EFFECT OF THE JOINT SHEAR RESISTANCE ON THE DYNAMIC RESPONSES OF STEEL PIPE SHEET PILE FOUNDATIONS

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Abstract

The effect of joint shear resistance characteristics of steel pipe sheet pile (SPSP) foundation on its frequency and intensity dependent dynamic responses are investigated in this study through scaled model testing on a shaking table under 1-*g* conditions. At first, the vertical shear resistance of joints is estimated experimentally by using an elemental model of SPSP joint. Obtained experimental results are in good agreement with the available field test results in the literature for regular SPSP joint. Finally, the effective foundation input motion (EFIM) and foundation head impedance functions (IFs) are evaluated through base excitation and foundation head excitation, respectively for two SPSP foundation models with different joint vertical shear resistance. A low-to-high amplitude of lateral excitation is applied in these dynamic experiments to induce low-to-high levels of strain in the soil and a wide frequency range is considered to encompass typical soil and structural natural frequency. Loading intensity and frequency dependent variation pattern of EFIM and IFs for both the SPSP foundation cases are found similar in nature. This behavior is understandable since the foundation vibration response is governed by the shear movement of the soil when the soil-SPSP foundation system is subjected to lateral base vibration. The dynamic stiffness characteristics of the soil-SPSP foundation system, on the other hand, is governed by the soil resistance and damping behavior when the foundation head is excited laterally. The total response of the superstructure and the foundation of the soil-SPSP foundation-superstructure (S-SPSP-S) system for the above mentioned two SPSP foundation cases are also evaluated through shaking table testing by laterally exciting the S-SPSP-S system at the base. Difference in the resonant behavior of superstructure and soil-foundation system is observed due to the difference in joint shear resistance between the two supporting SPSP foundations underneath the superstructure. The mass of the superstructure apparently has a profound influence on the joint shear behavior, resulting in the variation of stiffness of the SPSP foundation and causing the difference in resonant behavior of the superstructure and the foundation when the total S-SPSP-S system is subjected to base vibration.

Keywords: Dynamic response; steel pipe sheet pile (SPSP) foundation; soil-structure interaction; shaking table tests.

1. Introduction

Steel pipe sheet pipe (SPSP) foundation provides appropriate engineering solutions for effectively transferring the superstructure load from large-scale bridge structure to underneath soil stratum particularly in situations where the bridge is constructed on soft soil deposit. This type of foundation has been used in many parts of the world for connecting major highway system due to its high rigidity and large vertical bearing capacity. For instance, SPSP foundation is used to support three bridge structures to enhance their capacity in Kanchpur, Meghna, and Gumti (KMG) bridge project on national highway number one in Bangladesh which connects its major seaport to the rest of the country [1]. SPSP foundations are generally large-scale circular, rectangular, or oval shaped structure comprised of individual unit of steel pipe piles with couplings welded on its sides. The pipes are driven sequentially into the soil conforming the chosen foundation shape to anchor them in firm soil layer, and they are connected to each other through interlocking of the coupling and mortar grouting inside the coupled portion. The interlocked part is commonly known as SPSP joint. The structural behavior of such foundation system is considerably influenced by the joint shear characteristics since it contributes to the overall bending rigidity and vertical bearing capacity of the foundation structure. In design and analysis of this foundation system, thus, the joint shear resistance is inevitably a key item demanding attention. The behavior of the joint and overall foundation structure is likely to be much more complicated when the foundation comes under the influence of a dynamic loading event, for instance, an earthquake.

SPSP foundation is different from other popular type of deep foundations in terms of structural configurations. Its major structural components are individual unit of flexible steel pipe piles and the connection between them through interlocking of joints assumes a caisson like foundation body of smaller diameter to depth ratio, thus, it is considered to exhibits intermediate behavior between caisson and pile foundation [2-4]. Accordingly, it will interact with soil under dynamic loading due to the stiffness difference between the foundation structure and surrounding soil, and the superstructure inertia as seen for other types of foundations. The interactions will eventually influence the dynamic response behavior (for example, natural frequency, attenuation characteristics of response amplitude, damping etc.) of SPSP foundation and superstructures supported on it. The main influence is that the motion at the footing level is modified from the motion at the same level experienced in the free field due to such interaction process. The modifications between these motions are due to two reasons. One is the scattering of the seismic waves by the foundation (which is the inability of a foundation to conform to the deformations occurred in soil because of the stiffness difference between foundation and soil, predominantly for seismic excitation at higher frequencies). The other reason is the deformation induced in soil by the inertial forces from the vibrating structures that is transmitted through the foundation. The first effect is termed as kinematic interaction whereas the latter is called inertial interaction. Additionally, the mechanical characteristics of complex SPSP joint could potentially provide further influence into such dynamic responses during seismic events [5]. Available literature on the influence of joint behavior on the dynamic response of SPSP foundation, however, is scarce. The current work evaluates the effects of joint shear resistance on the dynamic behaviors (kinematic and inertial interactions) of SPSP foundation systems. Moreover, the effects of joint shear resistance on the total response of superstructure supported on SPSP foundation is also investigated. For this study, physical scaled model experiment approach is adopted. The details of the experimental program and result are discussed in the subsequent sections.

2. Experimental organization

2.1 Scaling relationship

Physical experimental model of soil, SPSP foundation, and superstructure has been prepared to conduct the scaled model experiments. Law of similitude derived by Kokusho and Iwatate [6] considering the effects of low confining pressure of soil in 1-*g* model testing using shaking table is adopted. The law provides loading frequency relationship between the model and the prototype as in Eq. (1) by considering the ratio of forces acting on the model and the prototype.

$$\frac{\omega_m}{\omega_p} = \eta^{-1/4} \lambda^{-3/4} \tag{1}$$

where, ω_m is the cyclic loading frequency on the model and ω_p is the cyclic loading frequency on the prototype. Subscripts m and p represents the model and the prototype, respectively, for all the equations in this section. In Eq. (1), η is the density scaling ratio of the model to the prototype and λ is the geometric scaling ratio of the model to the prototype.

$$\eta = \frac{\rho_m}{\rho_p} \text{ and } \lambda = \frac{l_m}{l_p}$$

The ratio of the dynamic strain between the model and the prototype is given as

$$\frac{\gamma_m}{\gamma_p} = \eta^{1/2}\lambda^{1/2} \tag{2}$$

where, γ_m is the dynamic strain in the model and γ_p is the dynamic strain in the prototype.

