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Soil-Pile-Structure Interaction (SPSI) in Bridges: A Review

A. Sharma[1,*], S. Adhikary [2]

[1] Department of Civil Engineering, Research Scholar, Visvesvaraya National Institute of Technology, Nagpur, 440010, India.
[2] Department of Civil Engineering, Assistant Professor, Visvesvaraya National Institute of Technology, Nagpur, 440010, India.

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Abstract

Response of soil influencing motion of pile supported structures or vice-versa is called Soil-Pile-Structure Interaction (SPSI). A part of SPSI is considered beneficial for the structure wherein it increases damping, and period of vibration. This study provides a comprehensive review addressing SPSI in bridge structures. Past research in this field has typically emphasised on Soil-Structure Interaction (SSI), rather than SPSI. An attempt is made here to compile the work done so far in this field. Detailed study, based on discretising the considered models in various articles, and the method for determining the stiffness of the underlying soil was carried out. The articles in this study were carefully chosen such that even if they have not considered SPSI, their models were worth reporting in this study. Response of soil and structure on the application of earthquake ground motion was also studied and discussed here with emphasis given on calculation of stiffness of soil and the interaction between them. It was observed that the material/spring used for modelling of soil is of utmost importance. The theories for the calculation of stiffness of the soil material for different locations of the pile length are also discussed. Few studies have also considered the vertical component of earthquake ground motion in the past. A detailed justification regarding the selection of method of analysis such as linear or non-linear analysis, and adopted approaches for analysis such as discrete or continuous approaches, and their overall influence on the study was observed, and reported here in a concise manner. This article primarily aims to summarize the previously published researches on SSI and SPSI, including their advantages and issues over the structure.

Keywords: Soil-Structure Interaction; Soil-Pile-Structure Interaction; Bridge Abutment: Foundation;

1. Introduction:

Soil-structure interaction is now a common term to discuss among the research fraternity, where the response of the soil influences the motion in the structure and vice-versa [1]. The components of SSI diversified the study into kinematic and inertial interaction. The inability of the heavy foundation to match the free-field motion is categorised as kinematic interaction, whereas the mass of structure induces inertial interaction phenomenon. In either way, the behaviour of the structure varies from the foundation to the superstructure. Taking this study further, researchers have moved to detail the soil-pile-structure interaction, considering the effect of long piles beneath the foundations.

The structures in earthquake prone areas with deep foundation suffer severely with the abnormalities in the near soil. This shaking of the ground greatly affects the soil-pile behaviour. Intensive research is already available in this direction. This article encloses the study done so far in this direction concerning the effect of soil-pile interaction. SPSI is considered partly beneficial for the structures, mainly buildings, where due to this effect, the damping increases and thereby the time of oscillation of the structure increases [2].

Gholipour et al. [3] conducted the numerical SSI analysis to assess the resistance offered by the soil, the energy distribution from the impact in all the other components of the bridge and pier system after collision of a barge and then compared the forces and displacements with experimental data referring [4]. They conducted the same study with the real scale experimental tests on same bridge-pier to assess the dynamic response of soil by the impact. Also, the energy distribution in the barge-pier system is compared by considering and once not considering SSI to study the effects of pier's substructure system and SSI on the pier's response by barge collision. In the end, they concluded that, in the collision with the stiffer pier, the barge itself has absorbed most of internal energy than the components of the bridge. Whereas, in the collision with relatively flexible pier, the pier, the piles and SSI had most of the internal energy contribution. Fig. 1a and 1b shows the structure and substructure of stiffer pier and flexible pier respectively. And when compared for the absorbed energy by the pier, considering and not considering SSI, the flexible pier shows larger effects of SSI compared to the stiffer pier on the response produced by the displacements.

Pétursson and Kerokoski [5] conducted his study focussing on the magnitude of the lateral earth pressure in the abutment of two jointless bridges (i.e. Integral bridges). Instruments were used to measure the change in the earth pressure, displacements, rotations and temperature. He has verified this field tests results with the prepared soil abutment structure model developed during the research. To measure.

