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Effect of Foundation Depth on High Speed Railway Cable Stayed Bridge by Considering Soil Structure Interaction

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***Abstract*—Cable stayed bridge has the highest popularity because of its aesthetic look & architectural marvelous. Although the analysis and construction, complicities are at its top because of its higher flexibility. In that case, the response of the bridge as a whole i.e the structure, the foundation, and the soil underlying and surrounding the foundation become more predominant because of load transfer mechanism and overall bridge behavior. The post-failure analysis deduces that soil-structure interaction (SSI) is a very pivotal phenomenon influencing the dynamic response of massive structures. Soil-structure interaction (SSI) analysis evaluates the collective response of the above three linked systems. Here, an attempt is made to understand the SSI effect for H shape pylon Cable stayed Bridge; for that FEM model is prepared with different foundation depth and different soil conditions. The effect of SSI is site-specific, it cannot be generalized. 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 Bridge, Dynamic High Speed Rail Load, Soil Structure Interaction.**

I. INTRODUCTION

Structural and Geotechnical engineering are closely connected subjects in the analysis of civil engineering structures, often analysis in neither of the two subjects can be performed independently with accurate results. To get the superstructure's real behaviour, the subgrade must be modelled sufficiently well. To capture the right behaviour of both superstructure and subgrade in one model, it must include a proper knowledge of soil-structure interaction (SSI). Structural engineers in practice often use software where the structure is modelled in detail, but the substructure is represented with simple structural element models that sometimes poorly describe the behaviour of the soil. Geotechnical engineers instead use software with an advanced soil model, but with a simple model of the structure. However, merging the most advanced commercial design software of two different disciplines would result in demand for unrealistic large computation time. The user would in such a model also need great knowledge in both of the subjects. Therefore, there is a need for simplified methods in practice to model SSI. [1-3] Consequently, it is of great interest how the simplifications influence the results. Earlier some of the researchers present basic formulation for SSI. [3, 4] In engineering practice there are different opinions on how to model SSI. In the design of the superstructure, some consider that it's enough with

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a structural element model of the subgrade i.e. soil properties assigned to substructure as spring, damper in the respective direction. Some researchers modelled soil as one united spring-damper and equivalent masses system [7-9] and some modelled soil by spring-damper system at different depth of substructure. [11-15] Others claim that the soil should be modelled more physically correct with a continuum model (FEM model), to achieve a good enough SSI analysis. [17-22]. Although literature also available for comparative study on modelling approach as a united spring-damper system and linked spring-damper system and FEM. [10,16].
Seismic soil-structure interaction is an important element in the understanding of seismic structural failure yet is very complex to analyze. 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 process in which the response of the soil influences the motion of the structure and the response of the structure influences the motion of the soil, which is referred to as soil-structure interaction. 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-damper system at various depths. The FEM based software Midas civil is used to solve the problem.

II. MODELLING OF THE BRIDGE

The geometry of the cable-stayed bridge chosen for this study is similar to that of the Quincy Bayview Bridge crossing the Mississippi River, the bridge is located in Illinois, United States of America. The bridge consists of two H-shaped concrete towers, double-plane fan type cables, and a composite concrete-steel girder bridge deck consisting of steel edge girders, steel floor beams, and a reinforced concrete slab deck. The bridge has 274 meters main span and two equal 134 meters side spans. The total length of the bridge is 542 meters. The tops of the towers are 71 meters from the waterline. There are a total of 56 cables, 28 supporting the main span, and 14 supporting each side span. The width of the deck from center to center of cables is 12 meter.

