Numerical Analysis of Seismic Response of a Piled Raft Foundation System

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ABSTRACT :Piled raft foundation is gaining popularity as a composite foundation system economizing foundation design for tall, heavy structures. The seismic response of a piled-raft foundation would involve complex raft-soil-pile interaction as well as pile-soil-pile interaction, which cannot be estimated efficiently by existing methods available for pile groups. This paper discusses the development of a numerical model to study the seismic response of piled raft foundation system by sub-structure method based seismic soil structure interaction (SSSI) analysis using SASSI 2010 program. The flexible volume substructure method is used to analyze SSSI problem. Published data from a centrifuge test to study earthquake response of a piled raft system in soft clay was selected for the simulation. Results from the analysis are compared with experimental data.

Keywords: Soil structure interaction, piled raft, sub structure method, flexible volume method, SASSI

1 Introduction

The concept of a piled-raft foundation that shares load between raft and pile is not new. Several papers published during the 1970's threw light onto the behavior and analysis of piled raft (PR) systems. Over the years, the use of piled raft foundation systems for buildings has gained popularity owing to an increase in the availability of case histories and guidelines. In regions where seismic activity is high, the design of any foundation system has to be done keeping in mind the seismic response characteristics. Ignoring soil structure interaction effects could potentially lead to unsafe design or even may cause failure. For composite foundation systems like the piled-raft particularly founded in multi layered soil system, dynamic analysis cannot be done by simple analytical techniques. However, a seismic response analysis requires the use of numerical tools like the finite element or finite difference methods for reliable results. This study aims to develop a 3D model to estimate the seismic response of a piled-raft system considering both inertial and kinematic interaction.

2 Literature Review

Several methods of static analysis of PR foundation systems have been published in literature. Soil structure interaction becomes significant for heavy structures, which may significantly interact with the ground. Hence the practice of using ground surface acceleration for seismic analysis cannot be deemed safe. Research on horizontal/seismic loads on piled rafts is limited. In comparison to pile groups, piled rafts usually have lesser number piles. This can result in higher loads on piles, under seismic loading compared to a pile group. To better understand the performance of piled rafts under seismic loading, several researchers including Yuksekol et al.(2015) have performed 1g shake table tests. They observed an increase in horizontal load resistance and the influence of vertical displacement due to horizontal loads on the vertical resistance of piles.

Centrifuge studies to evaluate seismic response of piled rafts was carried out by Sawada and Takemura (2014) and Horikoshi et al.(2002). They observed settlement of the piled raft during horizontal loading and shaking table tests, as well as reduction in raft resistance to horizontal load compared to a raft alone. Banerjee (2009) investigated the response of piled raft in soft clay subjected to seismic excitation. The piles used were of short nature, and the finding suggests that surrounding soil imposed an inertia load to the piled raft structure, thereby lengthening its resonance period. The 3D numerical simulation performed by the author could replicate the centrifuge model reasonably well.

Seismic response of a single degree of freedom superstructure on an idealized piled raft foundation was studied by Saha et al. (2015) using a simplified numerical model involving Winkler foundation concept. Mayoral et al. (2009) compared actual seismic response of an urban bridge support system on soft clay with computed results using SASSI 2000 program by flexible volume method.

A review of literature suggest that there is limited understanding of the seismic behavior of piled raft foundation systems. Given the capabilities of modern computational facilities, it is feasible to study the seismic response of piled-raft systems using numerical simulations. The present study was aimed at developing a numerical model for a substructure based seismic analysis of a piled raft foundation system using SASSI 2010.

3 Details of Piled Raft System

Experimental data from the centrifuge study on seismic response of a piled raft foundation in system, in soft clay by Banerjee (2009) was chosen for the numerical simulation. The PR foundation considered for modelling in the present study has a raft dimension of 12.5mx7.5mx0.5m, and four piles with diameter 0.9m and length of 13m. These prototype dimensions were modelled in the centrifuge test using a rigid steel plate of 25cmx15cmx1cm and the four solid steel piles of 1.8cm diameter and 26 cm long with the test being performed at 50g. The vertical load applied on the raft in prototype scale, would be 605 tonnes.