*Corresponding author. Tel: +919098935955; E-mail address: aakash@students.vnit.ac.in

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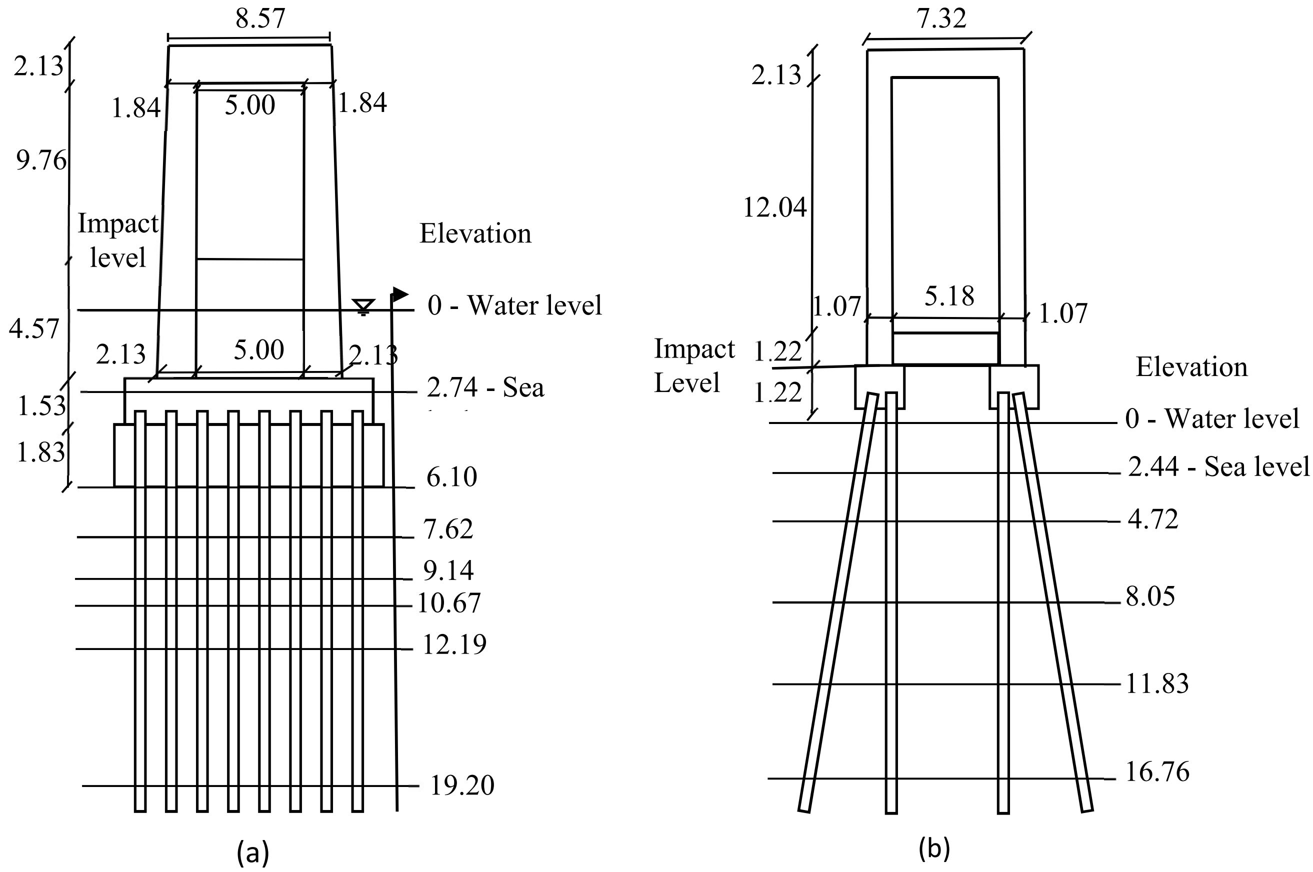

Figure 1: Section view of case study bridge pier; (a) Stiff pier, (b) Flexible pier (unit in meters) [3]

those changes in the abutment earth pressure cells, strain gauges and temperature gauges were installed. Bars were anchored in the bridge deck to observe the rotation of the bridge in the field.

The long term behavioural study period considered in this study is of initial 6 months after starting the functioning of the bridge. The results show that the biggest change in the measured values of earth pressure has taken place in the initial period itself and because of the increase in air temperature. Also the earth pressure in the coldest period against the abutment was found zero. Concluded that the values (displacement, earth pressure, etc.) measured from the field are lesser than that of calculated values with the help of mathematical computer simulation. The embankment appear stiffer because of the frozen backfill during the study period which has taken the Young's Modulus higher. The bridge has shown relatively larger restraints than the calculated model, implies that the backfill was stiffer in the field. Also, the rotation and the rotational stiffness is found stiffer during the winter time.

