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Dynamic Response of Bridge-Ship Collision Considering Pile-Soil Interaction

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Abstract

According to most countries' norms, and to find the effect of the bridge collision the equivalent static method was designed for bridge-ship collision, ignoring the dynamic effects of shocks. It is sharply different from actual situation. So based on the theory of Winkler foundation, shearing strain theory of Timoshenko and potential energy variation functional principle of Hamilton, the simulation models of bridge piers was built considering the pile–soil interaction. Lateral transient vibration equation of bridge piers was concluded. Based on the theory of integral transform, the differential equation of the collision system and the boundary conditions were transformed with Laplace transformation; the analytical solution of the stress wave in frequency domain was concluded. And then the inversion of solution in frequency domain was carried out using Matlab based on the Crump inverse transformation. Finally the dynamic response law of displacement, normal stress and the shear stress of bridge piers were obtained.

Keywords: Pile-Soil Interaction; Bridge Piers; Collide; Crump Inverse Transformation; Dynamics Response.

1. Introduction

Bridge-ship collision has not formed a complete theoretical system mechanics until now. Most of national norms are based on the equivalent static force method when considering the collision [1, 2], which has obviously overlooked the dynamic effect of collides, and sharply differs from the actual situation [3]. In classical mechanics, the two objects which collided are simplified to partials, ignoring the force change in the collision process and the resistance impact of specific materials, as well as the plastic and composition of objects [4, 5]. However, the actual bridge-ship collision is not as simple as the quality-speed hypothesis in classical mechanics; it is not only affected by the part energy loss and the retardation of water [6], but also influenced by pile-soil interaction. Therefore, this pile-soil interaction is taking into account, and pile foundation and piers are considered as Timoshenko members, pile-soil interaction comply with the Winkler elastic foundation, the elasticity and damping coefficients of soil are used to simulate the interaction between pile and soil, combined with engineering practice, the displacement, normal stress and dynamic response of shear stress of pile foundation and pier are analyzed.

Bridge-ship collision by train is discussed using finite element analysis (FEA) taking a long span cable-stayed bridge, they found that is the maximum allowable train speed decreased with the increase of the momentum of the impacting ship [7]. The finite element is also simulated of bridge-barge collision using a representative Jumbo Hopper barge model,

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through this simulation the simplified impact force history are developed and proposed a new model combination rule [8].

In this paper it will be used different numerical methods and the mathematically approach to modify the normal stress and the shear stress of bridge piers calculation with new methods.

2. Differential Equations of Transverse Vibration for Pier Element

2.1. Derivation of Basic Equations

The pier and pile foundation is divided into n elements and n+1 nodes, each element as a Timosheko component [9], the damping effect of structure is taken into consideration, cap and bridge superstructure are considered as a mass block; for the pile foundation, the interaction between soil and pile is considered, each soil layer has its own elasticity and damping coefficients [10, 11], as shown in Figure 1.

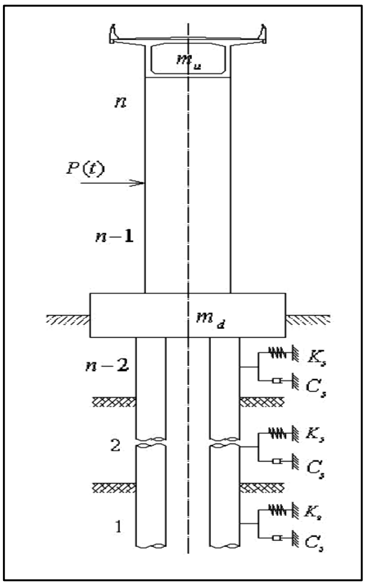

Figure 1. Mechanical sketch of bridge-pier element [10, 11]

According to Hamilton principle, the transverse vibration differential equation of each element is:

$$\kappa AG(\frac{\partial\varphi}{\partial x}-\frac{\partial^2 y}{\partial x^2})+\rho A\frac{\partial^2 y}{\partial t^2}+C\frac{\partial y}{\partial t}+K_s y=0 \tag{1}$$

$$EI\frac{\partial^2\varphi}{\partial x^2}=\kappa AG(\varphi-\frac{\partial y}{\partial x})+\rho I\frac{\partial^2\varphi}{\partial t^2} \tag{2}$$

Where $y(x,t)$ is element deflection; $\varphi(x,t)$ is angle caused by bend; ρ is material density; A is cross-sectional area; I is moment of inertia for cross-section; x is axis of coordinates; t is time; E is elastic modulus of the beam; κ is beam cross-section shape factor; G is shear modulus of the beam; K_s is elastic coefficient of soil and C is damping coefficient including the soil damping C_s and structure damping coefficient C_b.

