Simulation of P$_{1}$-Wave Differential Motions for a Water-Covered Convex Site with Tunnel Effects and the Nonlinear Response of a Long-Span Bridge

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Abstract

Differential seismic simulation of P1 wave incidence on a convex site with an underwater buried tunnel was conducted, and its influence on the nonlinear response of a cross-site bridge was investigated in detail. First, the theoretical solution of the P1 wave for the site was derived and the auto-power spectrum was obtained. An overlying-water coherence model was introduced and combined with the auto-power spectrum to obtain the cross-power spectrum. Together with the transfer function, the underground power spectrum matrix was successfully constructed, thereby realizing multi-support ground motion simulation and verifying its rationality. Then, the effects of tunnel burial depth and the overlying-water coherence effect on ground motion were discussed in detail. Finally, the ground motion excited by the site was regarded as the "free field" , and the equivalent nodal forces calculated by the program were directly input into the "boundary-soil-rigid frame bridge" finite element system to conduct nonlinear response analysis of the structure under differential seismic excitation. The results show that: (1) the amplitudes of underground multi-support ground motions in the case of a shallow-buried tunnel are greater than those of a deep-buried tunnel; (2) as the tunnel burial depth increases, the peak displacement and internal force responses of the bridge decrease; (3) compared with the traditional coherence model, the spatial variability of ground motion obtained using the overlying-water coherence model is significantly enhanced; (4) the peak responses of the bridge under multi-support ground motion excitation generated using the overlying-water coherence model are generally higher; (5) under super-large differential seismic excitation using the overlying-water coherence model, the initial damage time of the bridge is significantly advanced.

Full Text

Simulation of P_1-Wave Differential Motions for a Water-Covered Convex Site with Tunnel Effects and the Nonlinear Response of a Long-Span Bridge

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Abstract: This study conducts simulations of differential seismic motions for a convex site with a buried tunnel beneath overlying water under incident P_1 waves, and examines in detail their influence on the nonlinear response of a long-span bridge crossing the site. First, the theoretical solution for P_1 waves in the site is derived and the auto-power spectra are obtained. A water-covered

coherence model is introduced and combined with the auto-power spectra to obtain the cross-power spectra; together with the transfer functions, an underground power spectral matrix is successfully constructed, thereby realizing multi-support ground-motion simulation and providing a rationality verification. Then, the effects of tunnel burial depth and the water-covered coherence effect on seismic motions are discussed in detail. Finally, the site-excited seismic motions are regarded as the "free field," and the equivalent nodal forces calculated by the program are directly input into a finite-element system of "boundary–soil–rigid-frame bridge" to analyze the nonlinear response of the structure under differential seismic excitation. The results show that: under shallow-buried tunnel conditions, the amplitudes of underground multi-support seismic motions are all greater than those for a deeply buried tunnel; as the tunnel burial depth increases, the peak displacement and internal-force responses of the bridge decrease; compared with the traditional coherence model, the water-covered coherence model yields significantly enhanced spatial variability of seismic motions; under multi-support ground-motion excitation generated using the water-covered coherence model, the peak responses of the bridge are generally higher; under ultra-large differential seismic excitation using the water-covered coherence model, the initial damage time of the bridge is significantly advanced.

Keywords: bridge engineering; P_1-wave scattering; differential seismic input; tunnel effect; nonlinear response

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Simulation of P_1-Wave Multi-Support Seismic Motions for a Seawater Convex Topography Site with a Buried Tunnel and the Nonlinear Response of a Long-Span Bridge

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Abstract: This study made multi-support seismic simulations for a saturated half-space with buried tunnel and seawater convex topography with P_1-waves incidence. Effect of the resulting seismic motions was thoroughly investigated on the nonlinear response of a long-span bridge crossing the specific terrain. First, the frequency-domain solution for P_1-waves is theoretically derived to obtain the auto-spectrum. Cross-spec-

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trum is obtained by introducing a water-covered coherency model coupled with the transfer function. Construction of the underground power spectral matrix is finally performed for the site, enabling the realization of multi-support seismic motions. The rationality of the resulting seismic motions is further validated. A detailed discussion is then conducted on the effects of tunnel burial depth and coherency functions on seismic characteristics. Finally, the generated seismic motions are regarded as "free-field input" and are directly applied to the "artificial boundary–soil–constitutive finite element model" system in the form of equivalent nodal forces. Nonlinear response analysis of a continuous rigid-frame bridge subjected to underground multi-support motions is further carried out. The results indicate that: the amplitude of underground multi-support seismic motion for shallow-buried tunnels exceeds that for deep-buried tunnels. As tunnel depth increases, the peak internal-force response of the bridge decreases. The spatial variability of seismic motions obtained from the water-covered coherency model is significantly enhanced compared with that obtained from the traditional model. Under seismic excitation generated by the water-covered coherency model, the peak response of the bridge generally surpasses that obtained from the traditional model. Under the excitation of multi-support rare earthquakes using the water-covered coherency model, the initial failure time of the bridge is significantly advanced.

Key words: bridge engineering; P_1-wave scattering; input of spatially variable seismic motion; buried tunnel' s effect; nonlinear response analysis

Seismic analysis of long-span structures must consider the spatial variability of ground motion [1-2], and the key prerequisite is to obtain seismic differential motion related to the specific site. Studies show that P waves can propagate in seawater and cause seismic motion in offshore areas to differ from that on land [3]. In addition, the scattering of seismic waves by surface topography (valleys, hills, and seawater) and underground topography (caverns and tunnels) causes ground motion to exhibit pronounced spatial variability; therefore, carrying out ground-motion simulation for corresponding sites is of great significance.

