Ground Response and Seismic Mitigation Measures Under P-Wave Action

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Abstract. Canyons, as a typical form of irregular local topography, exert a substantial influence on the distribution of seismic motion. Numerous large-scale infrastructure projects such as water conservancy and bridges have been constructed in canyon areas. The seismic amplification effect of valley terrain cannot be overlooked in its impact on the disaster vulnerability of engineering facilities in this region. This paper investigates the seismic response of a semi-circular canyon site and proposes seismic mitigation measures for the two shoulders of the canyon, namely fillets and chamfers. Utilizing numerical simulation methods, the study delves into the site response under the vertical and oblique incidence of P-waves. By comparing and analyzing the seismic mitigation effects of the two measures on the canyon shoulders, differences in their effectiveness against P-wave-induced seismic response are revealed. The research findings offer valuable insights for the design and improvement of seismic-resistant structures in canyon sites, serving as a theoretical foundation for mitigating the impact of seismic disasters. This study not only contributes to an enhanced understanding of seismic influences but also presents new perspectives and approaches for seismic engineering in terms of mitigation techniques and design.

Keywords: semi-circular canyons; seismic mitigation measures; P-wave

1 INTRODUCTION

An earthquake is a natural disaster, the destructive potential of which can have serious impacts on human society and infrastructure. During an earthquake, ground shaking is caused by seismic waves, with P-waves (primary waves) being the first type of wave to arrive. The effect of P-waves on the ground surface directly relates to site response, making the study of site response under P-wave action and effective mitigation measures essential for enhancing structural seismic resilience.

Canyons, as a type of localized irregular topography, have a significant impact on the distribution of seismic effects, particularly near the canyon shoulders. In 1971, the United States Geological Survey observed for the first time a doubling of peak ground acceleration from the canyon top to the canyon bottom at the Pacoima dam[1]. Similarly,

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during the 6.7 magnitude Northridge earthquake in Southern California in 1994, anomalous peak ground acceleration was also detected near the shoulder of the Pacoima Dam, reaching 1.58g, which was three times greater than that at the valley bottom, thereby further confirming the existence of the canyon terrain amplification effect[2]. The Wenchuan earthquake of May 12, 2008 resulted in extensive loss of life, property damage, and structural destruction. The town of Beichuan, situated within a canyon formed by continuous low mountains, was severely affect-ed. Through investigations into seismic damage in Beichuan County, Zhang et al. (2010) found significant seismic amplification occurring on the sidewalls of the can yon during the earthquake[3]. Moreover, they discovered that as elevation increased, the seismic amplification factor progressively exceeded specified standards, leading to widespread landslides and collapses. This underscores the direct impact of canyon terrain amplification effects on the rationality of seismic input calculations for large-scale infrastructure projects in China, consequently greatly affecting the reliability of seismic design for such projects. To mitigate the destructive effects of canyon terrain effects on nearby structures, besides enhancing the seismic resistance of buildings, it is imperative to consider reducing the impact of site effects[4-5]. However, research in this area is currently lacking. Therefore, mitigation measures specifically tailored to can-yon sites constitute the focus of this study. Station observations based on existing seismic records are the most intuitive and reliable method for studying terrain effects. However, data from seismic arrays regarding terrain effects are relatively scarce, limiting in-depth exploration into the topic. In order to elucidate the mechanisms of terrain effects in valley terrain, extensive theoretical research has been conducted on the scattering and diffraction of seismic waves in valley sites, primarily divided into two categories: analytical studies and numerical simulations. Analytical studies primarily utilize wave function expansion methods[6], offering high precision and providing in-depth insights into the mechanisms and impacts of site effects. However, certain analytical methods necessitate complex mathematical computations and computing resources, particularly for large-scale earthquake simulations and site response analyses, which may incur high computational costs. Numerical simulation methods[7-9] mainly include finite difference and finite element methods, both of which entail finite truncation of infinite regions, making the setting of boundary conditions crucial. This study employs a finite element method based on viscoelastic artificial boundaries[10]. The physical concept of viscoelastic artificial boundaries involves applying a spring and damping component to each degree of freedom at the artificial boundary nodes, with the spring simulating the influence of infinite domains on finite domains, and the damping component providing energy dissipation. Viscoelastic artificial boundaries offer advantages such as high accuracy and computation-al stability, making them suitable for engineering applications.