Dehghanpoor et al. [6] studied the influence on the response of an isolated bridge by taking into account the vertical component along with the horizontal component of ground motion. They have carried out a nonlinear time history analysis on the bridge considering SPSI by developing a three dimensional advanced FEM model for 3 different supporting conditions. First is the simply-supported girder, second is the continuous girder with fixed bearing and the third is continuous girder with elastomeric bearing. They stated that, considering 2/3 as the reduction factor to the spectral acceleration of the horizontal component for analysis of vertical component is like assuming, that the frequency content for the vertical and horizontal components of all ground motions are same. But as per previous studies and recorded ground motions it is wrong. The earthquake records selected for study has magnitude ranging between 6 and 7.5, PGAH more than 0.6g and V/H more than 0.6. While selecting the ground motions, also brought to our notice that the vertical component arrive earlier than the horizontal component, but the difference voids if the distance between the source and station less than 10 km [7].

Results indicate that, by including vertical component, there is a significant change in the variation of axial loads in the pier [8]. While, with horizontal component only, there is no change in the axial force in bearing. To prove that, they have presented the comparable plot for axial load and displacement of pile-cap considering and ignoring the vertical component for the piles under piers and abutments. The difference in amount of the axial force in piers is presented for different support bearings. Also, shown the plot for variation in shear capacity and shear demand for a typical ground motion by including vertical component and for only horizontal component, and concluded that the difference is insignificant. Results indicate that, the maximum axial load ratio with and without vertical component ($P_{(H+V)}/P_{(H)}$) ranges from 1 to 1.4 for the pile below pier and ranges from 1.2 to 1.8 for the pile below abutment for all the three supporting cases. They have specified that the minimum in all cases is for simply supported bearing case for pile below pier, but there is no such special case for the pile below abutment.

Observed that, by considering vertical component for different seismic isolation systems, the axial load of the pier has amplified significantly. Whereas, variation in maximum axial force is not affected at the abutment for the few selected piles in the bridge isolation and elastomeric bearing.

Shamsabadi et al. [9] estimated the nonlinear force-displacement capacity of abutment depending upon the displacement of end wall and the backfill soil properties with a limit equilibrium method. The method uses a mobilized log-spiral failure surface with hyperbolic stress-strain soil behaviour (LSH). Then the same has been validated with several field experimental results conducted on different structural backfills. Using these results, a simple hyperbolic force-displacement (HFD) equation is developed, wherein just by substituting the UBC and backfill soil stiffness, same results are obtained. They claim that, their model can be applied to any soil type if the soil can be characterized by their predetermined parameters which includes general soil properties, soil-structure interaction friction angle coefficient and theoretical ultimate capacity of soil. Comparing the nonlinear force-displacement results on abutment and pile caps, on various structural backfills, with actual full scale field tests, centrifuge model tests and lab tests is validating the model. Their LSH model can be used to design a bridge after analysing it based on its performance. To study the dynamic performance of a bridge abutment, a 3D nonlinear seismic soil-abutment interaction analysis of a simple two-span bridge was performed. This analysis showed that ground motions can permanently displace bridge deck and abutments and the bridge deck may get unsettled if not provided the adequate seat width.

Karantzikis and Spyrakos [10] developed procedures which carry out non-linear analysis on soil and abutment interaction under the effects of seismic loads. One is a design procedure performing successive linear analysis. And other is a nonlinear static analysis, where two springs are used in the abutment in the direction of movement of structure and only one on the other abutment. One is a nonlinear spring to represent backfill soil stiffness and to represent lateral pile stiffness the other is a linear spring. When the developed structural bridge model moves towards the soil, the passive resistance of the backfill is fully mobilized and negligible resistance is observed when the structure slides away from the backfill. Hence suggested to not consider the total stiffness of the backfill soil to make the stiffness unrealistically high. The springs in the model then have half the backfill stiffness and full lateral pile stiffness. And full backfill stiffness is considered for abutment in the direction of movement of structure and full lateral pile stiffness at both abutments for the other test. They recommended to use their procedures or a method ignoring reduction in the stiffness of backfill, the forces and moments determined at the piers will be excessive from 25% to 60% and the determined displacements will be excessive from 25% to 75%.

