

Effect of Foundation Depth on Cable Stayed Suspension Hybrid Bridges by Considering Soil Structure Interaction

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Abstract—The immense Infrastructural development has induced a greatly increased desire and preference for long to super long . Cable supported bridges , comprising of Cable Stayed &/or Suspension Bridges generally constitute for Long to super long span bridges These are popular , also, due to its enhanced popularity owing to the aesthetics / marvelous architectural appearance. Supplimentarily,, owing to its flexibility besides the complicities for analysis, design and execution(construction); the priority of such bridges are high. Cable Stayed Suspension Hybrid Bridge (CSSHB) has an added advantage additional bit of leeway in inclination over suspension bridge as well as cable stayed bridge. Herein, the response of the bridge as a whole (inclusive of super and substructure , the foundation, and the soil underlying and/or surrounding the foundation plays a pivotal role in behavioral aspect of bridge thereby for its design and/or analysis. As Soil Structure interaction is an important element in the understanding of seismic structure failure, yet it is very complex to analyse.The damage caused with foundation of bridges in earthquake(s) has emphasized the importance of understanding SSI. Thus, Soil-structure interaction (SSI) analysis evaluates the collective response of the bridge structure / system. Here, an attempt is made to understand the SSI effect Cable stayed Suspension Hybrid Bridge (CSSHB) with H shaped Pylon (bridge similar to that of Bridge at LingDing Strait China is considered in the study); for that FEM model is prepared with different foundation depth and different soil conditions(spring and dashpots (Kelvin element) is adopted for Soil modeling for simulation of SSI effects), using SAP2000 software. The effect of SSI cannot be generalized as it purely is site specific. The depth of the foundation plays a vital role in bridge response. SSI effect increases time period of the structure by about 5-8 %. Bridge founded on stiff and soft clayey soil proves a more rigid connection as compared to sandy soil.

Index Terms— Cable Stayed Suspension Hybrid Bridge(CSSHB), Soil Structure Interaction(SSI) , SAP2000.

I. INTRODUCTION

There is a close vicinity/proximity/inter-relation between Structural and Geotechnical engineering. For effective Design and analysis of the Bridge structure as a whole,understanding its actual structural behaviour is needed to be understood andfor which modeling of the subgrade needs to be modeled precisely; which again in turn needs evaluation and understanding of the term known as SSI. It has been observed quite a times that oftenly,

Structural engineers, make use of software which incorporates detailed design (all aspects) while modeling the structure , but the substructure may be represented with comparatively simple structural element models that may not be able to precisely describe/represent the soil behaviour truly/apparently. Contrary to this, Geotechnical engineers prefer software with an advanced soil modeling tools and applications, but may adopt for a simple structural model. So, herein , need emerges out for blending these two concepts to evolve out simplified methods in practice to model SSI. In engineering practice there are different opinions on how to model SSI. Yong Gao et. Al ^[20] , in 2009, investigated by analyzing the performance of a suspension bridge which was self anchored , subjected to seismic loading. Mu Y N et.al.^[21] , in 2009, explained, the response of a self anchored CSSB , by considering its characteristics. The focus of the work covered observation regarding natural vibration frequencies and principal modes while taking in consideration nonlinearity in geometry. For getting THA. Zhang Xin-jun et. al. ^[105] , in 2015, submitted his research on the seismic response of the bridge ,under the horizontal and vertical seismic excitations ,numerically by Response Spectrum Analysis(RSA) and THA. The study covers the comparison of CSB and SB with the same main span, and thereon commenting on feasibility of using CSSHB in super long-span bridges in the discussion submitted. In the design of the superstructure, there stands variety of views/reviews adopted and proclaimed by researchers. Some consider it be sufficient to provide soil as a spring – damper. Some prefer modelled soil as one united spring-damper and equivalent masses system ^[7-9] and while certain researchers opt to model the soil element as spring-damper system at different depth of substructure. ^[11-15] It has been reviewed that and claimed that the soil should be modelled as a continuum model (FEM model), to achieve a good enough SSI analysis. ^[17-19,23-25]

