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Seismic Response of Cooperative System Bridge under Pile-Soil-Structure Interaction

Feng Miao *, De-Jin Tang, Yun - Ping Wang
College of Civil Engineering and Architecture
Dalian University
Dalian, China

***Abstract*—In order to study the pile-soil-structure interaction dynamic response to the dynamic characteristics of the large span cable supported bridge system and earthquake, this paper takes Dalian gulf cross-sea bridge as the background, established a 3-D numerical model of the cooperation system bridge, respectively using equivalent fixed model, lumped mass model and 6-spring model to consider pile-soil-structure interaction, conducting the nonlinear time history analysis under the longitudinal seismic input, and compared with the without considering the pile soil structure interaction on the bottom of the pier consolidation model, the analysis shows that: considering pile soil structure interaction , the integral rigidity of structure will be reduced, displacements of the key control node is increased; the calculated results of 6-spring model are too large, analysis results obtained by equivalent fixed model and lumped mass model are almost the same; the accuracy results of equivalent fixed mode meet the requirements of civil engineering, save the operation time at the same time, improves the efficiency of calculation.**

***Keywords*—self-anchored cable-stayed suspension bridge; pile-soil-structure interaction; pile foundation models; seismic response**

I. INTRODUCTION

Pile-soil-structure interaction under seismic action is an important research topic in many fields such as bridge engineering, earthquake engineering etc. [1-7]. The combined action of pile-soil-structure is regard pile, soil, superstructure as a whole body and satisfied the deformation compatibility condition at the contact position of the above three parts. The dynamic response of some type bridges [8-13], such as continuous girder bridge, long-span concrete-filled steel tubular arch bridge, cable-stayed bridge with single-tower, suspension bridge are analyzed under pile-soil-structure interaction. The analysis results shown that dynamic characteristics and seismic response of structure under pile-soil-structure interaction is different from on rigid foundation, mainly to extend the natural period, increase damping, change force and displacement. Therefore it is necessary to regard the system that composed of pile, soil, structure as a whole body in seismic designing for the structure that built on the pile foundation.

Self-anchored cable-stayed suspension cooperative system bridge (hereinafter self-anchored cable-stayed suspension bridge) is a new type that combined with cable-stayed and self-anchored suspension bridge organically, it has the following features: novel structure, reasonable load, better wind-resistant, construction safety and low cost etc., it became a very competitive type in long-span bridges. Dynamic and seismic response of this type is carried out, pile-soil-structure interaction is not considered. In this paper, based on the scheme of Dalian Bay bridge in China, established four space finite element models: tower bottom consolidation; equivalent fixed model considering pile-soil-structure interaction; 6-spring model considering pile-soil-structure interaction; lumped mass model considering pile-soil-structure interaction. Analyzed and researched the vibration characteristics and seismic response of this type bridge, some theoretical basis is provided for seismic design of self-anchored cable-stayed suspension bridge by the analysis results.

II. ANALYSIS METHOD OF PILE-SOIL-STRUCTURE INTERACTION

2.1 The Establishment of Motion Equations

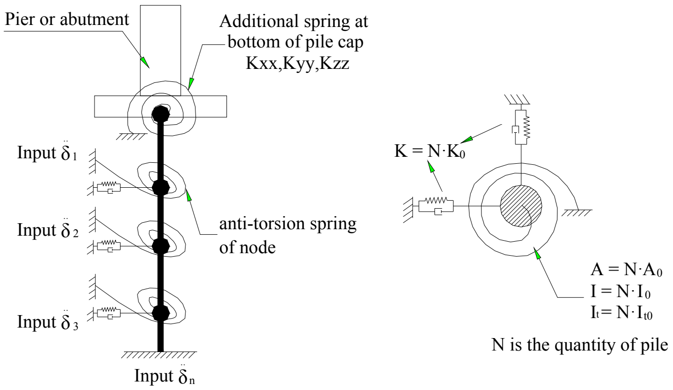
According to the reference, motion equation of pile-soil-bridge structure interaction can be obtained:

$$M\ddot{u}+C\dot{u}+Ku=-M_0\ddot{u}_g+M_h\ddot{u}_f+C_h\dot{u}_f+K_hu_f \tag{1}$$

Where: M, C and K is mass, damping and stiffness matrix of system that considering interaction, M_h, C_h, K_h presented as mass, damping and stiffness matrix of equivalent soil; M_0 is mass matrix without considering of interaction; $u_f, \dot{u}_f, \ddot{u}_f$ are displacement, velocity and acceleration response column vectors of a unit soil column in free site; $u, \dot{u}, \ddot{u}$ is column vectors of the system displacement, velocity and acceleration; $\ddot{u}_g$ is the acceleration input from the bottom of pile.