This study proposes a seismic mitigation measure, namely filleting and chamfering, targeted at mitigating the terrain amplification effects in canyons. The finite element method based on viscoelastic boundaries is employed to analyze and study the seismic mitigation effects of these measures. Through comparative analysis, it is found that these mitigation measures effectively reduce seismic motion on the shoulders of the canyon, providing theoretical guidance for earthquake-resistant measures.

2 MITIGATION MEASURES AND COMPUTATIONAL MODELS

As previously indicated, extensive seismic damage investigations have shown that seismic motion on the shoulders of canyons is significantly larger than in other areas, adversely affecting nearby structures. The reason for this phenomenon lies in the complex terrain of the canyon shoulders, which causes reflection of seismic waves. The superposition of reflected waves with scattered waves leads to the amplification and attenuation of ground motion during earthquakes. To mitigate seismic motion near the canyon shoulders, this paper proposes a mitigation measure, namely, terrain modification at the canyon shoulders. When seismic waves pass through this area, complex interactions are no longer generated. The specific measure is to apply fillets or chamfers to the canyon shoulders. Fillets refer to using circular curves to modify corners or edges of objects, with the fillet's dimensions determined by the radius of the arc; chamfers refer to using inclined surfaces or beveled edges to modify edges or corners of objects, resulting in inclined surfaces rather than right angles, with the dimensions determined by the distance from the arc point to the upper corner of the beveled edge, as illustrated in Figure 1.

To evaluate the effectiveness of two seismic mitigation measures, this study utilized numerical simulation to examine the seismic response of a semi-circular canyon when subjected to vertically and obliquely incident P-waves.

In numerical simulation analysis, selecting material parameters and model constitutive laws is crucial because they directly impact the accuracy and reliability of simulation results. Through extensive calculations and argumentation, this study has found that the following choices of material parameters can lead to higher numerical simulation precision. The site is assumed to be composed of a linear elastic material with a Young's modulus of $E = 1.92 \times 10^{10}\,\mathrm{Pa}$, Poisson's ratio is $\nu = 0.25$, and density is $\rho = 1800\,\mathrm{Kg/m^3}$. The model dimensions are $20000\mathrm{m} \times 2000\mathrm{m}$ and the canyon radius is $b = 1000\mathrm{m}$. Apply viscoelastic artificial boundaries to the left, right, and bottom sides of the model.

The frequency components of the input waveform and the wave velocity characteristics of the soil affect the numerical precision of wave propagation in the soil. According to the study by Kuhlemeyer and Lysmer (1973), for an accurate representation of wave propagation in the model, the grid size must be smaller than 1/8 to 1/10 of the wavelength corresponding to the highest frequency in the input waveform, which is shown as follows:

$$\Delta l \le \left(\frac{1}{8} \sim \frac{1}{10}\right)\lambda \tag{1}$$

In the equation, λ represents the wavelength corresponding to the highest frequency. Based on the wave velocities and frequencies of the P waves, the corresponding wavelength λ can be determined. Combining the material parameters provided earlier and the above formula, the grid size is chosen as $25\mathrm{m} \times 25\mathrm{m}$.

