Journal of Current Research in Engineering and Science
JCRES
Bi-Annual Online Journal (ISSN : 2581 - 611X)
Volume 3- Issue 2, Paper 12, August 2020

MODELLING AND EXPERIMENTAL INVESTIGATIONS ON SOIL PILE STRUCTURE INTERACTION: A REVIEW

Subramanya K G [1]
Department of Civil Engineering
Govt. S K S J T Institute
Bangalore, India
mail2subbu.kg@gmail.com

Govindaraju L [2]
Department of Civil Engineering
University Visvesvaraya College of Engineering
Bangalore, India

Ramesh Babu R [3]
Central Power Research Institute
Bangalore, India

Abstract— *The response of structure to earthquake loading is an important parameter in analysis and Design. It is evident from the past earthquakes that the damage to the structure not only depends on the behavior of the superstructure but also on the foundation and sub-soil below it. Since then, many researchers have studied the behavior of the soil-pile-structure system subjected to dynamic loading. The model test has long been recognized as a valuable supplement to the usual theoretical methods of structural analysis and design. Model tests for dynamic analysis can be divided into those performed under 1-g commonly carried out with the use of shaking tables and those performed under increased gravitational fields which are usually performed in a geotechnical centrifuge. Model tests on soil require an infinite soil medium to be modeled with a finite boundary, this was achieved by confining the soil in a model soil container. Structural systems can be scaled to a manageable model and can obtain meaningful results. However, in the model-scale soil inducing prototypical stress distribution is not so straightforward. Therefore, one of the most useful laboratory tools for geotechnical use in these applications is the geotechnical centrifuge. Soil structure interaction of framed structure supported on piles, pile groups and piled raft foundation during earthquakes still remains a challenging task because of its complexity. Many researchers have carried out experimental investigations on the behavior of Soil pile structure systems under dynamic loading. An attempt has been made to compile the earlier research works on the experimental investigations.*

Keywords — Soil Structure Interaction, Similitude Analysis, Shake-table studies.

I. INTRODUCTION

In conventional analysis of any civil engineering structures the super structure is usually analyzed by treating it as independent from the foundation and soil medium on the assumption that no interaction takes place. This usually means that by providing fixity at the support structural analyst simplifies the problem. When a structure is built on soil some of the elements of the structure are in direct contact with the soil. When the loads are applied on the structure, internal forces are developed in both the structure and as well as in soil. This results in deformations of both the components (structure and soil) which need to be compatible at the interface as they cannot be independent of each other. Because of this mutual dependence, which is termed as interaction, the stress resultants in structure and, stresses and strains in soil are significantly altered during the course of loading. Therefore it becomes imperative to consider the structure-foundation and soil as components of a single system for analysis and design of the structure and its foundation. The analysis that treats structure foundation-soil as a single system is called as Soil Structure Interaction (SSI) analysis.

It is evident from the past earthquakes that the damage to the structure not only depends on the behavior of super structure but also on the foundation and sub-soil below it. Since then, many researchers have studied the behavior of the soil-pile-structure system subjected to dynamic loading. The behavior of pile foundations under Seismic loading is a very important factor affecting the performance of the superstructure. Piles in firm soils have generally performed well during past earthquakes, while piles in soft and liquefiable soils have been a cause of major concern. Several studies have been made on Soil Pile Structure Interaction to obtain more realistic response of the system when subjected to dynamic loading. Most of the investigations focus on theoretical study and analysis, while less has been done on experimental study. Most importantly theoretical outcomes have to be verified experimentally to achieve accuracy for practical use, however experimental investigations are rather difficult because of its complexity. This paper presents a review on the experimental investigations on soil pile structure Interaction.