For the current experiments, the model is considered 16.5 times smaller than the prototype in geometrical dimensions. Standard aluminium pipe is selected to represent steel pipes of the prototype structure, leading to a density scaling ratio of 0.35 between the model and the prototype. The other scaling ratio between the model and the prototype of this experiment for parameters like young's modulus, stress, natural frequency etc. can be straightforwardly derived using Eq. (1) and Eq. (2).

2.2 Element model of SPSP foundation joint

A few large-scale field tests have been conducted on the vertical shear resistance of SPSP foundation joint in order to grasp the mechanical characteristics of such joint [2,7,8]. For example, in the field test carried out by Onda et al. [8] for ordinary P-P type SPSP foundation joint with four different mortar strength, one side of the joint was welded to a fixed reaction force column and the other side was welded to a loading column. The shear resistance of the joint in the vertical direction was estimated by pushing the loading column downward. The relative displacement of the joint with respect to the welded side with the fixed reaction force column and the reaction load were measured. The results exhibit bilinear hysteretic pattern of reaction load when plotted against relative displacement of joint [8]. To emulate the similar behavior pattern of vertical shear resistance behavior of ordinary P-P type SPSP foundation joint, a scaled element model for SPSP foundation joint (called "element model" hereafter) is prepared and tested so that the real joint behavior can be realized through the designed equivalent joint model.

The element model of SPSP joint (see Fig. 1) comprised of three hollow aluminium pipes each of length 990 mm, outer diameter of 30 mm, and thickness of 2 mm. These pipes are interlocked to each other by a type of joint as shown in Fig. 1 (section A-A). A similar type of SPSP joint model with the center of rotation at one end of the jointed part was used by Kimura et al. [9] to match the behavior of ordinary P-P type SPSP joint. The joint used in this study is modified from the one used by Kimura et al., with the center of rotation at the middle of the jointed part to make the joint interface symmetric, matching the real joint. The center pipe of the element model is rigidly connected to a vertical unidirectional actuator (±10 kN, ±150 mm) for the load application. The other two side pipes are rigidly connected to steel plates at top and bottom. The steel plate at bottom is further rigidly fastened to a base plate. The length of joint part on both side of center pipe is 950 mm, whereas the length of joint parts adjacent to the other two pipes is 990 mm. Different length of joint part on the pipes are provided so that a constant jointed length of 950 mm can be maintained during the application of vertical displacement of different amplitude to the center pipe through the vertical actuator.

The effect of soil pressure on the joint interface is considered by applying additional force through wire tension at different depth along the length of the element model as shown in Fig. 1. The details of the procedure adopted to calculate the soil pressure can be found elsewhere [10]. Two element models are prepared to realize different vertical shear resistance of SPSP foundation joint. The first model (referred as "Case- a" hereafter) is prepared in accordance with the above description and in the second model (referred as "Case- b" hereafter), additionally, the vertical shear resistance is increased by placing a transparent adhesive tape of thickness 0.065 mm between the aluminium pipe and the adjacent joint part (Fig. 1) along the entire length of all the pipes.

2.3 Shaking table unit

A one degree of freedom shaking table of size 1.8 m × 1.8 m and of capacity 5 (t-G) in full load is used. The table can provide maximum of ± 200 mm in stroke and can operate in the frequency range 1~100.

2.4 Laminar shear box

A specially designed laminar shear box of inner dimension of 1.2 m × 0.8 m × 1.035 m is used for housing the experimental model on the shaking table. The shear box is comprised of a series of rectangular metallic frames of thickness 65 mm, each stacked one over another. These frames contain ball bearing in between them to minimize the shear resistance of the housing. The bottom frame of shear box is securely fastened to the base plate of the shaking table. Raking or torsional mode of the shear box is negligible. The mass of the laminar shear box is considerably low enough in comparison to the mass of the sand used in the experiments, therefore, it does not possess significant influence on the behavior of sand to be tested. The shear box mounted on the shaking table is presented schematically in Fig. 2.

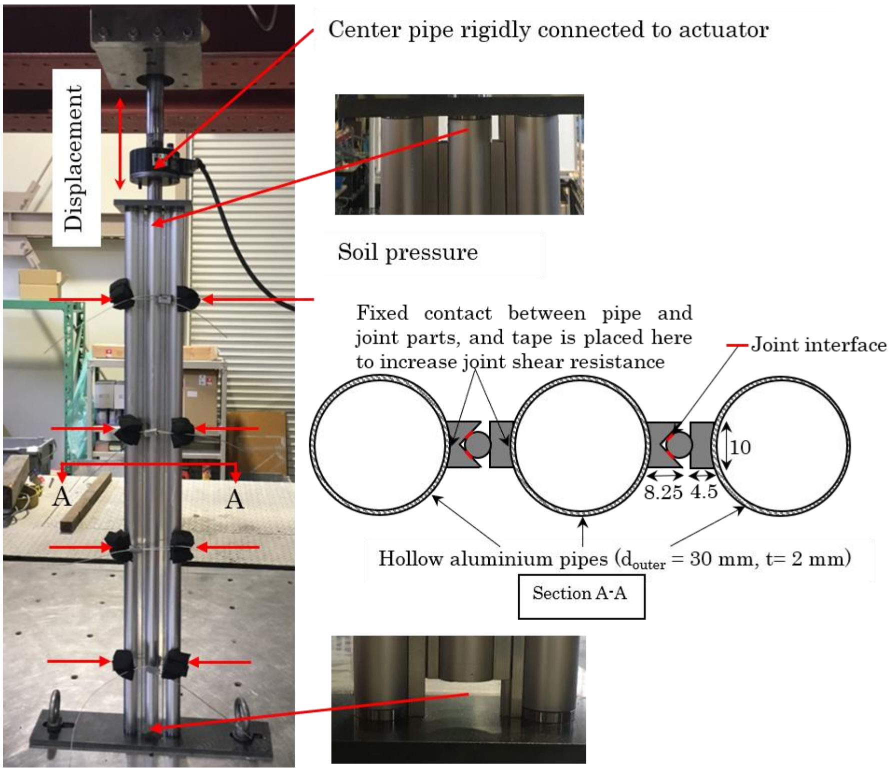

Fig. 1 – Element model of SPSP joint and joint vertical shear resistance test (all dimensions are in mm) [10].