2.2 Simulation of Pile Foundation

The main principle of the lumped mass method is to formulate the particle bridge superstructure multi - particle system and pile - soil system united as a whole and to establish equations of the whole coupling seismic vibration equations which can be solved numerically to solve. It is assumed in model formulation that the side soil of pile is continuous medium of Winkler. The quality of the pile-soil system is simplified by a certain thickness and concentrated into a series of particle, discrete an ideal system of parameter, simulating the dynamic properties of soil medium with a spring and a damper, to form an underground part of the MULTI BODY system, under the effect of earthquake the structure-pile-foundation soil modeled as a surrogate system to analyze its dynamic response. Each single pile in the same way concentration a plurality of particle. Then two horizontal of spring and damper add to the corresponding node of every group pile directly. This method the mechanical meaning is simple and clear , can calculate the internal force of single pile directly, the results also be the most accurate, but for pile group foundation of large scale, requiring a large number of springs and dampers, the model is very complex, not conducive to the practical application of engineering. In order to simplify the model of pile group, a natural idea is to merge the pile foundation. There were a large number of parametric studies of pile group is substituted by a simple surrogate model were carried out, the whole structure of pile group concentrate a synthesis pile, as shown in Fig.1.



(a) Elevation View (b) Plane View

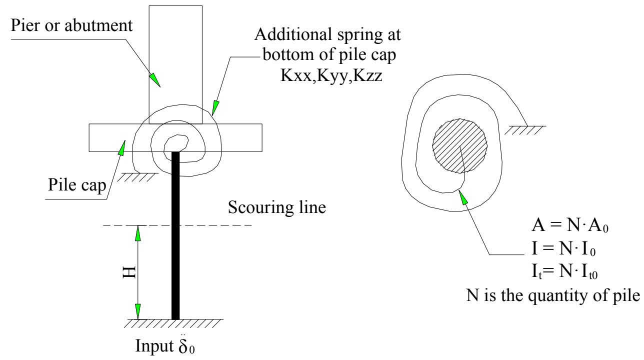
Fig. 1. The merging pile mode of lumped mass model

For the high-pile caps, in order to simplify calculation process, a simplified method in engineering field to formulate the pile at the position that under scouring line with length of 3~5 times pile diameter, the calculation diagram is shown in Fig.2. Generally, for dynamic problems, the reasonable embed depth *H* under scouring line for pile should be determined according to the equivalent principle of horizontal rigidity of single-pile. But lots of analysis for pile foundation showed that the embed depth which determined by equivalent principle of horizontal rigidity of single-pile is still in the range of 3~5 times pile diameter. Without considering the interaction between piles, the mathematical expression of general embed depth *H* can use the following formula:

$$H = \sqrt[3]{\frac{12EI}{\rho_2}} - l_0 \qquad (2)$$

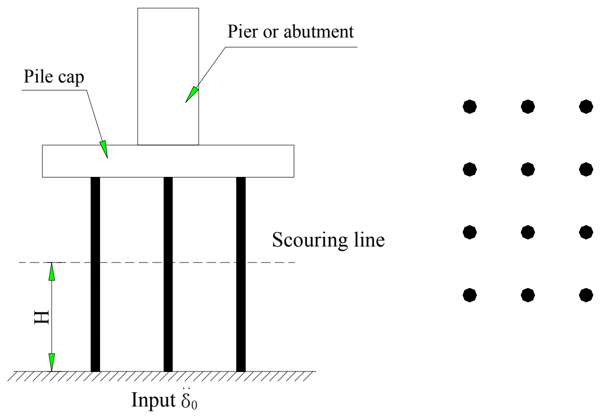
Where: EI is represented bending inertia moment of single pile, ρ_2 is the horizontal force on the top of pile (equivalent to horizontal anti-thrust rigidity) Which due to the unit of horizontal displacement that produced on top of one pile, l_0 is the length of pile above the erosion line or the ground.