II. Experimental Method

Engineers have turned to laboratory tests to study seismic building responses. It is always very difficult to analyze the prototype or full scale model in a laboratory. Hence testing the critical component of the structure with simulating the field conditions is usually done. In contrast to element tests, model tests usually attempt to reproduce the boundary conditions of a particular problem by subjecting a small-scale physical model(replica model) of a full-scale prototype structure. Model tests for dynamic analysis can be divided into those performed under the gravitational field of the earth (1g model tests) commonly carried out with the use of shaking tables and those performed under increased gravitational fields which are usually performed in a geotechnical centrifuge. Shaking tables are now routinely used for analysis of structural responses to ground motions but the laboratory approach to geotechnical-focused problems presents challenges. Model tests on soil requires an infinite soil medium to be modeled with a finite boundary, this was achieved by confining the soil in a model soil container. Structural systems can be scaled to a manageable model and can obtain meaningful results. However, in the model-scale soil inducing prototypical stress distribution is not so straightforward. Therefore, one of the most useful laboratory tools for geotechnical use in these applications is the geotechnical centrifuge. Applying a centrifugal force may be thought of as applying gravitational force in excess of the gravitation on earth. By scaling gravity other parameters also get affected; they are scaled according laws of similitude. The stresses induced in the centrifuge model will scale so as to match the stresses expected for the larger model at a standard gravitational state. Both shaking table and centrifuge model tests share certain drawbacks, among the most important of which are similitude and boundary effects.

III. Similitude Analysis

Similitude analysis is a mathematical framework which relates the quantities that are measured in scaled model to the prototype. Depending on the degree to which the scaled models meet the requirements of similitude, the models are classified as True, adequate and distorted models (Harris and Sabnis (2000)[8]. The true model satisfies all the requirement of similitude. In an adequate model, the first order (controlling) parameters maintain similarity while those which the second order parameters are allowed to deviate. The second order parameters are those that do not affect the prediction significantly. The selection of first order and second order parameters is dependant on the problem being investigated. Distorted model is one in which one or more first order parameters in the similitude analysis deviate. Several researchers like Wood et al. (2002)[26], Kagava (1978)[10], Harris and Sabnis (2000)[8] have given different similitude relations for different type of experimental investigations. Table No.1 gives the similitude scale factors for earthquake response of structures.

Parameter	Scaling Relationship
Mass density	1
Force	S^3
Modulus	S
Acceleration	1
Time	$S^{1/2}$
Frequency	$S^{-1/2}$
Length	S
Stress	E
Strain	1
EI	S^5

Table 1 Summary of Similitude Factors for Earthquake Response of Structures[9]

The reliability of the model depends on whether the model can represent the realistic behavior of the prototype or not. In all the experimental investigations similitude analysis should be taken in to account. Meymand (1998)[17] and moss et al. (2010)[18] have explained that no similitude theory can be directly applied to the complete system of soil and structure to achieve complete model similarity. Hence it can be inferred that in most of the similitude analysis on soil structure interaction, it is difficult to achieve a true model. In similitude analysis on soil structure interaction, the similitude of superstructure and substructure is generally taken into account. However, the similitude for soil is often ignored or not accounted for completely due to its complexity.

Scaled models for soil structure interaction studies are usually done with different material than that of the prototype. H.Suzuki et al.(2008)[20], Y Adachi et al.(2008)[1] and many others have modeled the reinforced concrete prototype with steel. Goit et al. (2008)[7] modeled the super structure with steel and substructure with acrylic material. A constant scaling factor is to be maintained for the materials to be used for modeling superstructure, substructure and soil. Most of the investigations material used for the model is not the same as that of the prototype, which conflicts the true replica of the model as it does not satisfy the similitude factor. Lu et al(2004)[16] presented similitude formula considering same similitude relation for soil, foundation and superstructure.

Similar to that of structure model piles should also be subjected scaling criteria, to achieve this principal govenrnig factors like slenderness ratio (l/d), flexural stiffness (EI), mo- ment curvatrure relationship and natural frequency of vibration should be addressed (Meymand 1998)[17]. Based on the L/D ratio and flexural stiffness factor of (scaling factor)5 the diameter, material and section of the pile needs to be selected. Previous researches have used different types of material like aluminum tubes, steel bars, concrete and acrylic material[9]. The similitude factor for shear wave velocity of the soil has to be satisfied between the prototype and the model during the shake table test. Aslan et al. (2015)[9] and Syed Hamid et al.(2012)[21] have designed a synthetic clay mix in order to meet the scale model criteria for shear wave velocity with adequate bearing capacity.