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

For the bridge modelling modulus of elasticity are taken as 2 x 108 KN/m^2 & 3 x 107 KN/m^2 for steel & Concrete respectively. Unit weight and Poisson ratios for steel & concrete are 76.97 KN/m^3 & 0.3 and 23.56 KN/m^3 & 0.25 respectively. Different nodes are provided at the place where element property changes and the cable connection locations. Bridge Tower modelled using 28 linear elastic beam elements. The bridge deck includes the concrete slab, main steel girder, five stringer steel beam, and parapet which convert into a spine beam. For high speed load, real train ETR500Y is adopted which has locomotive followed by eight passenger cars and locomotive. The high speed rail load is applied as a series of axle load. The average static axle loads for the locomotives and passenger cars are 176.4 and 113.01 KN, respectively.

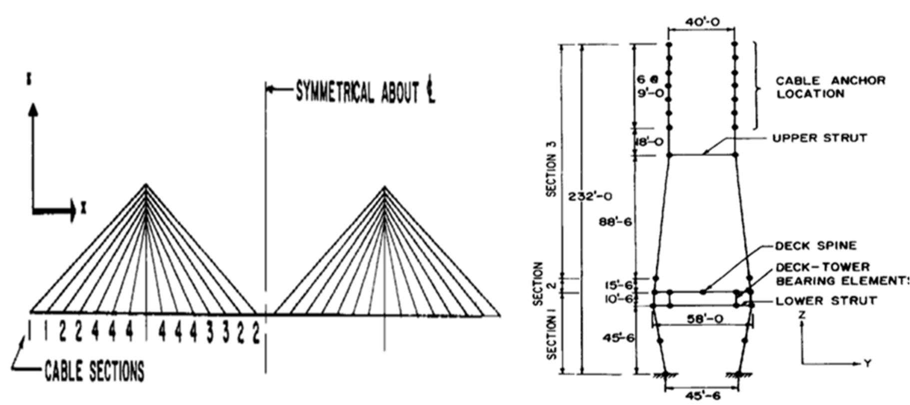

Figure 1 Cable Arrangement and Cross Section of Pylon

TABLE I. SECTIONAL PROPERTIES OF BRIDGE

	Bridge component	Area [m^2]	I_{XX} [m^4]	I_{YY} [m^4]	J [m^4]
1	Cable- 1	0.0089	0.0	0.0	0.0
	Cable- 2	0.0067	0.0	0.0	0.0
	Cable- 3	0.0053	0.0	0.0	0.0
	Cable- 4	0.0034	0.0	0.0	0.0
2	Girder	0.8268	0.3409	19.76	0.027
3	Pylon (section 3)	17.88	129.46	16.39	13.69
	Pylon (section 2)	08.77	3.5386	15.311	9.8824
	Pylon (section 1)	07.06	3.4092	14.025	7.6988
4	Girder beam	0.0499	0.0031	0.0447	0.1331
5	lower strut	6.3638	7.3708	13.37	13.835
6	Upper strut	7.2464	8.2339	13.999	14.983

TABLE II. VALIDATION PROBLEM RESULTS COMPARISON

	As per author	Result Obtained	% difference
First Mode frequency	0.371 Hz	0.390 Hz	5.12 %
Time period	2.695 sec.	2.563 sec.	4.88

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 soil was modelled as the nonlinear links. Lysmer and Richart's method is used to calculate stiffness and damping values of soil spring. The stiffness value of soil springs attached to piles are mentioned in Table 3 and 4 shows the formulas for stiffness and damping values of soil springs. [6] 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 values of modulus of elasticity, dynamic shear modulus, and Poisson's ratio are described in Table 5 for different type of soil. Figure 3 shows the representation of soil springs attached to the piles. The detailed view of the pile with spring has shown in Figure 4. The different types of soil considered here are the sand, Sandy clay, and saturated clay. Stiffness and Damping Properties of soil are mentioned in Table 6 which is used in this study.

