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研究課題名（和文）	Impedance functions of an interlocking Steel Pipe Sheet Pile (SPSP) caisson foundation under nonlinear soil-structure interaction (SSI)
研究課題名（英文）	Impedance functions of an interlocking Steel Pipe Sheet Pile (SPSP) caisson foundation under nonlinear soil-structure interaction (SSI)

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研究成果の概要（和文）：地盤と構造物の動的相互作用の影響を考慮して、鋼管矢板井筒基礎の非線形動的応答を1g条件下でのモデル試験を通して研究を実施した。 本研究では、乾燥砂に埋め込まれた長さ960 mmの20本の中空円形アルミニウムパイプからなる円形1/16.5モデルを検討した。広範囲の振動数領域と載荷領域を対象に、有効入力動特性（KIF）および基礎天端位置での水平インピーダンス関数（hIFs）を求めた。本研究により、KIFとhIFsの両方が地盤の非線形性に強く依存していることを示している。 これらの結果は、地盤を弾性または粘弾性材料と見なす従来の仮定は、常に安全側の評価になるとは限らないことを示唆している。

研究成果の学術的意義や社会的意義

Though the use of Steel Pipe Sheet Pile (SPSP) foundations is on the rise in recent years, their dynamic characteristics are largely unknown. This work details such characteristics considering the effects of soil-structure interaction that are essential for the seismic analysis of SPSP foundations.

研究成果の概要（英文）：Nonlinear dynamic response of a Steel Pipe Sheet Pile (SPSP) foundation is studied through model testing under 1g conditions, accounting for the effects of soil-structure interactions (SSI). A circular 1/16.5 model SPSP foundation comprising of 20 hollow circular aluminum pipes (outer diameter = 30 mm and wall thickness = 2 mm) with lengths of 960 mm, embedded in dry cohesionless soil, was considered. Specifically, the kinematic and inertial responses of the foundation were obtained in the form of kinematic interaction factors (KIF) and head level horizontal impedance functions (hIFs) under a low-to-high level of dynamic loading for a broad range of frequencies. Results obtained through this work show that both the KIF and hIFs (essential components for SSI calculations) are dependent on soil nonlinearity. In the light of such, it can be inferred that the general methodologies that assumes soil as an elastic or visco-elastic material may not be conservative for the analysis and design.

研究分野： Earthquake Engineering, Soil-Structure Interaction

キーワード： SPSP foundation　Nonlinear behavior　SSI　Impedance functions　Kinematic interaction

１．研究開始当初の背景

Construction of large-scale bridge structures has seen an increase all over the world in response to the demand created by the need for infrastructures such as coastal highways, arterial highways, etc. These bridges demand large scale foundations with strong rigidity, large vertical bearing capacity, short construction period, etc. To meet such needs, Steel Pipe Sheet Pile (SPSP) foundations are often adopted in the various parts of the world (Nhật Tân bridge, Vietnam; 2nd Meghna bridge, Bangladesh, etc.). The SPSP foundation system comprises of two components - a) steel pipe and b) couplings welded on the sides of the steel pipe. The interlocking of the couplings links steel pipes to construct SPSP foundation and the interlocked couplings form the joints of SPSP foundation.

It is well know that under the action of external forces (e.g., earthquakes), responses of structure-foundation system and supporting soil are interdepended on each other; the influence of one’s response to the other is termed as soil-structure interaction (SSI). Various modern design codes require that such frequency dependent SSI effect be appropriately considered in the analysis and design of foundations and supporting structures. More to this, it is well established that the behavior of soil changes with the increase in the level of soil strain. Thus, besides being frequency dependent, SSI behavior is also dependent on the intensity of loading. Though a range of solutions is available in the literature on the topic of SSI for various type of foundations, only a limited number of literature is available when it comes to SPSP foundation systems. Moreover, although a substantial number of literature can be found on the horizontal impedance functions (hIFs) of spread footings and pile foundations, no reference data till date are available for the SPSP foundations. These hIFs are one of the essential components in obtaining the dynamic responses of a foundation and structure system considering SSI.

