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EFFECT OF FOUNDATION DEPTH ON SEISMIC RESPONSE OF CABLE-STAYED BRIDGES BY CONSIDERING SOIL STRUCTURE INTERACTION

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Post-failure analysis of massive structure infers that Soil-structure interaction (SSI) is a crucial phenomena influencing seismic response of massive structures. Cable-stayed bridge popularity and numbers are increasing nowadays because of economical longer span &aesthetic good look. The current paper examines the effect of depth of foundation on seismic response of cable-stayed bridges. In total 16 cases are solved with and without SSI by time-history analysis with Finite Element Program. Full 3D bridge model is developed and soil is modeled by assigning the spring and dashpots as Kelvin element to simulate SSI effects. The result yielded that SSI effects must be considered for soft soil conditions irrespective of the depth of foundation. The effects of SSI are site specific and cannot be generalized. However the fundamental time period is increasing as high as 28% due to SSI effects. The depth of foundation has also a great role in seismic response of the bridge; the medium depth foundation is proven critical compared to other cases.

Keywords: soil-structure interaction, dynamic analysis, foundation soil, depth of foundation, time history analysis

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1. Introduction

Soil–structure interaction (SSI) is an important issue and must not be ignored in the seismic design of important structures including bridges. Soil-structure interaction is a complex phenomenon which can be illustrated in four steps: 1) Seismic waves pass through soil media; 2) Waves are amplified; 3) Soil imparts motion to structure; 4) Structure continues the motion and soil is again deforming because of inertia effects.

Thus SSI alters the dynamic characteristics of the structural response significantly. This interaction effects were neglected previously but due to the failure of so many massive structure during earthquake event the significance of SSI was realized. Thus SSI is given importance and lots of research work is going on to study the effects of SSI on various structures.

Bridges are critical life-line facilities which should remain functional without damage after an earthquake to facilitate the rescue and relief operations, Decal (2003). In recent years, several cable-stayed bridges have been constructed on relatively soft ground, which results in a great demand to evaluate the effects of soil–structure interaction (SSI) on the seismic behaviour of the bridges, and properly reflect it in their seismic design. This paper includes the study of effects of different pylon shape on structural response including SSI.

A number of studies investigated the influence of SSI on the earthquake response of conventionally designed bridges in recent years. Spyrakos (1990, 1992) utilizing simple linear elastic models has showed that SSI greatly affects the seismic response of bridges leading toward more flexible systems and increased damping. Ciampoli and Pinto (1995) conducted a large parametric study on conventionally designed bridges founded on shallow foundations considering inelastic response of the piers. The seismic input, they considered, consisted of seven artificially generated accelerograms compatible to Eurocode No. 8 spectra for intermediate stiffness type soils and for far field type of excitations. They concluded that SSI effects consistently decreased the ductility demands of the piers when compared to the system without SSI effects. In another study, Mylonakis and Gazetas (2000) using a simplified model for the bridge and the foundation, considering a set of actual acceleration time histories recorded on soft soil, showed that the period lengthening and increased damping due to SSI effects can have a detrimental effect on the imposed seismic demands. Jeremic et al, (2004) conducted a detailed finite element study on the seismic response of the I-880 viaduct in Oakland, Calif. and came into the same conclusions as Mylonakisand Gazetas (2000) that is: SSI can have both beneficial and detrimental effects on the response of the structure depending on the characteristics of the ground motion. Makris and Zhang (2004) investigated the effect of SSI on the response of 9/15 Overcrossing in Los Angles and reported that ignoring SSI would lead to an underestimation of seismic forces. Vlassis and Spyrakos (2001)using a two degree of freedom linear elastic model for the bridge linear elastic pier and isolation system and a massless foundation found that the fundamental period of the bridge soil system increases significantly when SSI is considered and that SSI reduces the base shear of the bridge if evaluated as recommended by the current AASHTO design procedures. Tongaonkar and Jangid (2003) looked at assessing the effects of SSI on three-span continuous deck bridges isolated with elastomeric bearings. They also assumed linear elastic behavior for the isolation system and the piers of the bridge and carried out a time–history analysis using the complex modal analysis method to account correctly for the large damping contributed to the system by the seismic isolators. They utilized three actual seismic motions and conducted a parametric study looking at the effects of soil flexibility and the isolation system parameters on the response of the isolated bridge system. They concluded that consideration of SSI in the analysis will result in the enhancement of safety and reduction in design costs. They also reported that under certain circumstances, isolation bearing displacements at abutment locations only might be underestimated if SSI is not accounted for in the analysis. The little attention placed on the effects of SSI on seismically isolated bridges by researchers might be because of SSI induces additional flexibility and damping into the bridge system, thus, it reinforces the beneficial "isolation" effect in the structure. Both the previously discussed publications seem to arrive at similar conclusions, that SSI enhances the performance of seismically isolated bridges. Investigating the validity of this premise is of great importance in earthquake engineering, especially now that seismic isolation has become quite popular among the practicing engineering community all over the world.