Unlike flat sites, seismic motion fields under local topographic effects are more complex and more difficult to obtain. As a common type of local topographic site in marine areas and on land, convex topography [4] has important research value. At present, studies of such sites have mostly focused on land [5-7], with relatively little attention paid to offshore convex topography. Reference [8] investigated the effects of local topography and seawater from a finite element perspective, but it could not reveal the characteristics of offshore seismic motion fields from a physical perspective. Offshore seismic studies involve multiphysics coupling among the seawater layer, seabed saturated soil, and bedrock media. In addressing such problems, the wave method has received extensive attention because it can solve the scattering and diffraction of seismic waves starting from the fundamental equations describing medium vibration [9]. Therefore, this study first adopts the basic theory of the wave method, combined with Hankel integral transform techniques [10] and a domain-decomposition strategy, to successfully solve the frequency-domain solution of the site seismic response of an underwater convex circular-arc terrain—buried tunnel site under P_1-wave incidence, and verifies its accuracy, finally obtaining the transfer function required for offshore seismic-motion simulation. In addition, the coherency function is the key to constructing multi-point seismic power spectra. In this study, the site is entirely underwater; therefore, the water-covered coherency function model given in Reference [11] is adopted so as to incorporate the water-covering effect into seismic-motion simulation.

In addition, in the field of soil–structure interaction (soil-structure interaction, SSI), attention has generally been paid to the seismic response of buried structures [12-13], while their influence on ground-surface displacement has been considered less often [14]. JIN et al. [15] studied the structure–soil–structure interaction (structure-soil-structure interaction, SSSI) between a tunnel and aboveground buildings under SH-wave excitation, and pointed out that tunnel–structure resonance can cause abrupt changes in the site transfer function, amplifying structural responses at certain frequencies. TSINIDIS et al. [16] discussed the influence of tunnels on superstructures from both numerical modeling and theoretical analysis perspectives. In fact, shallow-buried tunnels can significantly alter the wave-field distribution of a site [17], thereby producing effects on seismic motion and structural response that cannot be ignored. Therefore, it is necessary to explore the influence of tunnel burial depth on the characteristics of ground motion. Most of the above studies were carried out for a single medium and considered only the effects caused by simple SH-wave excitation; relatively few studies have addressed the effect of P_1-wave incidence in saturated soil.

In summary, starting from wave theory, this study realizes multi-point ground-motion simulation for an underwater convex topography—buried tunnel site under the scattering effect of P_1 waves. First, the site transfer function is solved based on frequency-domain theory, and the underground auto-power spectra are generated. Then, a water-covered coherency model is adopted to generate underground cross-power spectra, thereby generating underground multi-point ground motions within the time domain and verifying their rationality. The above steps make it possible to incorporate the water-covering effect, convex topographic effect, and tunnel burial-depth effect into parametric research from an analytical perspective. Finally, the multi-point seismic differential motions excited by the water-covered convex-topography–tunnel site are treated as "free-field" input into a soil-continuous steel bridge finite element model; nonlinear analysis of the bridge structure under multi-point excitation is performed, the structural response characteristics are revealed, and several reasonable recommendations are proposed. The theoretical methods and research conclusions of this study can provide···

provide a reference for multi-support seismic-response analysis of long-span structures at this type of site.

1 Water-Domain Convex Terrain–Tunnel Site Seismic-Response Simulation

1.1 Solution in the Frequency Domain and Accuracy Verification

The research model for the distribution of seismic wavefields is shown in Fig. 1. A tunnel with burial depth H is located below a semicircular convex terrain in a water area; its inner and outer radii are a and b, respectively; the radius of the semicircular terrain is c; the seawater depth is h_{sea}; and the lining material is an elastic medium. When a P_1 wave is incident upon the water-domain convex-terrain–tunnel site, seismic wavefields are generated inside and outside the lining, at the water–soil interface, in the semicircular convex terrain, and in the seawater layer, as indicated by the red and black arrows in Fig. 1. The wave function is usually expressed in the Fourier–Bessel series form shown in Eq. (1)[1]:

$$\exp\left(\pm i k_\alpha r\cos\theta\right) = \sum_{n=0}^{\infty} \varepsilon_n (\pm i)^n J_n(k_\alpha r)\cos n\theta \tag{1}$$

where $i = \sqrt{-1}$ is the imaginary unit; k_α is the wavenumber of the incident P_1 wave; $J_n(\cdot)$ is the Bessel function of the first kind of order n; and ε_n is a symbolic variable satisfying $\varepsilon_n = 1$ for $n = 0$ and $\varepsilon_n = 2$ for $n \geq 1$.

Note: The red lines denote the free wavefield, and the black lines denote the scattered wavefields excited by the soil–seawater interface, the convex terrain, and the lined tunnel; $n = 1$ or 2 denotes the P_1 or P_2 wave in the saturated porous medium.

Fig. 1 Distribution of seismic wavefields

The key to solving the problem shown in Fig. 1 is that the wave functions must strictly satisfy the continuity conditions at the interfaces. Using the Hankel integral-transform method given by Lin et al.[10], Eq. (2) is used to transform the wave functions between rectangular coordinates and polar coordinates. Its advantage is that it avoids the approximation of the horizontal ground surface by the "large-arc method" and the error thereby produced.

$$H_n^{(1)}(kr)e^{in\theta} = \int_{-\infty}^{\infty} \left[\left(\frac{i^{-n}}{i\pi v_i} \right) \left(\frac{k - v_i}{k_i} \right)^n \right] e^{ikx - v_i|z|} \, dk \tag{2}$$

where $H_n^{(1)}(kr)$ is the Hankel function of the first kind of order n; $v_i = \sqrt{k^2 - k_i^2}$; and k_i is the wavenumber.

To verify the accuracy of the obtained solution for the water-domain convex-terrain–embedded-tunnel site, the radius of the convex terrain can be set to $0.001b$, $h_{\text{sea}} = 10b$, and $H = 2b$, while the other parameters are kept consistent with Ref. [18]. The convex model can then degenerate into the site without convex terrain in Ref. [18]. Figure 2 presents the comparison between the frequency-domain solution obtained from the degenerated model of the present study and the solution in Ref. [18] for a P_1-wave frequency of $\eta = 0.25$ and an incident angle of $\theta_\alpha^{(i)} = 0$; the two are in complete agreement.