The dimensionless frequency is defined as follows:

$$\eta = \frac{2b}{\lambda} \tag{2}$$

In the equation, λ represents the wavelength of the incident wave, b is the radius of the semicircular canyon

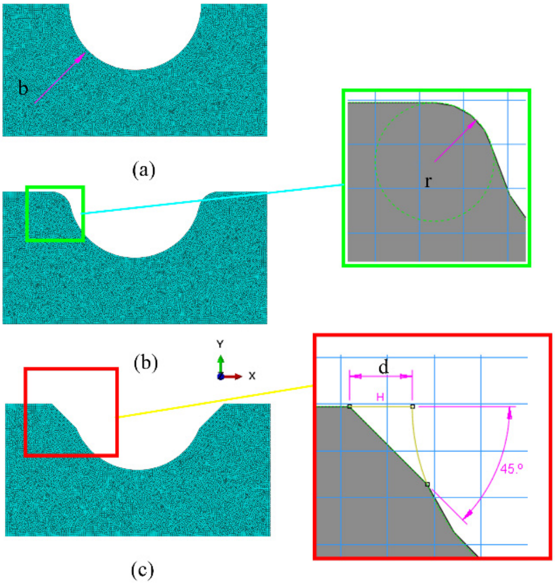
(a)
(b)
(c)

Fig. 1. Computational models: (a) Semi-circular canyon (b) Canyon with filleted shoulders, (c) Canyon with chamfered shoulders

3 COMPARE WITH PREVIOUS RESULTS

A semi-circular model was selected, with a dimensionless frequency $\eta = 2$ sinusoidal wave used as the incident P-wave, the incident angle of P-wave is 15°, as shown in Figure 2. Figure 3 presents a comparison between the results of this study and those of Kawase. In the graph, the horizontal axis x represents the ratio of the coordinate to the radius b of the canyon, while the vertical axis u_y / u_i represents the ratio of the vertical displacement amplitude caused by the P-wave to the incident wave's amplitude. From Figure 3, it can be observed that the results calculated in this study closely match those of previous studies[11], meeting the required accuracy.

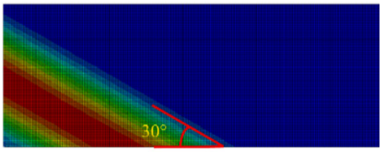

Fig. 2. Incident angle

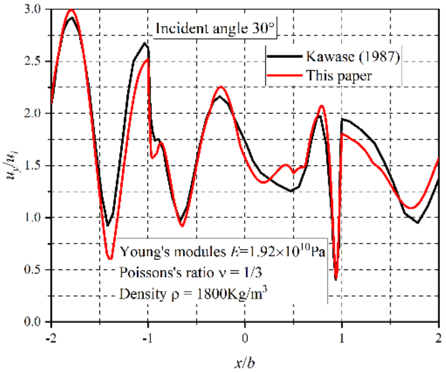

Fig. 3. Comparison of results with previous studies in this paper

4 EVALUATION OF sEISMIC mITIGATION eFFECTS UNDER P-WAVE aCTION

To assess the seismic mitigation effects of the two measures, this study computed the seismic motion responses of models with fillet radii $r = 0.1b$, $0.2b$, $0.3b$ and canyon models with chamfer widths $d = 0.1d$, $0.2d$, $0.3d$ under the influence of P-waves.

Figures 4,5 and 6 illustrate the vertical ground surface displacement distribution of the canyon under the action of vertical and oblique incident P-waves. The left and right columns depict the ground surface displacement for the fillet and chamfer mitigation measures, respectively. r represents the radius of the fillet, d represents the chamfer width, and u_y / u_f denotes the ratio of the vertical ground surface displacement caused by P-waves to the incident wave amplitude. Observing the figures, it becomes apparent that the corner points of the canyon exert a considerable influence on nearby seismic motion. This arises from the intricate interaction between incident and reflected waves at these locations, leading to substantial ground displacement. This is detrimental to the surrounding structures. However, after filleting or chamfering the corners of the canyon, the ground displacement at these points significantly decreases. It can be observed from the figure that the seismic mitigation measures proposed in this study have a good mitigation effect on P-waves at various incident angles, whether on the incident or opposite side. Additionally, the mitigation effect is related to the size of the filleted or chamfered corners. Choosing appropriate dimensions not only achieves good seismic mitigation but also reduces excavation volume, which is significant for practical engineering applications.