To understand the seismic structure failure , it is important to understand Seismic soil-structure. Several recent earthquakes have provided us with many examples of soil-structure interaction [9-10] improving the understanding of the phenomena and providing stimulation for research. The damage caused to the foundation of bridges in earthquakes has emphasized the importance of understanding soil structure interaction (SSI). The SSI study is initiated by the detrimental actions of several earthquakes, particularly the one in Kobe, 1995. It changed the previous opinion on the positive effects of the interaction. [7-9]. The analysis of seismic soil-structure interactions (SSI) induced by seismic actions deals with the question: how the interplay between soil, foundation, and structure affects the response of the structure. Consideration of soil-structure interaction (SSI) effects has become increasingly important when determining the seismic response of bridges. Some literature available for experimental analysis for SSI Considering SSI effects allows researchers and practicing engineers to design more seismically resilient bridges. [23-24] In the present paper, the SSI effect is analyzed by applying the spring and dashpots (Kelvin element) is adopted for Soil modeling for simulation of SSI effects.

II. MODELLING OF THE BRIDGE

The geometry of CSSHB chosen is similar to Bridge of East channel of Lingding Strait in China(Xiao 2000) as illustrated in Fig.1.

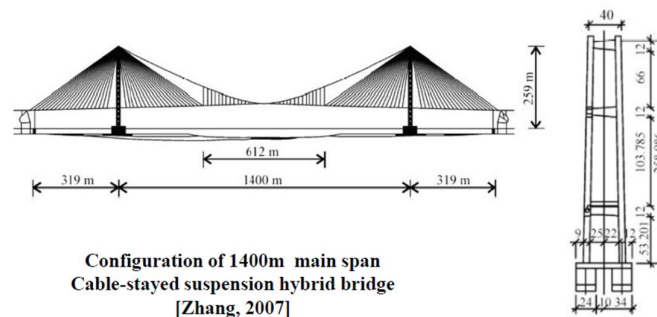


Figure 1. Lingding Strait Bridge (China) Bridge

The bridge considered , earth-anchored cable-stayed-suspension hybrid bridge has of a main span of 1400 m with two side spans of 319 m with H type (door-shaped) Pylon towers 259 m high approx., with three transverse beams. The central span consists of the cable-stayed portion of 788 m and the suspension portion of 612 m. The lateral spacing of two main cables is 34 m, the cable sag to span ratio is 1/10, and the interval of hangers is 18 m. The stay cables are anchored to the girder at 18 m intervals in the central span and 14 m in the side spans. The deck is a steel streamlined box steel girder of 36.8 m wide and 3.8 m high.

A. Material, sectional properties of cable stayed bridge and loading

For the bridge modelling modulus of elasticity are taken as 2.0×10^8 kN/m² (Fe345 grade)& 3.354×10^7 kN/m² (M45) for steel & Concrete respectively. Unit weight and Poisson ratios for steel & concrete are 76.973 KN/m³ & 0.3; and 24.993 KN/m³ & 0.20 respectively. Similarly the parameters like Shear Modulus and Coefficient for thermal expansion for Steel and concrete respectively are 1.115×10^6 kN/m² & 1.17×10^{-5} /°C ; and 1.397×10^6 kN/m² & 0.55×10^{-5} /°C.