Fig. 2 Accuracy verification of theoretical solutions

1.2 Integrated Underwater Subsurface Power Spectral Matrix

According to the definition of the transfer function in the frequency domain[11], the transfer function $TF_{im}(i\omega)$ between surface point i in the water area and underground point m can be expressed as

$$TF_{im}(i\omega) = |u_i(i\omega)/u_m(i\omega)| \tag{3}$$

where $u_i(i\omega)$ and $u_m(i\omega)$ are the frequency-domain displacement responses of the ground surface and the corresponding underground projection point, respectively, and can be obtained from Section 1.1.

Thus, the underground auto-power spectral element can be obtained as

$$S_{mm}(\omega) = |TF_{im}(i\omega)|^2 \cdot S_{ii}(i\omega) \tag{4}$$

where $S_{mm}(\omega)$ is the auto-power spectral matrix of the underground target point, and $S_{ii}(i\omega)$ is the auto-power spectral matrix of the surface point.

To account for the phase difference caused by seismic waves propagating in water, the water-covered coherence-function model[11] is adopted, and an improved underground coherence-function model based on the traditional coherence-function model is given as

$$\gamma_{mn}(i\omega) = \gamma_{ij}(i\omega)e^{i\omega(\tau_{im}-\delta_{im})}e^{-i\omega(\tau_{jn}-\delta_{jn})} = \tau^p\gamma_{ij}(i\omega)e^{i\omega(\tau_{im}-\tau_{jn})} \tag{5}$$

where $\gamma_{mn}(i\omega)$ is the water-covered underground coherence function; $\gamma_{ij}(i\omega)e^{i\omega(\tau_{im}-\tau_{jn})}$ is the traditional coherence model, for which Ref. [19] may be consulted; and $\tau^p = e^{-i\omega(\delta_{im}-\delta_{jn})}$ is the water-area influence factor, determined by the terrain coordinates and the water-cover depth.

$$\delta_{im} = \delta_{hi} - \delta_{hm} = (z_i - z_m)\cdot\sqrt{\rho_f/K^*_{\text{sea}}} \tag{6}$$

where $\delta_{h_i} = (h_{\text{sea}} + z_i)\cdot\sqrt{\rho_f/K^*_{\text{sea}}}$; h_{sea} is the height of the seawater layer, ρ_f is the seawater density, K^*_{sea} is the bulk modulus of seawater, and i and j may be located at any position on the ground surface shown in Figure 3.

[Figure 3 contains the labels: seawater layer; saturated half-space; A, A', B, B', C, C'; O; h_{sea}; H; P_1; $\varphi^{(i)}$; $\theta^{(i)}_\alpha$; and local coordinate axes.]

Figure 3. Illustration of target points

According to Ref. [19], the relationship among the underground cross-power spectrum, the transfer function, the underground coherence function, and the auto-power spectral density is

$$S_{mn}(\mathrm{i}\omega) = |TF_{im}(\mathrm{i}\omega)|\left|TF_{jn}(\mathrm{i}\omega)\right| S_{ii}(\mathrm{i}\omega)\gamma_{mn}(\mathrm{i}\omega) \tag{7}$$

where S_{mn} is the underground cross-power spectrum, and $\gamma_{mn}(\mathrm{i}\omega)$ is the water-covered coherence function.

By combining Eq. (4) and Eq. (7), the total underground power spectral matrix used for multi-point ground-motion generation can be obtained. Equation (8) gives the underground power spectral matrix $\mathbf{S}_{\mathrm{u}}(\mathrm{i}\omega)$ among the three underground points shown in Figure 3:

$$\mathbf{S}_{\mathrm{u}}(\mathrm{i}\omega) = \begin{bmatrix} S_{A'A'}(\omega) & S_{A'B'}(\mathrm{i}\omega) & S_{A'C'}(\mathrm{i}\omega) \\ S_{B'A'}(\mathrm{i}\omega) & S_{B'B'}(\omega) & S_{B'C'}(\mathrm{i}\omega) \\ S_{C'A'}(\mathrm{i}\omega) & S_{C'B'}(\mathrm{i}\omega) & S_{C'C'}(\omega) \end{bmatrix}_{3\times3} \tag{8}$$

where the diagonal elements $S_{i'i'}(\omega)$ are underground auto-power spectral elements, and the off-diagonal elements $S_{i'j'}(\mathrm{i}\omega)$ are underground cross-power spectral elements.

1.3 Generation of spatially varying underground ground motions

The underground power spectral matrix $\mathbf{S}_\mathrm{u}(\mathrm{i}\omega)$ is a Hermitian matrix; therefore, it is subjected to Cholesky decomposition:

$$\mathbf{S}_\mathrm{u}(\mathrm{i}\omega) = L(\mathrm{i}\omega)L^{\mathrm{T}*}(\mathrm{i}\omega) \tag{9}$$

where the specific expression of L_{ij} may be found in Ref. [1].

The ground-motion time history $a_j(t)$ at the j-th underground point can be expressed as

$$a_j(t) = \sum_{m=1}^{j}\sum_{n=1}^{N} A_{jm}(\omega_n)\cos\left[\omega_n t + \beta_{jm}(\omega_n) + \varphi_{mn}(\omega_n)\right] \tag{10}$$

where

$$A_{jm}(\omega) = \sqrt{4\Delta\omega}\,\left|L_{jm}(\mathrm{i}\omega)\right|, \qquad \beta_{jm}(\omega) = \tan^{-1}\left(\frac{\mathrm{Im}\left[L_{jm}(\mathrm{i}\omega)\right]}{\mathrm{Re}\left[L_{jm}(\mathrm{i}\omega)\right]}\right), \qquad 0 \le \omega \le \omega_N;$$

$\varphi_{mn}(\omega_n)$ is a random phase angle uniformly distributed over $[0, 2\pi]$, and ω_N is the cut-off frequency.