2.5 SPSP foundation model

20 hollow circular standard aluminium pipes of outer diameter 30 mm with thickness of 2 mm are arranged to form a circular unit of total diameter 316.5 mm for the steel pipe sheet pipe (SPSP) foundation model (see Fig. 2). Length of each pipe is 960 mm. These pipes are interlocked to each other by the same type of joint as described in section 2.2. This joint provides vertical shear resistance at joint interfaces through friction. Additionally, the lateral rigidity of the joint results from the hoop stress of the circular unit wall generated due to the pressure exerted from the soil located on both inside and outside of the circular unit in the laminar shear box. All the aluminium pipes are connected rigidly at the top to a steel circular footing of diameter 350 mm and thickness 8.5 mm. The bottom part of all the pipes are also rigidly connected to a steel circular plate of same dimension as the footing. Fixed tip condition is maintained during the dynamic loading experiments by rigidly connecting the bottom circular plate further to the bottom of the laminar shear box. Both the steel plates (at top and bottom) have a circular hole of diameter 125 mm at the center to enable sand filling inside the SPSP foundation model. Polyurethane foam is sprayed on the open joint parts along the whole jointed length to seal against the possible movement of sand into the joint from the sand column laid inside and outside of the circular SPSP foundation unit. For this current study, two SPSP foundation models are prepared with different joint vertical shear resistances. The first one is prepared with the same joint used in Case-a of element model. The second one is prepared with increased joint shear resistance by placing adhesive tape of thickness 0.065 mm between the contact surface of pipe and adjacent joint part for all the pipes as done in Case-b of the element model. The first SPSP foundation model is referred as Case-I and the other one with higher joint capacity is referred as Case-II in this current work.

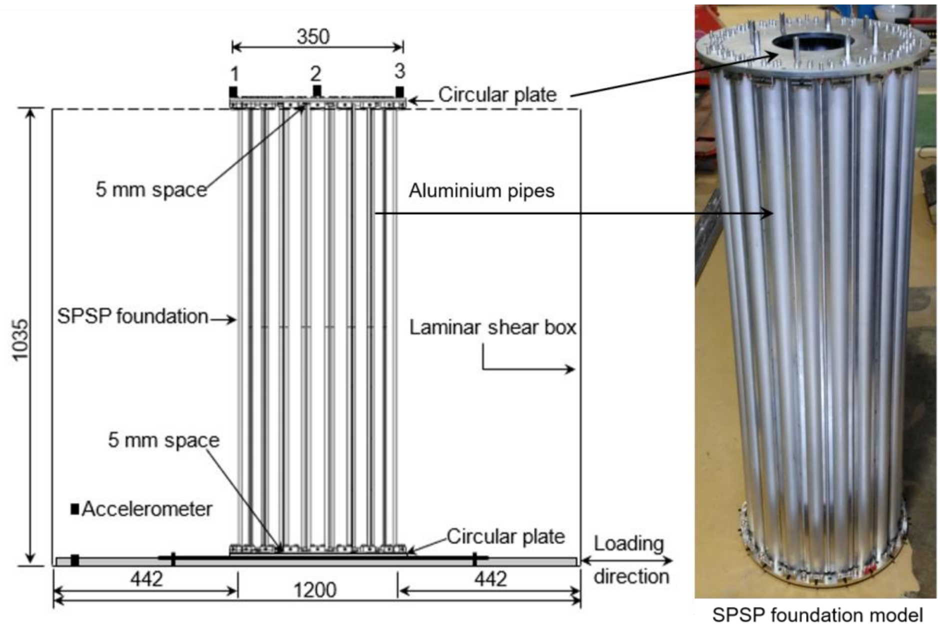

Fig. 2 – Schematic layout of experimental setup for EFIM estimation and SPSP foundation model [14].

2.6 Soil model

Homogeneous cohesionless dry Gifu sand is used. The strain dependent shear modulus degradation and damping behavior of Gifu sand was evaluated and presented in the works by Ishida et al. [11]. Goit et al. [12] investigated the strain dependent shear modulus degradation behavior of Gifu sand through dynamic model testing of the soil with the same experimental system (i.e. laminar shear box, shaking table etc.) adopted in this study and they obtained good agreement with the results found by [11].

2.7 Superstructure model

The superstructure model is comprised of 12 steel plates each of dimensions 180 mm × 180 mm × 9 mm and mass 2.2 kg rigidly bolted to the top of a vertical steel plate (6 plates on each side of the vertical plate). The dimension of the vertical plate is 503 mm × 125 mm × 16 mm, and the mass is 7.8 kg. The mass and stiffness of the superstructure model is designed in such a way that the natural frequency should fall within the experimental frequency range considered in this study (see section 2.8) and should not coincide with the soil-foundation system resonant frequency in order to observe distinct resonant behavior of the superstructure. The mass selected represents roughly that of a 2-lane bridge with span length of about 35 m [13]. The natural frequency of the superstructure is evaluated as 10 Hz by fixed base vibration experiment.

2.8 Loading, data recording, and processing

The vertical shear resistance test of the SPSP joint model is conducted by applying static pull-push displacement of different amplitude (±3 mm, ±6 mm, ±9 mm, ±12 mm, and ±15 mm) at a speed of 4 mm per minute on the center pipe through the vertical actuator rigidly connected to it. Small-to-large vertical displacement is chosen to check the consistency of the vertical shear resistance behavior pattern of the model joint throughout the considered range and the displacement is applied at a slow rate to maintain the static condition. The center pipe with its adjacent jointed parts on both side (see Fig. 1) moves up and down following the displacement applied through the actuator. This pull-push movement against the jointed parts adjacent to the other two pipe produces a frictional resistance in vertical direction at the joint interfaces. This vertical shear resistance force of the joint interface against the applied displacement are recorded.

