Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 80 (1999)

Artikel: Seismic response for cable-stayed bridge pylon foundation considering soil-structure interaction

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DOI: https://doi.org/10.5169/seals-60764

Seismic Response for Cable-Stayed Bridge Pylon Foundation Considering Soil-Structure Interaction

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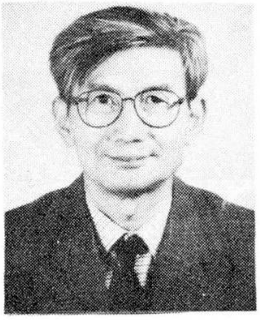

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SUMMARY

In this paper, soil-structure interaction was investigated in the simpler model called Single Pylon Model(SPM), and in order to attest the rationality of SPM, more elaborate model called Whole Bridge Model(WBM) was also used. The non-linearity of soil was dealt with equivalent linearity method in which the equivalent stiffness and equivalent damping ratio were calculated by special iterational program, the equivalent masses were calculated by the energy equivalent law. The foundation spring stiffness' of translation, rotation and coupling each other term are calculated by SPM. The pile foundations are substituted by SPM results in WBM. Using the seismic input motion of bed rock which have been proposed according to earthquake risk analysis, the acceleration history and the response spectrum at top of cap slab were evaluated by SPM which are used as the input spectra in WBM to evaluate the seismic response.

The natural periods and seismic responses of the bridge are calculated by the two proposed methods respectively. Those results by SPM are coincided favorably with those corresponding item by WBM. It is demonstrated the SPM method for seismic response analysis considering soil-pile-pylon interaction is worthy of continued study.

1 INTRODUCTION

The long-span (180m+312m+180m) cable-stayed bridge (Fig.1) is building at Wuhu City to cross Yangtze River. The pile foundation is adopted in this major bridge. The geological condition of the bridge is very complicated and every pylon's grounds are variant remarkably. The covering soil of the long pylon is 27m depth which is from -43m to -16m in altitude, while that of the short one is only 9.2m depth which is from -33.8m to -24m. It is obvious that the soil-pile-pylon interaction of each pylon is different. In order to calculate the seismic responses and dynamic behaviors of each pylon considering the interaction of soil-pile-pylon respectively, the simpler model called Single Pylon Model (SPM) is used. In order to attest the rationality of SPM, more elaborate model called Whole Bridge Model (WBM) is used also.

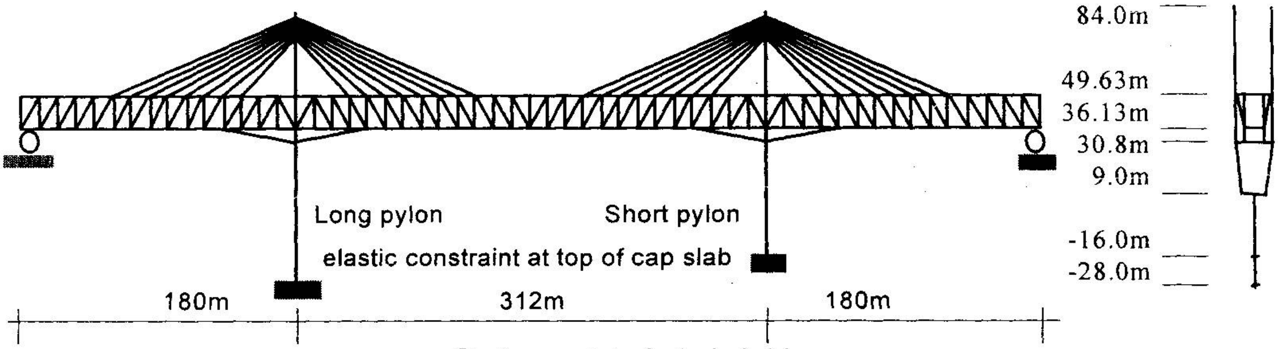


Fig.1 model of whole bridge

2 ANALYSIS METHOD

The analysis of soil-pile-pylon interaction in SPM mainly consists of two steps. The first is free field analysis of earthquake response and the second is the soil-pile-pylon interaction analysis in which the pile foundation elasticity-confined to the field is considered. The boundary conditions of the second are provided by the first.

