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Nonlinear seismic response analysis of long-span cable-stayed bridge

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ABSTRACT: The Yangpu Bridge and Nanpu Bridge are the two composite cable-stayed bridges over Huangpu River on the inner ring road of Shanghai. Both of its superstructures have been designed as a floating system to withstand the strong earthquakes. The nonlinear seismic response analysis of these bridges are investigated with the use of NSRAP program developed by authors. In this program, 3-D linear and nonlinear element of beam-column considering the effects of confind concrete, space nonlinear element of rubber bearings and boundary springs and soil-pile-stucture interaction are considered. The multi-support or uniform seismic excitation and the effects of travelling seismic wave are studied. A comparison of earthquak response results between the two bridges have been made in this paper.

1 INTRODUCTION

The Yangpu Bridge and Nanpu Bridge in Shanghai are composite cable-stayed bridge as shown in Fig.1. Both of the superstructure are designed as a floating system, no bearings are used in main span, only slide bearings are provided at extreme piers and prestressed strand bearings at auxiliary piers which is located in the side span. all of the pylon foundations are supported by a group of deep steel pipe piles. The composite girder of Nanpu Bridge is composed of two steel separated I-type plate girders with P.C slab decking, and that for Yangpu Bridge is two steel separated box girders.

The nonlinear seismic response analysis of these bridges was investigated by response spectrum analysis method with reduced coefficient C considering elasto-plastic behavior of structures in preliminary design stage, and time history analysis method by using artificial seismic wave as input motion in final seismic design stage.

The 3-D nonlinear seismic response program [1] have been made in consideration of following eight respects: (1) combination of artificial acceleration time history in different soil layer along the deep of pile according to the seismic risk analysis and the seismic motions responses in soil layer at the bridge site; (2) soil-pile-structure interaction; (3) multi-excitation along the deep of pile in different soil layer; (4) stress-strain relationship of confined concrete; (5) effect of P-Δ both in the deck and pylon legs; (6) the elastic-plastic characteristics of all elements; (7) the nonlinear characteristics of special bearings and (8) the effect of cable sags.

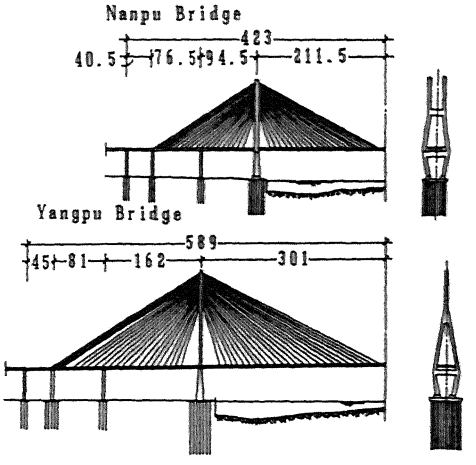


Fig. 1. General view of Nanpu Bridge and Yangpu Bridge in Shanghai

2 ANALYSIS METHOD

2.1 Analytical model and seismic design criteria

3-D analytical model, as shown in Fig.2, is adopted for response spectrum analysis. The group-piles foundation was simulated by six elastic springs. According to Chinese Code

