Seismic Response Analysis of Friction Pendulum Continuous Beam Bridge Considering Soil Pile Action

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Abstract: Taking a three-span continuous beam bridge as the research object, the finite element model of isolated bridge with friction pendulum bearing considering soil pile action is established by SAP2000. The vibration characteristics and dynamic response results of isolated bridge under earthquake excitation are obtained by using nonlinear dynamic time-procedure analysis method, and the law of the influence of soil pile action on the seismic response of isolated bridge is analyzed. The results show that: the soil pile action has a small influence on the isolation period of isolated bridge with friction pendulum bearing; however, the influence of soil pile action should be considered in the seismic response analysis of isolated bridges, as soil pile action has a great influence on the displacement and acceleration response amplitude of the main beam and the pier top. At the same time, ignoring the soil pile will cause serious overestimation of the shear force and bending moment amplitude at the bottom of the isolated pier.

Keywords: soil-structure interaction, continuous bridge, friction pendulum system, seismic response

1. Introduction

As a new type of anti-seismic bearing, friction pendulum has both friction energy dissipation and self-resetting ability, and is widely used in isolation engineering because of its superior isolation performance and economic efficiency [1-2]. When an earthquake comes, the friction pendulum bearing uses its spherical friction surface to dissipate the input seismic energy, prolongs the natural vibration period of the bridge, and increases the damping of the bridge body, thus achieving the effect of blocking the seismic response [3]. However, the seismic performance of bridges built on flexible foundation is also affected by the interaction between pile and soil. Therefore, it is necessary to study the interaction between soil and pile in the nonlinear time-procedure analysis of bridge-related structures, otherwise the real bridge response results may not be obtained [4].

Currently, the research at home and abroad on friction pendulum bearings, isolated bridges and their soil piles has been extensive and in-depth. Osman M.O. Ramadan [5] etc. made incremental nonlinear dynamic analysis of continuous bridge under different earthquake propagation speeds, and found that the performance level of bridge body would be significantly affected after considering soil pile. Emanorouz Zadeh Tochaei [6] et al. conducted different types of seismic experiments on a 1/60 scale typical cable-stayed bridge model, and found that the response of the bridge would be amplified when the simulated foundation stiffness was small. Amin Rahmani [7] et al. replaced the pile foundation and other structures with equivalent linear springs and buffer groups, which simplified the modeling of the soil pile structure. They also proposed that the substructure established by the substructure method would cause overestimation of the partial response of the pier. A. krishnamorthy [8] established a three-degree-of-freedom friction pendulum isolation system considering the soil pile action. Through parameter research, it was found that considering the soil pile action would increase the response of the structure in most cases. Farshad Homaei [9] et al. studied the seismic response of a mid-span bridge considering soil pile action through incremental dynamic analysis. The results show that soil pile action will shorten the recovery period of bridge damage. Lixin Zhang [10] studied the essence of the point seismic wave input analysis model considering the soil-structure interaction based on the mass method, and proposed that the spatial variation of the vibration should be fully described when considering the soil pile action, otherwise the structural response might be underestimated.

To further study the influence of soil pile action on the seismic response of a three-span continuous beam bridge, a finite element model of the bridge with friction pendulum bearing is established in this paper. The “p-y curve” method is used to simulate the soil pile interaction, and the influence of soil pile action on the vibration characteristics of the bridge under earthquake excitation is studied. The influence of soil pile action on the displacement and acceleration amplitude of the main beam and pier top, the shear force and bending moment amplitude at the bottom of the bridge pier under different friction coefficients of friction pendulum bearing is also analyzed.

2. Project Overview

Taking a three-span continuous beam bridge as the research object, the whole bridge schematic diagram is shown in Figure 1. The span of the bridge is 32m+32m+32m. The main beam adopts concrete box beam structure. The piers are circular double-column piers which are 8m high and 1.5m in diameter. See Figure 1(b) and Figure 1(c) for the elevation of the main beam and the piers respectively. The main beam and the piers are linked by friction pendulum bearings. 12 sub-piles with a diameter of 0.6m and a height of 20m are set at the bottom of each pier. See Figure 1(d) for the elevation of the sub-piles.