TABLE I. SECTIONAL PROPERTIES OF BRIDGE

Cross-sectional properties of different elements in Cable-stayed suspension hybrid bridge (CSSHB) (Zhang, 2007)							
Members	E (Mpa)	A (m ²)	J_y (m ⁴)	J_z (m ⁴)	J_{yz} (m ⁴)	M (Kg/m)	J_m (Kg.m ² /m)
Order	2.1×10^5	1.2481	5.034	1.9842	137.754	18386.5	1.852×10^5
Stay cable	2.0×10^5	0.008	0.0	0.0	0.0	62.5	0.0
Hanger Cable	2.0×10^5	0.0065	0.0	0.0	0.0	30.19	0.0
Main Cable in center span	2.0×10^5	0.3167	0.0	0.0	0.0	2445.80	0.0
Main Cable in Side span	2.0×10^5	0.3547	0.0	0.0	0.0	2979.5	0.0
Pylon C	3.3×10^4	30	350	320	220	78000	5.7×10^3
Pylon TB	3.3×10^4	10	150	70	70	26000	4.7×10^3

E - Modulus of Elasticity; A - Cross section area;
 J_y - torsional constant; J_z - Lateral bending moment of inertia; J_{yz} - Vertical bending M O inertia;
 M - Mass per unit length; J_m - mass moment of inertia per unit length.

Cable No.	Diameter (m)	Area (m ²)	Cable wt. (kN/m)
Hanger	0.0903	6.4×10^{-3}	0.493
Main Cable (SS)	0.635	0.367	28.238
Main Cable (CS)	0.672	0.3547	27.302
Stay Cable(1)	0.1009	8.00×10^{-3}	0.616
Stay Cable(2)	0.1059	8.00×10^{-3}	0.678
Stay Cable(3)	0.1106	9.61×10^{-3}	0.740
Stay Cable(4)	0.1156	10.41×10^{-3}	0.802
Stay Cable(5)	0.1194	11.20×10^{-3}	0.863
Stay Cable(6)	0.1277	12.81×10^{-3}	0.987
Stay Cable(7)	0.1316	13.61×10^{-3}	1.048
Stay Cable(8)	0.1354	14.41×10^{-3}	1.109

TABLE II. VALIDATION PROBLEM RESULTS COMPARISON

Particulars/Validation	Modes	Zhang , 2006	Sevaliya, 2015	Our Result	% difference Wrt Sevaliya
First Mode frequency, f, Hz	Lateral bending, (1-S)	0.0689	0.0761	0.0764	+0.39 %
Time period, T, sec		14.51 .	13.14	13.089	-0.38 %

III. SOIL CLASSIFICATION, PROPERTIES AND MODELLING

To understand the behavior of the pile foundation of cable stayed bridge, a parametric study is performed by varying different parameters of soil. The interaction between the pier footing and the soil is modelled using translational & Rotational springs. 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 B_e and E must be centimeters and kgf/cm² (1 kgf/cm² = 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 .

$$k_0 = 1.2E / 30 \dots \dots \dots (1)$$

$$k = k_0 - 0.75 \sqrt{(B_e / 30)} \dots \dots \dots (2)$$

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.

The values of modulus of elasticity, dynamic shear modulus, and Poisson's ratio are described in Table 3 for different type of soil. Figure 2 shows the representation of soil springs attached to the piles. The different types of soil considered here are Hard Clayey Soil (Type I), Soft Silty Soil (Type II) and Medium Sandy Soil (Type III).

Three types of soils are in this study, thus designated as soil type I, II, III in the Table 3 below

TABLE III. PROPERTIES OF SOIL CONSIDERED^[12]

Sr. No	Soil Properties	Soil-I Hard Clayey soil	Soil-II Soft Silty soil	Soil-III medium Sandy soil
1	Unit weight of soil- γ (kN/m^3)	20	18	19
2	Shear Strength- τ_s (kN/m^2)	200	75	150
3	Poisson's Ratio- ν	0.3	0.4	0.35
4	Damping of soil- ξ	0.02	0.06	0.04
5	Shear wave velocity- V_s (m/sec)	1050	83	309
6	Shear Modulus- G_s (kN/m^2)	269×10^4	12500	192 310
7	Young's modulus of Elasticity- E (kN/m^2)	700×10^4	35000	500×10^3
8.a	Soil stiffness K_x (kN/m)	252×10^4	4.60×10^4	8.62×10^5
8.b	Soil stiffness K_y (kN/m)	1050×10^4	5.52×10^4	10.3×10^4
8.c	Soil stiffness K_z (kN/m)	1028×10^4	5.36×10^4	10.0×10^4
8.d	Soil stiffness $K_{\theta x}$ (kN m/rad)	8094×10^4	156×10^4	292×10^4
8.e	Soil stiffness $K_{\theta y}$ (kN m/rad)	309×10^4	21.6×10^4	40.4×10^4
8.f	Soil stiffness $K_{\theta z}$ (kN m/rad)	9808×10^4	532×10^5	729×10^5

