Seismic Analysis of Long Span Bridge Considering Topography Effect with Oblique Incidence of SV Wave

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ABSTRACT :
In this paper, the explicit finite element method to solve single-phase elastic solid media nodal points dynamic response with incidence of SV wave is introduced, Combined with local transmitting artificial boundary, the finite element method which can be used to simulate dynamic response analysis of single-phase elastic media of any topography when obliquely incident SV wave happened. With this method, the ground seismic response of an irregular topographic site is computed, and the related seismic ground motion is input to long span bridge, the seismic response of long span bridge considering asynchronous excitation is also computed. The effect of the change of incident angle and height/width ratio to earthquake response of ground surface and long-span bridge is analyzed, and some preliminary conclusion is concluded. It can be referred when the long-span structures which suffered asynchronous excitation is built through the irregular topography.

KEYWORDS:
Topography Effect, Long Span Bridge, SV Wave

1. INTRODUCTION

During the happened earthquake, the topography amplification effect is often observed, especially the irregular topography influences greatly to the wave propagation. In earthquake engineering, it displays that the ground movement greatly enlarges or shrinks, so it directly influences the distribution of earthquake damage. Generally, the mountain ridge suffers serious earthquake damage, but the flat topography suffers a light earthquake damage. Actual records and theoretical analysis express that the earthquake motion of mountain ridge is larger than the flat site. This fully shows that topography plays an important role on earthquake motion. For long span bridge stepping across irregular topography, the topography effect to the influence is more notable. Therefore, we must study the wave propagation and scatterance in local sites, to gain the exact seismic ground motion to serve for the bridge earthquake design. The main two factors influence the topography effect: (1)incidence angle, (2) the parameters of local site topography, like height/width ratio etc. This paper mainly discusses the two factors to the influence of seismic response of bridge with obliquely SV wave incidence when SV wave goes through the irregular topography.

2. Explicit finite element method simulating dynamic response analysis of local site

At present, the finite element methods solving the seismic response of local site mostly are implicit or implicit-explicit. But these methods have a disadvantage that they must solve one set of coupled linear equation during every time step space in time domain. When the number of DOF of system which we want to solve is small, maybe these methods are suitable. But if the number of DOF is large, these methods will lead to an immense work, so their application is largely limited. At present, these methods rarely apply for actual engineering, it is especially inconvenient for dealing with nonlinear questions. To conquer the shortcomings mentioned above, Liao zhenpeng[1]etc. proposed one kind of explicit finite element method whose characteristics are listed as below: uncoupled, only need single stiffness matrix instead of total stiffness matrix, don't need solve simultaneous equations. In addition, the nodal motion to be solved only relates with its near nodes. Therefore, this method can save computer memory space and raise the computation speed. Combined with local transmitting artificial boundary[1], the finite element method which can be used to simulate dynamic response analysis of single-phase elastic media of any topography is proposed.

2.1 Local Transmitting Artificial Boundary

Transmitting artificial boundary is developed by the guiding idea that the propagation characteristics are directly simulated in artificial boundary. The transmitting artificial boundary divides the wave field of artificial boundary area into inner-transmitting wave motion field and scattering wave motion field. Transmitting artificial boundary mainly simulates the movement of artificial boundary caused by scattering wave motion field. The inner-transmitting wave motion field goes from the outside area of the artificial boundary to inside area of the artificial boundary. In actual project, inner-transmitting wave motion field is known which can be solved by the theory of wave propagation. But scattering wave motion field is not known, in most boundarys, it has no theoretical solution. Therefore, the total movement of artificial boundary nodes have no theoretical solution, it can only be solved by numerical methods. In order to simulate the movement of the artificial boundary nodes, transmitting artificial boundary establishes the approximate movement relation between artificial boundary and inner areas through the propagation law. The motion equation of nodes of the artificial boundary is Eq.2.1.

$$u_J^{P+1} = \frac{1}{2}(1\text{-S})(2\text{-S})\,u_J^P + \text{S}(2\text{-S})\,u_{J-1}^P + \frac{1}{2}\text{S}(\text{S-1})\,u_{J-2}^P \tag{2.1}$$

where $S=\frac{c_a \Delta t}{\Delta x}$,P, P+1 respectively means at the time P and the time P+1,J-1, J-2 respectively means the node that lies in the inner normal line of J node of artificial boundary. Δx is space step of discrete mesh that is perpendicular to the artificial boundary surface.