2. Analysis Methodology for Soil-structure Interaction Problems

Numerical techniques considering soil-structure interaction effects fall into two main categories. In the first, the soil-structure system is represented by equivalent masses, viscous dashpots and springs, or equivalent impedance functions. The second class of such techniques applies a domain-type method such as a boundary element, finite difference, or finite element method, in which the soil-structure system is modeled as a mesh of finite dimensions. Both approaches have found extensive applications and were shown to yield similar results for a wide range of problems. However, it appears that the finite element approach has the distinct advantage of being able to model a complex physical situation, including system nonlinearities, with a greater degree of realism. In this study a direct method approach is used to analyze the SSI effects. The finite element based computer program SAP 2000 has the ability to handle these types of problems and can be used as a tool and this software is verified by Vlassis (2003), Jangid(2003,2009) and Spyrakos(2007).

3. Modeling of the Bridge

Typical Cable-stayed bridge like any other structure is divided in two main components superstructure and substructure, superstructure includes pylon (pier or tower), cables, bridge deck, isolation bearings, etc. Substructures include pile cap, piles, foundation soil etc. The bridge model used in this study is the Quincy Bay-View Bridge crossing the Mississippi River at Quincy, IL. The bridge consists of two H-shaped concrete towers, double plane semi-harp-type cables and a composite concrete-steel girder bridge deck. The detailed description of the bridge is given in Wilson and Gravelle(1991). For finite element modeling of Cable-stayed Bridge, each element must be assigned with proper elements representing the actual force condition. For example the cables are subjected to axial tensile forces thus, they should be modeled by line element subjected to axial force only. In the ready-made software these elements are readily available like truss element.

Table 1. Details of Quincy Bay View Cable-stayed Bridge

Particulars	Values
Main span	274m
Side span	134m
Total length	542m
Cables	28-main span; 14+14 -side spans; total 56 cables
Road deck	0.23m- thickness , 14.3 m - 46.5cm 4-lanes wide composite deck of RCC pre-stress slab and steel I beams
Towers	72m-232ft; H shape tower; 3 variable c/s along height

- After Wilson &Gravele (1991)

3D structural model of the bridge is built and analyzed by finite element program. The deck and the tower members are modeled as space frame elements. The cables are modeled as linear elastic space truss elements. The stiffness characteristics of an inclined cable can exhibit a nonlinear behavior caused by cable sag. This nonlinear behavior can be taken into account by linearization of the cable stiffness using an equivalent modulus of elasticity that is less than the true material modulus.