TABLE III. FORMULAS FOR SOIL SPRING STIFFNESS [3]

Sl. No.	Direction	Spring Value	Equivalent	Radius Remarks
1	Vertical	$K_z = \frac{4Gr_z}{(1-\upsilon)}$	$r_z = \sqrt{\frac{LB}{\pi}}$	K_z is spring stiffness of soil in vertical Z direction
2	Horizontal	$K_x = \frac{32(1-\upsilon)Gr_x}{(7-8\upsilon)}$	$r_x = \sqrt{\frac{LB}{\pi}}$	K_x induce sliding in horizontal x or y direction
3	Rocking	$K_{\phi x} = \frac{8Gr_{\phi x}^3}{3(1-\upsilon)}$	$r_{\phi x} = 4\sqrt{\frac{LB^3}{3\pi}}$	$K_{\phi x}$ produces rocking about y axis
3.1	Rocking	$K_{\phi y} = \frac{8Gr_{\phi y}^3}{3(1-\upsilon)}$	$r_{\phi x} = 4\sqrt{\frac{L^3B}{3\pi}}$	$K_{\phi y}$ produces rocking about x axes
4	Twisting	$K_{\psi} = \frac{16Gr_{\psi}^3}{3}$	$r_{\psi} = 4\sqrt{\frac{L^3B+BL^3}{6\pi}}$	K_{ψ} produces twisting about vertical Z axis

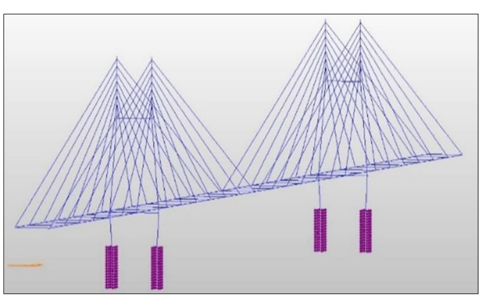
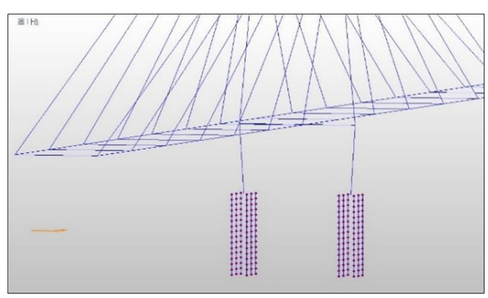

Figure 2 Soil spring attached in pile foundation Figure 3 Enlarge view of soil spring

TABLE IV. FORMULAS FOR SOIL SPRING DAMPING BY RICHART AND LYSMER

Sl No.	Direction	Mass ratio (B)	Damping ratio & Damping value	Remarks
1	Vertical	$B_z = \frac{0.25m(1-\upsilon)g}{\rho_s r_z^3}$	$\zeta_z = \frac{0.425}{\sqrt{B_z}}$, $C_z = 2\xi_z\sqrt{k_z m}$	ζ_z is damping value in Vertical Z direction
2	Horizontal	$B_x = \frac{m(7-8\upsilon)g}{32(1-\upsilon)\rho_s r_x^3}$	$\zeta_x = \frac{0.288}{\sqrt{B_x}}$, $C_x = 2\xi_x\sqrt{k_z m}$	V_s damping value in lateral X or Y direction

Where, V_s = shear wave velocity of soil, m = mass of machine and foundation, J = mass of the moment of inertia of machine and foundation, K= equivalent spring stiffness of the soil, C= Damping Value of the soil, B= inertial factor contribution to the damping factor, L= Length of the foundation, B=width of the foundation, G= Dynamic shear modulus of soil, υ= Poisson's ratio of soil, ρ_s = mass density of soil.