2.2. Establishment of Dynamic Analysis Equation of Inner Area Nodes

According to finite element method, the physical quantity of one node can be expressed by neighboring nodes'. We take out one set of local nodes which is illustrated in Fig.2.1, we supposed one node's number is 1, whose neighboring nodes and the node consists of the local nodes. When the motion equation of number 1 is built, the lumped-mass matrix is adopted. Also, to simplify the computation, the change of inertia force in one element is ignored. That is to say, the inertia force in one element is supposed to be constant. For the set of nodes listed in Fig.2.1, the total number of nodes is supposed to be N, and the displacement vector of this set of nodes is expressed as Eq.2.2.

$$[u]^T = [u_1 \quad u_2 \quad \cdots \quad u_N] \tag{2.2}$$

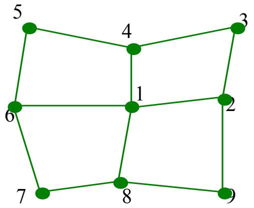

Figure 2.1 one set of local nodes

To SV wave, the motion equation is Eq.2.3.

$$u_i = \lfloor u_{ix} \quad u_{iy} \rfloor \tag{2.3}$$

In this set of nodes, the relation between the node number n and the node number of one of the element whose number is e can expressed as Eq.2.4 and Eq.2.5.

$$n=n\ (j) \tag{2.4}$$

$$u_n = u_{n(j)} = u_j^e \tag{2.5}$$

According to the document[2], the explicit solution to the equation of motion of local nodes is Eq.2.6, Eq.2.7 and Eq.2.8.

$$u_1^{P+1} = \frac{1}{2}\frac{\Delta t^2}{M_1}R_1 + u_1^P + \Delta t\,(1 - \frac{1}{2}\Delta t\alpha)\dot{u}_1^p - \frac{1}{2}\frac{\Delta t^2}{M_1}\sum_{n=1}^{N}K_{1n}(u_n^p + \beta\,\dot{u}_l^P) \tag{2.6}$$

$$\dot{u}_1^{P+1} = \frac{1}{2}\frac{\Delta t}{M_1}(R_1^{P+1} + R_1^P) + \dot{u}_1^P\alpha(u_1^{P+1} - u_1^P) - \frac{1}{2M_1}\sum_{n=1}^{N}K_{1n}\left[\Delta t(u_n^{P+1} + u_n^P) + 2\beta(u_n^{P+1} - u_n^P)\right] \tag{2.7}$$

$$\ddot{u}_1^{P+1} = -\ddot{u}_1^P + \frac{2}{\Delta t}(\dot{u}_1^{P+1} - u_1^P) \tag{2.8}$$

Eq.2.6, Eq.2.7 and Eq.2.8 are the equations to solve the dynamic response of the node 1. Those equations are suitable to any node i if we substitute i for 1.

2.3. Establishment of Dynamic Analysis Equation of Nodes in Artificial Boundary Nodes

Eq.2.6, Eq.2.7 and Eq.2.8 are the equations of motion of area inside the artificial boundary. To realize the recursion computation of inner nodes, we must establish the recursion formula of nodes that lie in artificial boundary. The formula can be referred as Eq.2.1.

3. Input of Earthquake Motion

The total wave field of inside the artificial boundary equals to the sum of scattering and inner-transmitting wave field. But the total wave field can be solved by computing the motion equation. So the main work to gain the scattering wave field is to confirm the inner-transmitting wave field. The artificial boundary area can be divided into 4 parts which is illustrated in Fig.3.1. Left artificial boundary area, right artificial area, bottom artificial boundary and inner computing area. It is supposed that the displacement of origin of coordinates is $w_o(t)$ which is caused by incidence of SV wave. C_s and C_p respectively are the velocity of S wave and P wave. According to document[2], the inner-transmitting wave field of four parts mentioned above can be solved.

3.1. Right Artificial Boundary Area

Because there are not inner-transmitting wave field in right artificial boundary area, the value of inner-transmitting wave field is zero.

3.2. Bottom Artificial Boundary Area

The value of inner-transmitting wave field in bottom artificial boundary area equals to the value of wave field going through from outside of the computing area to the bottom artificial area. So the displacement value of inner-transmitting wave field of bottom artificial boundary is Eq.3.1 and Eq.3.2.

$$u_x(\mathrm{t, x, y}) = w_o(\mathrm{t} + \frac{y\cos\theta - x\sin\theta}{C_S}) \bullet \cos\theta \quad (3.1)$$

$$u_y(\mathrm{t, x, y}) = w_o(\mathrm{t} + \frac{y\cos\theta - x\sin\theta}{C_S}) \bullet \sin\theta \quad (3.2)$$

Where x, y are the coordinates of nodes which lie in bottom artificial boundary.