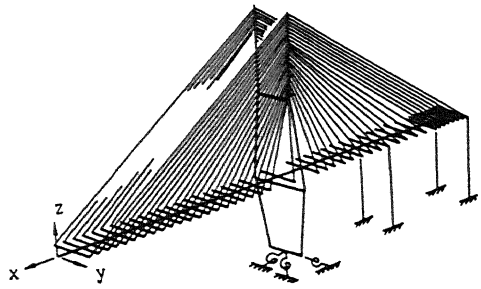


Fig. 2. Aanlytical model of Nanpu Bridge

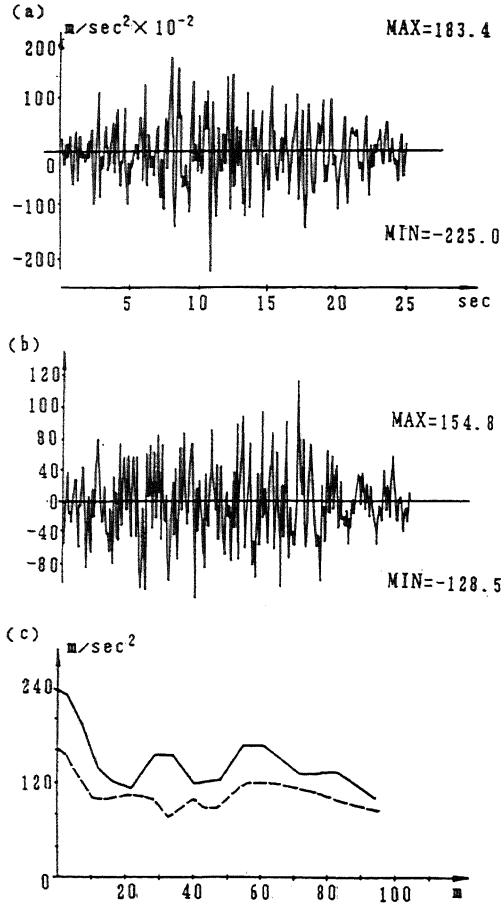


Fig. 3. Artificial seismic records

for Aseismic Design in Highwag Engineering, four cases were investigated, as (1) longitudinal seismic force; (2) longitudinal seismic force with vertical seismic force adopting 2/3 longitudinal seismic force; (3) transverse seismic force and (4) transverse seismic force with vertical seismic force adopting 2/3 transverse seismic force. The reduced coefficient C_z is taken as 0.35 for main girders and 0.5 for pylon legs.

For comparison, the different 3-D analytical models were adopted in time history analysis, such as, with or without auxiliary piers and considering or unconsidering the pile-soil interaction.

2.2 Seismic design criteria and input motions

According to Chinese Code for Aseismic Design of Highway Bridge and referring to other concerned code at home and abroad, for the moderate earthquakes that may occur with high probability in the life of the structure should perform elastically without damage; for the strong earthguakes with 0.1 probability of exceedence in 50 years (P) the bridge may suffer repairable damage, but it should keep the emergency passage; for the rare earthquakes with 0.1 propability of exceedence in 100 years(P) the bridge may have serious damage, but no life loss. It is recognized that the foundations of bridge should be strengthened to withstand the strong earthquake. because it could not be easily repaired.

The input motions used for time history analysis have been made according to estimate the expected seismic motions by the earthquake risk analysis. For Yangpu Bridge and Nanpu Bridge, the risk level of 0.1 propability of exceedence in 50 years and 100 years was chosen by Shanghai Earthquake Bureau, and the correspondent artificial seismic records at bridge site have been computed. For example, Fig.4.a & b show that the artificial accelerations at eastern plyon and western pylon of Nanpu Bridge, only ones of horizontal direction taken out of the three group datums of acceleration.

2.3 Soil-pile-structure interaction

In this paper, the analysis of soil-pile-structure interaction consists mainly of (1) earthquake response analysis of free field, and (2) the analysis of the interaction considering the elastic confining action of soil to structural foundation. Therefore, the nonlinear seismic response analysis of long-span bridge could be equated to 1-D nonlinear seismic response analysis of free field and the nonlinear seismic response analysis of the bridge structure with group-pile foundation (considering the elastic confining action of the soil springs) under the multi-support excitation. The 1-D nonlinear seismic response analysis of free field are simulated to the vibration analysis of 1-D shear beam model under the action of the artificial seismic wave on bed rock. The time history records of acceleration were calculated in the soil layer 290-300m under the ground at the eastern pylon and western