２．研究の目的

The main purpose of the carried out work was to obtain the frequency and intensity dependent dynamic response of SPSP foundation system. Specifically, the effective foundation input motion (EFIM) and in-turn the kinematic interaction factors (KIF), and the horizontal impedance functions (hIFs) of a SPSP foundation system embedded in cohesionless soil were targeted. The former relates to the kinematic response of the SPSP system while the latter relates to the inertial response. With these quantities known, the dynamic response of SPSP system and the supporting superstructure can be computed based on the commonly used sub-structuring technique for SSI.

３．研究の方法

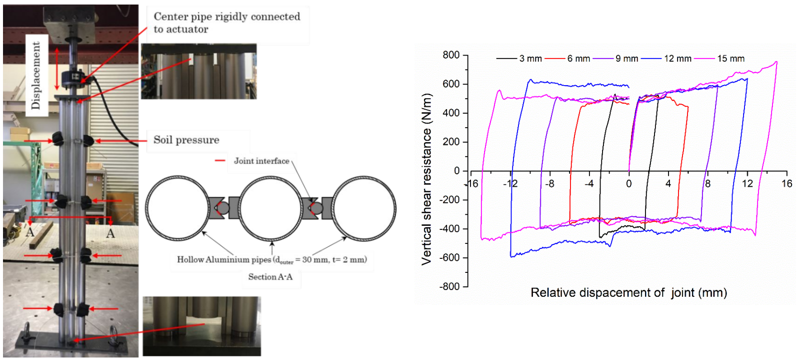
Physical scaled model testing under natural gravity condition (i.e., 1*g*) was employed in obtaining the frequency and intensity dependent effective foundation input motion (and in-turn the kinematic interaction factors) and horizontal impedance functions of a SPSP foundation system. A circular 1/16.5 scaled model of SPSP foundation comprising of 20 hollow circular aluminum pipes (outer diameter = 30 mm and wall thickness = 2 mm) with lengths of 960 mm and embedded in dry Gifu sand was considered. A shear box (1200 mm × 800 mm × 1000 mm) bolted on a uni-directional shaking table (1800 mm × 1800 mm) housed the soil-SPSP model where the base of the SPSP model was fixed rigidly at the base of the shear box, i.e., fixed tip conditions. With the consideration that SPSP foundations comprise of joints between the pipes, firstly, the vertical shear resistance of joints based on elemental testing (comprising of only 3 pipes) was obtained under static loading conditions. The soil-SPSP foundation model was prepared next and the model was excited at the base using the shaking table to obtain the effective foundation input motion (EFIM) and kinematic interaction factors (KIF); the top of the model was free. A broad range of loading amplitudes in the form of harmonic accelerations (0.5 – 5 m/s^2) for a wide range of loading frequencies (6 – 35 Hz) was employed to encompass both the intensity and frequency dependent responses. Finally, the same model of soil-SPSP model was excited at the head (without any base excitation) to obtain the horizontal impedance functions (hIFs) under the same range of loading amplitudes and frequencies; a low-level acceleration loading of 0.2 m/s^2 was also considered additionally.

４．研究成果

Results were obtained for the dynamic response of SPSP foundation system. Specifically – 1) vertical shear resistance of SPSP joint, 2) kinematic response of SPSP foundation, and 3) horizontal impedance functions at the head of SPSP foundation were obtained.

(1) Shear resistance of SPSP joints

The vertical shear resistance of the SPSP joint was estimated through an elemental model testing comprising of only 3 pipes where only the central pipe was allowed to undergo vertical



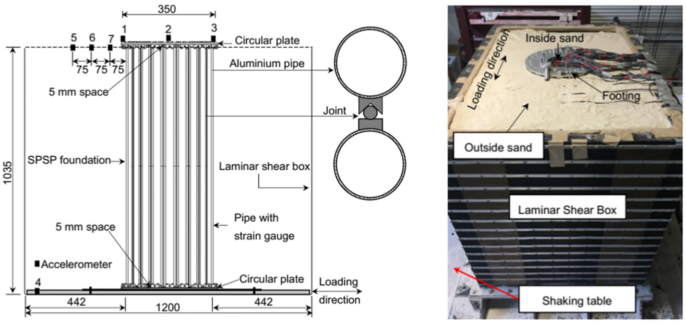
(a) elemental testing (b) vertical shear resistance

Figure 1: Response of SPSP joints

vibration, i.e., other two piles were constrained both at the head as well as at the base. The experimental layout of such system is shown in Figure 1a. The joint shear resistance was recorded for different amplitude of applied displacements at the head of the center pipe. Results were obtained in the form of resistance force per unit jointed length. Figure 1b shows the vertical shear resistance of joints; the results are comparable to the required design vertical shear resistance of the SPSP joints. Moreover, the obtained results show a good agreement with the results available in literature for the in-field tests on SPSP joint.