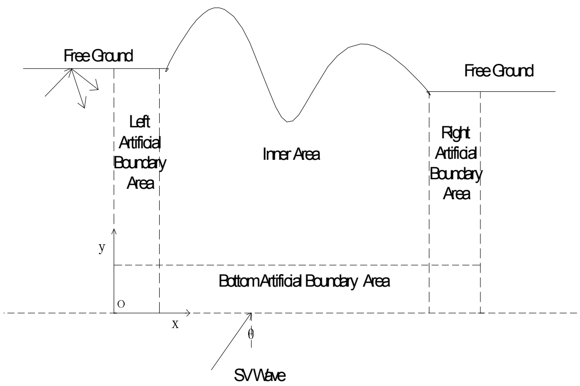

Figure 3.1 Model of Earthquake Motion Input

3.3. Left Artificial Boundary Area

The value of inner-transmitting wave field of left artificial boundary area equals to the sum of two parts of wave field: one part is directly going into the left artificial boundary area, the other part is the wave field which first reflects by the left free ground and then goes through the left artificial boundary area. The first part of wave field can be solved by Eq.2.6, Eq.2.7 and Eq.2.8. The wave field value of the other part can be solved as follows. The SV wave reflects after the free ground, it will produce SV wave and P wave. Their reflection angles respectively are Eq.3.3 and Eq.3.4.

$$\theta_s = \theta \quad (3.3)$$

$$\theta_p = \sin^{-1}(C_P \sin\theta / C_S) \quad (3.4)$$

Their reflection coefficients respectively are Eq.3.5 and Eq.3.6.

$$R_S = \frac{C_S^2 \sin 2\theta_S \sin 2\theta_P - C_P^2 \cos^2 2\theta_S}{C_S^2 \sin 2\theta_S \sin 2\theta_P + C_P^2 \cos^2 2\theta_S} \quad (3.5)$$

$$R_P = \frac{-2C_S C_P \sin 2\theta_S \cos 2\theta_S}{C_S^2 \sin 2\theta_S \sin 2\theta_P + C_P^2 \cos^2 2\theta_S} \quad (3.6)$$

To prevent producing nonhomogeneous plane wave, we suppose Eq.3.7.

$$\theta < \sin^{-1}(C_S / C_P) \quad (3.7)$$

The displacement value of left artificial boundary caused by inner-transmitting wave field after reflecting by the left free ground is Eq.3.8 and Eq.3.9.

$$u_{XR}(\text{t, x, y}) = -u_{RS}\cos\theta - u_{RP}\sin\theta_P \quad (3.8)$$

$$u_{YR}(\text{t, x, y}) = u_{RS}\sin\theta - u_{RP}\cos\theta_P \quad (3.9)$$

where

$$u_{RS} = R_S w_o\left(t + \frac{-y\cos\theta - x\sin\theta}{C_S}\right) \quad (3.10)$$

$$u_{RP} = R_P w_o\left(t + \frac{-y\cos\theta_P - x\sin\theta_P}{C_P}\right) \quad (3.11)$$

The equations of solving the value of displacement of inner-transmitting wave field are given above. These equations are also suitable to the solution of velocity if we substitute velocity function to displacement function.

4. Influence of Incident Angle and Height/Width Ratio to Topography Amplification Effect

To show the influence of incident angle and height/width ratio to topography amplification effect, some real site is selected to compute. We suppose the medium is homogeneous and isotropy, and the computing area size is 496m×160m including the irregular topography. The left, right and bottom side of the site is set up transmitting artificial boundary, and the upper side of the site is free. The time step space is 0.001s. The medium parameter of the site: λ=4.2×109Pa, μ=1.85×109Pa, ρ=2700kg/m^3. The discrete model of the site is illustrated as Fig.4.1. The seismic motions were recorded in 1989 when SAN FRANCISCO earthquake happened. Its history curve is illustrated in Fig.4.2. We use this seismic acceleration to be the input of the site, then the seismic responses of ground point A(112,160), B(184,96), C(312,72), D(384,160) are computed. We define the vertical distance form point C to the free surface is H, and the distance between point A and point D is L. Then the height/width ratio is H/L. Because of SV wave incidence, the incident angle θ must conform to the condition $\theta < \sin^{-1}(C_s / C_p)$. Where C_S and C_P respectively refers to S wave velocity and P wave velocity. So $\theta < 23.6^0$, we take θ as $\theta = 0^0$, 10^0 and 20^0. We take H/L as 0.26, 0.32and0.38. Then maximum displacements of A, B, C and D are listed in Table 4.1.