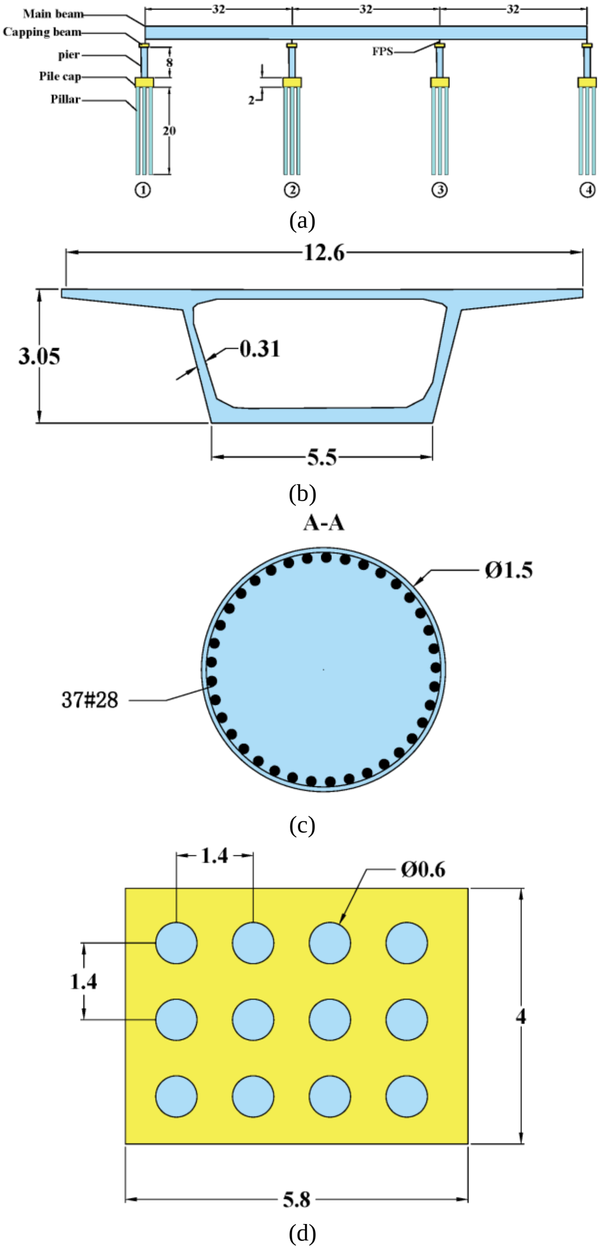


Figure 1. Schematic diagram of the whole bridge (unit: m)

3. Calculation Model

3.1. Finite Element Model

The finite element model of a three-span continuous beam bridge established by SAP2000 is shown in Figure 2. The finite element model includes main beam, pier, friction pendulum bearing, pier and sub-pile. Beam elements are used to simulate main beam, pier and sub-pile; thick plate elements are used to simulate piers; non-linear isolation elements are used to simulate friction pendulum bearing to connect main beam and pier. At the same time, non-linear spring is established according to "p-y curve" to simulate soil-pile interaction, and all sub-piles are fixed at the bottom [11].

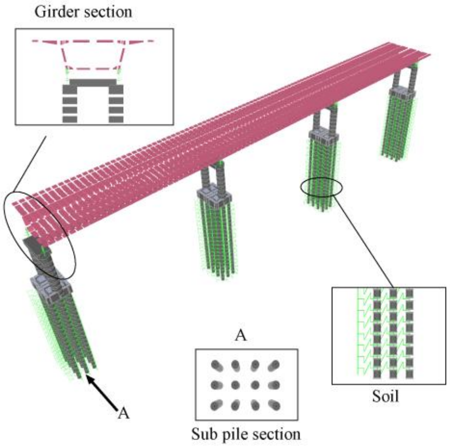


Figure 2. Finite element model of the three-span continuous beam bridge

3.2 Seismic input

El-Centro seismic wave (as shown in Figure 3) is widely used in seismic structure design as the first recorded seismic wave. Therefore, in this study, El-Centro (1940) seismic wave is selected as the seismic excitation of nonlinear dynamic time-procedure analysis, and the time-procedure curve of seismic excitation is shown in Figure 3.