2.1 Seismic response analysis of the free field

The assumptions about the soil are: The surface is horizontal; The soil in one layer is homogeneous; The soil is boundless. One-dimension soil column model is adapted to simulate the free field. The kinetics equation of the free field is:

$$\mathbf{M}^{\mathbf{G}}\ddot{\mathbf{U}}^{\mathbf{G}} + \mathbf{C}^{\mathbf{G}}\dot{\mathbf{U}}^{\mathbf{G}} + \mathbf{K}^{\mathbf{G}}\mathbf{U}^{\mathbf{G}} = -\mathbf{M}\mathbf{I}^{G}\ddot{u}_g$$

in which: $\mathbf{U}^G$ vector of seismic 3-dimensional response; $\ddot{u}_g$ acceleration of the base rock; $\mathbf{M}^{\mathbf{G}}$ mass matrix with the diagonal elements $m_i^G = \frac{1}{2}(\rho_i h_i + \rho_{i+1} h_{i+1})$; $\mathbf{K}^{\mathbf{G}}$ stiffness matrix with verticalital and horizontal elements respectively $K_{wi}^G = \frac{2G_i}{h_i}\left(\frac{1-\gamma_i}{1-2\gamma_i}\right)$ and $K_{ui}^G = \frac{G_i}{h_i}$; $\mathbf{C}^{\mathbf{G}}$ Rayleigh damping matrix. In preceding formula : ρ_i, h_i, G_i, γ_i are mass per meter, height, shear modulus, Poisson ratio of the *i*th layer respectively.

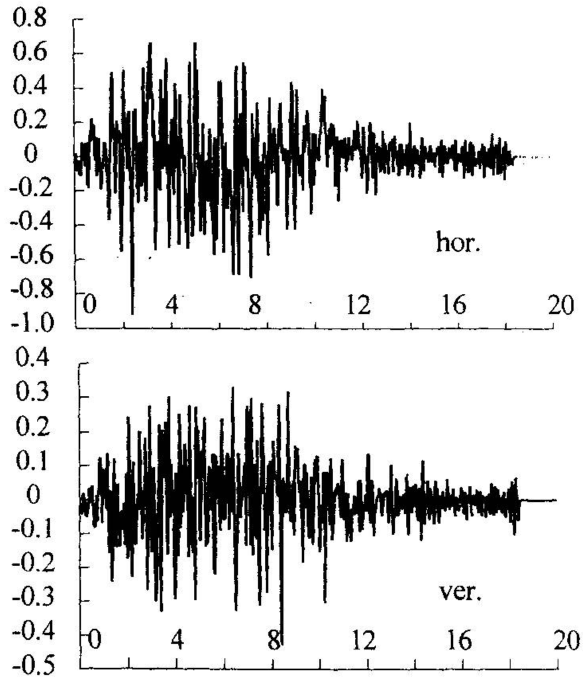


Fig.2 acc. input history

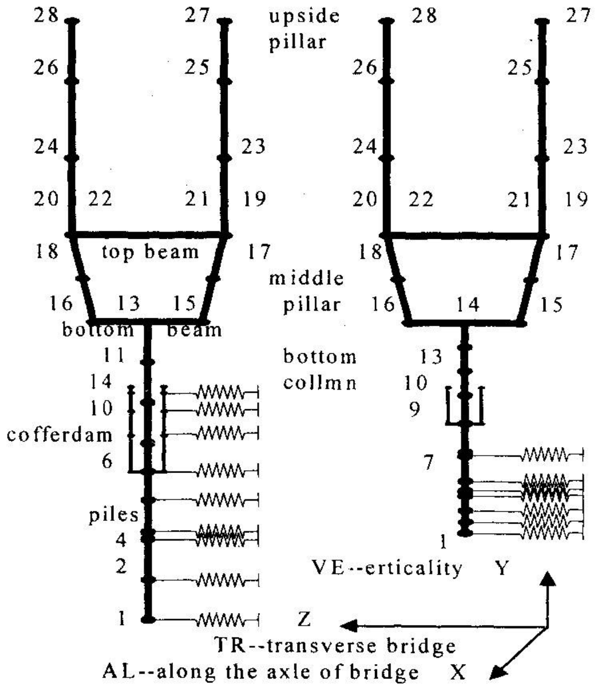
The non-linearity of soil is dealt with equivalent linearity method in which the equivalent stiffness and equivalent damping ratio were calculated by iterational. Special program is compiled for the purpose.