The EFIM experiment is conducted by applying dynamic loading at the base of the soil-SPSP foundation system (as shown in Fig. 2). No superstructure is present over the circular footing plate to discard any form of inertial influence in the experiment. Lateral harmonic acceleration of amplitude 0.5, 1, 2, 3, 4, and 5 m/s^2 are applied at the base of the laminar shear box in the frequency range 6-35 Hz. The response acceleration at the top of the SPSP footing was measured by the accelerometer placed at central position (accelerometer #2 as in Fig. 2) of the circular footing.

The SPSP foundation head IFs is estimated by solitary application of lateral harmonic acceleration of amplitude 0.2, 0.5, 1, 2, 3, 4, and 5 m/s^2 at the head of a loading plate (rigidly fixed on the footing of the soil-SPSP foundation system) in the frequency range 6-35 Hz by a digitally controlled unidirectional hydraulic actuator (±10 kN, ±150 mm). The lateral response of SPSP footing is measured by the accelerometer placed at central position (accelerometer #2 as in Fig. 2) of the circular footing. The corresponding reaction force is also recorded from the actuator for each loading case. Then, finally the SPSP foundation head IFs are obtained by taking the ratio of the measured reaction forces to the corresponding footing displacement for each loading case. More details on this SPSP foundation head IFs experimental setup is available in [10].

Total dynamic response experiment for the soil-SPSP foundation-superstructure (S-SPSP-S) system is conducted by applying lateral harmonic acceleration of amplitude 0.5 and 1 m/s^2 in the frequency range 6-35 Hz at the base of the laminar shear box containing the S-SPSP-S system. In the experimental setup shown in Fig. 2, additionally, the superstructure model detailed in section 2.7 is rigidly fixed on the SPSP foundation footing to prepare the S-SPSP-S model. Higher amplitude of base excitation (2, 3, 4, and 5 m/s^2) is avoided in this experiment because for such loading the strong superstructure response possess risk to the experimental premises. The responses of superstructure and footing are recorded in terms of accelerations through the accelerometers positioned at the top of the superstructure and footing, respectively.

Low-to-high amplitude of lateral harmonic accelerations is considered in this experimental program to induce low-to-high levels of strain in the soil. A wide range of frequency is selected to encompass typical structural and soil natural periods. All the data are recorded in time domain for the dynamic loading tests mentioned above and the recorded data is passed through a band pass filter of range 0.80–1.20 times the frequency of respective loading to eliminate any noise from the recorded data. Fast Fourier Transform (FFT) technique is employed to convert the recorded time domain data into frequency domain.

3. Experimental results

3.1 Vertical shear resistance of SPSP foundation joint

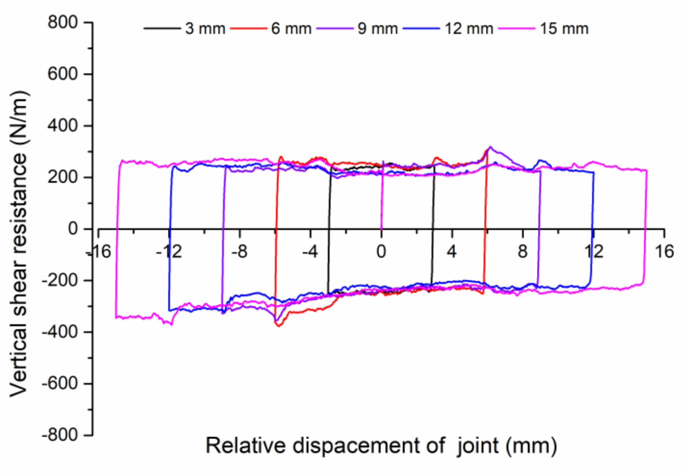

Fig. 3 – Vertical shear resistance vs relative displacement of SPSP joint (Case-a).

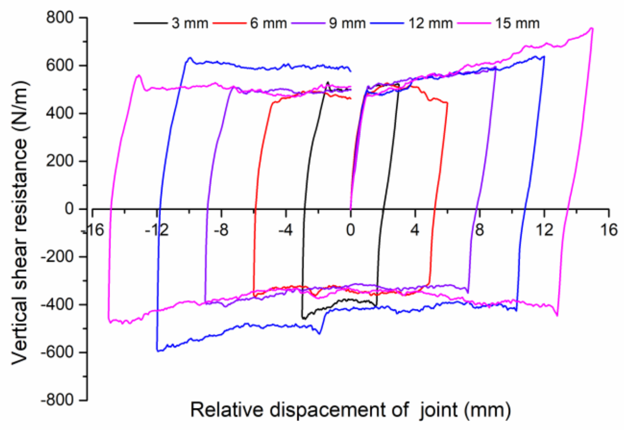

Fig. 4 – Vertical shear resistance vs relative displacement of SPSP joint (Case-b) [10].

The vertical shear resistance is evaluated in terms of resistance force per unit jointed length. The relationship between the vertical shear resistance and the relative displacement of the joint (Case-a) for all the loading cases (as mentioned in section 2.8) are presented in Fig. 3. A bilinear hysteretic behavior pattern is seen for all the cases analogous to the trend seen in the field test results [8]. The design vertical shear resistance of the SPSP joint is 200 kN/m [5,7]. The corresponding scaled down shear resistance value for the experimental model is 256 N/m. From Fig. 3, it is apparent that the vertical shear resistance of the joint model satisfies such aforesaid requirement for all the experimental cases. Fig. 3 also shows a consistent vertical shear resistance behavior pattern for small-to-large relative displacement of joint model. It can be summarized from the above discussions that the joint model considered in this present study is adequate to emulate the behavior of real field ordinary P-P type joint. In addition to this, another element model test is conducted with the SPSP joint model described as Case-b in section 2.2. The results of vertical shear resistance vs the relative displacement for Case-b joint is presented in Fig. 4 and similar joint behavior trend as seen for Case-a is seen for this case also. And the joint shear resistance is found approximately 2.5-3 times larger than Case-a.