However, for large-scale high-pile caps, amount of piles often appeared and length is usually very long, so a lot of soil springs will be related to be simulated that it would greatly enhance the complexity of model and waste calculating times. In order to simplify the pile group model, generated the model with incorporated pile. Massive parameter study on model with incorporated pile is carried out, made the pile group structure merged into a synthetic pile, as shown in Fig.3. The area, bending inertia moment and torsional inertia moment of synthetic pile is the area, bending inertia moment and torsional inertia moment sum of each single-pile. This model is relatively simple with less element and node, furthermore, it only depend on the dividing number of site soil, independent of the number of pile in pile group, so the more the number of pile groups, the more obvious advantages.



(a) Elevation View (b) Plane View

Fig. 2. The model of equivalent embed fixation



(a) Elevation View (b) Plane View

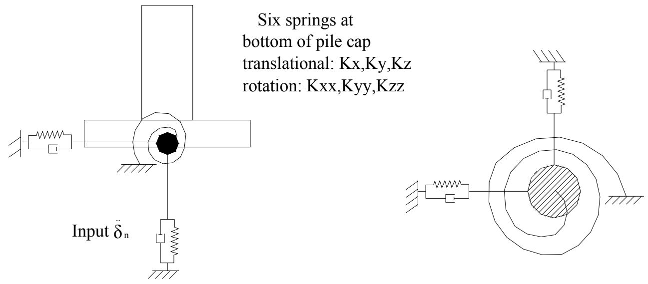
Fig. 3. The merging pile model of equivalent embed fixation

The result error of seismic response is very small by using simplified model with incorporated pile, meanwhile, could save calculation amount greatly. In long-span bridges, dynamic analysis is made between superstructure and group piles according to using the model of incorporated piles could improve calculation efficiency under the condition that only increased a bit of elements. Established finite element model of single-pile by using equivalent embed model, obtained related dates shown in Tab.1 through calculated according to geological data and programs drawings.

TABLE I. CHARACTERISTIC OF EQUIVALENT FIXED MODEL

Variable	**Embed depth (m)**	**Equivalent area (m^2)**	**Torsional moment inertial I_{xx} (m^4)**	**Bending moment inertial I_{yy} (m^4)**	**Bending moment inertial I_{zz} (m^4)**
Value	10	78.54	61.36	30.68	30.68

In the seismic response analysis of long span bridges, another common treatment methods of pile foundation is in the bottom of cap add six direction of spring to simulate the role of pile foundation see Fig.4, and the internal force of the pile caps bottom according to the method of statics to push worst force of single pile. The spring stiffness is determined according to static equivalent principle. This processing method is very simple, but in essence is use the method of static to analysis the pile foundation especially for high pile cap. Free part length of pile is actually part of structure. Six spring model is a bit rough.



(a) Elevation View (b) Plane View

Fig. 4. The merging pile mode of lumped mass model

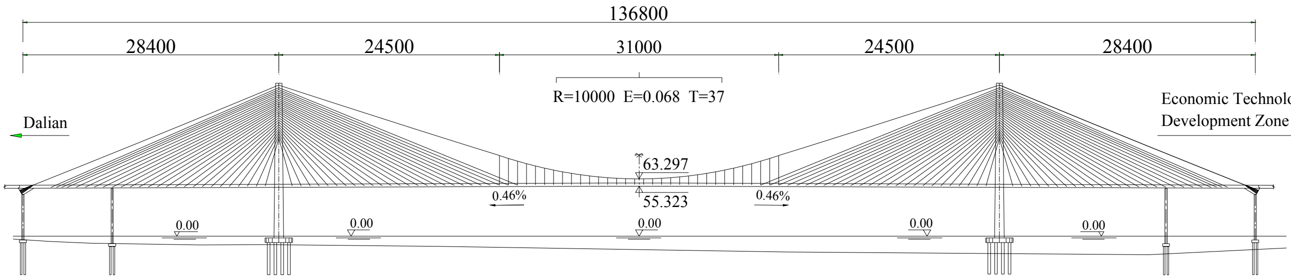


Fig. 5. Elevation view of Dalian Gulf Cross-sea Bridge

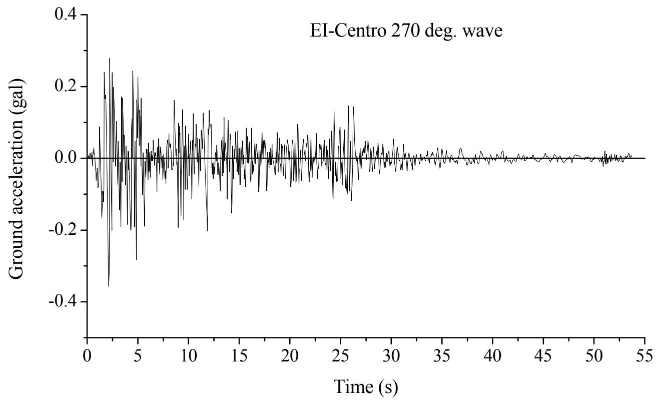
III. Seismic Response Analysis of Self-Anchored Cable-Stayed Suspension Bridge Under Pile-Soil-Structure Interaction