Maheshwari et al. [11] presented a 3D method to analyse the seismic response of the structures with pile foundation. The analysis is carried out on two different pile foundation systems: one is with single pile and the other with a 2x2 pile group. The model is a 3D FEM nonlinear model divided into two subsystems; one is a structure subsystem and the other is a pile foundation system and are connected at pile head and at the base of the superstructure. The model is symmetric in both cases, hence a quarter of the actual models is prepared. The piles used in the model are square in shape, embedded in the soil and rest deep in the bedrock. The spacing between the piles in the 2x2 pile group case is 5 times the size of pile. The superstructure for a single pile model is a huge rectangular column fixed directly to pile head. A rigid cap is connected to pile group. The superstructure in this case is four huge columns fixed on the cap so as the centre of gravity of the superstructure coincides with the pile group. Analysis is performed using a FORTRAN code developed to carry out the study. A definite constitutive relation is used to model the nonlinear behaviour in the analysis. The loading is applied as bedrock motion either as harmonic or transient excitations and the response is obtained at pile head and the top of structure. Harmonic loading is sinusoidal waves with varying frequency and transient is a component of an earthquake. The analysis is carried out for two considerations, the first is considering inertial and kinematic interaction where pile head displacements and column base forces are intermittently transferred. And the second is ignoring inertial interaction where the kinematic interaction is used to calculate response of the pile head which is then used as input excitation. The analysis was performed for varying frequencies and the result of which is shown in Figure 2 as amplification w.r.t. input motion. It is clear from the figure that the free field motion is in agreement with the pile head response (when ignoring inertial interaction). Figure also depicts that there is increase in period of oscillation of the structure and decrease in the maximum response amplitude when considered inertial interaction. Hence proved that the interaction increases the period and decreases the peak response. They concluded that the inertial interaction increases the response of pile head and decreases the structural response and the group effect of piles decreases the maximum response amplitude for both the excitations.

Boulanger et al. [12] analysed seismic soil-pile-structure interaction using dynamic beam on a nonlinear Winkler foundation analysis method by following the scaling relationships given by Kutter [13]. Also, they compared the results with dynamic centrifuge model tests for nine different earthquake events. Several dynamic centrifuge tests of pile supported model structures is performed. These centrifuge tests includes two different structures supported on single pile. Dynamic response of free-field soil is obtained by performing 1-D equivalent-linear site response analysis. And the calculation of the dynamic response of structural models is performed by the dynamic p-y analysis. The calculated responses from the Winkler foundation method are proved promising with the recorded responses in all earthquake events for both structures. Author quote that the dynamic p-y method is comparably easier than FEM and FDM modelling of soil-continuum and pile. SP1 and SP2 are the two single-pile-supporting systems consists the mass of the superstructure attached to the pile head. Csp4 and Csp5 are the two configurations for the centrifuge model.

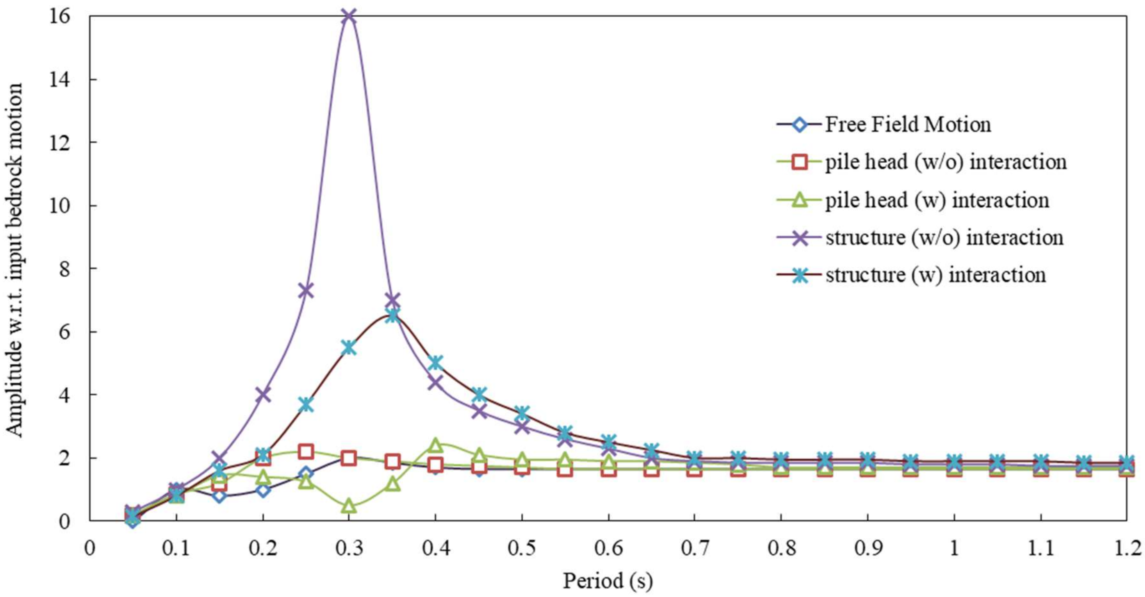

Figure 2: Effects of kinematic and inertial interactions on the response of the foundation and of the structure for an elastic soil model [11]