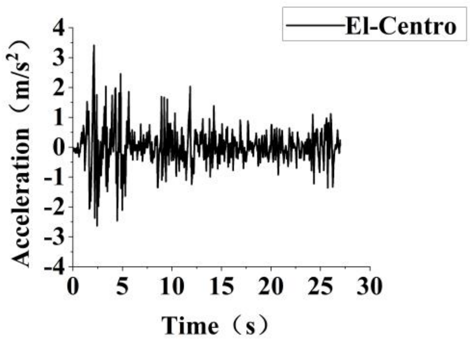
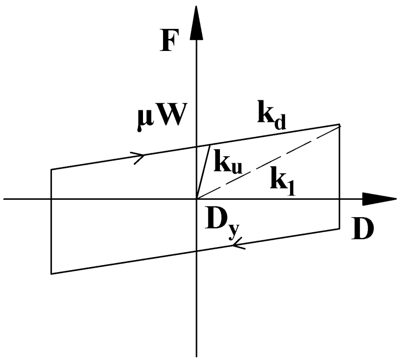


Figure 3. Seismic wave and response spectrum

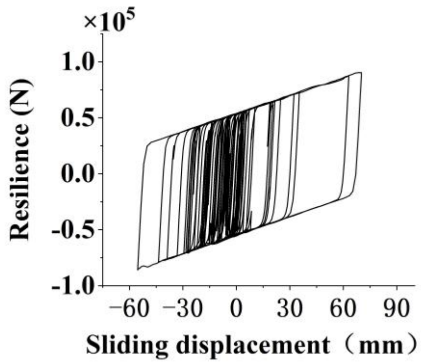
4. Result Analysis

4.1. Hysteresis Curve

The theoretical mechanical model of the pendulum bearing is shown in Figure 4(a). In the bilinear hysteretic curve, F is the horizontal restoring force of the bearing; D is the sliding displacement of the bearing; k_u is the yield stiffness; k_d is the swing stiffness; k_1 is the equivalent stiffness; μ is the friction coefficient of the bearing, and W is the vertical bearing weight. When the radius of the friction pendulum is 2m and the friction coefficient is 0.05, the hysteretic curve of the friction pendulum is obtained by numerical simulation as shown in Figure 4(b). From Figure 4(b), it can be seen that the hysteretic curve of the friction pendulum is basically consistent with the theoretical model. Since the hysteretic curve of the friction pendulum is full, the friction pendulum has good isolation and energy dissipation capacity.



(a) Theoretical mechanical model



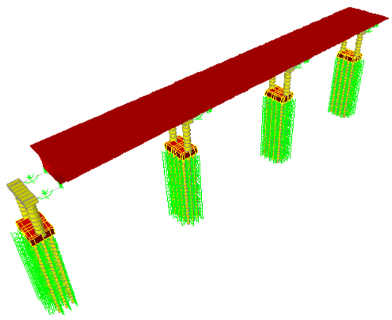
(b) Finite element model

Figure 4. Hysteresis curve

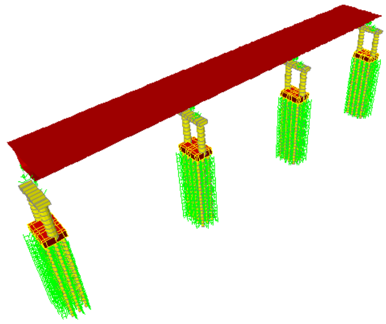
4.2. Modal Analysis

See formula (1) for the theoretical calculation formula of the isolation period of the friction pendulum bearing, where R is the spherical radius of the friction pendulum bearing and g is the acceleration of gravity. From formula (1), the theoretical isolation period is 2.81s when the spherical radius of the friction pendulum bearing is 2m. The first six vibration modes obtained by numerical simulation when the spherical radius of the friction pendulum bearing is 2m are shown in Figure 5. From Figure 5, it can be seen that the isolation period of the bridge obtained by numerical simulation is 3.01s, and the error with the theoretical calculation result is only 6.0%.