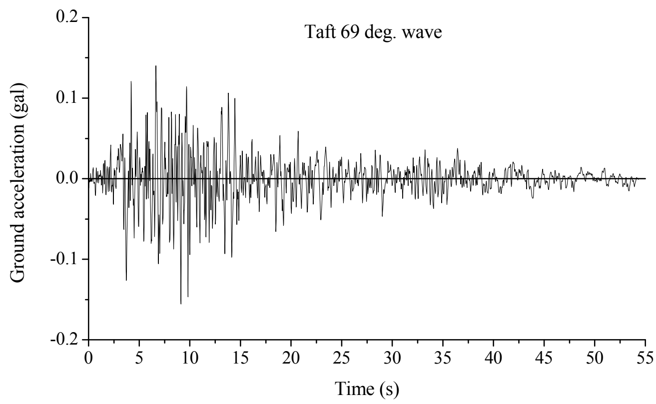
3.1 Project Overview

The recommended scheme of Dalian Bay crossing-sea bridge in China with span arrangement 284m+800m+284m of main navigable spans and bridge width 34m for bidirectional 6 lanes is a self-anchored cable-stayed suspension bridge which used modified Dischinger system, the girder stiffness beam with height 3.5m is concrete box-girder beam except the hanging part which in middle span used steel box-girder, the tower is concrete gate-shaped frame, vertical layout of the program shown in Figure.5.

3.2 Seismic Motion Input

According to the specific site condition of bridge location, selected 3 stripes seismic wave accord with the site condition from existing strong motion recording, in paper selected EI-Centro 270°,Taft 69°and Taft 339°, the major cycle of above 3 stripes wave lies between 0.3~0.35, respectively suitable for medium-hare and soft site. The selected acceleration wave shape is shown in Fig.6.





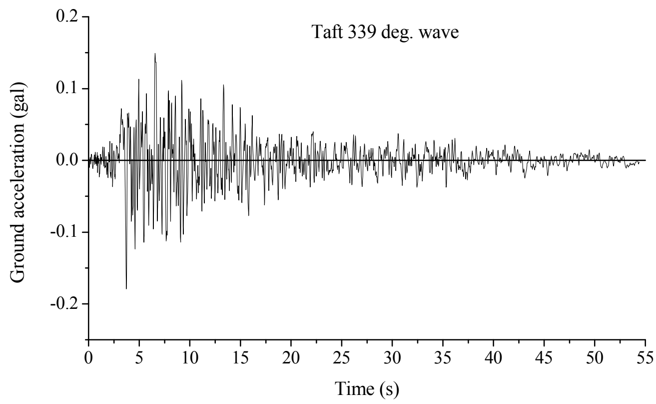


Fig. 6. Seismic wave for calculation

3.3 Effect of Seismic Response

Seismic response analysis used EI-Centro 270° ,Taft 69° and Taft 339° waves input, just considering the longitudinal wave action, the time-history of displacement and moment for main control section shown in Fig.7 to Fig.12. (Due to the structural symmetry, It only gives the bottom of left tower axial force and bending moment) from the result of displacement and internal force time history can be seen, the results of six spring model and the model of consolidation pier bottom are almost the same, the design process can be considered as the consolidation pier bottom; result of equivalent fixed model and lumped mass model are similar, when considering the interaction of pile soil, the overall structure of the stiffness decline, thus the internal force has the tendency of increase.