According to Winkler elastic foundation, and an infinite length and rigid cylinder with transient transverse vibration in homogeneous elastic medium, Ks and Cs can be calculated from the following formulas:

$$K_s=\frac{\pi\rho_s v_s^2(-1+4\eta-\eta^2)}{2\eta^2} \tag{3}$$

$$C_s=\frac{2\pi r_0\rho_s v_s(1+\eta)}{2\eta} \tag{4}$$

Where r_o is the pile radius; ρ_s is density of soil around the pile; v_s is shear wave velocity of soil; η is a function of Poisson's ratio of soil, which can be expressed as $\eta=\sqrt{(1-2\mu_c)/2(1-\mu_c)}$ and μ_c is Poisson's ratio of soil.

2.2. Frequency Domain to Solve the Differential Equations

The initial conditions for each element is $y|_{t=0}=0, \frac{\partial y}{\partial t}|_{t=0}=0, \frac{\partial^2 y}{\partial t^2}|_{t=0}=0, \frac{\partial^3 y}{\partial t^3}|_{t=0}=0, \varphi|_{t=0}=0$ and $\frac{\partial \varphi}{\partial t}|_{t=0}$, So the Equations 1 and 2. after the Laplace transform on t, written and solved in the following matrix form:

$$\begin{bmatrix} e^{n_1 x} & e^{-n_1 x} & e^{n_2 x} & e^{-n_2 x} \\ b_3 e^{n_1 x} & -b_3 e^{-n_1 x} & b_4 e^{n_2 x} & -b_4 e^{-n_2 x} \\ b_1 e^{n_1 x} & b_1 e^{-n_1 x} & b_2 e^{n_2 x} & b_2 e^{-n_2 x} \\ b_5 e^{n_1 x} & -b_5 e^{-n_1 x} & b_6 e^{n_2 x} & -b_6 e^{-n_2 x} \end{bmatrix} \begin{Bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{Bmatrix} = \begin{Bmatrix} \tilde{y}(x,p) \\ \tilde{\varphi}(x,p) \\ \tilde{M}(x,p) \\ \tilde{Q}(x,p) \end{Bmatrix} \tag{5}$$

2.3. Boundary Conditions and Continuity Conditions

Ignoring constraints on the bottom of pile foundation, the boundary conditions on the bottom of pile foundation is:

$$\begin{cases} \tilde{Q}_0^{(1)} = 0 \\ \tilde{M}_0^{(1)} = 0 \end{cases} \tag{6}$$

Since each element of pile foundation is linearly elastic and there are no external effects, the soil displacement, rotation, bending moment and shear force are continuous, and expressed as follows:

$$\begin{cases} \tilde{y}_i^{(i)} - \tilde{y}_i^{(i+1)} = 0 \\ \tilde{\varphi}_i^{(i)} - \tilde{\varphi}_i^{(i+1)} = 0 \\ \tilde{Q}_i^{(i)} - \tilde{Q}_i^{(i+1)} = 0 \\ \tilde{M}_i^{(i)} - \tilde{M}_i^{(i+1)} = 0 \end{cases} \tag{7}$$

The mass block of the pile foundation and pier cap is taken into consideration, the displacements and rotations are continuous, and the expression is as follows:

$$\begin{cases} \tilde{y}_{n-2}^{(n-1)} - \tilde{y}_{n-2}^{(n-2)} = 0 \\ \tilde{\varphi}_{n-2}^{(n-1)} - \tilde{\varphi}_{n-2}^{(n-2)} = 0 \\ \tilde{M}_{n-2}^{(n-1)} - \tilde{M}_{n-2}^{(n-2)} = J_d p^2 \tilde{\varphi}_{n-2} \\ \tilde{Q}_{n-2}^{(n-1)} - \tilde{Q}_{n-2}^{(n-2)} = m_d p^2 \tilde{y}_{n-2} \end{cases} \tag{8}$$

Where J_d is the moment of inertia of the cap; m_d is the quality of the cap;

According to pier-ship collision model in the European normEuro code 1 [12], the expression is:

$$P(t) = v\sqrt{km}\sin\sqrt{\frac{k}{m}}t \tag{9}$$

Where $0 \le t \le \pi\sqrt{\frac{m}{k}}$; v is the collision speed; k is equivalent stiffness; m is quality.

2.4. The Whole Pier Collision System Matrix Equation

Considering the pier boundary conditions, continuity conditions, and unite n pier together, all that is abbreviated as the following matrix form:

$$[B]_{4n\times 4n}\{C\}_{4n\times 1} = \{Z\}_{4n\times 1} \tag{10}$$

By solving Equation 10, $\{C\}_{4n\times 1}$ can be obtained, the displacement $\tilde{y}(x,p)$, the angle $\tilde{\varphi}(x,p)$, the moment $\tilde{M}(x,p)$ and the shear $\tilde{Q}(x,p)$ in the frequency domain can be calculated.