2 Ground-motion characteristics under water-covering and tunnel effects

2.1 Research procedure

Figure 4 gives the flowchart of this study. To investigate the influence of the coherence model on the time-domain characteristics of underground ground motions, the H-V coherence model [20] is adopted as a comparison.

[Figure 4 flowchart text:]

- Problem formulation
  - 2D wave theory for complex water-area sites
  - Establish mathematical model
  - Establish coordinate system
  - P_1-wave field analysis
  - Multi-field coupled wave equation
- Solving the theoretical frequency-domain solution
  - Unknown wave function
  - Series expansion
  - Wave function in series form
  - Hankel integral transform

  - Substitute
  - Boundary conditions
  - Rigorous derivation
  - Frequency-domain theoretical solution
  - Tunnel effect
  - Frequency-domain transfer function
  - Compile/debug program
  - Accuracy verification
  - Is it accurate?
    * No
    * Yes
  - Transfer function
- Generation of spatially varying ground motions in the time domain
  - Construct underground coherence function for water-area sites
  - Introduce water-layer effect
  - Solve
  - Construct underground power spectral matrix
  - Assemble
  - Multi-point ground-motion simulation
  - Programming implementation
  - "Free-field" ground motion
  - Compile/debug program
  - Fitting verification
  - Is it accurate?
    * No
    * Yes
  - Seismic input
- Nonlinear bridge response under differential seismic input
  - Ground-motion factors:
    1. Ground motions generated by the water-covered/traditional coherence models
    2. Ground motions produced by changes in tunnel position
  - Interaction of the structure-soil-boundary system
  - Establish nonlinear finite element model
  - Multi-point nonlinear seismic response pattern of long-span bridges
  - "Soil-bridge" differential response

Figure 4. Flowchart of the research

Tunnel burial depth is taken as the two cases $H = 2b$ and $H = 5b$. The inner and outer radii of the tunnel are $a = 5.795\,\mathrm{m}$ and $b = 6.10\,\mathrm{m}$, respectively; the Poisson' s ratio is $\nu_l = 0.25$, the elastic modulus is $E_l = 34\,500\,\mathrm{MPa}$, and the density is $\rho_l = 2\,500\,\mathrm{kg} \cdot \mathrm{m}^{-3}$. The density of the seawater layer is $\rho_{\mathrm{sea}} = 1\,000\,\mathrm{kg} \cdot \mathrm{m}^{-3}$, and the modulus is $K_{\mathrm{sea}} = 2\,000\,\mathrm{MPa}$. The radius of the semicircular convex terrain is taken as $c = b$, and the height of the seawater layer is $h = 2b$. The physical parameters of the saturated soil are listed in Table 1 (the specific meanings may be found in Ref. [1]), and the coordinates of the target points are listed in Table 2.

Table 1 Physical parameters of the saturated soil

Tab. 1 Physical parameters of the saturated soil

ν	ρ_s/(kg/m^3)	A/MPa	N/MPa	Q/MPa	R/MPa	ρ_f/(kg/m^3)	K_f/MPa	$K_{\rm cr}$/MPa	K_g/MPa	n_s	$\gamma_{\rm cr}$
0.25	2 650	5 397	3 700	963	546	1 000	2 000	200	36 000	0.30	29.30

Table 2 Coordinates of target-point positions

Tab. 2 Position of target points

A	A'	B	B'	C	C'
$(-3b, 0)$	$(-3b, 2b)$	$(b, 0)$	$(b, 2b)$	$(0, -b)$	$(0, 2b)$

2.2 Study on seismic ground-motion characteristics in water areas

This section aims to investigate the influence of tunnel burial depth on underground seismic motion. Figure 5 presents the ground motions obtained from the water-covered and traditional H-V coherence models when the burial depth is $H = 2b$. For A' and B', the peak values of the ground motion under the water-covered coherence model are generally smaller than those under the H-V model. However, for point C' above the tunnel, the peak value under the water-covered coherence model (1.883) is larger than the result of the traditional H-V coherence model (1.689). The reason is that the water-cover effect enhances the attenuation of the coherence-function value and leads to an increase in the differential effect. Figure 6 presents a comparison of the ground motions generated by the two coherence models when $H = 5b$. Because the tunnel position affects the scattering of seismic waves and thus affects the site transfer function [15], the seismic-motion amplitudes are reduced to varying degrees compared with those when $H = 2b$. The above study indicates that, relative to the traditional model, the water-covered coherence function considers the time influence factor $\tau^p = e^{-i\omega(\delta_{im}-\delta_{jn})}$ generated by P-wave propagation between two points, which reduces the coherence between target points at the water-area site and increases the differential effect.

Figure 5 Acceleration time histories at A', B', and C' for the shallow-burial tunnel case $(H = 2b)$

Fig. 5 Underground accelerations of A', B' and C' for shallowly buried case of tunnel $(H = 2b)$

Visible plot labels and annotations:

- Common labels: tunnel burial depth $H = 2b$; vertical axis, amplitude $/(\mathrm{m \cdot s^{-2}})$; horizontal axis, time $/s$; legend, water-covered coherence model and H-V coherence model.
- (a) A' acceleration time history: $PGA = 1.303,\ \sigma^2 = 0.337$; $PGA = 1.626,\ \sigma^2 = 0.336$.
- (b) B' acceleration time history: $PGA = 1.379,\ \sigma^2 = 0.315$; $PGA = 1.585,\ \sigma^2 = 0.329$.
- (c) C' acceleration time history: $PGA = 1.689,\ \sigma^2 = 0.430$; $PGA = 1.883,\ \sigma^2 = 0.395$.