Journal of Current Research in Engineering and Science
Bi-Annual Online Journal (ISSN : 2581 - 611X)
Volume 3- Issue 2, Paper 12, August 2020

IV. Model Soil Container for SSI

Model tests on soil requires an infinite soil medium to be modeled with a finite boundary, however the confining effect as in continuous medium needs to be incorporated in the soil model. This is achieved by confining the soil in a model container. Initially researchers conducted experiments using rigid soil container. The drawback of the rigid soil container is that the wave reflections from side walls which otherwise radiate away in prototype problem can result in P-waves generation due to the artificial boundary. Whitman and Lambe (1986)[25] and Fishman et al. [6] conducted a numerical study and reported that zones up to 1.5 to 2 times the height of the container close to end walls are affected by artificial boundary. S Bhattacharya et al. (2015)[14] suggested that the ratio of the length to height of the container should be more than 4 in order to minimize the artificial boundary effect. To overcome the drawbacks of the rigid container, several researchers have studied and proposed alternatives or modifications to the rigid container. Bhattacharya et al. (2015)[14] used a rigid container with flexible boundary in order to limit reflection of waves from rigid boundary. The flexible boundary is introduced by gluing a soft material like sponge along the end walls of the container Fishman et al. (1995)[6] and Dash(2010)[3] have used other types of soil container like rigid containers with hinged end walls. The end walls were permitted to rotate about the base to minimize boundary effect.

Many researchers have used laminar container which commonly consists of stack of laminae supported individually by bearings and a steel guide connected to an external frame. The laminar box is designed for the required lateral stiffness. The complete design of rectangular laminar container is discussed by Alson(2015)[9] while Meymand(2000)[17] and few others have used circular laminar container. Lou et al (1999) suggested that the width of the container should be at least five times the width of the model to minimize boundary effect. Fig.1 shows the different types of soil containers.

V. Experimental Investigations on Soil Pile Structure Interaction

Several researchers have conducted analytical investigations of soil foundation structure interaction, concluded and accepted that the behavior of structure get altered considering flexibility of the foundation and soil. The structure with pile and raft foundations will have greater influence of SSI on the response of the system subjected to dynamic loading. Hence the experimental investigations on pile, raft and piled raft is carried out by several researchers. In this section of the paper, the discussion is limited to only soil pile structure interaction. Centrifuge tests were conducted by lombardi et al. (2013)[13] designed in level ground to avoid the effects of lateral spreading and the main aim was to study the effect of axial load as soil liquefies. The failure mode observed in the tests was similar to those observed in the field in laterally spreading soil. It is concluded in his thesis that it is not necessary to invoke lateral spreading of the soil to cause a pile to collapse, the pile may even collapse before lateral spreading starts. The key parameter identified to distinguish whether buckling is a likely failure mechanism is the slenderness ratio of the pile in the liquefiable region. The critical value of this parameter is approximately 50. Author highlights that the current codes of practice for pile design omit considerations necessary to avoid buckling of fully embedded piles in liquefiable soils. Author has proposed a design method taking into consideration the buckling effect. Many of the structures designed based on the current codes of practice may be unsafe and may need retrofitting. Liang Tang et al.(2009)[22], H Suzuki et al.(2008)[20],Goit et al. (2008)[7], have conducted shake table tests on soil pile interaction with superstructure modeled as a lumped mass with columns which represents similitude frequency of the prototype. All these authors have considered

Liquefaction in their study.

Goit et al (2008)[7] with scaled model of structure in steel resting on 3X3 pile groups embedded in liquefiable soil with two end conditions - end bearing and floating. The study concludes that the centre pile shows the least bending strain in both end conditions. The study also concludes that the radiation damping provided by floating pile is higher than end bearing pile. A similar study conducted by H Suzuki et al. have conducted shake table test but under two dimensional shaking with two different ground motions recorded at kobe in 1995 and Akasaki in 2000. Super structure resting on 3X3 pile groups is scaled and modeled in steel. The pile is embedded in liquefiable soil. Author concludes that the bending strain is high in leading pile and lowest in the following pile and the state of stress in soil around the pile is completely different in liquefied and non-liquefied state.