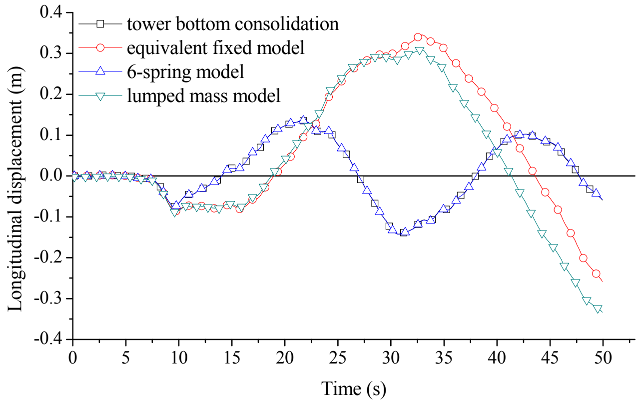


Fig. 7. Longitudinal displacement time histories in middle of main girder

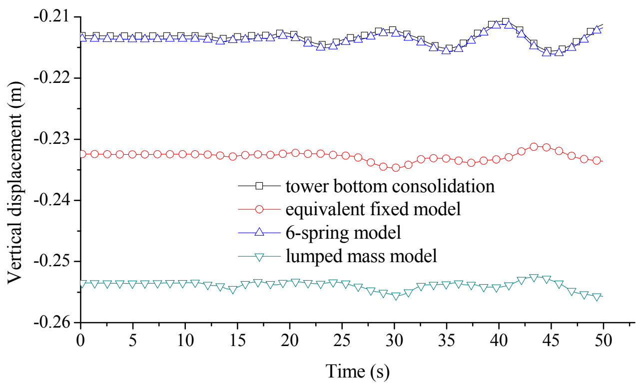


Fig. 8. Vertical displacement time histories in middle of main girder

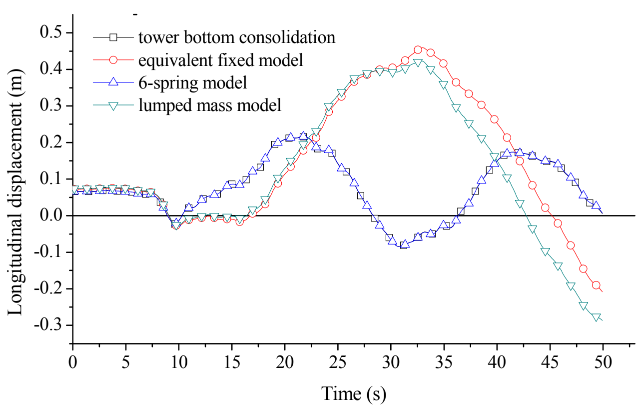


Fig. 9. Longitudinal displacement time histories at top of left tower

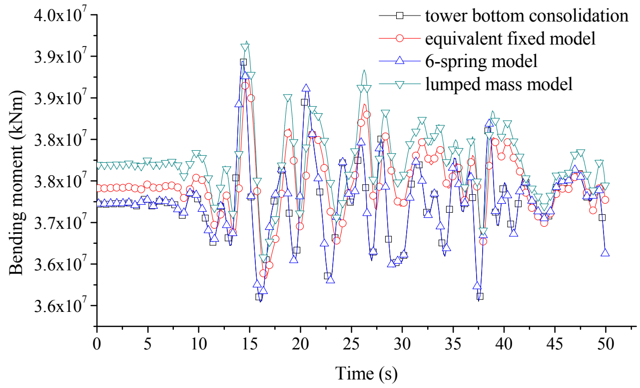


Fig. 10. Longitudinal moment time histories of the main girder

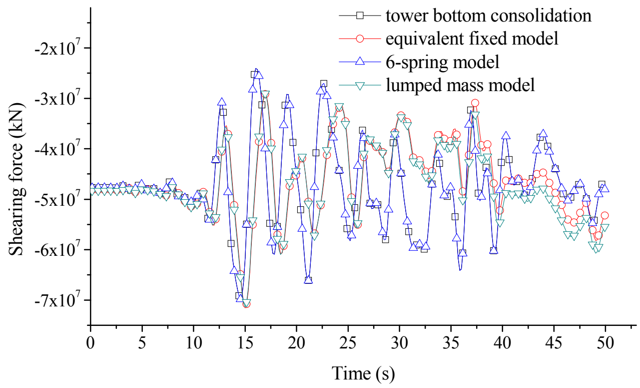


Fig. 11. Shearing force time histories of main girder

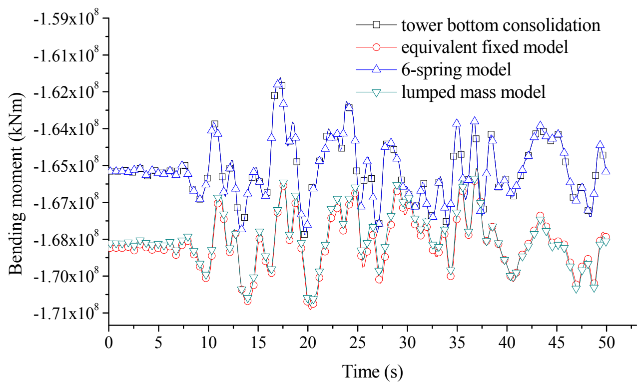


Fig. 12. Longitudinal moment time histories at mixture junction of main girder steel