2.5. Numerical Inversion

By using Crump inverse transformation method, the inversion formula is as follows [13]:

$$f(t) \approx \frac{e^{at}}{T}\{\frac{1}{2}\mathrm{Re}[F(a)] + \sum_{k=1}^{N}\mathrm{Re}[F(a+i\frac{k\pi}{T})]\cos(\frac{k\pi}{T})t - \sum_{k=1}^{N}\mathrm{Im}[F(a+i\frac{k\pi}{T})]\sin(\frac{k\pi}{T})t\} \tag{11}$$

3. Case Study

A river bridge is pretested concrete continuous rigid frame bridge $60 + 110 + 60\ m$. The main pier is $30\ m$ high of a solid wall, the wall thickness is $2\ m$ and the pier width is $6\ m$. Cap is low pile cap, the main pier foundations are the four $2\ m$ diameter bored piles (Figure 1). Considering the effect of the subsoil, the first soil layer parameters are: elastic modulus $E_{s1} = 10\ MPa$, Density $\rho_{s1} = 1780\ kg/m^3$, Poisson's ratio $\mu_{s1} = 0.35$ and Shear wave velocity $v_{s1} = 45\ m/s$. The second layer parameters are: elastic modulus $E_{s2} = 12\ MPa$, Density $\rho_{s2} = 1800\ kg/m^3$, Poisson's ratio $\mu_{s2} = 0.32$ and shear wave velocity $v_{s2} = 50\ m/s$. Shipping weight is $2000\ t$ (consider additional water quality), impact speed of $3\ m/s$, the ship's collision stiffness $5\ MN/m$ and the impact position is at $15\ m$ of the pier height.

4. Results Analysis

4.1. Displacement Dynamic Response

Figure 2. shows the displacement response along the pier and pile. It can be noticed from the figure that displacements at both the top and the bottom of the pile are quite large, while displacement in the-18mis near to zero, and displacement at the top of the pier is much greater than any other part, and the displacement of pier is greater than pile displacement, which is caused by the constraints on pier top and the pile-soil interaction. Figure 3. shows displacement-time curve of the pile bottom, pier bottom and pier top, it also can be noticed that the first peak of the bottom of pile foundation, pier base, the top of pier appeared in the $2\ s$ or less, and because of the soil damping and structural damping effects, the displacement response decayed. It can also be seen that displacement of piers top is larger than of all other parts and the maximum is $184\ mm$.

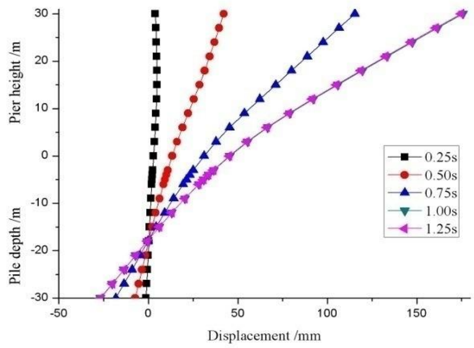

Figure 2. Displacement dynamical response of bridge pier and pile foundation

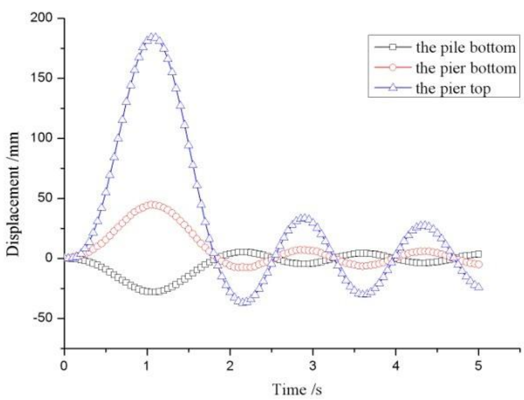

Figure 3. Dynamical response of displacement

4.2. Dynamic Response of Normal Stress

Figure 4. shows the normal stress response along the bridge pier and pile foundation. It can be noticed that near of

depth of $-5\ m$ the pile foundation has its maximum normal stress. Figure 5. shows the stress-time curve, the first peak of each part also appeared in 2sor less, and it decayed because of soil damping and structural damping effects. It can also be seen from the figure that the stress response is larger in the bottom of the pier than any other part. The maximum normal stress is $3.88\ MPa$; therefore when the ship collided, the bottom of the pier is most vulnerable to tensile failure.