3.2 Effective foundation input motion (EFIM)

For both the SPSP foundation cases (Case-I and Case-II), the amplification of motion at the SPSP foundation footing level (EFIM) due to input excitations (discussed in section 2.8) at the base of the laminar shear box have yielded with almost identical results. For example, the maximum amplification ratio is 6.7 for case-I (Fig. 5a) and 6.1 for case-II (Fig. 6a) for base excitation of amplitude 0.5 m/s^2. The loading amplitude and frequency dependent amplification ratio and resonant frequency variation pattern are found similar for both case-I and case-II. The corresponding phase difference values (as shown in Fig. 5b and Fig. 6b) between the input ground motion and the EFIM also shows same variation pattern for both the foundation cases under consideration. These similarities seen in the presented results indicates that the EFIM of SPSP foundation is independent of the joint vertical shear resistance capacity. The joint vertical shear resistance capacity does not significantly influence the kinematic response of the soil-SPSP foundation system, and the foundation vibration response is governed by the soil shear movement.

Besides, the EFIM and phase data presented here for Case-II are also available in [14] with more detail insight on the changes in foundation response compared to soil surface response depending on input loading excitation amplitude and frequency.

3.3 Impedance function's (IFs) for SPSP foundation

The real and imaginary part of SPSP foundation IFs for case-I and case-II are presented in Fig. 7 and Fig. 8, respectively. The real part (Fig. 7a) shows a decreasing trend with increasing foundation head excitation amplitude in the lower frequency region (6-19 Hz). For higher excitation amplitude (3-5 m/s^2), the foundation stiffness becomes identical signifying a possible occurrence of local soil failure in the vicinity of the foundation. After that, in the frequency range around 25 Hz, a sudden reduction in stiffness value marks the resonance of soil due to the decrease in stiffness of the soil-foundation system. Past the soil resonance, the stiffness value shows undulating and increasing pattern which is possibly due to the change in phase and vibrating mode of the soil-foundation system. The imaginary part (Fig 7b), on the other hand, shows an increasing trend after the soil resonance due to radiation damping whereas there is no significant damping before the resonant frequency of soil. An almost similar pattern in stiffness and damping behavior (Fig. 8a and 8b, respectively) as discussed above is seen for case-II foundation with joint of relatively higher shear capacity. Such similar values and trends in real part and imaginary part of IFs for both the SPSP foundation cases reflects that these characteristics are influenced by the soil resistance and soil shear modulus degradation behavior with increasing excitation, rather than the joint mechanical property, i.e., the vertical shear resistance capacity.

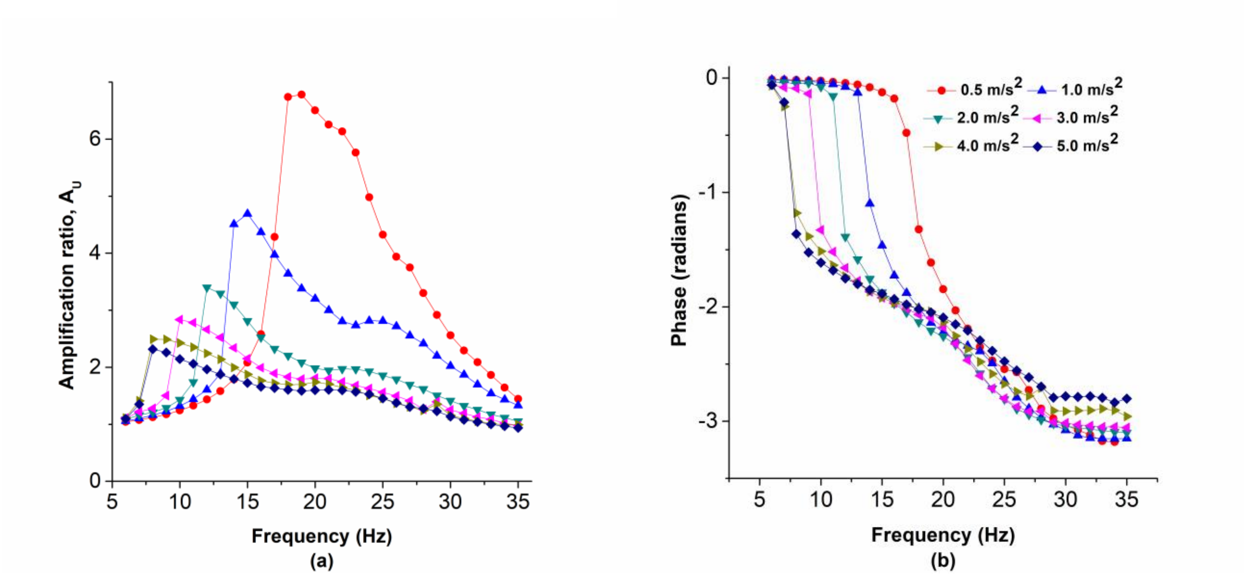

Fig. 5 – EFIM results- (a) amplifcation ratio and (b) phase for (Case-I).