Figure 6 Acceleration time histories at A', B', and C' for the deep-burial tunnel case $(H = 5b)$

Fig. 6 Underground accelerations of A', B' and C' for deeply buried case of tunnel $(H = 5b)$

Visible plot labels and annotations:

- Common labels: tunnel burial depth $H = 5b$; vertical axis, amplitude $/(\mathrm{m \cdot s^{-2}})$; horizontal axis, time $/s$; legend, water-covered coherence model and H-V coherence model.
- (a) A' acceleration time history: $PGA = 1.293,\ \sigma^2 = 0.321$; $PGA = 1.442,\ \sigma^2 = 0.327$.
- (b) B' acceleration time history: $PGA = 1.211,\ \sigma^2 = 0.326$; $PGA = 1.271,\ \sigma^2 = 0.314$.
- (c) B' acceleration time history: $PGA = 1.581,\ \sigma^2 = 0.366$; $PGA = 1.511,\ \sigma^2 = 0.379$.

Figure 7 gives a comparison of the peak acceleration values and variances at points A', B', and C' under different tunnel burial depths for the water-covered and traditional H-V coherence models. Compared with the shallowly buried tunnel ($H = 2b$), the peak acceleration values and variances for the deeply buried tunnel ($H = 5b$) are reduced to varying degrees. The reason is that, as the tunnel burial depth increases, the scattering effect on waves weakens, which is then reflected in the ground-motion amplitudes and variances. Figure 8 shows the fitting of the power spectrum and coherence function for the accelerations (to save space, only the power spectrum at point A' and the fitting of the coherence function between points A' and B' are given), from which it can be seen that the simulated values

agree well with the target values.

Fig. 7 Effect of tunnel burial depth on seismic motions

Fig. 8 Verification of underground PSD and coherence functions

3 Nonlinear Response of the Bridge under Underground Differential Excitation

3.1 Finite-Element Model of the Bridge

As shown in Fig. 9(a), a variable-section prestressed-concrete rigid-frame bridge crosses a water-covered convex terrain–tunnel site. The total length is 200 m, and the span arrangement is $(30 + 70 + 70 + 30)$ m. The computational domain contains three bridge piers. For the left and right piers, the upper supports are both 48 m and the lower parts are both 12 m; for the middle pier, the upper part is 44 m and the lower part is 9 m. The upper parts of the piers adopt a rectangular section of 8.5 m $\times$ 4.0 m. Fig. 9(b) gives the pier-top and midspan sections of the main girder. Fig. 9(c) gives the finite-element model of the bridge. The model was built using SAP2000 and converted into an ABAQUS model through an interface program; the TJU-Plastic-E subroutine was called for elastoplastic analysis

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. The main girder, pile caps, and soil all use C3D8R solid elements, while the piers and pile foundations use fiber beam elements. The constraints $U_3 = UR_1 = UR_2 = 0$ are applied at both ends of the girder, and the piers, piles, and soil are fully constrained together. The concrete is C40, and the reinforcing steel is HRB335.

Fig. 9 Illustration of a continuous rigid-frame bridge crossing the complex site with seawater

3.2 Analysis of Differential Seismic Response of the Bridge

3.2.1 Case Settings

To investigate the influence of the selection of the coherence model and of different seismic-motion input modes—underground uniform input and multi-support excitation—on the seismic response of the bridge, three cases were set up, as shown in Table 3. According to the relevant theory in this study, multi-support ground-motion time histories at the three piers were generated, as shown in Fig. 10. The developed artificial-boundary program was used to finally convert the time-domain seismic acceleration generated in this study into equivalent nodal forces. The application of the viscoelastic boundary and equivalent nodal forces is shown in Fig. 11. The seismic motions were normalized, and three-directional seismic excitation was adopted; the amplitudes were taken as longitudinal bridge direction : transverse bridge direction : vertical direction = 1 : 0.85 : 0.65.

Table 3 Case settings
Tab. 3 Considering cases for different conditions

Case	Tunnel burial depth H	Seismic-motion characteristics
1	$2b$	H-V coherence function + underground multi-support seismic motion
2	$2b$	Water-covered coherence function + underground multi-support seismic motion
3	$5b$	Water-covered coherence function + underground multi-support seismic motion

Fig. 10 Underground acceleration time histories at each pier of the bridge

Fig. 10 Underground multi-support accelerations input at each pier of the bridge

(a) Left pier (b) Middle pier (c) Right pier

Visible plot labels: amplitude $/(\mathrm{m} \cdot \mathrm{s}^{-2})$, time /s, Case 1, Case 2, Case 3.

Fig. 11 Application of VSB and equivalent seismic node force

Visible labels in the figure include: left-pier artificial boundary; left-pier main body; two-node spring element; X-direction equivalent nodal force; Y-direction equivalent nodal force; Z-direction equivalent nodal force; equivalent seismic force; Case 1 equivalent seismic force at the lower-right corner of the right pier; right-pier seismic motion; equivalent nodal force; far-field bottom fixed; amplitude /kN; time /s.

3.2.2 Results Analysis

Tables 4–6 present the structural responses of the bridge at the observation points under the three cases when the peak ground-motion values are $0.2g$ and $0.4g$. Comparing Table 4 with Table 5, relative to $0.2g$, the displacement amplitudes at the observation locations all increase to varying degrees under the action of $0.4g$ ground motion. When $H = 2b$, under the underground seismic-motion excitation generated by the H-V coherence model (Case 1), the bridge displacements are all smaller than those in Case 2. This indicates that when different coherence models are adopted, the displacement responses obtained for the bridge structure are completely different. Examining Tables 5 and 6, for the displacement responses of the bridge structure under multi-support seismic excitation generated by the water-covered coherence model, it can be seen that the peak displacement in Case 3 is also smaller than that in Case 2. This is because, as the tunnel location becomes farther from the ground surface, its scattering effect on seismic waves at the water–soil interface weakens, resulting in changes in the peak value of the underground ground motion and in the frequency-domain energy distribution. Fig. 12 gives the displacement time histories at the tops of the left and right piers when the peak ground motion is $0.4g$. It can be seen that the displacement amplitudes vary greatly among the three cases, indicating that the coherence function and tunnel location have an important influence on the structural response.