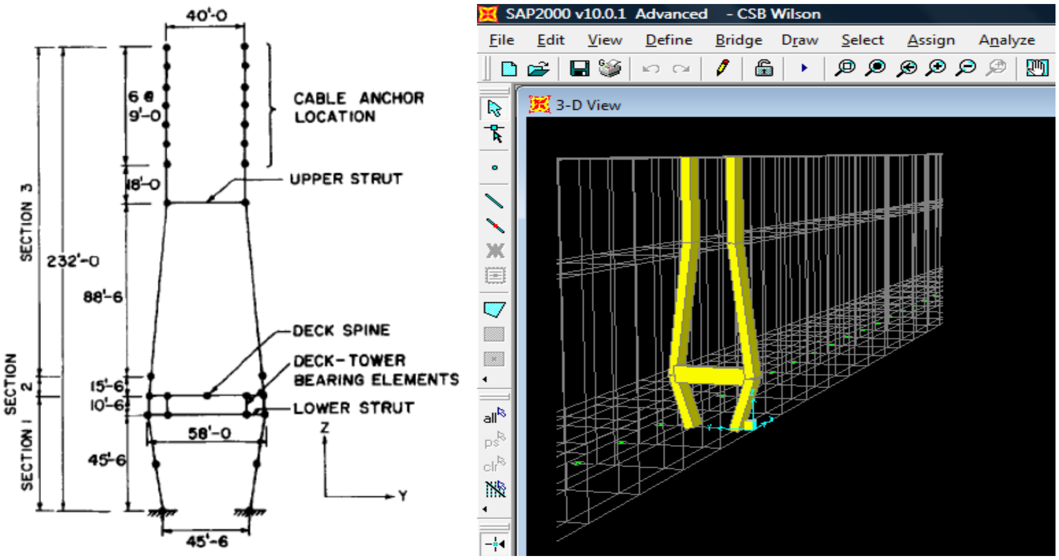


Figure 1. Finite element model of the quince bay view bridge H –tower

4. Modeling of Soil

The interaction between the pier footing and the soil is modeled using translational and rotational springs**.**

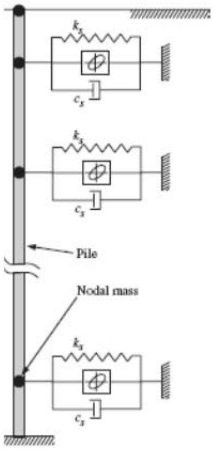
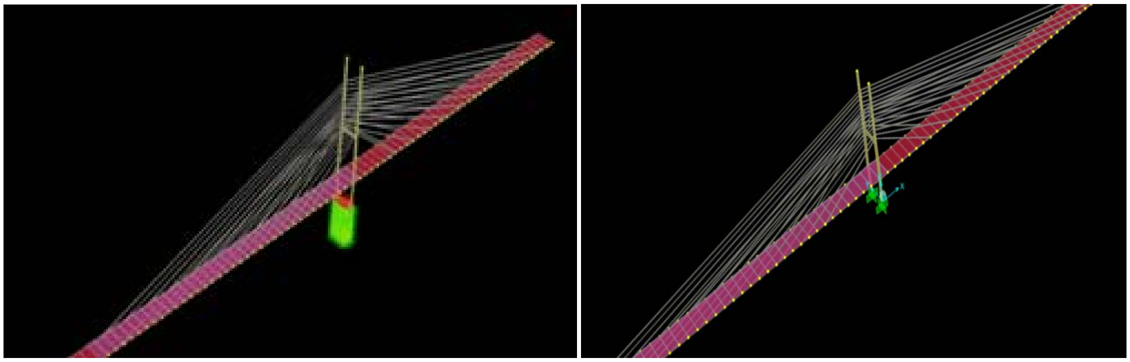


Figure 2. Modeling of soil as spring & Dashpot-(Kelvin Element) applied at nodes of pile (Adopted from Soneji, B. B & Jangid 2009)



SSI case

Fixed base-NOSSI

Figure 3. Modeling of bridge foundation with and without SSI effects.

Table 2. Details of PGA for the Bhuj earthquake used in this study

Earthquake	Recording station	Applied in longitudinal direction of the bridge		Applied in transverse direction of the bridge	
		Component	PGA (g)	Component	PGA (g)
Bhuj,2001	Ahmadabad	N120 W	0.080	N780 E	0.106

Table 3. Soil properties and lateral and rocking stiffness coefficients for different types of soil

Soil Properties	Soil-I Hard Clayey soil	Soil-II Soft Silty soil	Soil-III medium Sandy soil
Unit weight of soil-γ ; kN/m3	20	18	19
Shear wave velocity –Vs ; m/ sec	1050	82.54	309
Shear Modulus-Gs; kN/m2	269.23 x 104	12500	192 310
Young’s modulus of Elasticity-E ; kN/m2	700.00 x 104	35000	500.00 x 103
Poisson’s Ratio-ν	0.3	0.4	0.35
Kx (kN/ m)	252 x 106	4.60 x 106	8.62 x 106
Kr (kN m/rad)	8094 x 106	156 x 106	292 x 106

The spring coefficients have been computed by the method suggested in Specification for Highway Bridges issued by Japan Road Association. In the suggested method, it should be mentioned that, when using equations (1) and (2), the units of Beand E must be centimeters and kgf/cm ^{2} (1 kgf/cm ^{2} = 98 kPa), respectively. The horizontal and rotational spring coefficients for each part of foundation are obtained by multiplying k by the area and the inertia moment of its surface perpendicular to the excitation direction, respectively. As for the bottom face of foundation, the soil reaction coefficient per unit area in horizontal direction is taken as 1/3 of k.

$$k_0 = \frac{1.2\,E}{30} \tag{1}$$

$$k = k_0 \sqrt[-3/4]{Be/30} \tag{2}$$

Where,

k_0= reference soil reaction coefficient, E=Young’s modulus of elasticity for soil, k =The soil reaction coefficient per unit area, B_e= the width of foundation perpendicular to the considered direction.