When comparing any set among the centrifuge test and dynamic analysis' results, recorded accelerations at varying depths shows a progressive amplifications of motion upwards in the soil profile. The recoded and calculated responses are quantitatively matching as seen in the acceleration time histories and response spectra. Also, there are plots for the peak bending moment and displacements with respect to depth for calculated and recorded values. For a typical configuration of centrifuge test, the calculated p-y behaviour at same location was compared, and the results are matching here as well. Definitely there was some approximations and uncertainties in the centrifuge data, but the recorded responses was reasonably modelled in the performed site response analysis. The range of variation among the recorded and calculated peak superstructure acceleration is observed between -25% and +10%. Similarly, the range of variation among the recorded and calculated peak superstructure displacement is observed between -25% and +25%. The ratio of peak superstructure response and peak input motion reduces with increase in peak of base acceleration. The fundamental period of the structure model also increased considerably through low shaking events to high shaking events. Frequency content of the earthquake and the shaking affected the calculated and recorded superstructure response. Also, they have presented plots for the calculated and recorded peak superstructure acceleration and displacement with respect to peak input/base acceleration. The study has proved that, for problems relating to seismic soil-pile-structure interaction, dynamic p-y analysis method is a possible alternative. Also, the centrifuge modelling tests performed is proved particularly valuable.

The simplest way to analyse the soil-structure interaction is by superimposing the inertial interaction on kinematic interaction and is a conventional method. Guin and Banerjee [14] devised a coupled finite-element approach to replace the time-consuming multistep method. Throughout the study, structural components are modelled in finite-element method for which the analytical formulations has been prepared and elaborated for several complex problems performed in the study. To begin with a single pile, modelled as linear beam, the structure and the pile are coupled with a set of equations and the displacement compatibility condition at the interface. Formulation becomes bigger when more structural components are introduced, simple equations got converted into matrix from for easy computation and same is the compatibility conditions. In the study, two real life bridge-pier systems are modelled and analysed with two different considerations. The first model is a single column bent on a single drilled pile and the other is single column bent supported on a group of a pile-group. The two different considerations is the case when rotation of the bridge deck is free to rotate and the case when the bridge deck is restrained against rotation. The results of the response of the models for all the cases are compared and conclusions are made. For the case of structure supported on single pile and the bridge deck restrained against rotation, there is a considerable difference in the magnitude of the peak of the response. Also, the fundamental time period is 0.65 seconds for both the case. For the case of structure supported on single pile and the bridge deck allowed to rotate, the fundamental time period is 1.25 seconds and the peak of the response are much higher than the peak of the first case. For the case of structure supported on pile group and the bridge deck restrained against rotation, the nature of the curves is same but there is difference in the magnitude of peak response. Also, a shift is observed in the peak of response which is estimated because of the stiffer foundation in this case compared with the single pile supported foundation. For the case of structure supported on pile group and the bridge deck allowed to rotate, the magnitude of the peak is observed lower because of the stiffer foundation. For the same problem, author also observed the effect of inertial interaction on seismic response. And for the case of foundation supported on single pile, kinematic seismic analysis is performed and this response is fed as support displacement to the structure. Author concluded that the two type of foundation changes the distribution of the structural loading transferred to the pile but doesn't change the dynamic characterization of the structure.

2. Conclusion:

This study provides a comprehensive review wherein addressing the SPSI in the bridge structures. Earlier research in this field has focussed on Soil-Structure Interaction (SSI), as compared to the SPSI. With this article, an attempt is made here to combine these studies and present it. Response of soil and structure on application of earthquake ground motion was also studied and discussed herein. Few studies have also considered the vertical component of earthquake ground motion in the past. A detailed justification regarding the selection of method of analysis such as linear or non-linear analysis, and adopted approaches for analysis such as discrete or continuous approaches, and their overall influence on the study was observed, and reported here in a concise manner. This article primarily aims to summarize the previously published researches on SSI and SPSI, including their advantages and issues over the structure.

Disclosures

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