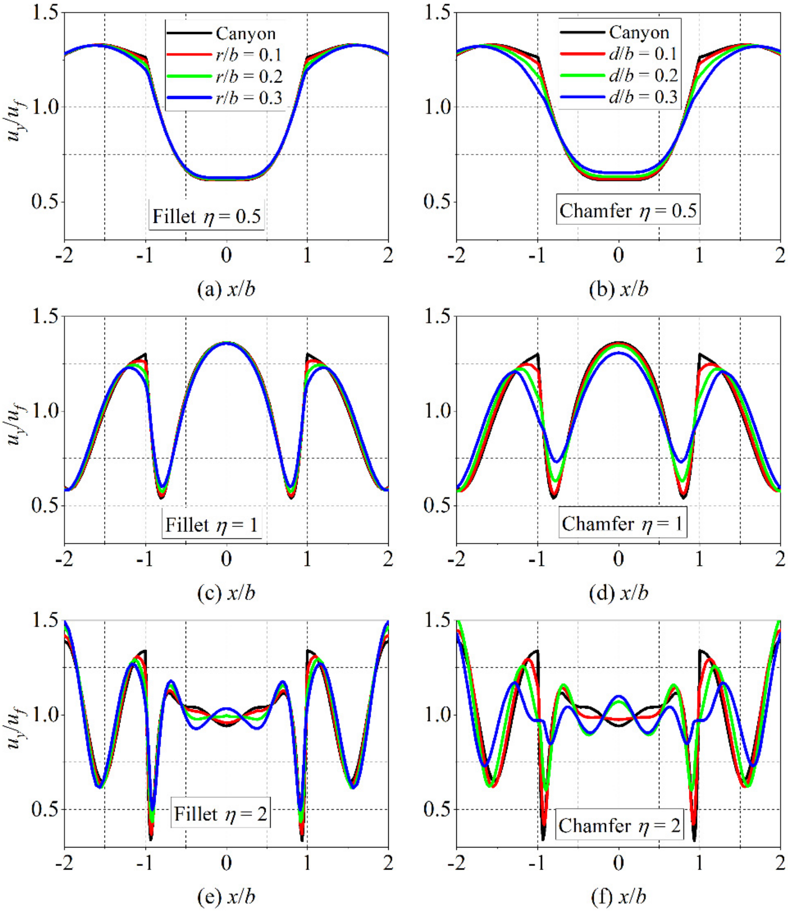

Fig. 4. P-wave vertical incidence

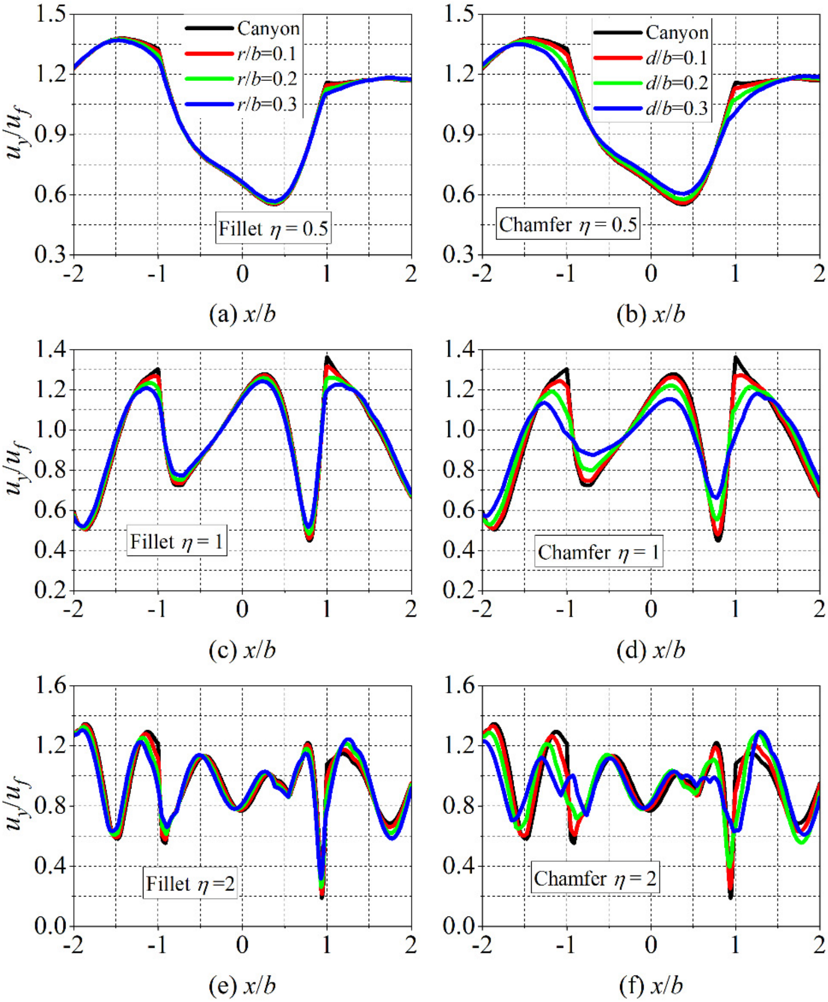

Fig. 5. P-wave incident at 15° angle

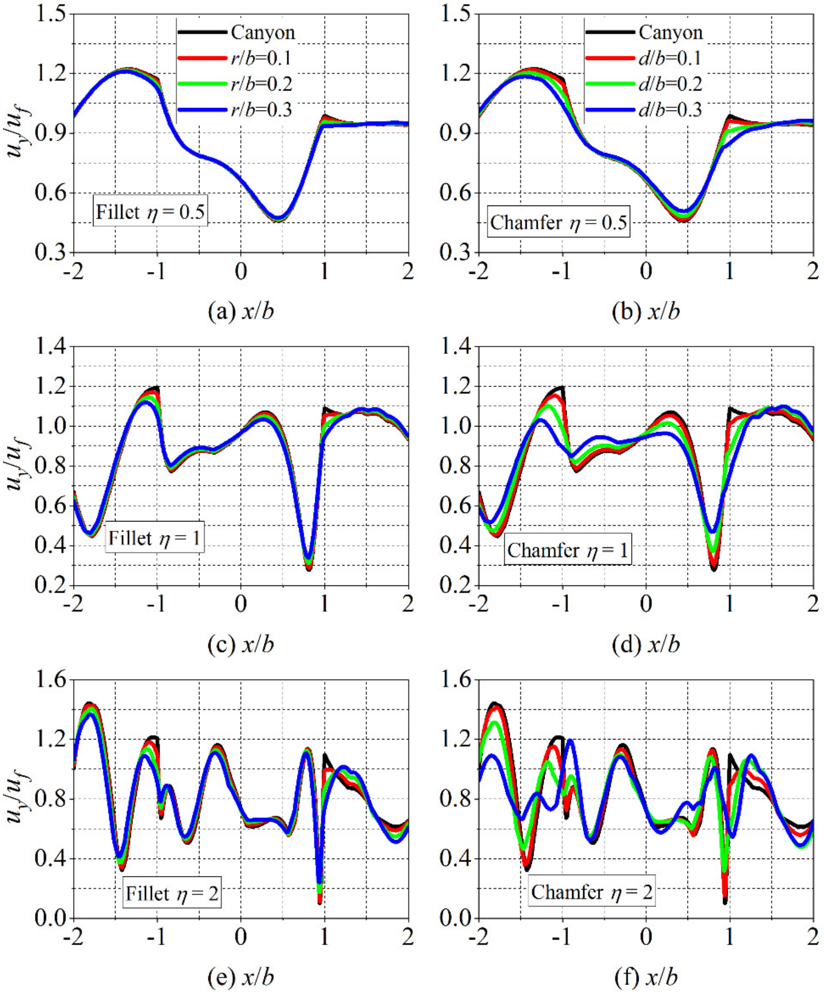

Fig. 6. P-wave incident at 30° angle

In order to more accurately demonstrate the seismic mitigation effects near the shoulders of the canyon, this study respectively selects the maximum and minimum displacement values at $x/b = -1$ or $x/b = 1$. As shown in Figure 7, the maximum displacement value (Max_val) corresponds to the displacement at the shoulder of the canyon without seismic mitigation treatment, while the minimum displacement value (Min_val) corresponds to the smallest ground displacement at the same position after seismic mitigation treatment. As shown in Figure 5, the difference between these two values is taken and presented in a table format, as shown in Table 1 and Table 2, by calculating the ratio of this difference to the maximum displacement value.

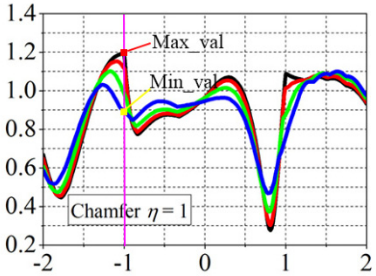

Fig. 7. Illustration of the sampling method

Table 1 and Table 2 respectively demonstrate the seismic mitigation effects at the shoulders of the canyon on the incident and opposite sides under different incident angles and frequencies. From the tables, it can be observed that as the frequency of the incident waves increases, the seismic mitigation effect improves. For oblique incident seismic waves, there are differences in the seismic mitigation