For more details, see Ref. 12. Although it has been recognized that spring coefficients are frequency-dependent, the spring coefficients computed using the method are frequency-independent for practical use. In the seismic response calculation, one-dimensional analysis of soil deposit is first conducted, and accelerations at various depths are computed, which are then used as the input from the springs at corresponding depth.

5. Analysis Cases

The cable-stayed bridge is analyzed for same bridge span, same cable arrangement but for two conditions; i.e. with soil-structure interaction and another as considering the fixed base; i.e. NO SSI. The effects of SSI are investigated by performing seismic analysis in time domain using a direct integration method. Influence of SSI on the given bridge is tested by 2001Bhuj earthquake. The peak accelerations of these earthquake ground motions are shown in Table (1). The displacement and acceleration response spectra of the above four ground motions for 2% of the critical damping are shown in Figure (3). The bridge seismic response is studied in form of displacement of mid span, displacement of tower top, tower base shear by time history analysis.

Table 4. Different analysis cases with variation of depth of foundation and foundation soil

Case No.	Foundation depth	Soil foundation system	
1	10m	NO SSI	Fixed support
2		With SSI	SSI-soil-I
3			SSI-Soil-II
4			SSI-Soil-III
5	20m	NO SSI	Fixed support
6		With SSI	SSI-soil-I
7			SSI-Soil-II
8			SSI-Soil-III
9	30m	NO SSI	Fixed support
10		With SSI	SSI-soil-I
11			SSI-Soil-II
12			SSI-Soil-III
13	40m	NO SSI	Fixed support
14		With SSI	SSI-soil-I
15			SSI-Soil-II
16			SSI-Soil-III

Jangid & Soneji (2009) used the symmetrical structure with asymmetrical earthquake loading about vertical axis of symmetry, the results at the symmetrical nodes of the structure are found similar in magnitude and direction. Hence, results of the response quantities are presented for the left half part of the bridge.

6. Results and Discussion

The results of seismic time history analysis are shown in Table (5) for all the sixteen cases. The table demonstrates that decreasing soil stiffness (soil type-II) leads to large increment of fundamental period of bridge in comparison with No SSI case. This trend agrees for the cases of stiff (soil type I) and medium stiff soil (soil –III). However this increase in time period is less in cases of medium stiff (soil type III) and stiff (soil type I) compared to soil type II (soft soil). The reason behind this could be the effects of wave amplification is predominant in soil type-II whereas it reduces in the cases of soil type-III and is negligible in soil type-I. Thus it can be concluded that SSI effects are predominant in the case of soft soils which is the fact mentioned in the literature.

The Time period is also affected by the depth of foundation, this is also depicted in table-5. For moderate depth of foundation (d=30m) soft soil yields severe changes up to 30 %. However for deep foundations (d=40m) this difference reduces to about 22% probable reason behind this could be at d=40m the foundation soil system is imparting rigid body displacement to the superstructure and SSI effects are little negotiated; therefore value of time period is more in case of d=30m.

Table 5. Values of Fundamental time period of the bridge with and without SSI effects different soil conditions and depths for earthquake in longitudinal directions

Depth of Foundation	Values of fundamental time period –(Sec)						
	For different cases						
Units	NO SSI	With SSI					
(meter)	Fixed base	Soil-I	% diff	Soil-II	% diff	Soil-III	% diff
d=10	4.50	4.83	7.33	5.16	14.67	4.93	9.56
d=20	4.59	4.96	8.06	5.20	13.29	5.12	11.55
d=30	4.82	5.21	8.09	6.30	30.71	6.10	26.56
d=40	4.75	4.98	4.84	5.80	22.11	5.63	18.53