TABLE V. VALUES OF MOE, SHEAR WAVE VELOCITY & POISSON'S RATIO FOR DIFFERENT SOILS

Sl No	Types of soil	Modulus of elasticity (KN/m^2)	V_s (m/s)	Poisson's Ratio
1	Soft clay	1500-4000	125	0.5
2	Hard clay	6000-15000	140-250	0.5
3	Silty sand	6000-20000	250	0.4
4	Loose sand	10000-25000	220	0.4
5	Dense sand	40000-80000	200	0.4
6	Dense gravel	1×10^5 to 2×10^5	300	0.4
7	Rock	196×10^5 to 980×10^5	320	0.4

TABLE VI. STIFFNESS AND DAMPING PROPERTIES OF SOIL

Sl. No.	Soil layer	K_z	K_x, K_y	$K_{\phi x}$	$K_{\phi y}$	K_ψ	C_z	C_x
1	Saturated Clay	148933	112875	1905277	5390108	4149485	14948	7482
2	Sand	4251000	2972000	54386000	153859000	106141000	79847	38390
3	Sandy Clay	335100	253970	253970	4286875	12127743	93363	47634
4	Rock	2×1012	4×1012	8×1012	4.72×1012	5.18×1012		

IV. PARAMETRIC STUDY ON BRIDGE PILE FOUNDATION

To understand the behavior of structure due to soil-structure interaction understanding of geological condition i.e. soil type, soil depth, composition & groundwater table is must. Pile foundation is designed for respective forces and moments. Pile cape is provided with 6.5 m X 4 m and 2 meters in depth. 6 numbers of 1-meter diameter piles are provided. For the detailed performance of structure due to soil-foundation interaction different soil condition is adopted with different pile length. The cases which are considered in this study are narrated in table 7. Figure 5 & 6 present the H shape pylon with substructure and enlarge the view for the same.

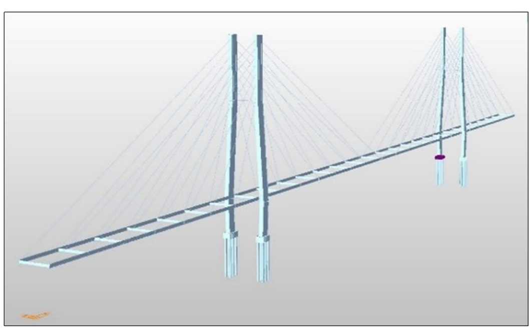

Figure 4 H shape CS Bridge with pile foundation

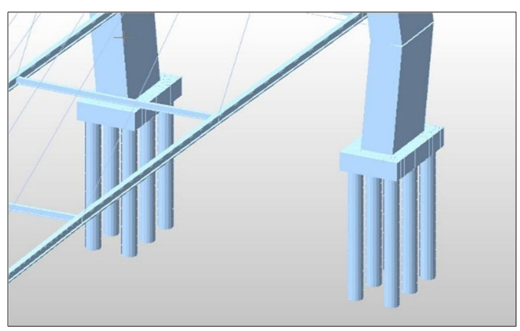

Figure 5 Enlarge view of pile foundation

TABLE VII. PARAMETRIC DATA FOR DETAILED STUDY

Case No.	Foundation Depth	Soil Foundation System	
1	10 meter	No SSI	Fixed Support
2		With SSI	Sand
3			Soft Clay
4			Stiff Clay
5	15 meter	No SSI	Fixed Support
6		With SSI	Sand
7			Soft Clay
8			Stiff Clay
9	20 meter	No SSI	Fixed Support
10		With SSI	Sand
11			Soft Clay
12			Stiff Clay

V. ANALYSIS RESULT & DISCUSSION

H shape pylon cable stayed bridge, with the No SSI condition, time period is observed 2.66 second where for stiff clay, soft clay & sandy soil it observed as 2.871, 2.862 & 2.838 second respectively. After reviewing the results, one can conclude that by the modelling of a structure as a whole; time period will increase and it shows the exact behavior of structure. Time period has increased significantly for sandy soil; where there is no much variation is noted in stiff clayey and soft clayey soil.

