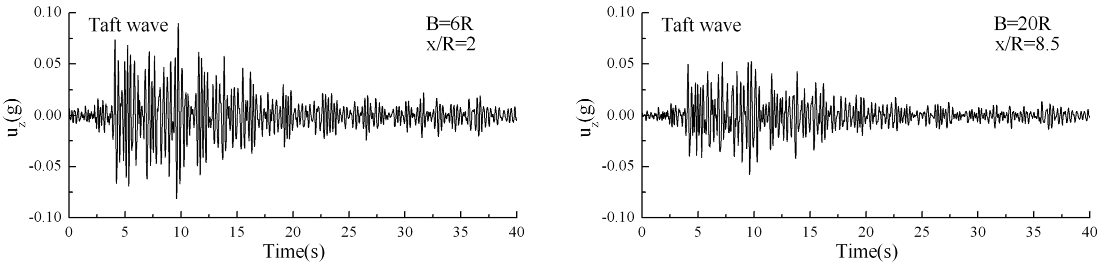

Figure 12. Vertical acceleration time histories with twin cavities for incident Taft wave

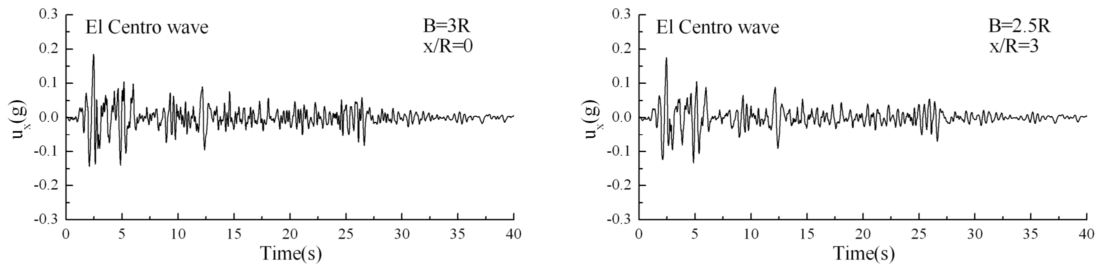

Figure 13. Horizontal acceleration time histories with twin cavities for incident El Centro wave

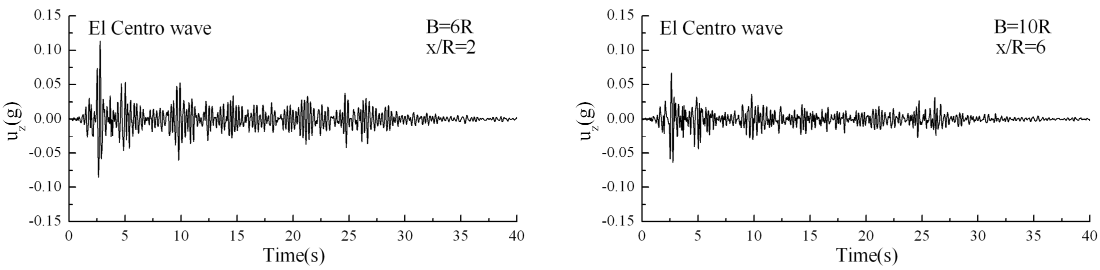

Figure 14. Vertical acceleration time histories with twin cavities for incident El Centro wave

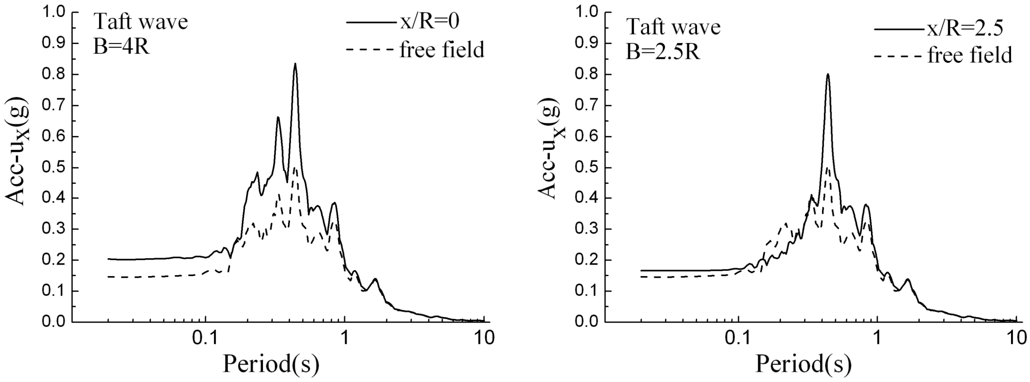

Figure 15. Horizontal response spectrum with twin cavities for incident Taft wave