pylon using a 1-D nonlinear model. Then 2-D model considereing the geographical conditions at the bridge site was applied and using the finite boundary analysis method, finally, the artificial accelerograms both in horizontal and vertical direction at 16 points along pile depth at the eastern and the western pylon for each of three accelerograms on bed rock were obtained as input motions for multi-support excitation along the pipe depth in different soil layers. Fig.3. c shows that one of peak value of acceleration varies in the different soil layers. Through the analysis the followiny results were obtained: (1) The ratios of the peak values of acceleration at ground surface to those on bed rock are about 1.25 to 2.00, even up to 3.0 in individual case. (2) Acceleration response spectra of the bed rock given by shanghai Earthquake Bureau is approximate to that of the earthquake of MMS7, while acceleration response spectra on the ground surface obtained from above investigation is approximate to the earthquake of MMS8.

2.4 Equation of motion

The motion equation of the dynamic equilibrium of the bridges subjected to multi-support excitation is as follows:

$$M\ddot{y} + C\dot{y} + Ky = F \qquad (1)$$

where

$$M = \begin{bmatrix} M_s & 0 \\ 0 & M_b \end{bmatrix} \qquad C = \begin{bmatrix} C_s & C_{sb} \\ C_{sb}^T & C_b \end{bmatrix}$$

$$K = \begin{bmatrix} K_s & K_{sb} \\ K_{sb}^T & K_b \end{bmatrix} \qquad F = \begin{Bmatrix} 0 \\ F_b \end{Bmatrix}$$

the subscript 'b' designates the degrees of freedom corresponding to the point of application and direction of ground motions, and the subscript 's' corresponds to all other structural degree of freedom of the bridge model, vector $\{\ddot{y}_s\}$, $\{\dot{y}_s\}$ and $\{y_s\}$ are absolute acceleration, velocity and displacement respectively of non-support nodes. $[M_s]$, $[C_s]$ and $[K_s]$ are mass, damping and stiffness matrixes, respectively of element of corresponding non-support nodes $[F]$ is reaction force of support.

Assuming that the displacement can be separated into vibrational and pseudo-static displacements,

$$y = \begin{Bmatrix} y_s \\ y_b \end{Bmatrix} = \begin{Bmatrix} u_s \\ 0 \end{Bmatrix} + \begin{Bmatrix} y_s^s \\ y_b \end{Bmatrix} \qquad (2)$$

for the given support displacements $\{y\}$ can be expressed by

$$\{y_s\} = -[K_s]^{-1}[K_{sb}]\{y_b\} = [R]\{y_b\}$$

where, $[R]$ is called as effect matrix.

Generally, the contribution due to damping term resulted from support velocity $\{\dot{y}_b\}$ is neglected, equation (1) can be simplified as

$$[M_s][\ddot{U}_s^d] + [C_s][\dot{U}_s^d] + [K_s]\{U_s^d\} = -[M_s][R]\{y_b\} \qquad (3)$$

Because of the nonlinearity of the bridge structure, $[C_s]$, $[K_s]$ and $[R]$ are the function of time, in order to analysis conveniently, equation (3) can be expressed by the incremental motion equation

$$[M_s][\Delta\ddot{U}_s^d] + [C_s][\Delta\dot{U}_s^d] + [K_s][\Delta U_s^d] = -[M_s][R]\{\Delta y_b\} \qquad (4)$$

The vibrational displacement and acceleration can be obtained by step-by -step intergration with the use of Wilson-θ method. The total displacement of nodes are the sum of vibrational displacement and the pseudo-static displacement, then the inner forces of element could be obtained.