Fig. 13 presents a comparison of the peak amplitudes of axial force, shear force, and bending moment at the bridge observation points under the three cases for different peak ground-motion values ($0.2g$ and $0.4g$). It can be seen that under $0.2g$ excitation, the internal forces of the bridge are relatively small and the differences are not obvious. When the peak ground motion is $0.4g$, compared with the other two cases, the peak axial force, shear force, and bending moment of the bridge structure are all the largest under Case 2, further indicating that the tunnel location

and the selection of the coherence model have an important influence on the seismic response of the structure. When seismic analysis of structures is carried out for this type of site, these effects should be fully considered so that corresponding designs can be made more appropriately.

Fig. 12. Displacement time-history curves at pier tops along the bridge direction at $0.4g$.
(a) Left pier top, $0.4g$; (b) right pier top, $0.4g$. Axes: displacement/m and time/s. Legend: Case 1, Case 2, Case 3.

Fig. 13. Peak values of bridge internal force for different cases.
(a) Left pier; (b) middle pier; (c) right pier. Legends: PGA = $0.2g$, PGA = $0.4g$. The plotted quantities are axial force / (10^3 kN), shear force / (10^3 kN), and bending moment / (10^3 kN · m).

Table 4. Maximum internal force and displacement of the bridge for Case 1

Observation point	Axial force /(10^3 kN), $0.2g$	Axial force /(10^3 kN), $0.4g$	Shear force /(10^3 kN), $0.2g$	Shear force /(10^3 kN), $0.4g$	Bending moment /(10^3 kN·m), $0.2g$	Bending moment /(10^3 kN·m), $0.4g$	Along-bridge displacement/m, $0.2g$	Along-bridge displacement/m, $0.4g$	Transverse displacement/m, $0.2g$	Transverse displacement/m, $0.4g$	Vertical displacement/m, $0.2g$	Vertical displacement/m, $0.4g$
Left pier top	54.76	48.61	3.16	7.155	24.36	77.95	0.157	0.298	0.129	0.243	0.092	0.192

Observation point	Axial force (×10^3 kN), 0.2g	Axial force (×10^3 kN), 0.4g	Shear force (×10^3 kN), 0.2g	Shear force (×10^3 kN), 0.4g	Bending moment (×10^3 kN·m), 0.2g	Bending moment (×10^3 kN·m), 0.4g	Along-bridge displacement/m, 0.2g	Along-bridge displacement/m, 0.4g	Transverse displacement/m, 0.2g	Transverse displacement/m, 0.4g	Vertical displacement/m, 0.2g	Vertical displacement/m, 0.4g
Left pier base	32.63	52.08	2.49	11.75	35.54	58.65	0.123	0.308	0.074	0.206	0.097	0.179
Middle pier top	28.55	41.78	9.25	8.562	20.64	120.75	0.169	0.318	0.089	0.224	0.131	0.223
Middle pier base	16.25	94.65	6.85	18.96	43.92	89.95	0.120	0.301	0.151	0.258	0.113	0.245
Right pier top	45.95	108.9	4.97	8.155	21.46	105.25	0.142	0.281	0.092	0.275	0.108	0.173
Right pier base	19.71	90.85	2.57	8.916	19.72	75.82	0.157	0.260	0.114	0.224	0.088	0.183
Midspan of Span 2	17.16	49.27	1.825	6.305	34.66	203.9	0.128	0.314	0.124	0.230	0.143	0.234
Midspan of Span 3	18.05	62.49	2.918	14.16	27.94	133.46	0.143	0.248	0.086	0.206	0.131	0.262

Table 5. Maximum internal force and displacement of the bridge for Case 2

Observation point	Axial force (×10^3 kN), 0.2g	Axial force (×10^3 kN), 0.4g	Shear force (×10^3 kN), 0.2g	Shear force (×10^3 kN), 0.4g	Bending moment (×10^3 kN·m), 0.2g	Bending moment (×10^3 kN·m), 0.4g	Along-bridge displacement/m, 0.2g	Along-bridge displacement/m, 0.4g	Transverse displacement/m, 0.2g	Transverse displacement/m, 0.4g	Vertical displacement/m, 0.2g	Vertical displacement/m, 0.4g
Left pier top	19.48	100.9	6.83	18.72	16.05	99.28	0.252	0.314	0.111	0.201	0.114	0.175

Observation point	Axial force /(10^3 kN), 0.2g	Axial force /(10^3 kN), 0.4g	Shear force /(10^3 kN), 0.2g	Shear force /(10^3 kN), 0.4g	Bending moment /(10^3 kN·m), 0.2g	Bending moment /(10^3 kN·m), 0.4g	Along-bridge displacement/m, 0.2g	Along-bridge displacement/m, 0.4g	Transverse displacement/m, 0.2g	Transverse displacement/m, 0.4g	Vertical displacement/m, 0.2g	Vertical displacement/m, 0.4g
Left pier base	22.37	26.68	4.43	8.82	35.85	125.8	0.171	0.320	0.149	0.260	0.133	0.192
Middle pier top	12.30	40.53	5.89	13.01	25.58	166.8	0.190	0.303	0.095	0.171	0.111	0.274
Middle pier base	26.65	101.2	3.22	41.79	51.22	148.4	0.105	0.252	0.124	0.199	0.120	0.196
Right pier top	4.88	136.7	10.12	31.84	17.73	73.82	0.263	0.307	0.103	0.192	0.105	0.177
Right pier base	7.63	201.3	17.73	11.46	6.75	97.67	0.183	0.297	0.147	0.264	0.116	0.187
Midspan of Span 2	12.07	221.1	3.32	33.80	18.30	81.45	0.206	0.337	0.187	0.178	0.146	0.174
Midspan of Span 3	8.18	61.34	6.34	17.31	10.41	43.29	0.191	0.336	0.129	0.173	0.163	0.245