effects at the canyon shoulders, and these differences increase with increasing incident wave frequency. Overall, the seismic mitigation effect is slightly better on the opposite side. Additionally, there are significant differences in the effects produced by the two seismic mitigation measures. The data in the tables show that chamfering treatment produces better results compared to filleting treatment.

Table 1. Statistical analysis of seismic mitigation effects at the shoulder of the incident wave side

Incident angle	Fillet			Chamfer		
	n=0.5	n=1	n=2	n=0.5	n=1	n=2
0°	0.0517	0.1191	0.2052	0.1394	0.2597	0.2812
15°	0.0463	0.1193	0.2491	0.1224	0.2477	0.3227
30°	0.0403	0.1215	0.2510	0.1104	0.2519	0.3156

Table 2. Statistical analysis of seismic mitigation effects at the shoulder of the opposite wave side

Incident angle	Fillet			Chamfer		
	n=0.5	n=1	n=2	n=0.5	n=1	n=2
0°	0.0517	0.1191	0.2052	0.1394	0.2597	0.2812
15°	0.0479	0.1253	0.2861	0.1486	0.3898	0.4440
30°	0.0512	0.1315	0.3244	0.1399	0.3018	0.4800

5 CONCLUSION

The following conclusion was drawn from the numerical simulation conducted in this study to investigate the seismic mitigation effects of two different measures on the shoulders of the canyon under the influence of P-waves at various angles:

(1)When the incident P-wave frequency is higher, the damping effect is more pronounced, and chamfered damping measures are more effective than rounded corner damping measures.

(2)Under oblique incidence of P-waves, the damping effect on the two shoulders differs. The damping effect on the back-wave surface is better than that on the incident-wave surface.

Based on our research findings, future seismic disaster mitigation measures can be designed and implemented targeting the canyon terrain amplification effects. In addition to strengthening the seismic resistance of buildings, specific terrain modification measures such as rounding or chamfering can be considered on the shoulders of the canyon to alleviate the amplification effects of seismic motion. These measures are expected to enhance the seismic resilience of buildings and infrastructure in can-yon areas, thereby reducing the risk of seismic disasters. However, our study also has some limitations and unanswered questions. Firstly, our research primarily focuses on numerical simulation analysis, lacking support from field verification and observational data. Additionally, our study has not extensively explored the effects of different types of canyon terrain on the amplification of seismic motion, as well as the differences in the effectiveness of various seismic mitigation measures. Therefore, future research can further validate and refine our numerical simulation results through field investigations and station observations, and delve into the impact of different terrains and seismic mitigation measures on seismic motion.

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