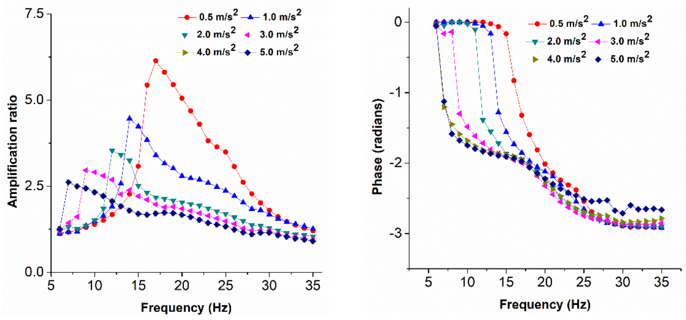
(2) Kinematic response

This experiment layout to obtain the kinematic response of SPSP foundation system is shown in Figure 2. The acceleration response at the top of the SPSP foundation is measured by the accelerometers as shown in Figure 2. The effective foundation input motion (EFIM) is estimated in the form of amplification ratio of motion at the top of the SPSP foundation with respect to the input motion applied at the base of the laminar shear box through shaking table. The corresponding phase difference between the motions were also estimated. These response quantities for all the input loading amplitudes are presented in Figure 3. It is apparent from the presented results that the resonant frequency and the maximum amplification ratio of the soil-SPSP foundation system decreases with the increase in the input loading amplitude. This decreasing trend of resonant frequency and maximum amplification ratio with the increasing loading amplitude is attributed to the decreasing stiffness of the soil-foundation system accompanied by the increase in soil's strain level due to the increasing loading amplitude.



(a) schematic (dimensions in mm) (b) experimental

Figure 2: Model setup for kinematic response



(a) amplification ratio (b) phase information

Figure 3: Effective foundation input motion (EFIM)

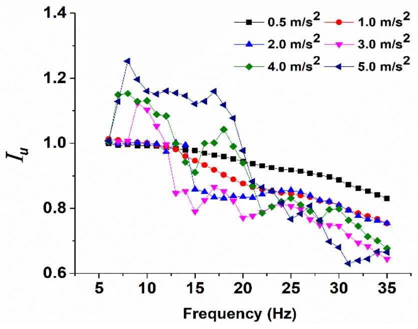


Figure 4: Kinematic interaction factors

The difference between the SPSP foundation's top response compared to the free-field soil response (response at the surface of soil) was obtained in the form of kinematic interaction factor (KIF), evaluated as the ratio of the foundation top motion to the soil surface motion. The KIF are presented in Figure 4. The results show that for lower amplitude of input excitation (0.5 - 2 m/s^2), the KIF are approximately equal to unity around the lower frequency region (up to resonant frequency of the soil-SPSP foundation system) while the KIF decrease (less than unity) in the higher frequency region above the resonant frequency showing the filtering of high frequency component of soil surface motion by the soil-SPSP kinematic interaction. However, for higher input loading amplitudes (3 - 5 m/s^2), the KIF values are found larger than unity for a number of frequencies particularly around the lower frequency region.

(3) Horizontal impedance functions (hIFs)

The experimental setup to measure the head-level horizontal impedance functions (hIFs) of the SPSP foundation is shown in Figure 5. The system uses the same experimental setup as that shown in Figure 2a, with addition of a loading plate rigidly fixed on the top of the foundation and the use of head loading using the horizontal actuator (±10 kN, ±150 mm). The frequency dependent complex-valued horizontal impedance functions (hIFs) are expressed as $K_f^* = k_f + iC_f$, where k_f and C_f are the real and imaginary parts of the hIFs, respectively. The real part represents the stiffness of the soil-SPSP foundation system, while the imaginary part represents the damping of the soil-SPSP foundation system. The real and imaginary parts of the hIFs are presented in Figure 6. The real part shows a decreasing trend in the stiffness with the increase in the loading amplitude throughout almost the entire frequency range; a clear indication of expected amplitude dependent soil behaviour. A significant drop in the value of stiffness is seen at the resonant frequency of the soil (e.g., at 19 Hz for 0.2 m/s^2). This is also expected considering that stiffness offered by soil at resonance becomes rather negligible. On the other hand, stiffnesses tend to increase for higher frequencies particularly above 30 Hz. This could be attributed to the anti-phase movement of the foundation, resulting in a larger reaction force even for a very small amount of displacmeent.