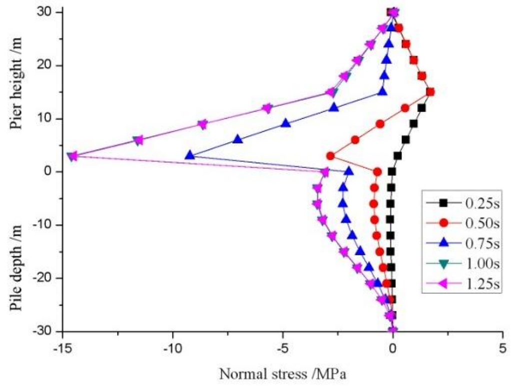

Figure 4. Normal stress dynamical response of bridge pier and pile foundation

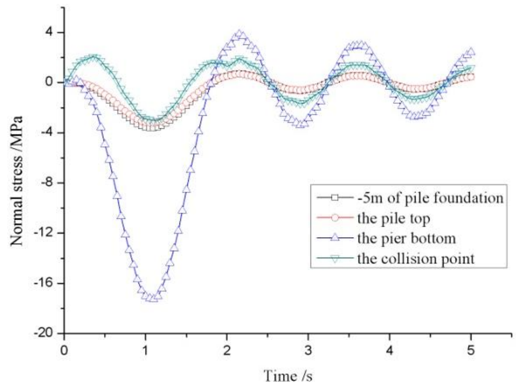

Figure 5. Dynamical response of normal stress

4.3. Dynamic Response of Shear Stress

Figure 6. shows the shear stress dynamical response of bridge pier and pile foundation, from the figure, it can be noticed that the maximum shear stress is at $-18\ m$ near the pile foundation, the area from pier bottom to the impact point has a larger shear stress, which is a high stress area that caused by the local concentrated load. Figure 7. shows the shear stress-time curve, at the depth of $-18\ m$, the top of pile foundation, and bottom and pier top. The first peak also appeared near $2\ s$ or less. Then because of soil damping and structural damping effects, responses to shear stress are weakened. It can also be seen that the shear stress response at the bottom of the pier is larger than other parts and the maximum shear stress is $1.54\ MPa$. Therefore when a ship hits against a pier, the bottom of the pier is the most vulnerable to shear failure.

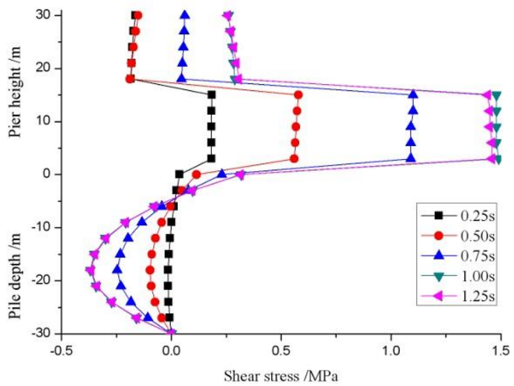

Figure 6. Shear stress dynamical response of bridge pier and pile foundation

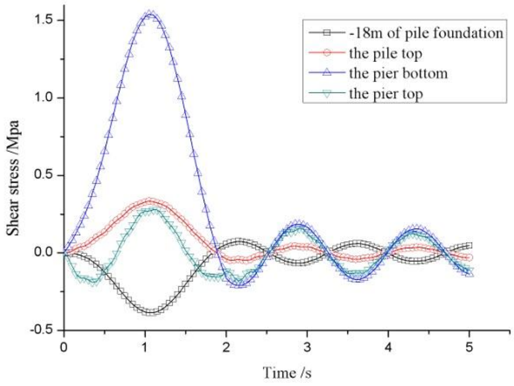

Figure 7. Dynamical response of shear stress

5. Conclusion

Considering the effects of pile-soil interaction, the pier model following Winkler elastic foundation is established. Dynamic differential equations are derived and by using the integral transform, the wave solutions are obtained in frequency domain. By Crump inverse transformation method and Matlab numerical inversion, the dynamic response of displacement, normal stress and shear stress in the time domain of a collision system are obtained.

Due to the attached example, the displacement, normal stress and shear stress dynamic response of pile foundation and pier are obtained. Under the collision force, the dynamic response of bridge piers at the top has the largest displacement of $184\ mm$, a deformation has occurred in the whole bridge. From the collision point to the pier bottom, which is a high stress area, the normal stress and shear stress are greater than other parts, leading concrete to effective part fracture; pier bottom is the maximum stress zone of the entire system and the most fragile part under the huge collision force. Therefore appropriate measures should be taken to prevent the destruction, avoiding the collapse of the whole structure.

6. Acknowledgment

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