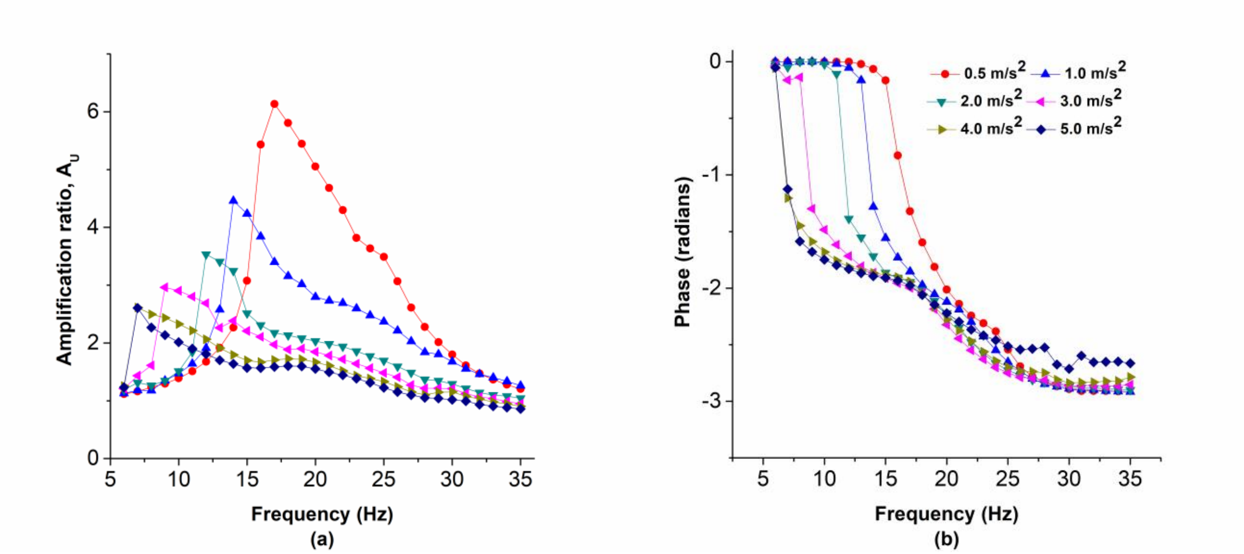

Fig. 6 – EFIM results- (a) amplifcation ratio and (b) phase for (Case-II) [14].

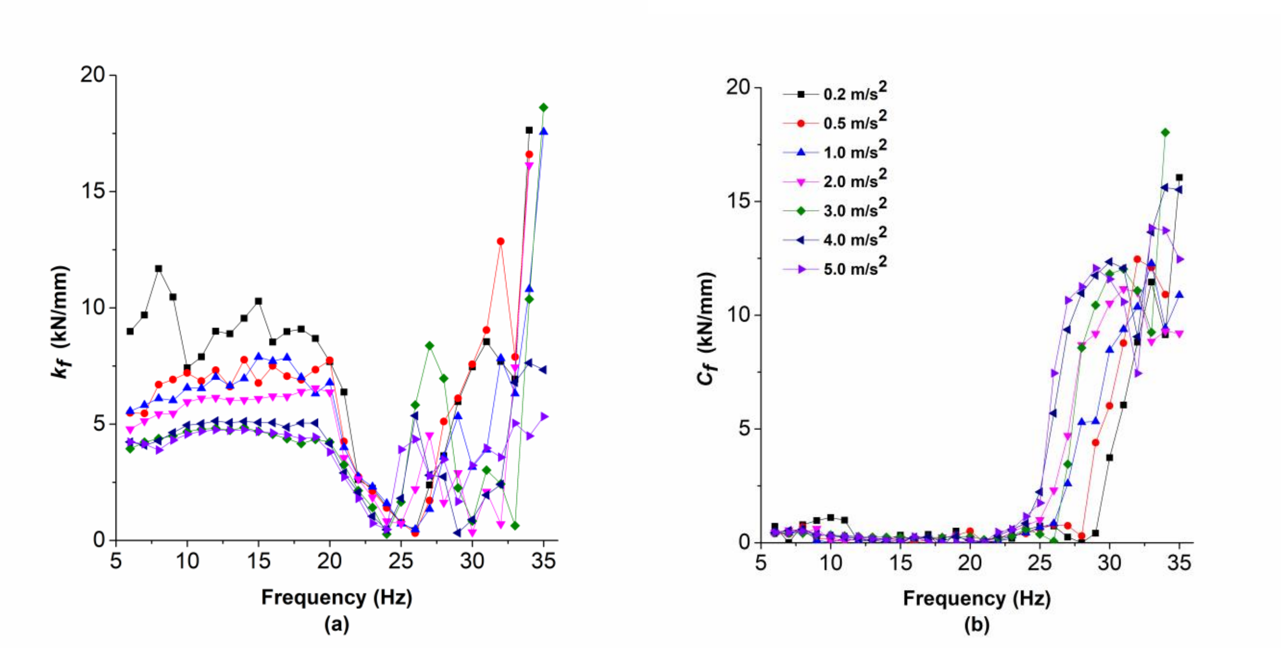

Fig. 7 – IFs results- (a) real part and (b) imaginary part for (Case-I).

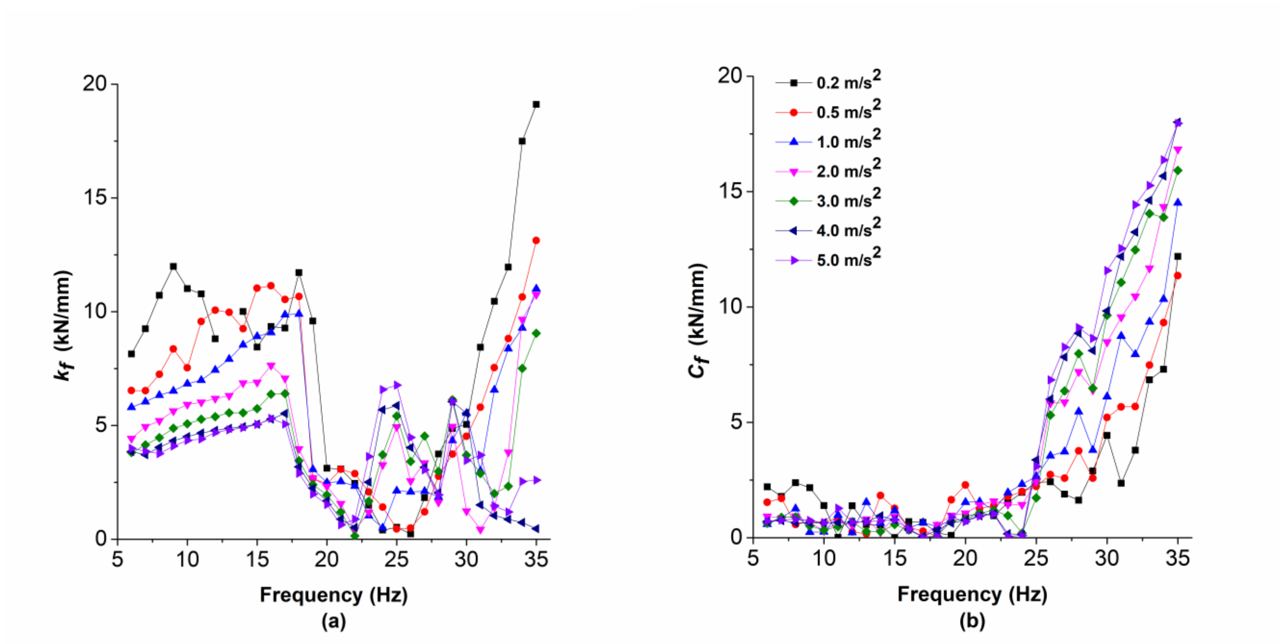

Fig. 8 – IFs results- (a) real part and (b) imaginary part for (Case-II). [10]