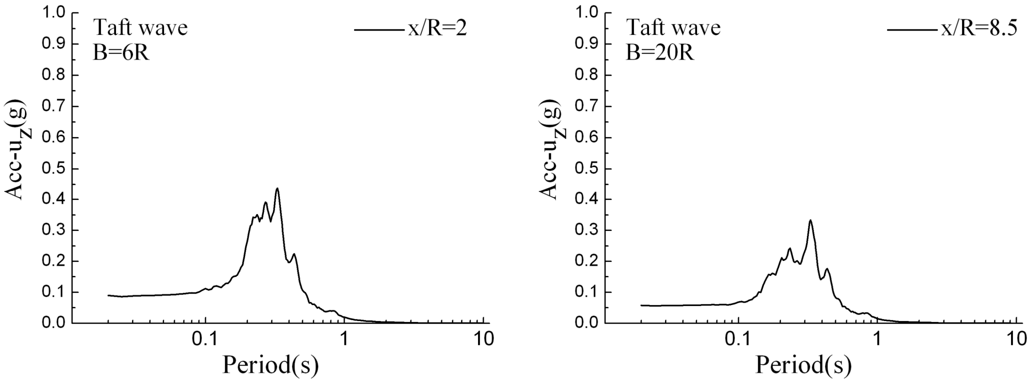

Figure 16. Vertical response spectrum with twin cavities for incident Taft wave

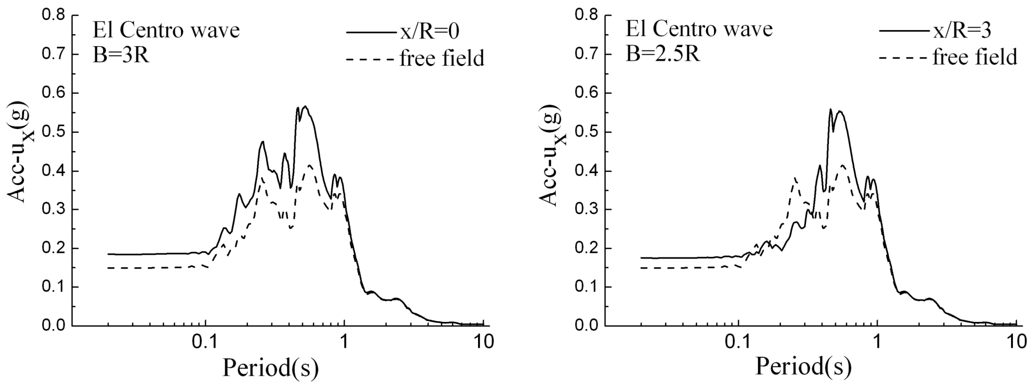

Figure 17. Horizontal response spectrum with twin cavities for incident El Centro wave

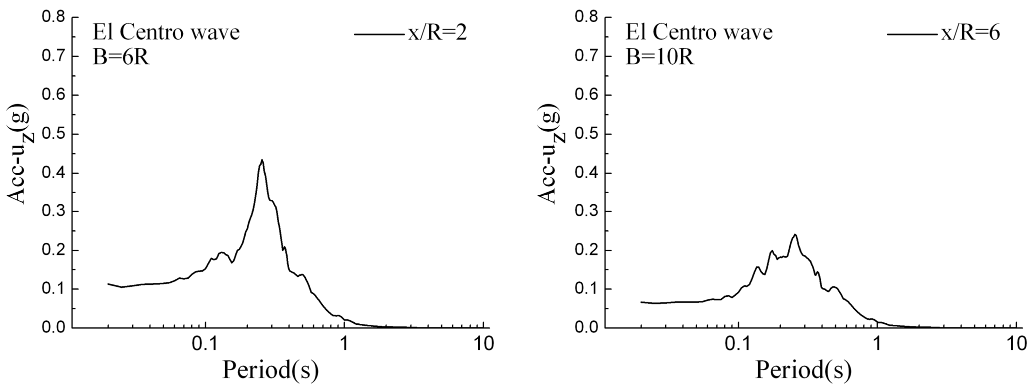

Figure 18. Vertical response spectrum with twin cavities for incident El Centro wave

For the response spectrum for incident Taft wave, the peak is 0.84g at x/R=0 when B=4R, and the amplification can be 64.7%, compared with the peak 0.51g of the free field; the peak is 0.80g at x/R=2.5 when B=2.5R, and the amplification is 56.9%.

For the response spectrum for incident El Centro wave, the peak is 0.57g at x/R=0 when B=3R, and the amplification can be 35.7%, compared with the peak 0.42g of the free field; the peak is 0.56g at x/R=3 when B=2.5R, and the amplification is 33.3%.

4. CONCLUSIONS

This paper studies the amplification of seismic ground motion by underground cavities in poroelastic layered half-space in time domain using indirect boundary element method by frequency transform, and discusses the effect of the cavity interval and spectrum of incident waves on the amplification. It is shown that the effect of underground cavities on seismic ground motion is significant, and the amplification of peak ground acceleration and its peak response spectrum can be up to 38.8% and 64.7%, respectively, for the case of Metro in Tianjin, China, excited by Taft wave and El Centro wave. It is suggested that the effect of underground cavities on design seismic ground motion be considered.

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