Whereas the Tang et al. (2009)[22] address the low cap pile group and elevated cap pile group in liquefiable soil. Shake table test was performed with laminar shear box excited with El Centro earthquake, it shows that the seismic performance of low cap pile group is better than that of elevated cap pile group in liquefiable soil. The acceleration of the pier top on low cap pile decreased as the ground liquefied completely.

Dihoru et al. (2009)[4] conducted a series of 1-g shake table experiments to clarify certain aspects of kinematic and inertial interaction affects. Pile was placed in layered deposit and the stiffness of the layers were varied and tested for different earthquake loading. Results of the experiment show that soil pile kinematic interaction is strongly influenced by soil configuration. Pile end conditions and the presence of the superstructure change the pattern of the bending moment in pile. Peizhen li et al. (2008)[11] conducted shaking table test with a similitude factor of 10.pile group in layered soil the model structure supported on pile group embedded in top layer clay and bottom layer of saturated sand.

Lei SU et al (2014)[23] conducted a shake table investigation for RCC pile group in two layered liquefiable soil. Study concludes acceleration response of the medium dense and dense sand stratum gradually attenuated but did not vanish after liquefaction. Pile bending moment in liquefied dense sand stratum is larger than medium dense sand stratum. Tang et al. (2008)[22] conducted a test on single pile embedded in layered soil with saturated sand sandwiched between soft clay layers. It was observed that there was a little pore water pressure difference of the sand near the pile and far away from the pile. The pile had a elastic dynamic deformation with strain increased from top to bottom of the pile, the strain peak in sand was much greater than upper clay layer.

Adachi et al. (2006)[1] conducted a full scale model test on pile group for lateral and dynamic loading. The study aimed to increase the stiffness of the pile foundation by ground solidification technique. The reinforcement body was constructed by ground solidification treatment to bind the pile group at its middle length, so that together with the footing they form a 2-layer structure, the restraining effect of which enhances the pile foundation rigidity. The vibration test shows that the reduction in horizontal displacement by 20-30% and 30-40% in vertical displacement corresponding to excitation in those directions. The investigations after the vibration test showed that the reinforcement was well adhered to the piles. Elgamal et al. (2006)[5], Motamed et al. (2008)[19] and Yasuda et al.(2000)[27] studied pile foundation in liquefiable soil without superstructure. Susuma Yasuda et al. conducted large scale shake table test with level ground and sloping ground. The tests show that the dynamic response of the pile was affected by connection between footing and pile. Piles with rigid connections were damaged at both top and bottom while pinned piles were damaged at bottom only during liquefaction. Liquefaction in the sloping ground were associated with ground flow, causing cracks and bending in pile. Ramin Motamed et al. (2008)[19] also conducted similar studies with sloping ground and concludes that lateral force distribution is carried by upstream and downstream row than middle row piles.

Wada et al. (2001)[24] attempted a different type of test on soil pile structure interaction with short stiff piles to take lateral force due to earthquake and long flexible piles to support the gravity load. The modeling of soil is done with the help of mechanical springs at regular interval like a Winkler model. The study concludes the capacity of the short piles to absorb the additive energy decreases the bending in long piles and reduces the input earthquake input to the super structure. The experiment setup was proposed as a verification method. Aslan et al. (2014)[9] , Li et al. (2012)[12] and Xilin Lu et al. (2002)[15] carried out scaled model test for superstructure on pile group embedded in clay. Aslan et al. (2014)[9] experimented three models with different height of superstructure and concludes that lateral deflections were amplified in comparison with fixed base analysis. Increase in lateral deflection also increases inter storey drift which causes performance level near to collapse and Xilin Lu et al. (2002) their study says that SSI influences frequency and damping ratio of the system. It is observer in the study that soft soil can filter and isolate vibration. The strain amplitude along the length of the pile is large at the top and least at the tip. Vertical excitations have little effect on the response of the dynamic soil structure Interaction. Li et al. (2012)[12] conducted two shake table test one with single model of soil pile structure system and other considering two adjacent structure in SSI. The author concludes that the adjacent structures would damage seriously than the single one. Structure Soil Structure Interaction(SSSI) have some influence on soil frequency and damping butt less influence on frequency and characteristics of modes of vibration. Peak accelerations of the soil between piles is larger in SSSI system then SSI system.