The seismic input motions of bed rock are provided by the Seismic Bureau of Anhui province, in which province the bridge is building. The probability of exceedence in 100 years is 10%. As the results of seismic risk analysis at bridge site, there are 12 inputs provided, which include 6 in horizontal and 6 in vertical respectively. One of six inputs in each direction is shown in Fig.2. Its maximum acceleration is 0.952m/s*s in horizontal and 0.436m/s*s in vertical respectively.

2.2 Analytical model

The group piles are simulated by a fictitious pile. The equivalent spring's stiffness at the bottom of cap slab caused by pile's support are computed according $K_{\varphi u} = \sum_{i=1}^{Q} x_i^2 \cdot k_{pi}$ in which: Q the total number of piles, k_{pi} the axial stiffness of the ith pile according to Sato assumption, x_i the coordinate of the ith pile. The SPM is shown in Fig.3. The characters of cross sections of the pylons are shown in table 1. The stiffness matrix is assembled by beam elements, and the mass matrix by lumped mass. In order to reduce the freedom for consider soil-pile-pylon interaction, the mass of main truss and other auxiliary is allocated reasonably with lumped mass in SPM. In order to ensure the comparability, the method of calculating the data in SPM is conformed with those in WBM.

Using those foundation spring stiffness proffered by SPM, the WBM is shown in Fig.1, in which the pylon is simulated by beam elements as well as main truss and auxiliary.



long pylon short pylon

Fig.3 Single pylon model

	section area	polar inertia moment	inertia moment		linear density
	m**2	m**4	m**4	m**4	t/m
single pile	7.069	7.952	3.976	3.976	18.732
long pylon fictitious pile	134.303	151.091	75.545	75.545	355.903
short pylon fictitious pile	120.166	135.183	67.593	67.593	318.440
cap slab	730.617	84957.0	42478.51	42478.5	1936.134
cofferdam	127.988	27158.2	13579.1	13579.1	339.169
long pylon	144.7	6060.9	7311.1	2889.4	383.46
bottom column	300.7	11652.0	11982.0	4756.7	796.96
short pylon	135.240	5517.0	6972.8	2562.0	358.545
bottom column	284.020	10003.0	11455.0	3945.0	752.653
bottom beam	68.340	550.360	738.824	205.02	181.101
middle pillar	34.700	212.610	92.510	445.370	91.955
top beam	16.900	78.740	67.826	48.348	44.785
	30.900	174.760	212.490	96.760	81.885
upside pillar	25.200	116.310	53.450	202.680	66.780

note : pylon elements E=0.35e11 pa, G=0.129e11 pa; pile elements E=0.31e11 pa ,G=0.122e11 pa

Table 1 The character of cross section in SPM

	long pylon			short pylon		
	AL	VE	TR	AL	VE	TR
joint of pylon and truss	1771	6833	3574	5597	7565	10179
top of pylon	3330.7	168.3	382.6	4916.0	168.33	548.57

Table 2 The allocated mass of main truss and other auxiliary in SPM (t)

2.3 Equation of Soil-Pile Interaction

The equations of motion considering the soil-pile-pylon interaction are:

$$\left(m_i^P + m_i^s\right)\cdot \ddot{u}_i + \sum_{j=1}^{n} c_{ij}^P \dot{u}_j + c_i^s \dot{u}_i + \sum_{j=1}^{n} k_{ij}^P u_j + k_i^s u_i = -m_i^P \ddot{u}_g + m_i^s \ddot{u}_i^G + c_i^s \dot{u}_i^G + k_i^s u_i^G$$

in which: the relative displacements of the pile and pylon $\{u\} = \{u_i\}$; the relative displacement of the soil $\left\{u^G\right\} = \left\{u_j^G\right\}; i = 1,\cdots,n$. Other parameters are shown in reference [1].

2.4 Equivalent Parameter of Soil-Pile Interaction

The equivalent horizontal stiffness between soil and the fictitious pile are calculated by Mindlin formula and Elasto Winkler assumption[1]. The equivalent vertical stiffness between soil and the fictitious pile are calculated according Sato assumption. The equivalent masses of the soil-pile interaction were calculated by the energy equivalent theory. At last the stiffness matrix and mass matrix of soil's equivalent effect are assembled according degree of freedom. Certainly the data of equivalent effect relevant to the pylon element is zero.