4 Flexible Volume Substructure Method

The flexible volume sub-structuring method is based on the concept of partitioning the total soil structure system into three substructures (SASSI 2010) as presented in Fig. 1.The first sub-structure consists of free field site, second substructure consists of excavated soil volume, and third sub-structure consists of structure, of which the foundation represents excavated soil volume.

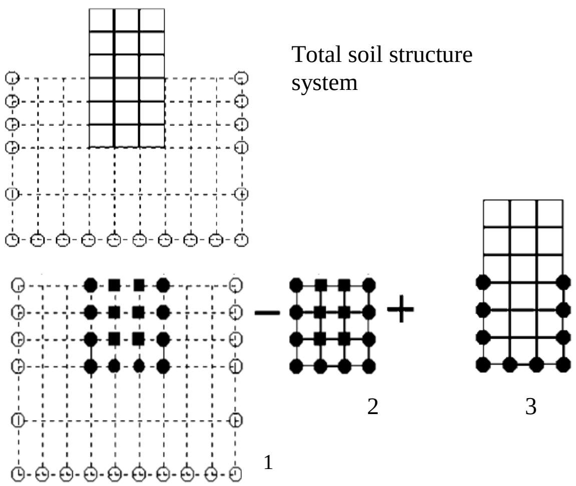


Fig. 1: Sub-structuring in the flexible volume method (Ostadan and Deng, 2010)

The three substructures together form the soil structure interaction system. The flexible volume method considers interaction between free field site and excavated soil volume at the boundary as well as within the excavated soil volume. The sub-structuring in the SASSI code is formulated using the complex response method and finite element technique. Free field soil is modelled using horizontal layers of viscoelastic material, resting on a viscoelastic half space. Both horizontal layering and viscoelastic material property are inherent limitations of the SASSI code. It should also be noted that analysis in frequency domain is several times faster than an analysis using the direct method.

5 Description of Numerical Model

5.1 Foundation

The raft is modelled using 4 noded brick elements with stiffness property similar to that of steel used in the experiment. Material properties of structural elements used in the analysis for the PR system is presented in Table 1.The load of 605tonnes was applied uniformly on the top surface of the raft. There are several techniques of modelling piles including the use of beam elements, volume elements and inter-pile elements available in the SASSI finite element library. Beams could be used for modelling piles owing to their flexural characteristics, however due to their inability to simulate actual soil resistance the model is predicted to be less accurate. Nakaia et al. (2004) suggests that beam elements modelling underestimates impedance functions and over estimates foundation input motions.

Table 1: Material properties used for structural elements

Component	Modulus of Elasticity (GPa)	Poisson's Ratio	Unit Weight (kN/m^3)
Raft	32.0	0.25	78.5
Pile	32.0	0.25	78.5

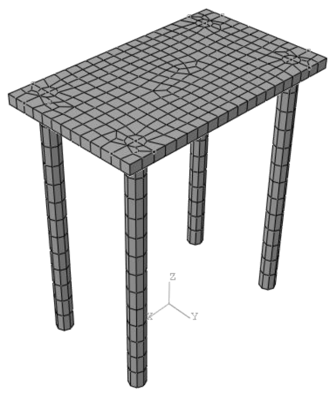


Figure 2: Finite element mesh of the piled raft foundation

In the present study, piles in the piled raft system were modelled using brick elements. Flexural rigidity of the prototype pile dimension is 10308351 kN-m^2 (Banerjee, 2009). The modulus of elasticity of pile was then back calculated using the flexural rigidity and moment of inertia of the pile section. Fig. 2 shows the finite element mesh of the piled raft system with both raft piles modelled using four noded brick elements. The total number of interacting nodes in the model was 1550.