A series of 1-g shaking table tests was performed by choi et al. [2] using a pile-soil model to verify the existing similitude law used in 1-g shaking table tests. Modeling of the model technique was used for three different sizes of the model, manufactured according to Iai's similitude law, and tests were carried out while varying input parameters, such as input frequency and input ground acceleration. Evaluation of the accuracy of Iai's scaling factor of a frequency showed that the maximum error in the converted frequency could be within 17%, 35% and 55% when the scaling factor is 2, 5 and 20, respectively. Combining the error occurring in the estimation of frequency, with the possible error occurring in the test results, the maximum error was found to be less than 9%, 21% and 59% when the scaling factor was 2, 5, and 20, respectively, when the frequency ratios in the model tests were smaller than 0.6. Therefore, it has been concluded that the 1-g shaking model test, based on Iai's similitude law, can be used on a quantitative basis to predict the dynamic behavior of a pile foundation.

VI. SUMMARY

Experimental investigations play important role in validating the theoretical analysis and also gives an insight into the actual behavior of the soil structure foundation system. The accuracy of response of the SPS system depends on the degree similarity achieved in the model. It is observed that SSI influences frequency and damping ratio of the system and the lateral deflection of the structure are amplified in comparison with fixed base response. It is reported that the bending strain in the centre pile of a group is least but under flow due to liquefaction bending strain is highest in leading pile than in follower pile. Limited studies on layered soil say that kinematic interaction is strongly influenced by soil configuration. A pile connections and end conditions determines the pattern of bending in pile. Researchers have also

Journal of Current Research in Engineering and Science
Bi-Annual Online Journal (ISSN : 2581 - 611X)
Volume 3- Issue 2, Paper 12, August 2020

tested the influence of earthquake resistant technique along with Soil pile Structure Interaction.

REFERENCES

[1] Y Adachi, K Urano, M Mihara, M Kawamura, and S Futagawa. Full-scale model test for earthquake-resistance reinforcement of pile foundation using ground solidification body.

[2] Jung-In Choi, Min-Taek Yoo, Eui-Kyu Yang, Jin-Tae Han, and Myoung- Mo Kim. Evaluation of 1-g similitude law in predicting behavior of a pile-soil model. Marine Georesources & Geotechnology, 33(3):202–211, 2015.

[3] Suresh R Dash, Subhamoy Bhattacharya, and Anthony Blakeborough. Bending–buckling interaction as a failure mechanism of piles in liquefi- able soils. Soil Dynamics and Earthquake Engineering, 30(1-2):32–39, 2010.

[4] L Dihoru, S Bhattacharya, CA Taylor, D Muir Wood, F Moccia, AL Simonelli, and G Mylonakis. Experimental modeling of kinematic bending moments of piles in layered soils. Interface, 1:h2, 2009.

[5] Ahmed Elgamal, Liangcai He, Jinchi Lu, Akio Abe, Tarek Abdoun, Ricardo Dobry, Masayoshi Sato, Kohji Tokimatsu, and Thomas Shantz. Liquefaction-induced lateral load on piles. In Fourth international conference on earthquake engineering, 2006.

[6] KL Fishman, JB Mander, and R Richards Jr. Laboratory study of seismic free-field response of sand. Soil Dynamics and Earthquake Engineering, 14(1):33–43, 1995.

[7] CS Goit, M Saitoh, H Kawakami, and S Nishiyama. Experimental studies on non-linear response of soil-pile-structure systems subjected to strong ground motion. In The 14th World Conference on Earthquake Engineering, 2008.

[8] Sabnis G M Harris H G. Structural modeling and experimental techniques. 2nd edition, Boca Raton, CRC Press, 2000.

[9] Aslan S Hokmabadi, Behzad Fatahi, and Bijan Samali. Physical modeling of seismic soil-pile-structure interaction for buildings on soft soils. International Journal of Geomechanics, 15(2):04014046, 2015.