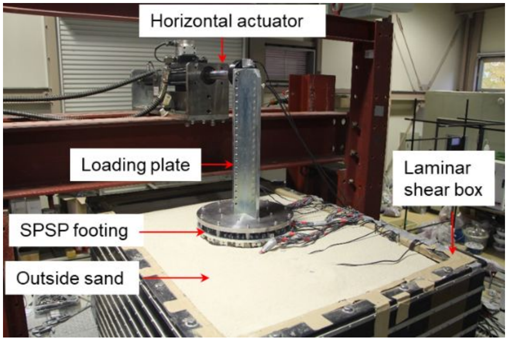
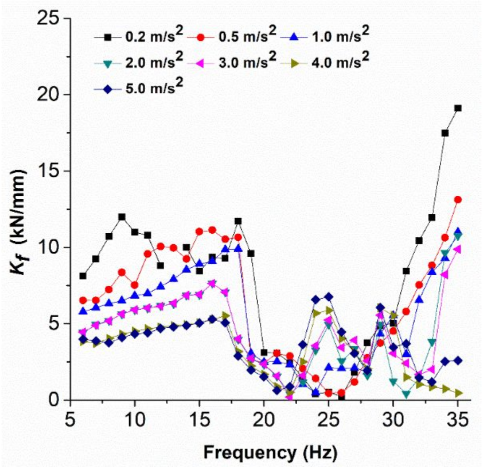
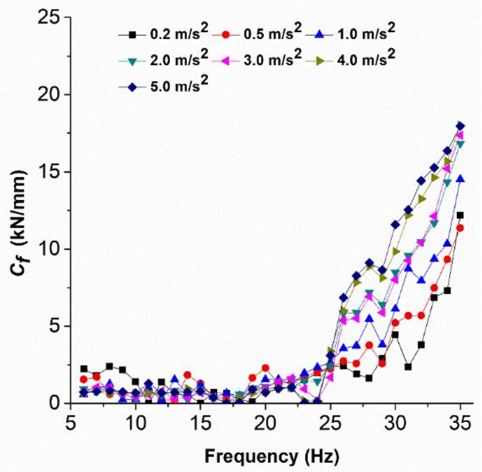


Figure 5: Setup for hIFs measurement



(a) Real part



(b) Imaginary part

Figure 6: Horizontal Impedance Functions

The imaginary part of the hIFs, on the other hand, shows an increasing trend with the increase in the loading amplitude, particularly for the higher frequency range (> 22 Hz). As the energy dissipation occurs in the form of radiaion damping post resonance frequency, the higher value of damping induced by the vibration of the soil-foundation at higher frequency range can be seen as an expected outcome. The imaginary part below the frequency of 22 Hz shows almost identical values of damping for all the loading amplitudes (however, a subtle degree of decrease is present for the lower amplitude of loading at the lower frequency range) reflecting the absence of significant radiation damping. In this region, only the hysteretic material damping (resulting from the degradation of shear modulus due to the increase in soil strain induced by loading amplitude) apparantly dominates the damping values.

Both the kinematic responses and the head level horizontal impedance functions of SPSP foundation show a significant dependency on the frequency and the intensity of loading. Considering linear approaches (i.e., soil is assumed to be elastic) in obtaining the dynamic response of SPSP foundations might not be a conservative approach. The curren work reflects on the fundamental dynamic behavior of SPSP foundation system that dominates the response characteristics of SPSP foundations and supporing structures.

５．主な発表論文等

〔雑誌論文〕（計　１件）

Ullah MS, Kajiwara K, Goit CS, Saitoh M (2019) Effective foundation input motion for soil-steel pipe sheet pile (SPSP) foundation system. In Proceeding of the International Conference on Computational & Experimental Engineering and Sciences, Peer Reviewed, March 25-28, Tokyo, Japan.

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