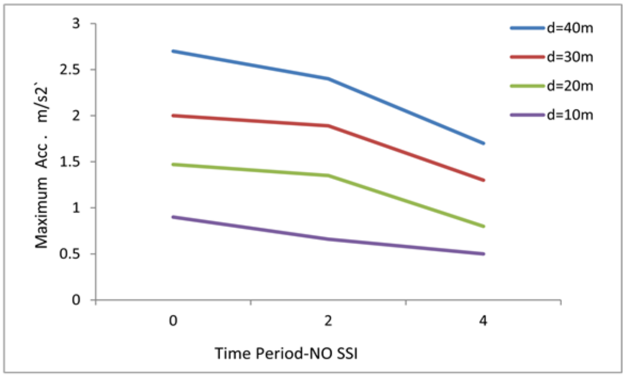


Figure 6. Tower top acc. values –No SSI

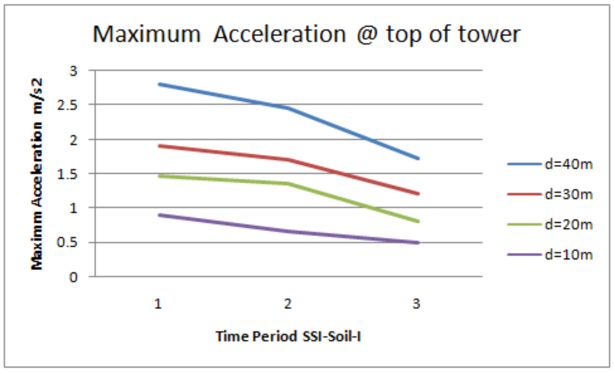


Figure 7. Tower top acc. values – SSI-Soil-I

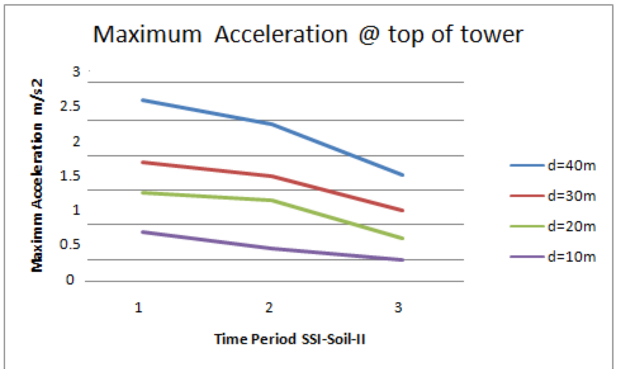


Figure 8. Tower top acc. values – SSI-Soil-II

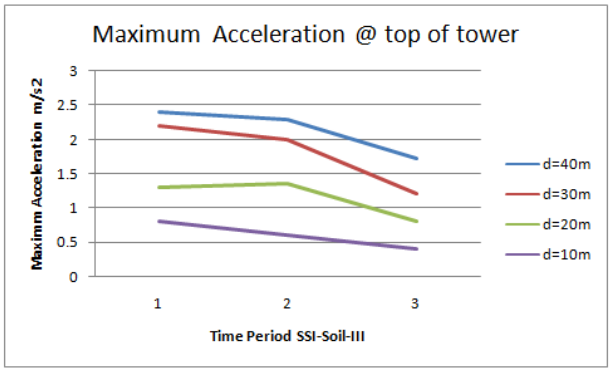


Figure 9. Tower top acc. values – SSI-Soil-III

For the depth of d=10m & d=20m the effects are almost the same and does not yield significant change but there is moderate change of about 5-10%

Figure (6-9) shows the tower acceleration for different cases under this study. It clearly demonstrates the effects of SSI are predominant when the soft soil is encountered at foundation. The acceleration values are decreasing as the depth of tower foundation is decreasing for all the cases. However, in the case of soft soil this value significantly changes and drops to about 7%.

7. Concluding Remarks

In the present work, the effect of soil structure interaction for a cable-stayed bridge is studied using time history analysis for hard, soft and medium soil conditions, and for various foundation depths. The following major remarks can be given from the study:

1. The type of soil has great influence in the seismic response of bridge –particularly for soft soil (type-II) which increases the fundamental time period as high as 30%.

2. SSI studies must be considered whenever the soft soils conditions are encountered, irrespective of foundation depth. The neglection of SSI may result in considerable damage of the structure under severe earthquakes.

3. Depth of foundation affects the seismic response of bridge, for moderate depth of foundation fundamental time period increases up to 30% because of inertial effects. But that effect is not predominant in the case of shallow & deep foundations.

4. The tower acceleration reduces as the depth foundation decreases. This effect is predominant in the case of soft soil and value reduces about 7% in comparision to No SSI case.

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