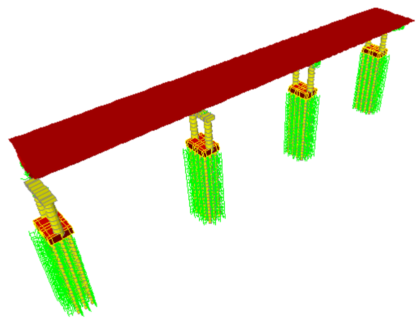
$$T_p = 2\pi\sqrt{\frac{R}{g}} \quad (1)$$



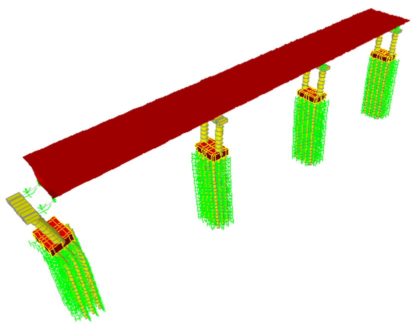
(a) First-order main vibration mode (3.01s)



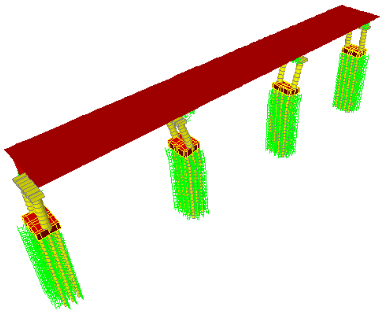
(b) Second-order main vibration mode (3.00s)



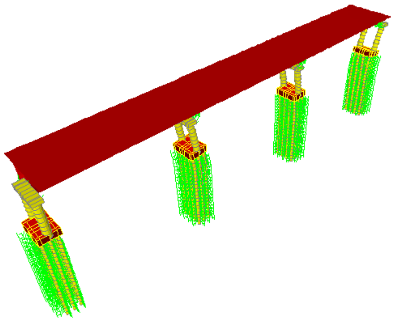
(c) Third-order main vibration mode (2.34s)



(d) Fourth-order main vibration mode (0.33s)

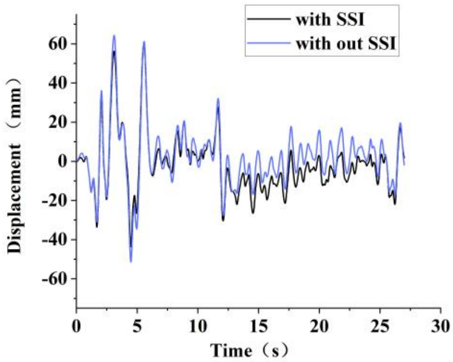


(e) Fifth-order main vibration mode (0.32s)

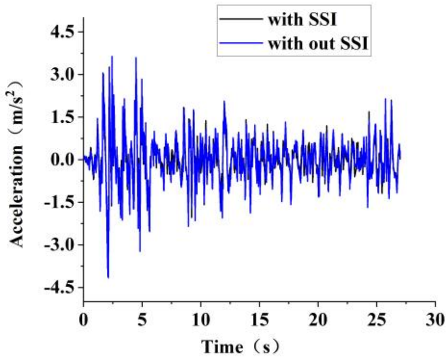


(f) Sixth-order main vibration mode (0.32s)

Figure 5. Vibration modes of the first six orders



(a) Main beam displacement response



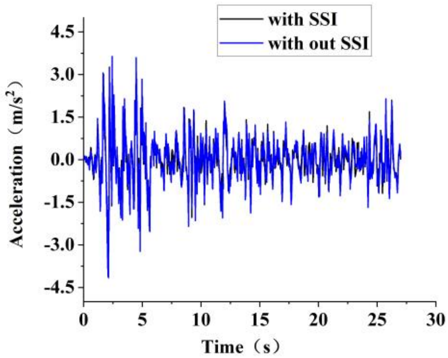
(b) Main beam acceleration response

Figure 6. Response of main beam

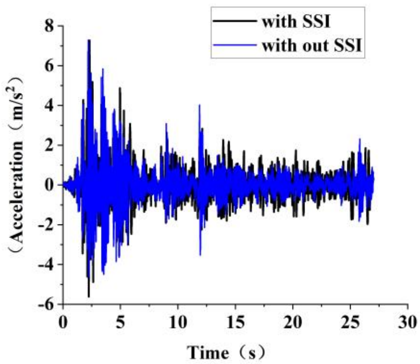
4.3. Analysis of Influence of Soil Pile Action on Seismic Response of Bridge

When the spherical radius of the pendulum bearing is 2m and the friction coefficient is 0.05, the response curves of displacement and acceleration of the main beam of the isolated bridge with or without soil pile are shown in Figure 6. The response curves of displacement and acceleration at the pier top are shown in Figure 7, and the response curves of shear force and bending moment at the pier bottom are shown in Figure 8.