TABLE VIII. COMPARISON OF FREQUENCY AND TIME PERIOD FOR H SHAPE PYLON CS BRIDGE WITH PILE FOUNDATION & DIFFERENT SOIL CONDITION (15-METER PILE LENGTH)

H shape								
	No SSI		Stiff Clay		Soft Clay		Sand	
Mode No	Frequency (rad/sec)	Period (sec)	Frequency (rad/sec)	Period (sec)	Frequency (rad/sec)	Period (sec)	Frequency (rad/sec)	Period (sec)
1	2.362	2.660	2.188	2.871	2.195	2.862	2.214	2.838
2	2.869	2.190	2.784	2.257	2.788	2.253	2.797	2.246
3	3.475	1.808	3.491	1.799	3.493	1.799	3.496	1.797
4	3.639	1.727	3.651	1.721	3.653	1.720	3.657	1.718
5	4.546	1.382	4.538	1.385	4.539	1.384	4.541	1.384
6	4.600	1.366	4.599	1.366	4.601	1.366	4.603	1.365
7	4.612	1.362	4.663	1.348	4.663	1.347	4.664	1.347
8	4.673	1.345	4.733	1.327	4.734	1.327	4.735	1.327
9	5.243	1.198	5.238	1.199	5.239	1.199	5.239	1.199
10	5.293	1.187	5.363	1.171	5.363	1.171	5.363	1.171

TABLE IX. 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	Sandy soil	% difference
D – 10 m	2.660	2.875	8.08 %	2.864	7.69 %	2.838	6.69 %
D – 15 m	2.660	2.871	7.93 %	2.862	7.59 %	2.838	6.69 %
D – 20 m	2.660	2.869	7.86 %	2.861	7.56 %	2.836	6.62 %

The comparative analysis results are presented in Table 8 for H shape pylon cable stayed bridge. The table demonstrates that increasing soil stiffness leads to a large increment of the fundamental period of the bridge in comparison with the No SSI case. Hike in time period is more in cases of medium-soft and stiff clay compared to sandy soil. The reason behind this could be the effects of wave amplification is predominant in the soil whereas it reduces in the cases of soft clayey soil and stiff clayey; for sandy soil it is negligible. 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-9. For shallow depth of foundation i.e. d=15 m soft soil yields severe changes up to 8 %. However for deep foundations i.e. d=20 m this difference reduces to about 2.72% probable reason behind this could be at d=20m the foundation soil system is imparting rigid body displacement to the superstructure and SSI effects are little negotiated.

TABLE X. SUPPORT REACTION AND MOMENT VALUES COMPARISON FOR DIFFERENT SOIL

Depth of foundation (meter)	Support reaction (KN)			Support moment (KN.m)		
	Stiff Clayey soil	Soft Clayey soil	Sandy soil	Stiff Clayey soil	Soft Clayey soil	Sandy soil
D – 10 m	865.2	1077.6	2927.0	2678.0	1825.3	3922.6
D – 15 m	718.8	970.9	2808.0	2500.5	1744.1	3920.2
D – 20 m	660.6	939.7	1512.1	2423.4	1710.2	3701.8

The support reaction and support moment is presented in table 10. Support reaction observed more in the case of sandy soil whereas for stiff clayey soil and soft clayey soil values observed less. As the depth of foundation increases values of support reaction decreases; the reason for such results is, as the depth of foundation increases more contact of the pile to soil increase which leads to more load transfer to the soil beneath and surrounding. Sandy soil has greater friction resistance; it will lead to less load transmission. This proves well with the results.

VI. CONCLUSIONS

The effect of SSI for a cable-stayed bridge is studied for soft clay, stiff clay, and sandy soil conditions, and various foundation depths. The conclusive remarks are narrated below:

- The soil type has great influence in the bridge response –particularly for soft soil which increases the fundamental time period as high as 8 %.
- When the soft soil conditions are encountered, SSI studies must be considered. Irrespective of foundation depth. The omission of SSI may result in considerable damage to the structure under severe earthquakes.
- The depth of the foundation affects the response of the bridge, for shallow depth of foundation fundamental time period increases because of inertial effects. But that effect is not predominant in the case of deep foundations.

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