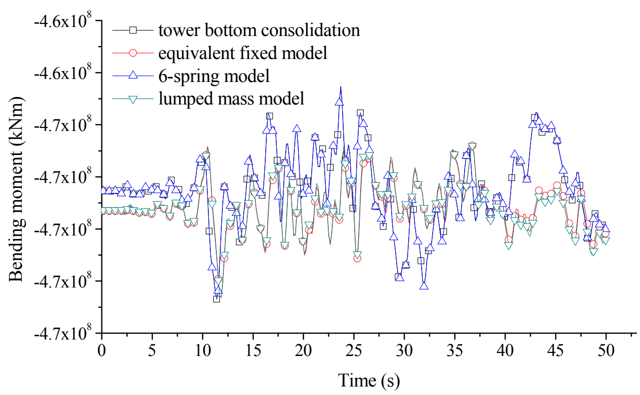


Fig. 13. Longitudinal moment time histories at junction between tower and beam

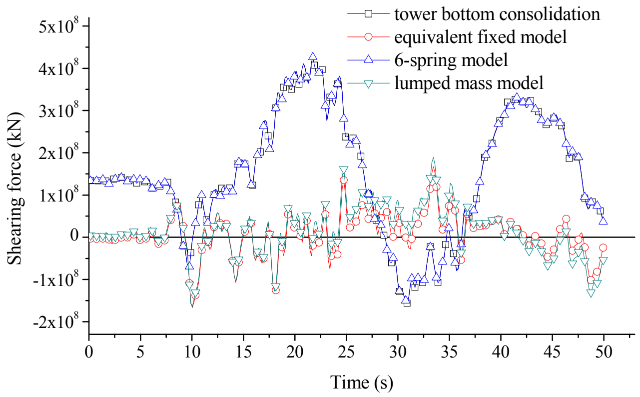


Fig. 14. Shearing force time histories at junction between tower and beam

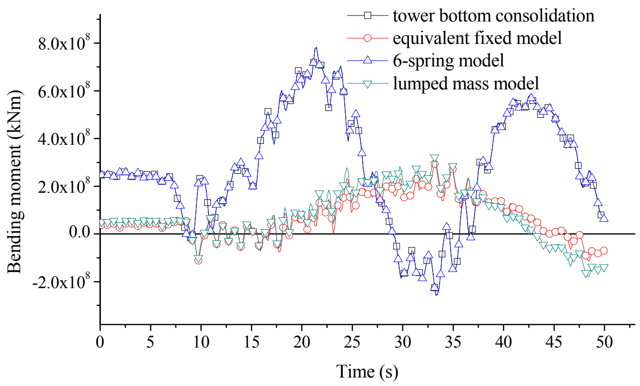


Fig. 15. Longitudinal moment time histories of left tower bottom

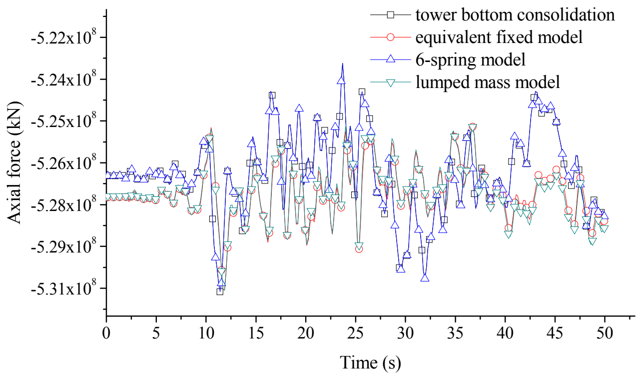


Fig. 16. Axial force time histories of left tower bottom

IV. CONCLUSION

Through analysis self-anchored cable-stayed suspension bridge of four calculation modes, we can draw the following conclusions:

(1) The integral rigidity of structure could be reduced and natural vibration period be extended by pile-soil-structure interaction;

(2) The effects of longitudinal components by pile-soil-structure interaction that mainly manifested in increase of longitudinal, vertical displacement and moment which in middle of main span of stiffening girder;

(3) The effects of vertical components by pile-soil-structure interaction that mainly manifested in increase of longitudinal displacement on top of tower and axial-force at bottom of tower, decrease of moment at bottom of tower.

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