[10] Takaaki KAGAWA. On the similitude in model vibration tests of earth- structures. In Proceedings of the Japan Society of Civil Engineers, volume 1978, pages 69–77. Japan Society of Civil Engineers, 1978.

[11] Peizhen LI, Hongmei REN, Xilin LU, and Lei CHENG. Shaking table test on free field considering soil liquefaction [j]. Journal of Earthquake Engineering and Engineering Vibration, 2, 2008.

[12] PZ Li, XY Hou, YM Liu, and XL Lu. Shaking table model tests on dynamic structure-soil-structure interaction during various excitations. In Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, pages 23–28, 2012.

[13] Domenico Lombardi and Subhamoy Bhattacharya. Modal analysis of pile-supported structures during seismic liquefaction. Earthquake Engineering & Structural Dynamics, 43(1):119–138, 2014.

[14] Domenico Lombardi, Subhamoy Bhattacharya, Fabrizio Scarpa, and Matteo Bianchi. Dynamic response of a geotechnical rigid model container with absorbing boundaries. Soil Dynamics and Earthquake Engineering, 69:46–56, 2015.

[15] Xilin Lu, Yueqing Chen, Bo Chen, and Peizhen Li. Shaking table model test on the dynamic soil-structure interaction system. Journal of Asian Architecture and Building Engineering, 1(1):55–64, 2002.

[16] Xilin Lu, Peizhen Li, Yueqing Chen, and Bo Chen. Shaking table model testing on dynamic soil-structure interaction system. In Proc., 13th World Conf. on Earthquake Eng, 2004.

[17] Philip James Meymand. Shaking table scale model tests of nonlinear soil-pile-superstructure interaction in soft clay. 1998.

[18] Robb Eric S Moss, Vic Crosariol, and Steven Kuo. Shake table testing to quantify seismic soil-structure-interaction of underground structures. 2010.

[19] Ramin Motamed, Vlatko Sesov, and Ikuo Towhata. Shaking model tests on behavior of group piles undergoing lateral flow of liquefied subsoil. In The 14 th World Conference on Earthquake Engineering, Beijing, China, 2008.

[20] H Suzuki, K Tokimatsu, M Sato, and K Tabata. Soil-pile-structure interaction in liquefiable ground through multi-dimensional shaking table tests using e-defense facility. In 14th World Conference on Earthquake Engineering, Beijing, China, number 0177, 2008.

[21] Sayed Hamid Reza Tabatabaiefar. Determining seismic response of mid- rise building frames considering dynamic soil-structure interaction. PhD thesis, 2012.

[22] Liang Tang, Xianzhang Ling, Pengju Xu, Xia Gao, and Liquan Wu. Case studies for shaking table tests on seismic soil-pile group-bridge structure interaction in liquefiable ground. In ICCTP 2009: Critical Issues In Transportation Systems Planning, Development, and Management, pages 1–8. 2009.

[23] Liang Tang, Xiaoyu Zhang, Xianzhang Ling, Lei Su, and Chunhui Liu. Response of a pile group behind quay wall to liquefaction-induced lateral spreading: a shake-table investigation. Earthquake Engineering and Engineering Vibration, 13(4):741–749, 2014.

[24] A Wada, S Yamada, K Kobayashi, and H Inagaki. Shaking table tests for interaction of soil and structure on short-stiff-piles and long-flexible- piles. In Proc. 15th AIMETA Congress of Theoretical and Applied Mechanics, Taormina, Italy, volume 2001, 2001.

[25] Robert V Whitman and Philip C Lambe. Effect of boundary conditions upon centrifuge experiments using ground motion simulation. Geotech- nical Testing Journal, 9(2):61–71, 1986.

[26] David Muir Wood, Adam Crewe, and Colin Taylor. Shaking table testing of geotechnical models. International Journal of Physical Modelling in Geotechnics, 2(1):01–13, 2002.

[27] Susumu Yasuda, Kenji Ishihara, Iwao Morimoto, Rolando Orense, Masatoshi Ikeda, and Shuji Tamura. Large-scale shaking table tests on pile foundations in liquefied ground. In Proc., 12th World Conf. on Earthquake Engineering. Citeseer, 2000.