3.4 Total response of superstructure and foundation of S-SPSP-S system

From the results presented in Fig. 9 and 11, an increase in amplification ratio of superstructure is seen with the increase in SPSP joint shear resistance, particularly at the resonant frequency zone of superstructure and of soil-foundation system. Moreover, the resonant frequency shifts towards the higher frequency region with the increase in the joint shear capacity. The corresponding phase difference also shows an analogous shift with the increased joint shear capacity. The footing amplification ratio and corresponding phase difference results (see Fig. 10 and 12) also represent similar trend as discussed above. The increase in amplification of motion at superstructure and footing level, and the increase in resonant frequency with increase in joint shear resistance of the SPSP foundation model characterizes an overall increase of stiffness of the foundation system when the total S-SPSP-S system is under the influence of dynamic loading. The superstructure load is transferred through the aluminium pipes and the joints. This additional contribution of load from the superstructure on the joint friction surface in the normal direction increases the frictional resistance of the joint which eventually increases the overall stiffness of the foundation structure when both kinematic and inertial loading are combinedly acting on the foundation system. The increased stiffness of the foundation locally influences its vibration response and consequently the total response of the foundation and superstructure supported on it get influenced. Due to the stiffer foundation, the dynamic responses are not completely governed by the soil shear movement and resistance as seen for EFIM and IFs experiment, respectively.

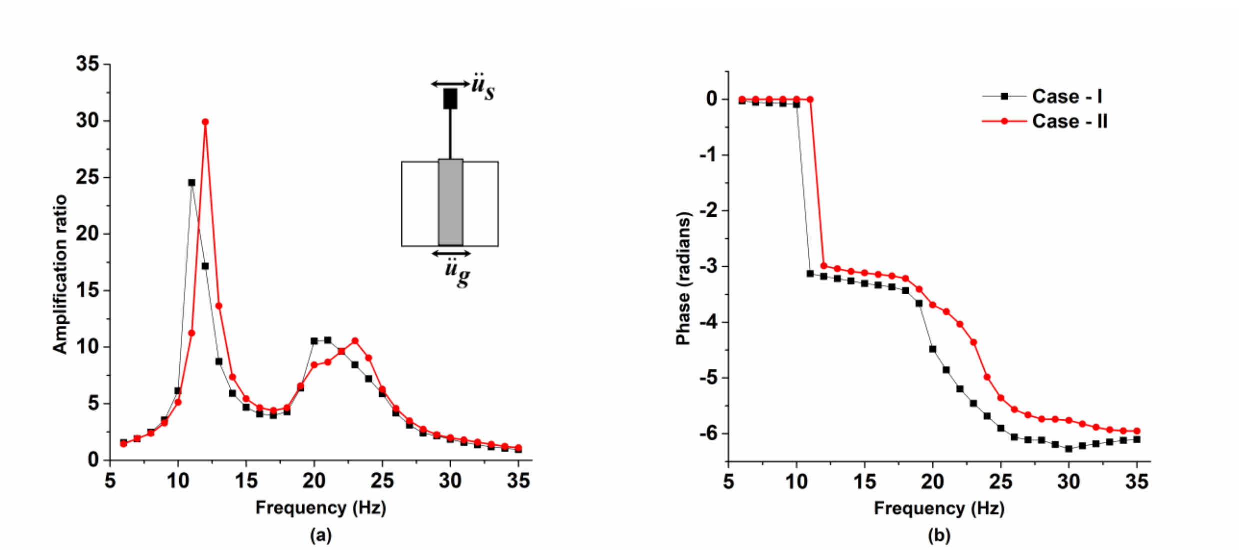

Fig. 9 – (a) Amplifcation ratio and (b) phase difference at the top of the superstructure for base harmonic excitation of amplitude 0.5 m/s^2.

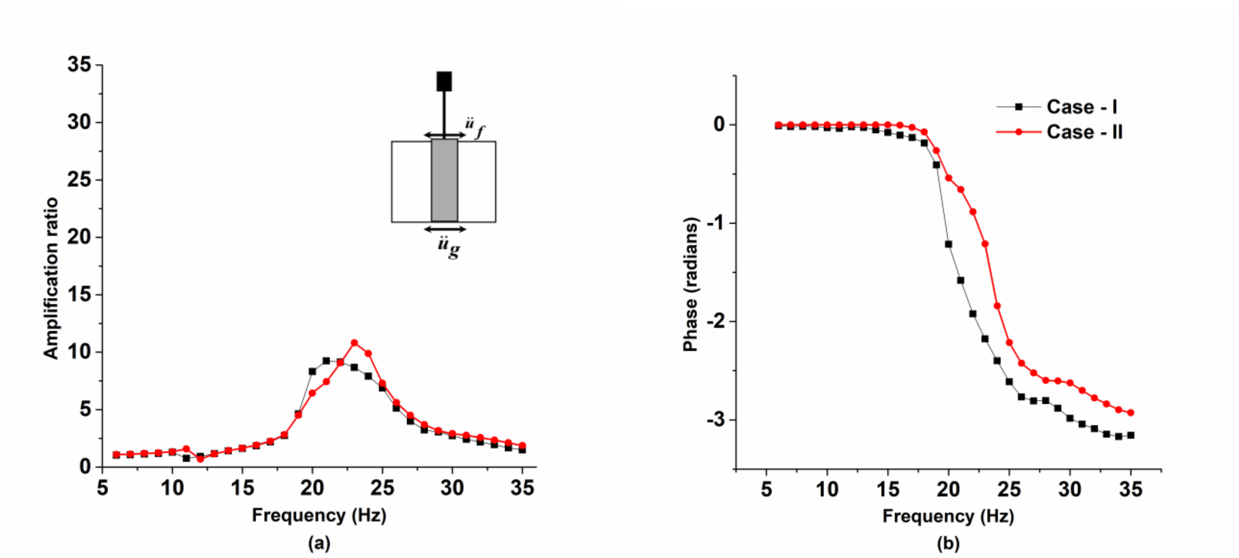

Fig. 10 – (a) Amplifcation ratio and (b) phase difference at the top of the footing for base harmonic excitation of amplitude 0.5 m/s^2.