2.5 Seismic response spectra

The response spectra analysis method is used to calculate the seismic response in WBM. Using those 12 seismic input motions of bed rock, 18 acceleration histories--six respective in each of AL,VE,TR directions--at top of cap slab are analyzed by SPM to get the response spectra at the same location. Six response spectra are obtained in each direction by Duhamel integral. The envelope curve of the six response spectra is used as the input after studying the conformity of the six in each direction.

3 NATURAL PERIOD

The dynamic behaviors of the bridge are calculated by the two proposed models respectively. The natural periods are shown in the table 3. The SPM results are agreement with those of WBM.

	WBM	character of WBM	long pylon	short pylon	character of SPM
1	2.6843	truss,TR,symmetrical bending			
2	2.4420	two pylon, AL, floating	2.4369	2.55240	two pylon, AL
3	2.2460	truss and pylon,VE,symmetrical bending			
4	1.7088	long pylon and relevant beam,TR	1.73718		Long pylon TR
5	1.5718	short pylon and relevant beam,TR		1.68529	Short pylon TR
6	1.3606	short pylon and relevant beam,TR,torsion			
7	1.3446	long pylon and relevant beam,TR,torsion			
8	1.2982	short pylon ,TR		1.32631	Short pylon's limb TR
9	1.1666	long pylon ,TR	1.23953		Long pylon's limb TR
10	1.1624	truss and pylon,VE,anti-symmetrical bending			
11	1.1484	truss torsion			

Table 3 Period of bridge in WBM and SPM (s)

4 ANALYSIS RESULT

4.1 Stiffness Coefficient of Cap Slab of Pile Foundation

The foundation spring stiffness' of translation, torsion and coupling each other term that are calculated by SPM are shown in table 4.

These springs' coefficients are the constraint conditions at the cap slab to alternate the pile foundations in the WBM.

		long pylon	short pylon
length of piles	m	30	20
number of piles		19	17
diameter of piles	m	3.0	3.0
VE translation k_y	kN/m	1.683E8	4.085E8
TR translation k_z	kN/m	0.116E9	0.439E9
TR coupling k_{z,φ_x}	kN/rad	-1.730E9	-7.503E9
TR rotation k_{φ_x}	kN*m/rad	34.72E9	151.47E9
AL translation k_x	kN/m	0.115E9	0.439E9
AL coupling k_{x,φ_z}	kN/rad	1.718E9	7.503E9
AL rotation k_{φ_z}	kN*m/rad	34.86E9	151.47E9

table 4 The constrain coefficients at cap slabs

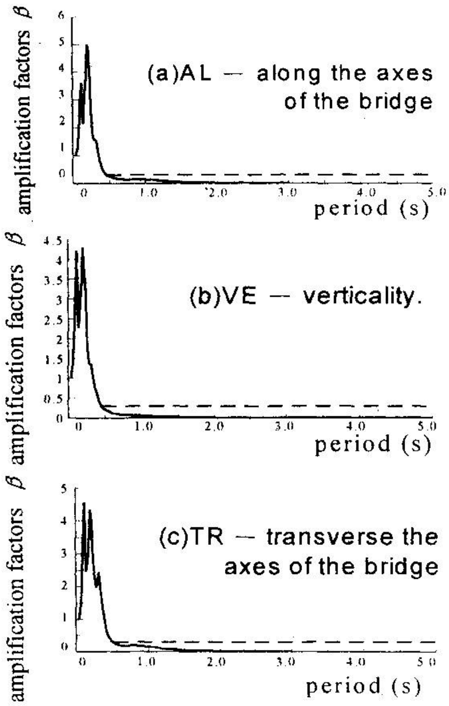


Fig.4 Envelope curves (response spectra at the top of cap slab in long pylon)

4.2 Envelop Curve of the Response Spectra

The envelope curves of the response spectrum at the top of cap slabs which are shown in Fig.4 and table.5 are calculated by SPM.