5.2 Soil Properties

The modelling of sol layers using viscoelastic layers makes it a linear model, which cannot predict the cyclic changes in dynamic soil properties. In order to account for modulus reduction and damping increase, due to shear strain developed as the shear wave propagates, an equivalent linear ground response analysis is first performed using the program SHAKE 2010.The soft kaolin clay used in the laminar shear box for the centrifuge test, had a bulk unit weight of 16kN/m^3, water content of 66%, liquid limit of 80% and plastic limit of 35%.Initial modulus and damping values is taken from the results of dynamic tests on the kaolin clay as reported in Banerjee (2009). The variation of G_{max} with depth (or mean effective stress,p') was calculated based on equation (1), suggested by Banerjee, 2009. The resulting s-wave velocity, V_s, p-wave velocity, V_p and damping ratio, ξ for each layer are then used in the SASSI analysis.

$$G_{max} = 2060p'^{0.653} \quad (1)$$

Table 2: Dynamic soil properties used in the analysis

Layer no.	Thickness (m)	V_s (m/s)	V_p (m/s)	ξ
1	0.5	45.71	76.56	0.001
2	1	64.53	108.08	0.006
3	1	75.30	126.12	0.009
4	1	83.53	139.90	0.011
5	1	90.19	151.06	0.012
6	1	95.83	160.50	0.013
7	1	100.84	168.89	0.013
8	1	105.40	176.53	0.013
9	1	109.60	183.56	0.014
10	1	113.51	190.11	0.014
11	1	117.19	196.28	0.014
12	1	120.68	202.12	0.014
13	1	124.00	207.68	0.014
14	1	127.17	212.99	0.014
15	0.5	124.94	201.86	0.056

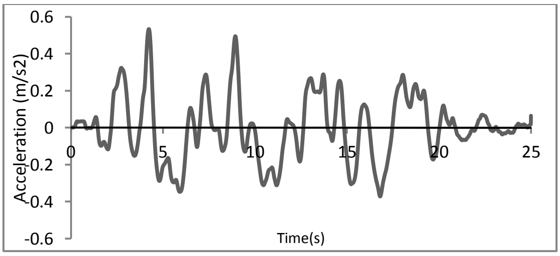
The dynamic soil properties obtained from ground response analysis for the earthquake motion is presented in Table 2. In short, non-linearity of soil is accounted for, partially by using soil properties that that will result after a seismic event. A total of 15 soil layers were defined in addition to the half-space below the 15th layer. Viscous boundary developed by Lysmer and Kuhlemeyer (1969) is used in the SASSI program.

5.3 Input Motion

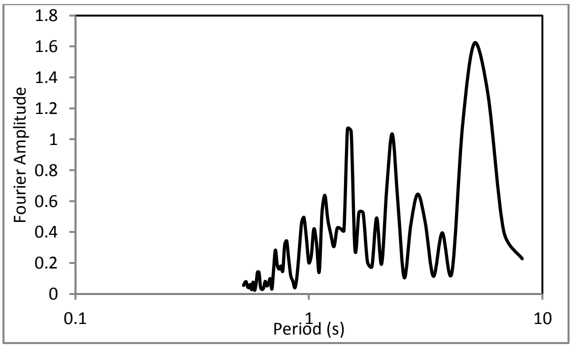
The earthquake motion used in the centrifuge test as reported in Banerjee (2009) was used in the present study. The time history of acceleration was synthetically developed using typical response spectra of Sumatran earthquakes measured at rock sites in Singapore. The input motion time history with peak ground acceleration (PGA) of 0.053g is presented in Fig 3(a) along with its Fourier spectrum in Fig. 3(b). The earthquake has typical characteristics of far field events including long periods and long durations.