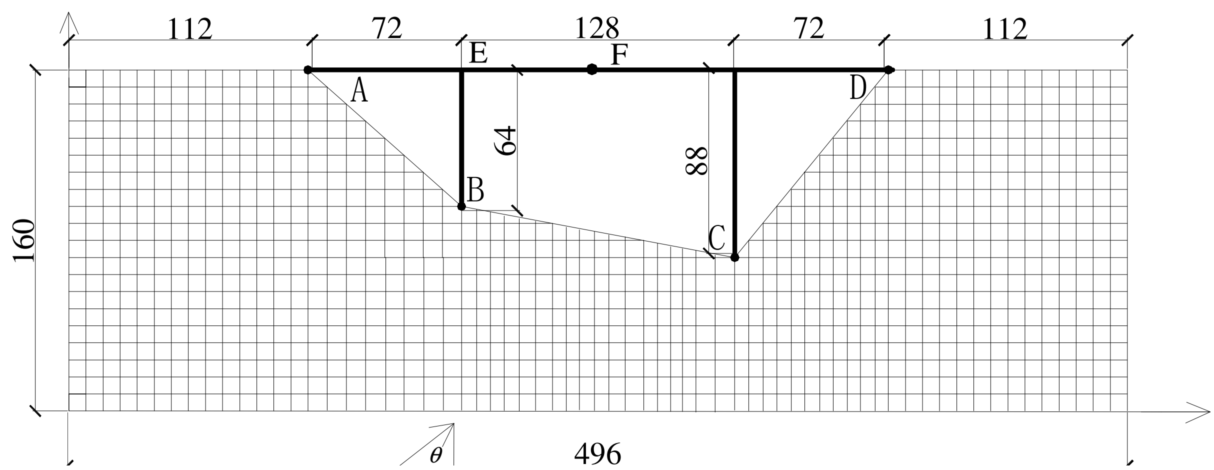

Figure 4.1 Model of Bridge and Site

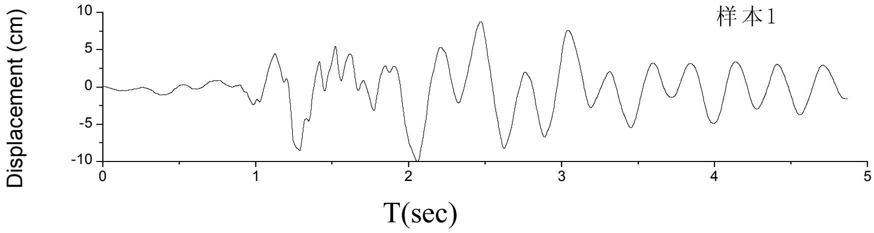

Figure 4.2 Seismic Motion History Cure

Table 4.1 Maximum Displacement Value of Free Ground

H/L		0.26			0.32			0.38		
θ		0^0	10^0	20^0	0^0	10^0	20^0	0^0	10^0	20^0
A	X	-52.3	-54.9	-45.7	-56.0	-59.7	-38.8	26.2	28.0	-31.2
	Y	0	38.2	52.2	0	44.8	40.9	0	-6.7	-10.9
B	X	-43.8	-47.4	-40.7	-56.9	-49.9	-28.5	13.9	12.9	17.4
	Y	0	17.7	48.6	0	20.8	29.8	0	-4.5	-7.1
C	X	-43.6	-41.4	-48.0	-55.2	-59.5	-39.0	-49.8	14.6	10.5
	Y	0	11.8	27.2	0	28.4	22.2	0	-3.7	-6.3
D	X	-33.6	-34.0	-30.3	-41.6	-33.8	-28.7	11.4	8.6	-5.7
	Y	0	31.8	53.0	0	33.8	32.5	0	-11.1	-12.3

The displacement history curves when the H/L is 0.38 and the incident angle is 10^0 和 20^0 are illustrated in Fig.4.3 and Fig.4.4.