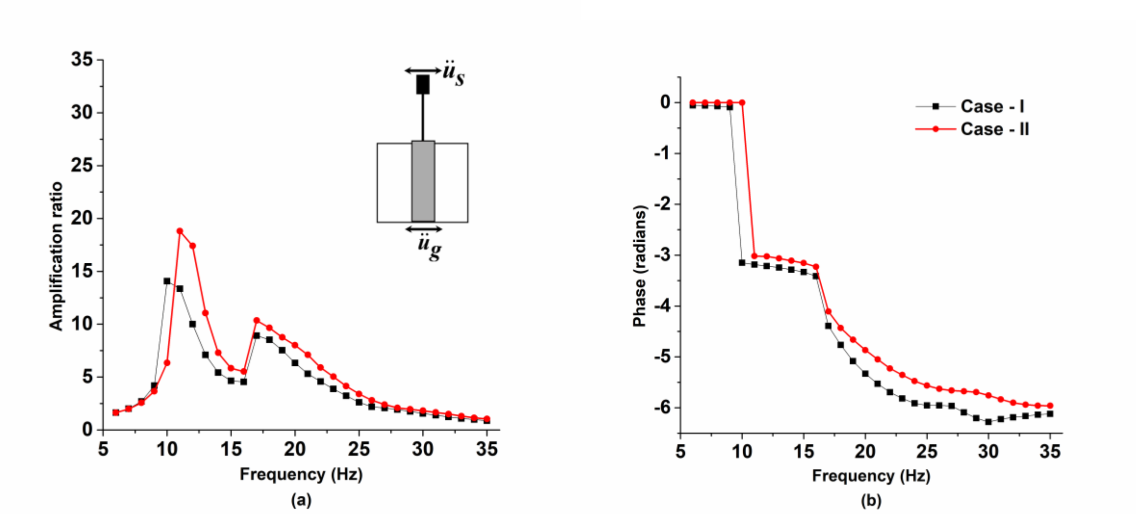

Fig. 11 – (a) Amplifcation ratio and (b) phase difference at the top of the superstructure for base harmonic excitation of amplitude 1 m/s^2.

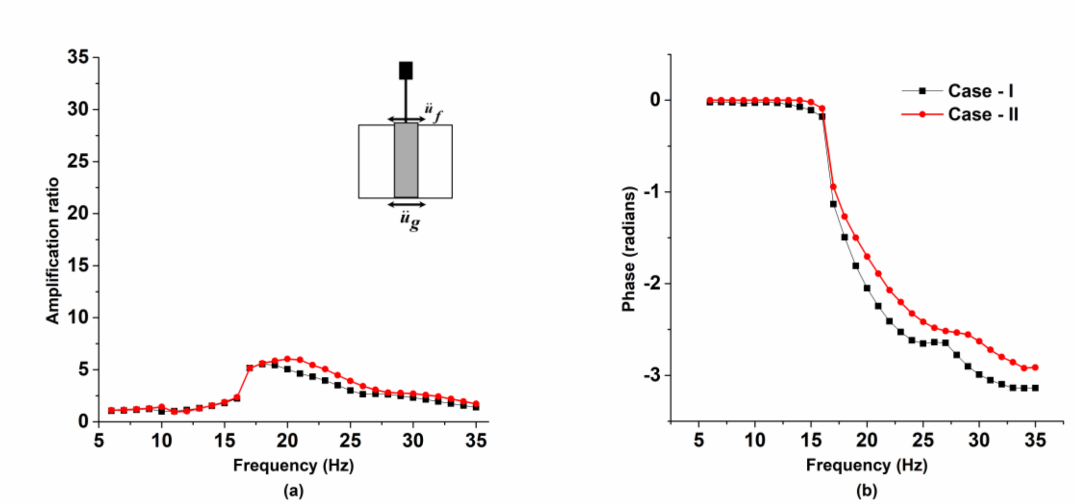

Fig. 12 – (a) Amplifcation ratio and (b) phase difference at the top of the footing for base harmonic excitation of amplitude 1 m/s^2.

4. Conclusions

The influence of joint vertical shear resistance capacity on the dynamic response (kinematic and inertial interactions) of steel pipe sheet pipe (SPSP) foundation is investigated experimentally through scaled physical model testing. For the two SPSP foundation models studied, the EFIM and the IFs results show a similar trend for the considered loading range. Such results suggest that the EFIM of the SPSP foundation, in general, is governed by the shear movement of soil while the IFs are dependent on the resistance and damping characteristics of soil rather than the joint shear resistance. On the other hand, an increase in the resonant frequency of superstructure and foundation system along with increase in amplification of response is observed with the increase in the vertical shear resistance of SPSP foundation joint while the total soil-SPSP foundation-superstructure (S-SPSP-S) system is subjected to dynamic ground motions. Such differences in response can be attributed to the increased stiffness of joint that contributes to the possible increase in the stiffness of the foundation system. When kinematic and inertial interactions for SPSP foundation system are considered independently, no significant influence of joint mechanical properties is observed. However, when the total system is considered, the change in joint shear capacity influences the response due to its complex resistance behavior in conjunction with superstructure load. The experimental results and discussions presented in this paper provides some valuable insight on the influence of SPSP joint shear resistance properties in solving soil-SPSP foundation-superstructure interaction problem. Furthermore, the presented EFIM and IFs can be employed in the sub-structuring method of soil-structure interaction to compute the structural and foundation responses.

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