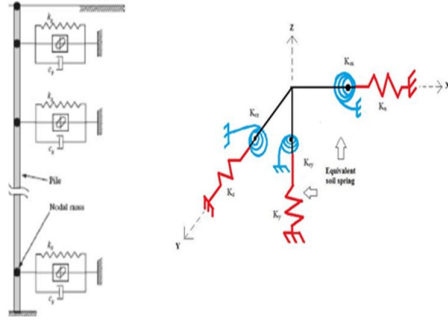
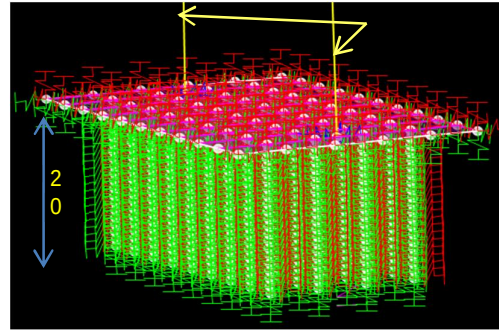
Figure 2. Modeling of soil as spring & Dashpot (Kelvin Element) applied at nodes of pile^[28] (Adopted from Soneji, B. B & Jangid 2009)

Figure 3. Pile Cap +Piles with Springs :Extruded View

IV. PARAMETRIC STUDY ON BRIDGE PILE FOUNDATION

To understand the behavior of structure due to soil-structure interaction Piles, of M45 grade concrete, 2m diameter, 20m deep, with a c/c spacing of 5m are provided with a pile cap(raft) 60m x 30m in plan and 2m thick, thereby incorporating 9 x 4 array of piles below each Pylon Tower. The pile cap was modelled as plate elements and divided into fine mesh with soil springs attached to each mesh. Similarly, piles were modelled as beam elements and divided into fine nodes and springs have been attached to it. The detailed view of the pile with spring is shown in Figure 3. The cases which are considered in this study are narrated in Table 4.

TABLE IV. PARAMETRIC DATA FOR DETAILED STUDY

Case No.	Foundation Depth	Soil Foundation System	
1	10 meter	No SSI	Fixed Support
2		With SSI	Hard Clayey
3			Soft Silty
4			Medium Sandy
5	15 meter	No SSI	Fixed Support
6		With SSI	Hard Clayey
7			Soft Silty
8			Medium Sandy
9	20 meter	No SSI	Fixed Support
10		With SSI	Hard Clayey
11			Soft Silty
12			Medium Sandy

V. ANALYSIS RESULT & DISCUSSION

H shape pylon cable stayed bridge, with the No SSI condition, time period is observed 13.089 second where for Hard clayey soil , soft silty soil & Medium sandy soil it observed as 13.093, 13.199 & 13.172 seconds respectively. Table 5 represents Time periods upto 10 modes for the cases considered.

The results tabulated in Table 6 against Modal Time History analysis illustrate all the sixteen cases. The table apparently and clearly demonstrates that large increment of fundamental period of bridge is resulted due to decreasing soil stiffness (soil type-II) as compared to with No SSI case. This trend agreeably is observed for the cases of stiff (soil type I) and medium stiff soil (soil –III). This analogy yields a conclusion that by the modelling of a structure as a whole shows the exact behavior of structure.