Those spectra are the input spectrum in the WBM.

		displacement	a_{max}	β_{max}	$\beta_{max} \times a_{max}$	a_{max} at period	β_{min} start period	$\beta_{min} \times a_{max}$
		mm	m/(s*s)		m/(s*s)	s	s	m/(s*s)
long pylon	AL	3.717	1.4476	5.01996	7.26689	0.20	0.46	0.4343
	VE	2.785	1.0735	4.29193	4.60738	0.20	0.45	0.3221
	TR	3.240	1.2041	4.55865	5.4888	0.12	0.52	0.3612
short pylon	AL	1.073	0.4034	4.22372	1.7038	0.28	0.56	0.1210
	VE	0.389	0.2784	4.02578	1.1208	0.08	0.44	0.0835
	TR	1.180	0.4103	5.02317	2.0610	0.28	0.60	0.1231

Note : 1. The probability of exceedence in 100 years is 10%, damp ratio is 0.05; 2. Refer to 《Highway Engineering Aseismic Design Code》 β_{min}=0.30, that is when the natural period is greater than the data in the last row of the table, amplification factor β is 0.30 .

Table 5 envelope curves of response spectrum at the top of cap slabs

4.3 Seismic responses

The section forces and displacement of the bridge are calculated by the two proposed models respectively. The results were shown in the table 6. Clearly the SPM results are agreement with those of WBM

		SPM 4 modes	WBM 10 modes		WBM 30 modes	SPM 8 modes	WBM 54 modes		WBM 70 modes
the displacements of middle joint of the main truss and top joint of each pylon									
main truss TR	cm		9.7957		9.8016		9.8022		9.8022
main truss AL	cm		7.8944		7.8946		7.9027		7.9033
main truss VE	cm		3.1576		3.2597		3.2632		3.2711
long pylon TR	cm	5.6203	4.1317		4.1438	5.67	4.1599		4.16
long pylon AL	cm	9.4638	7.9649		7.9677	9.46	7.9743		7.9742
short pylon TR	cm	5.6542	3.7510		3.7656	5.71	3.7729		3.773
short pylon AL	cm	9.8567	8.3616		8.3639	9.82	8.3655		8.4059
the section forces of bottom joint of each pylon: M is moment, Q is shear force, N is axial force									
long pylon TR M	t-m	43428	44864	3.31%	46346	50838	47827	5.92%	47826
long pylon TR Q	t	550.05	617.42	12.24%	721.64	1957.2	1776.9	9.25%	1777.6
long pylon AL M	t-m	81747	78402	4.27%	79376	84981	79692	6.22%	79685
long pylon AL Q	t	898.73	989.53	10.1%	1085.6	1208.5	1268.0	4.73%	1263.1
long pylon N	t	.06513	114.55		282.14	650.89	371.75		621.06
short pylon TR M	t-m	43140	40500	6.12%	43087	50150	45722	8.83%	45723
short pylon TR Q	t	620.80	618.52	0.037%	774.44	915.49	880.95	3.77%	880.95
short pylon AL M	t-m	88091	91411	3.63%	91495	90578	93852	3.48%	103510
short pylon AL Q	t	1101.7	1303.5	15.49%	1387.2	1279.5	1504.8	14.97%	2851.1
short pylon N	t	.06691	121.73		272.24	481.12	334.02		471.00

Table. 6 section forces and displacements of seismic response in WBM and SPM

5 CONCLUSIONS

Considering this study, the following conclusion can be made:

1. Because the bridge is so major and the geological conditions of each pylon are so complex, the effects of dynamic soil-pile-pylon interaction should be considered. It is possible and expedient to make these considerations into reality in SPM. The elastic constraints at the top of cap slab are calculated by SPM for replacing pile foundation in WBM.

2. It is convenient to calculate the response spectra at the top of cap slab by SPM. The envelope curves of those spectra are used as the input spectra in WBM to evaluate the seismic responses.

3. The section forces and displacements of seismic response are evaluated by SPM and WBM respectively. Those results by SPM are coincided favorably with those identical items by WBM. It is demonstrated the SPM method for seismic response analysis considering soil-pile-pylon interaction is worthy of continued study.

Note: In the whole paper direction symbol (which has been shown in Fig.3) : AL — along the axes of the bridge; TR — transverse the axes of the bridge; VE — verticality.

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