3 DYNANIC BEHAVIOR OF CABLE-STAYED RIDGE

The frist ten computed 3-D Natural frequencies for 3-D analytical model with auxiliary pier are shown in Table 1, where (S) denotes symmetric mode, (A) asymmetric mode. The following analysis results can be found: (1) The frist mode shape of both bridges appears to be floating form due to these bridges designed as a floating system allowing the deck to swing freely at the pylons. For the longitudinal seismic responses, the component part of seismic force caused by the floating mode shape constitutes the majority of the total seismic force. (2) The first frequency of Yangpu Bridge is less then half of Nanpu Bridge. It is very advantageous for the structures of Yangpu Bridge with long natural period under earthquakes, even if the span length and total mass of Yangpu Bridge is larger than

Table 1. Natural Frequencies of Yangpu Bridge and Nanpu Bridge

	Nanpu Bridge		Yangpu Bridge	
No	3-D model	mode	3-D model	mode
1	0.149(A)	In plane	0.073(A)	In plane
2	0.306(S)	Out of plane	0.259(S)	Out of plane
3	0.361(S)	In plane	0.266(S)	In plane
4	0.371(A)	Out of plane	0.324(A)	In plane
5	0.416(S)	Out of plane	0.375(A)	Out of plane
6	0.427(S)	torsion	0.388(S)	Torsion
7	0.450(S)	In plane	0.417(S)	Out of plane
8	0.458(A)	Torsion	0.464(S)	In plane
9	0.517(A)	Out of plane	0.492(A)	Torsion
10	0.605(S)	Out of plane	0.548(A)	In plane

that of Nanpu Bridge. (3) The mode shapes of first three natural frequences of both bridges is very in similar. Then it is evident that the order of the mode shapes with high grades is changed for both bridge, the main reason is that the transverse retaining brock is setted on the extreme piers of Yangpu Bridge to set a limit to transverse swing displacements of both end of girders.

4 COMPARISON OF ANALYSIS RESCUTS

For comparison, the four cases of 3-D analytical model and theree groups of input motion were adopted in nonlinear seismic response analysis of both bridge, so a lot of datums of calculating results and a series of time history curves of inner forces and displacements in the structures have been obtained by using the program NSRAP. In this paper, the effects of differcnt cases have been discussed with a few examples.

Fig. 4 shows that the time history curve of longitudinal bending monent at eastern pylon bottom (a) and western pylon bottom (b) of Naupu Bridge, in this case, the 3-D analytical model with auxiliary piers in the side span was adopted and different artificial seismic records were used as input motions at many point in 5 soil layers to consider soil-pile-structure interaction. The peak value of acceleration of input gronnd motion is takon as 225gal at western pylon and 154gal at eastern pylon (Fig.3).

The maximum responses of bending moment in pylons thus calculated for the same model in longitadinal direction are presented in Fig.5. For Nanpu Bridge, the peak value of acceleration of input ground motion is taken as 164gal at western pylon and 167gal at eastern pylon, for Yongpu Bridge, that is 222gal at western pylon and 175gal at eastern pylon. Fig.7. shows that the envelope of longitudinal bending moment in structures of Nanpu Bridge, where (1) denotes the 3-D analytical model with auxiliary piers in side span and group piles foundation in consideration of soil-pile-structure interaction under multi-suppot excitation, (2)denotes that of assuming the fixed supporting at the pylon bottom.

The results of analysis were summarized as follows:

a) Comparing Fig. 5 with Fig.6a, we can see that the maximun responses of bending monent ot pylon bottom will be occurs when both of these input ground motions approach to a first approximation. It is worth notice that the effects of pseudo-statics term always are not disadvantageous for seismic responses of cable-stayed bridge, especially in floating system. In addition, this conclusion is also applicable to the effects if phase-difference or multi-support excitation.