Table 6. Maximum internal force and displacement of the bridge for Case 3

Tab. 6 Maximum internal force and displacement of bridge for case 3

Observation point	Axial force / (10^3 kN), 0.2g	Axial force / (10^3 kN), 0.4g	Shear force / (10^3 kN), 0.2g	Shear force / (10^3 kN), 0.4g	Bending moment / (10^3 kN·m), 0.2g	Bending moment / (10^3 kN·m), 0.4g	Longitudinal bridge displacement / m, 0.2g	Longitudinal bridge displacement / m, 0.4g	Transverse bridge displacement / m, 0.2g	Transverse bridge displacement / m, 0.4g	Vertical displacement / m, 0.2g	Vertical displacement / m, 0.4g
Top of left pier	49.37	77.11	4.87	10.43	44.40	85.60	0.113	0.282	0.125	0.251	0.119	0.195
Base of left pier	13.47	41.61	3.84	17.36	61.18	124.6	0.133	0.291	0.086	0.225	0.099	0.234
Top of middle pier	17.79	25.04	5.78	6.191	16.79	105.7	0.167	0.309	0.159	0.203	0.135	0.211
Base of middle pier	43.39	27.58	3.22	14.64	47.90	43.85	0.140	0.289	0.092	0.249	0.091	0.189
Top of right pier	14.23	125.12	6.92	27.75	11.46	82.28	0.163	0.218	0.109	0.196	0.116	0.166
Base of right pier	6.10	87.89	9.80	6.15	17.78	69.16	0.196	0.260	0.149	0.166	0.131	0.171
Midsection of Span 2	20.99	61.75	10.49	12.96	37.81	63.84	0.202	0.273	0.126	0.164	0.112	0.192
Midsection of Span 3	12.07	33.13	2.87	33.80	18.30	94.93	0.176	0.269	0.087	0.178	0.126	0.174

3.3 Nonlinear failure characteristics of the bridge under an extremely strong earthquake

Figure 14 presents, for the extremely strong earthquake case with a peak value of 2.0g, the stress–strain relationship of the reinforcement at the location where the bridge first fails—the base of the left pier—under seismic excitations generated by the conventional and water-covered coherency models. It reflects the differences in bridge failure modes under the two excitation patterns. For the water-covered model, the bridge failure time is 10.24 s, later than the 11.12 s of the H–V model. For the water-covered model, because the spatial variability of ground motion at the piers becomes larger, the bridge deformation is pronounced and finally enters yielding failure rapidly. Figure 15 shows the failure process of the bridge under multi-point excitation from the water-covered coherency model. At 2.80 s, the three piers undergo transverse antisymmetric torsion; at 6.24 s, obvious deformation begins to appear at the top of the left pier, and bending deformation can also be observed in the middle and right piers; at 8.12 s, the deformation in the middle portions of the three piers further intensifies; and at 10.24 s, transverse yielding instability occurs at the pier bases, the girder collapses, and the bridge fails. It is worth noting that, because the P_1 wave velocity is relatively high, the bridge failure mode differs from that under SV waves.

Fig. 14(a) Hysteresis curve; (b) strain–time curve; (c) stress–time curve.

Fig. 14. Hysteresis curves and time-varying relationships of strain and stress for the reinforcement at the base of the left pier.

Fig. 15(a) 2.80 s; (b) 6.24 s; (c) 8.12 s; (d) 10.24 s.

Fig. 15. Failure process of the bridge under an extremely strong earthquake.

Fig. 15 Failure mode of the bridge subjected to rare seismic motions

4 Conclusions

1) Based on wave theory, multi-point ground motions related to site characteristics were generated and their rationality was verified. The effects of tunnel burial depth and the water-covered coherence function on ground motions were revealed. The study shows that tunnel location has a significant influence on the seismic wave field of the site. Compared with the deep-buried case, the peak values of the multi-point ground motions obtained for the shallow-buried tunnel case are amplified to varying degrees. Because the phase difference of P waves in seawater is considered, the spatial variation effect of the ground motions obtained by the water-covered coherence model is more pronounced than that obtained by the traditional coherence model.

2) Nonlinear response analysis of a bridge under multi-point excitation was carried out considering boundary–soil–structure interaction. The results

show that, when the tunnel location is fixed, the bridge displacement and internal-force responses under excitation by the multi-point ground motions generated using the water-covered coherence model (with an increased differential effect) are larger than those obtained using the traditional coherence model. In addition, when the tunnel burial depth is shallower (i.e., the tunnel is closer to the ground surface), its scattering effect on seismic waves is stronger, the seismic differential effect is likewise enhanced, and the peak values of the bridge internal-force and displacement responses increase.

3) The differences in bridge failure modes and material hysteretic effects under strong ground-motion excitations generated by different coherence models were revealed. The results show that, under multi-point excitation using the water-covered coherence model, the bridge reinforcement first undergoes yielding failure, and the hysteresis curves of the reinforcement obtained by the two models differ significantly.

References:

[1] LIU G H, LI X Y. Theoretical solutions for variable ground motions of media-transition canyons with partly filled water subjected to SV-waves incidence [J]. Journal of earthquake and tsunami, 2023, 17(3):2350009.

[2] CHEN Xinyu, LIU Guohuan, FEI Qixiang. A coherence function model for seismic differential motions of water-covered canyon–hill composite topography, and its characteristic laws and influences [J]. Journal of Applied Mechanics, 2024, 41(2):392-403.