6 Results and Discussion

The results extracted from the program after analysis presented in this paper includes time history acceleration and response spectrum at the top of raft. The time history of acceleration obtained at the top of raft, along with time history obtained from the centrifuge test and presented in Fig. 4. The peak acceleration value recorded at the top of raft in the centrifuge test was 0.69 m/s^2 while the simulation produced a peak acceleration of 0.57 m/s^2.



(a)



(b)

Fig. 3: (a) Time history of acceleration and (b) Fourier amplitude spectrum of input motion

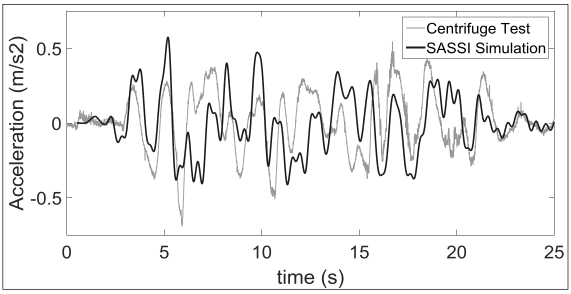


Fig.4: Comparison of time histories of acceleration at top of raft for second earthquake

Fourier spectra of acceleration recorded at the top of raft from both experiment and the simulation is presented in Fig. 5. The simulation has been able to reproduce most of the predominant frequencies, however with some variation in Fourier amplitude. It is observed from the Fourier spectra that in the simulation the amplitude is de-amplified by about 10% to 20% at the range of period from 2s to 3s whereas at a period of around 5s the amplification is about 23%. Response spectra obtained at the top of raft, from both experiment and simulation is presented in Fig. 6. For the simulation, the highest peak spectral acceleration is observed near a period of 1.46s, which is close to the peak from centrifuge test.

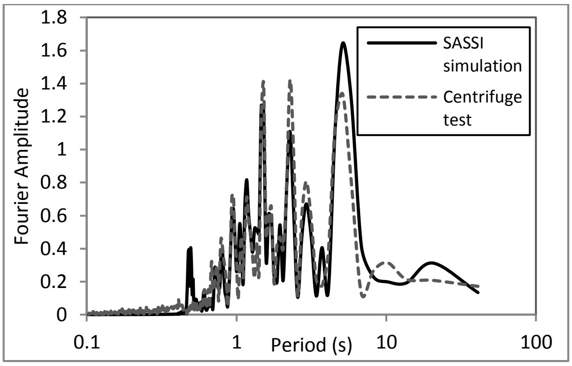


Fig.5: Fourier spectra of acceleration at the top of raft

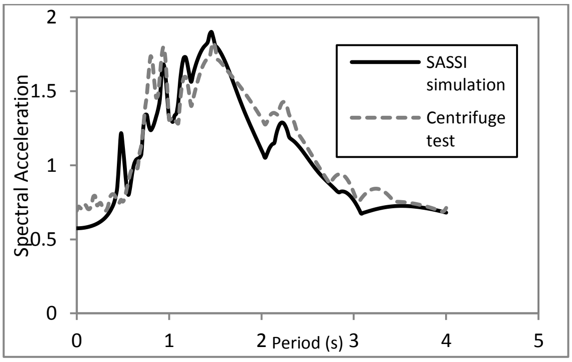


Fig.6: Response spectra at the top of raft

7 Conclusion

A model to study seismic response of piled raft foundation is developed in the substructure based soil structure interaction program SASSI 2010. Published data from a dynamic centrifuge test on a piled raft system in soft clay subjected to an earthquake excitation was selected for the simulation. A pile raft foundation system with four piles, in homogeneous soft clay was subjected to earthquake excitation, and its behavior was studied. Degraded soil properties from a one dimensional ground response analysis were used in the SSSI analysis. The results in terms of time history of acceleration, Fourier spectrum and response spectrum are compared with data from the centrifuge test. The simulation was found to be in reasonable agreement with measured data. The applicability of the model needs to be further verified by analysis using different input motions.

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