b) The results obtained from seismic

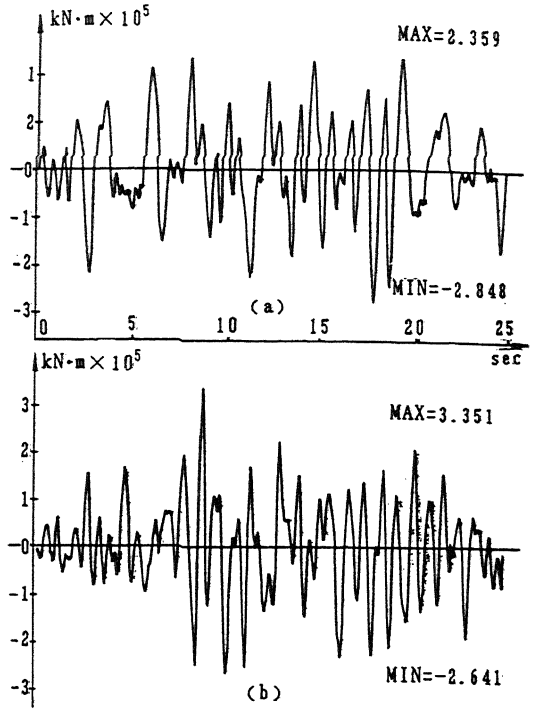


Fig. 4. Time history curves of bending moment

response analysis of both bridge show that the inner forces and displacements of the pylon calculated by considering soil-pile-structure interaction are large than that one of the simplified analytical model with fixed end on the bottom of the pylons. Because the group-piles foundation is subjected to multi seismic excitation of horizontal motion as well as swinging motion which is caused by the different peak acceleration varied along the pile depth.

For Nanpu Bridge the bending momemt at the bottom of the eastern and western pylon increases of 49.6% and 47.7% respectively; the horizontal displacement at the top of both pylons ncreases of 36.6% and 37.8% respectively and the vertical displacement at the center of main span increases of 16%.

c) As shown in Fig.6., the transrerse bending moment in pylons of both bridge are not large than the longitudinal bending moment in pylon. The strength requirements of the section at pylon bottom is satisfied both in wosk stress design and ultimate strength design. But it is to be noted that the strength of the section at the connection *of pylon legs inth up or lower tranverse* bracing for H-type pylon and up-cross-joint for A-type pylon could be strengthened, there is a danger that although the bending moment at these sections is reduced, the strength of these section may be also decreased.