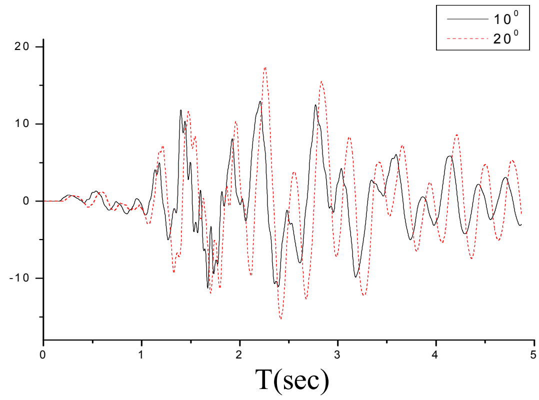

Figure 4.3 X Direction of Point B

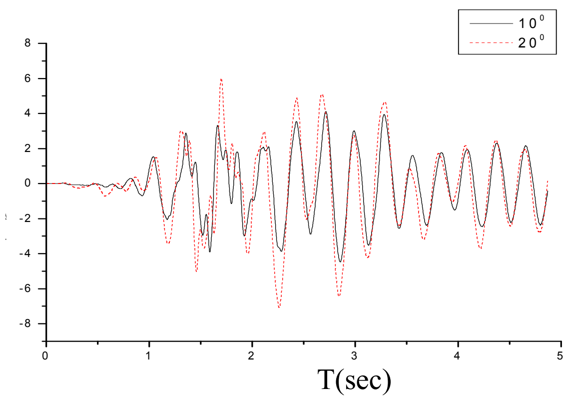

Figure 4.3 Y Direction of Point B

According to Table.4.1, when height/width ratio remains the same, the seismic response of free ground of X direction has the trend to decrease, and Y direction has the trend to increase; also, with the incident θ increases, the change of height/width ratio to the influence of the ground response becomes more and more important.

5. Seismic Response of Long Span Bridge Considering Topography Effect

In this part, the seismic motions considering topography effect solved above are input to the long span bridge. Therefore we can get the seismic response of long span bridge considering the topography effect. We suppose the bridge structure is elastic, and the bridge model is two dimensional. We choose a continuous frame bridge to analyze its seismic response. The box girder section is illustrated in Fig.5.1 ; and the pier section is illustrated in Fig.5.2 ; the computation model of the bridge and the site is illustrated in Fig.4.1. The computing area size is 496m×160m. The left, right and bottom side of the site is set up transmitting artificial boundary, and the upper side of the site is free. The time step space is still 0.001s. The site parameters and the seismic motion are the same mentioned above.

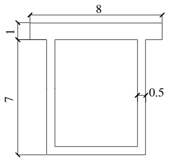

Figure 5.1 Box Girder Section (m)

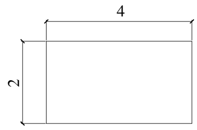

Figure 5.2 Pier Section (m)

The seismic motions of A, B, C, D nodes are regarded as the input motions to analyze the seismic response of the long span bridge. Then the seismic response of the middle point F of the middle span is computed. The maximum values of displacement response of F point under uniform and multiple-support excitations are listed in Table.5.1.From the Table.5.1, we can find that if we consider topography effect, the displacement response is much larger than that we don't consider topography effect. Therefore we draw that topography effect plays an important role in seismic response analysis of long span bridge. It is necessary to consider topography effect when long span bridge steps across the irregular topography.

表5.1 Maximum Displacement Value of Middle Point F (cm)

H/L		0.26			0.32			0.38		
θ		0^0	10^0	20^0	0^0	10^0	20^0	0^0	10^0	20^0
uniform excitations	X	-5.0	9.9	9.4	-5.0	9.9	9.4	-5.0	9.9	9.4
	Y	0	-1.7	-3.4	0	-1.7	-3.4	0	-1.7	-3.5
multiple-support excitations	X	-52.3	-54.9	-45.7	-56.0	-59.7	-38.7	26.2	28.0	-31.2
	Y	0	38.2	52.2	0	44.6	40.8	0	-6.7	-10.9

6. Conclusion

According to the result listed above, when SV wave goes through irregular topography sites, if we remain the height/width same, with the increase of incident angle θ, the seismic response of points in free ground decreases along X direction, but increases along Y direction. Also, with the increase of θ, the height/width plays more and more influence in seismic response of the free ground.

The seismic response of long span bridge considering topography effect is much larger than that don't consider topography effect. Therefore, topography effect plays an important role in seismic response analysis of long span bridge with the incidence of SV wave. We must pay more attention to topography effect when the long span bridge is designed.

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