It can be seen from Figure 6 and Figure 7 that compared with the response amplitude of the displacement and acceleration of the main beam, the soil pile action has greater influence on the response amplitude of the displacement and acceleration of the pier top; from Figure 8, it can be seen that the response amplitude of shear force and bending moment at the pier bottom after earthquake considering the soil pile action is much smaller than that without considering the soil pile action.

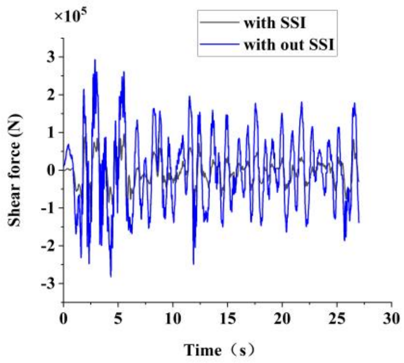


(a) Pier top displacement response

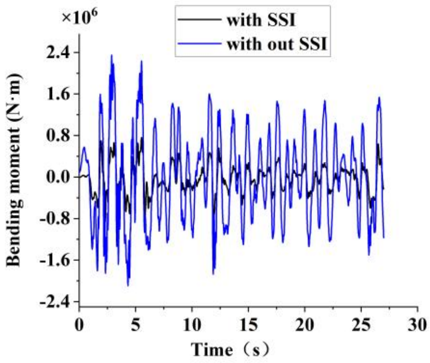


(b) Acceleration response at the pier top

Figure 7. Response of the pier top



(a) Shear force at the pier bottom



(b) Bending moment at the pier bottom

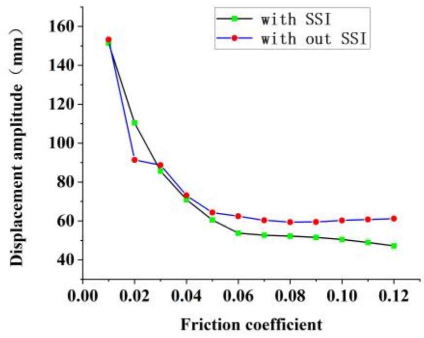
Figure 8. Response of the pier bottom

4.4. Influence of Friction Coefficient

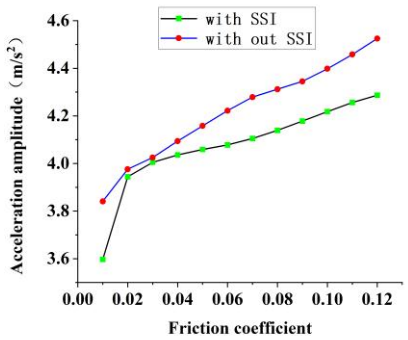
Because the soil pile action has a significant influence on the amplitude of seismic response of isolated bridges, to further explore its action law, the law of the influence of soil pile action on the amplitude of seismic response of isolated bridges is studied when the spherical radius of friction pendulum bearing is 2m and the friction coefficient ranges from 0.01 to 0.12.

4.4.1. Response of main beam

The influence of soil pile action on the displacement and acceleration response amplitude of the main beam under different friction coefficients is shown in Figure 9. As can be seen from Figure 9, the displacement amplitude of the main beam decreases with the increase of friction coefficient and the acceleration amplitude of the main beam increases with the increase of friction coefficient when considering and not considering the soil pile, respectively; the maximum error of the displacement and acceleration amplitude of the main beam is 29.66% and 6.7% when considering and not considering the soil pile, respectively. The soil pile has certain influence on the displacement and acceleration amplitude of the main beam.