CHEN Xinyu, LIU Guohuan, FEI Qixiang. A coherence function model for simulating multi-support seismic motions of canyon-hill composite topography and characteristics [J]. Chinese journal of applied mechanics, 2024, 41(2):392-403 (in Chinese).

[3] HE Y, LIU Z X, YU Q, et al. Simulation of the spatially correlated multiple-station earthquake ground motions of the coupled alluvial valley-hill terrain [J]. Engineering analysis with boundary elements, 2020, 118:41-53.

[4] SONG Y Q, LI X Z, YANG Z L, et al. A series solution for SH wave scattering by irregularly shaped surface topographies [J]. Journal of earthquake engineering, 2023, 27(8):2145-2165.

[5] YUAN X M, MEN F L. Scattering of plane SH waves by a semi-cylindrical hill [J]. Earthquake engineering & structural dynamics, 1992, 21(12):1091-1098.

[6] LIANG J W, ZHANG Y S, LEE V W. Scattering of plane P waves by a semi-cylindrical hill: analytical solution [J]. Earthquake engineering and engineering vibration, 2005, 4(1):27-36.

[7] TSAUR D H. Scattering and focusing of SH waves by a lower semielliptic convex topography [J]. Bulletin of the Seismological Society of America, 2011,

101(5):2212-2219.

[8] NAKAMURA T, TAKENAKA H, OKAMOTO T, et al. FDM simulation of seismic-wave propagation for an aftershock of the 2009 Suruga Bay earthquake: effects of ocean-bottom topography and sea-water layer [J]. Bulletin of the Seismological Society of America, 2012, 102(6):2420-2435.

[9] LIAO S, ZERVA A. Physically compliant, conditionally simulated spatially variable seismic ground motions for performance-based design [J]. Earthquake engineering & structural dynamics, 2006, 35(7):891-919.

[10] LIN C H, LEE V W, TODOROVSKA M I, et al. Zero-stress, cylindrical wave functions around a circular underground tunnel in a flat, elastic half-space: incident P-waves [J]. Soil dynamics and earthquake engineering, 2010, 30(10):879-894.

[11] LIU Guohuan, CHEN Xinyu, FEI Qixiang. An underground coherence function considering the water-covered effect, and simulation of multi-support seismic motions of media-transition V-shaped canyons and their characteristic laws [J]. Journal of Vibration Engineering, 2023, 36(5):1437-1446.

LIU Guohuan, CHEN Xinyu, FEI Qixiang. An underground coherence function considering water-covered effect and the simulation of multi-supports seismic motions of media-transition V-shaped canyon and its characteristics [J]. Journal of vibration engineering, 2023, 36(5):1437-1446 (in Chinese).

[12] PITILAKIS K, TSINIDIS G, LEANZA A, et al. Seismic behaviour of circular tunnels accounting for above ground structures interaction effects [J]. Soil dynamics and earthquake engineering, 2014, 67:1-15.

[13] SANDOVAL E, BOBET A. Effect of input frequency on the seismic response of deep circular tunnels [J]. Soil dynamics and earthquake engineering, 2020, 139:106421.

[14] ZHAO W S, GAO H, CHEN W Z, et al. Analytical study on seismic response of subsea tunnels in a multi-layered seabed subjected to P- and SV-waves [J]. Tunnelling and underground space technology, 2023, 134:105015.

[15] JIN L G, ZHU J, ZHOU W, et al. 2D dynamic tunnel-soil-aboveground building interaction : analytical solution for incident plane SH-waves based on rigid tunnel and foundation model [J]. Tunnelling and underground space technology, 2022, 128:104625.

[16] TSINIDIS G, DE SILVA F, ANASTASOPOULOS I, et al. Seismic behaviour of tunnels: from experiments to analysis [J]. Tunnelling

and Underground Space Technology, 2020, 99: 103334.

[17] LIU Zhongxian, JU Xin, LIANG Jianwen. IBIEM solution for scattering of plane SV waves by tunnel lining in a saturated poroelastic half-space[J]. Chinese Journal of Geotechnical Engineering, 2015, 37(9): 1599–1612.

LIU Zhongxian, JU Xin, LIANG Jianwen. IBIEM solution to scattering of plane SV waves by tunnel lining in saturated poroelastic half-space[J]. Chinese Journal of Geotechnical Engineering, 2015, 37(9): 1599-1612 (in Chinese).

[18] ZHU Sainan, LI Weihua, VINCENT W L, et al. Seismic response analysis of an undersea lining tunnel under incident plane P waves[J]. Chinese Journal of Geotechnical Engineering, 2020, 42(8): 1418-1427.

ZHU Sainan, LI Weihua, VINCENT W L, et al. Seismic response of undersea lining tunnels under incident plane P waves[J]. Chinese Journal of Geotechnical Engineering, 2020, 42(8): 1418-1427 (in Chinese).

[19] LIU G H, LIU Y Q, HAN B, et al. Theoretical and numerical approach for simulating spatially variable seismic underground motions in layered saturated media[J]. Journal of Earthquake Engineering, 2020, 24(4): 601-627.

[20] HARICHANDRAN R S, VANMARCKE E H. Stochastic variation of earthquake ground motion in space and time[J]. Journal of Engineering Mechanics, 1986, 112(2): 154-174.

[21] LIU Guohuan, LIAN Jijian, GUO Wei. Elasto-plasticity and collapse analysis of structures (II)—SAP2ABAQUS interface technology, development, and verification[J]. Journal of Seismological Research, 2014, 37(1): 132-140.

LIU Guohuan, LIAN Jijian, GUO Wei. Elasto-plasticity and collapse analysis for large-span and high-rise structure (II)—technology, development and verification of SAP2ABAQUS interface[J]. Journal of Seismological Research, 2014, 37(1): 132-140 (in Chinese).

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Note: Figure translations are in progress. See original paper for figures.