It is apparent that this increase in time period is less in cases of soil type II (Medium sandy-medium stiff) and soil type I (Hard Clayey soil – Stiff) when compared with to soil type II (soft silty soil). The possible cause for this behaviour can be attributed to wave amplification effect; which is predominant in case of Soil type II (contrarily it reduces in the cases of soil type-III and is negligible in soil type-I). This yields the predominance of SSI in soft soils.

TABLE V. COMPARISON OF FREQUENCY AND TIME PERIOD FOR H SHAPE PYLON CS BRIDGE WITH PILE FOUNDATION & DIFFERENT SOIL CONDITION (20-METER PILE LENGTH)

H shape								
	No SSI		Hard Clayey		Soft Silty		Medium Sandy	
Mode No	Frequency (Hz)	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)	Period (sec)
1	0.076	13.089	0.076	13.093	0.076	13.199	0.076	13.172
2	0.104	9.587	0.104	9.587	0.104	9.587	0.104	9.587
3	0.119	8.371	0.119	8.377	0.116	8.619	0.117	8.553
4	0.124	8.093	0.124	8.097	0.122	8.164	0.123	8.155
5	0.133	7.539	0.133	7.539	0.133	7.540	0.133	7.540
6	0.146	6.848	0.146	6.848	0.146	6.848	0.146	6.848
7	0.163	6.139	0.163	6.139	0.163	6.142	0.163	6.141
8	0.170	5.866	0.170	5.866	0.170	5.868	0.170	5.867
9	0.196	5.107	0.196	5.107	0.196	5.111	0.196	5.110
10	0.199	5.024	0.199	5.024	0.199	5.024	0.199	5.024

TABLE VI. VALUES OF FUNDAMENTAL TIME PERIOD OF THE BRIDGE WITH & WITHOUT SSI EFFECTS DIFFERENT SOIL CONDITIONS & DEPTHS

Depth of foundation (meter)	Values of fundamental time period for 1st mode For different soil & depth						
	No SSI	With SSI					
	Fixed base	Stiff Clayey soil	% difference	Soft Clayey soil	% difference	Medium Sandy soil	% difference
D – 15 m	13.089	13.836	5.71 %	14.090	7.65 %	13.906	6.24 %
D – 20 m	13.089	13.893	6.14 %	14.105	7.76 %	13.941	6.51 %
D – 25 m	13.089	13.903	6.22 %	14.206	8.53 %	14.103	7.75 %
D – 35 m	13.089	13.828	5.64 %	14.017	7.09 %	13.956	6.62 %

The Time period is also affected by the depth of foundation, this is also depicted in table-6. For shallow depth of foundation i.e. d=15 m soft clayey soil yields severe changes up to 7.65 %. However for deep foundations i.e. d=35 m this difference reduces to about 7.09 % probable reason behind this could be attributed to the probability of foundation soil system imparting rigid body displacement to the superstructure at d=35m thereby negotiating a bit SSI effects.

VI. CONCLUSIONS

The effect of SSI for a cable-stayed suspension hybrid bridge is studied for stiff clayey soil, soft silty soil and medium sandy soil, and various foundation depths. The conclusive remarks are enlisted below:

- The soil type imparts significant influence on the response of the bridge –specifically for soft soil, wherein $\ln$ increase in the fundamental time period as high as 8 % on an average for all depths of pile foundation considered in the study
- This gives us a direct pointer that SSI studies must be considered whenever we come across conditions where soils are soft, as neglecting SSI effect may lead to consequential damage to the structure as a whole under seismic loads; irrespective of foundation depth.
- Secondly, it can be concluded that the Depth of foundation does affect the seismic response of bridge, for shallow moderate depth of foundation, resulting in an increase in modal time period upto moderate depths owing to probable inertial effects. But that effect is not predominant in the case of greater depths i.e deep foundations.

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