(a) Main beam displacement

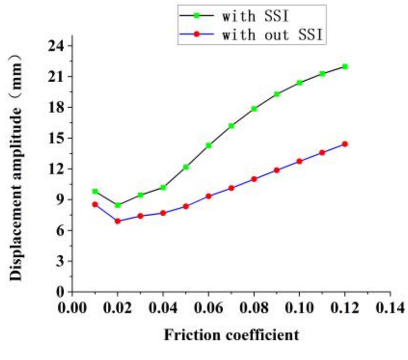


(b)Main beam acceleration

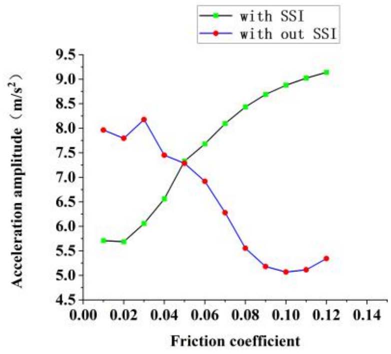
Figure 9. Influence of friction coefficient on response amplitude of main beam

4.3.2. Response of the pier top

The influence of soil pile action on the displacement and acceleration response amplitude of the pier top under different friction coefficients is shown in Figure 10. It can be seen from Figure 10 that the change trend of displacement amplitude at the pier top is basically the same with that without considering the soil pile action, but the change trend of acceleration amplitude at the pier top is opposite. The maximum error of the displacement and acceleration amplitude of the main beam is 38.43% and 43.33% when considering and not considering the soil pile action, respectively. The soil pile action has a great influence on the displacement and acceleration amplitude of the pier top.



(a) Displacement of the pier top

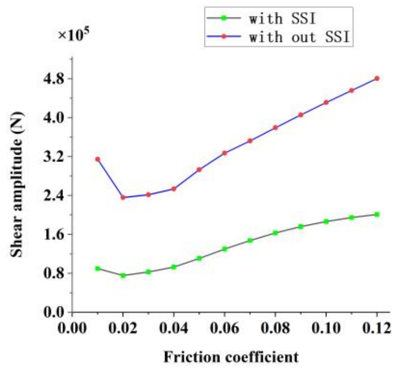


(b)Acceleration at the pier top

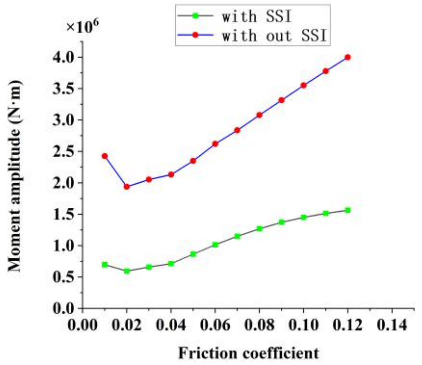
Figure 10. Influence of friction coefficient on response amplitude of the pier top

4.3.3. Response at the pier bottom

The influence of soil pile action on the response amplitude of shear force and bending moment at the pier bottom under different friction coefficients is shown in Figure 11. As can be seen from Figure 11, the amplitude of shear force and bending moment at the pier bottom considering the action of soil pile is much smaller than the response result without considering the action of soil pile, and the maximum errors of shear force and bending moment at the pier bottom are 249.75% and 248.36% respectively. Therefore, the influence of soil piles must be considered in the seismic response analysis of isolated bridges, otherwise the seismic capacity of piers will be seriously underestimated.



(a) Shear force at the pier bottom



(b)Bending moment at the pier bottom

Figure 11. Influence of friction coefficient on response amplitude of the pier bottom

5. Conclusion

(1) The isolation period of continuous beam bridge with friction pendulum bearing mainly depends on the spherical radius of the bearing, and the soil pile action has a small influence on its isolation period.

(2) Compared with the response amplitude of the main beam displacement and acceleration, the soil pile has a more significant influence on the response amplitude of the main beam displacement and acceleration at the pier top of the continuous beam bridge with friction pendulum bearing.

(3) The influence of soil pile action must be considered in the seismic response analysis of continuous beam bridge with friction pendulum bearing, otherwise the response amplitude of shear force and bending moment at the pier bottom will increase significantly.

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