d) Since some complicated factors, such as

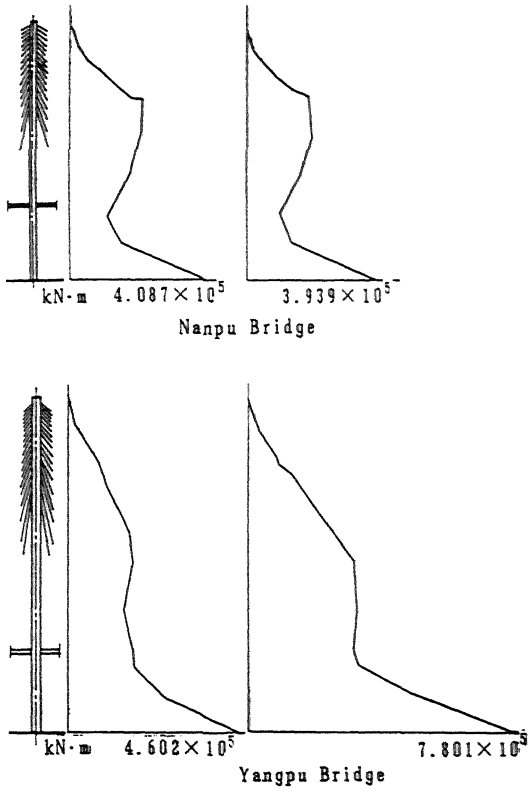


Fig. 5. Longtitudinal bending moment in pylon

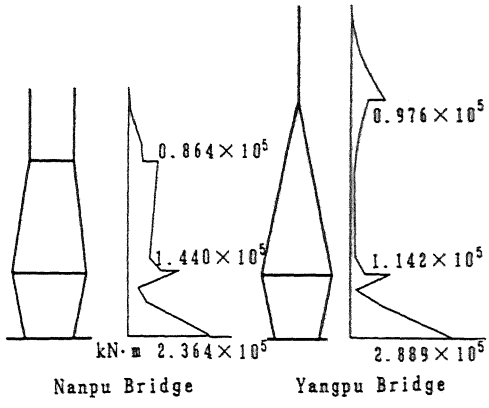


Fig. 6.Transverse bending moment in pylon

soil-pile-structure interaction, multi-support excitation and so on, can not be taken into account by response spectrum analysis method, the results obtained by response spectrum analysis method are larger than those by time history analysis method. Therefore, the response spectrum analysis method are only used for preliminary design stage for both bridges. The evaluation of the earthquake resistance of both bridges was checked by time history response analysis method.

e) According to investigated systematically the earthquake resistance design of both bridges, that the Yangpu Bridge and Nanpu Bridge structures are in safty to subject to 8 degree of earthquake intensity.

f) in order to ensure the further ductility requirements of pylons of both bridge under potential strong earthquakes, the transverse reinforcement in pylon, commonly in the form of closely spaced steel spiral or hoops, have been strengthened to incrcase the strain limit and the compression strength of concrete in pylon.

5 CONCLUSION

Based on results of this study, the following conclusion were reached,

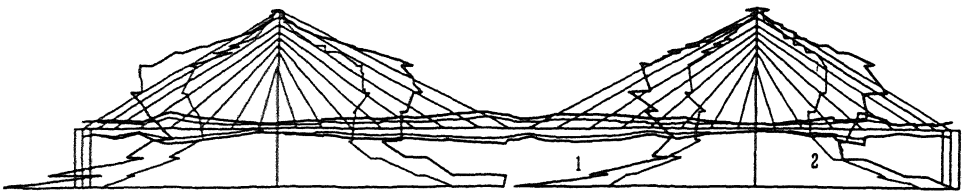
1) It is necessary that the effects of dynamic soil-pile-structure interaction should be considered in seismic response analysis for long-span cable-stayed bridge with pile foundation, specially for these bridges constructed on soft soil ground. At the construction site of Yangpu Bridge and Nangpu Bridge the thickness of the soft soil deposit reaches about 300m. Through this deposit the response of ground motions of higher frequency will be attenuation, while that of lower frequency will be amplification, which is the main reason to consider the soil-pile-structure interaction for seismic response analysis of long-span cable -stayed bridge with low natural frequency.

2) For the response spectrum analysis method, the given value of the reduced coefficient C_z and dynamic magnifing coefficient β in the concerned code should be revised, because the reliability of calculating results by this method is depend upon the accuracy of both coefficients, especially for long-span bridges with long natural period.

3) To strengthen the transverse reinforced in pylons or piers could be a effective manner, therefore, the concepts of confined concrete may be put emphasis on the asiesmic design of bridges. The hysteretic capacity of the bridge pylon or piers with different type of section should be studied in good time.

REFERENCES

Yuan W. Fan L. & Xiang H. 1992.3-D Nonlinear seismic response analyses of long-span bridges. Journal of Tongji University, vol. 19 Issue, 13-21.



Nanpu Bridge

Fig. 7. The envelope curve of bending moment in structure

Fan L. Yuan W. & Hu S. 1992. The nonlinear earthquake response analysis of Nanpu bridge. Journal of Civli Engineering vol.25 (3).

Scott B.D., Park R. & Preiestley M.J.N. 1982. Stress-strain behaviour of concrete confinedd by overlapping hoops at low and hign strain rates. ACI Journal, 79 (1).

Fan L. & Yuan W. 1989. Study on the behaviour of seismic isolation and energy absorption of elastomeric pad bearings for bridges. Jounal of Tongji University, vol.17 (4).

Wolf,J.P. 1985. Dynamic soil-structure interaction. Prentice-Hall, Inc. Englewood Cliffs, New Jersey

Abdel-Ghaffar A.M. 1991. Cable-stayed bridges under seismic action. Elsevier Science Publisherss B.V.