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http://publisher.uthm.edu.my/ojs/index.php/emait
e-ISSN : 2773-5540

Emerging Advances in Integrated Technology

Numerical and Experimental Analysis of Seismic Soil Pile Structure Interaction

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DOI: https://doi.org/10.30880/emait.2021.03.02.001
Received 16 October 2022; Accepted 22 December 2022; Available online 31 December 2022

Abstract: The fundamental design of the piles is finished by static analysis, but particularly in seismically dynamic locales, the last configuration requires dynamic study. Dynamic soil-pile-structure interaction analyses require the stress-strain conduct of soils under dynamic loading conditions. The material nonlinearity can be addressed by comparable linear or completely nonlinear strategies. The correlation of these methodologies in the free-field site reaction analyses has been concentrated in recent years. In any case, the impacts on the soil-pile-structure interaction analyses have not been illustrated. In this study, a well-known centrifuge test was demonstrated and analyzed in the frequency domain (ACS SASSI) and in the time-domain (FLAC 3D) for equivalent-linear and fully nonlinear methods, respectively. The soil space was displayed with solid components in the projects, while the structural beam elements were utilized for the pile and the superstructure. The scaled speed acceleration time history of the Kobe earthquake was applied to the lower part of the soil-pile-structure model, and the acceleration-time histories were acquired at the ground surface and the superstructure. The outcomes obtained from the ACS SASSI and the FLAC 3D were compared with the centrifuge test. As per the outcomes, the peak ground and the superstructure accelerations were close to the experimental outcomes; however, the periods at the peak spectral accelerations were slightly different from the test results. The difference is more pronounced in SASSI than in FLAC, which may be attributed to the solution methods. Apart from the solution methods, the difference might be the inability to fully simulate the complex centrifuge test.

Keywords: Soil-pile-interaction, dynamic, equivalent linear, nonlinear, FLAC 3D, SASSI

1. Introduction

Dynamic soil-pile-structure interaction is a perplexing issue that the way of behaving of the parts should be obviously characterized. While the stress-strain conduct of behavior of man-made structural elements is known with a specific exactness, the fundamental trouble in the analyses emerges from the vulnerability in the soil behaviour. The most widely recognized techniques in dynamic soil-pile-structure analyses are the continuum, and the discrete component (utilizing Winkler springs) approaches [1]. Numerous specialists have concentrated on the point and consider the soil as linear-elastic or elastic-perfectly plastic material [2], [3]. Notwithstanding, the soils show high nonlinearity even at little shear strains (<0.1%). The ground reaction investigated under seismic loading conditions can be performed by an identical linear methodology in the frequency domain. As per [4], the justification for playing out the analysis in the frequency domain rather than the time domain is simply the constituents of the situation of movement (stiffness, K and damping, C) are frequency subordinate boundaries and it is simple to settle the condition of movement in the frequency domain. By the by, time-domain analysis is becoming more normal with the headway in PC innovation. The fundamental benefit of the time domain analysis is its capacity to display the genuine nonlinear way of behaving of materials, while the frequency domain analysis takes on an iterative comparable straight methodology. The correlation of the equivalent linear and fully nonlinear techniques in site response analyses has been concentrated by [5], [6], [7], be that as it may, the impacts on the soil-pile-structure interaction analysis investigations have not been

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concentrated completely. In this study, the single pile model in the centrifuge test of [8] was simulated in FLAC 3D and ACS SASSI, and dynamic soil-pile-structure analyses were done utilizing fully nonlinear and equivalent linear techniques. The accelerations at the ground surface and the superstructure were compared with the experimental test results and presented.

2. Experimental Work in Literature Used for Verification

In this consideration, a well-known centrifuge test [9] was chosen to approve the dynamic investigations to be performed in FLAC 3D and ACS SASSI for completely nonlinear and equivalent linear approaches, separately. A flexible shear beam holder with 1.7 m long, 0.7 m wide, and 0.7 m profundity was utilized within the test, and the soil in which the piles were inserted was the saturated Nevada sand set at two diverse relative densities (55% and 80%), the denser one being at the foot. The demonstrate pile was an aluminum pipe area, and strain gages were located to degree the bending minutes at the particular profundities. The distance across and the length of the highly instrumented single pile were 0.67 m and 16.7 m, separately, in model units. A single degree of freedom system for the superstructure was made by expanding the pile over the ground surface and putting a 45 Mg mass on the pile. The free stature of the single pile was 5.4 m. The cross-section sees of the holder is appeared in Fig. 1.

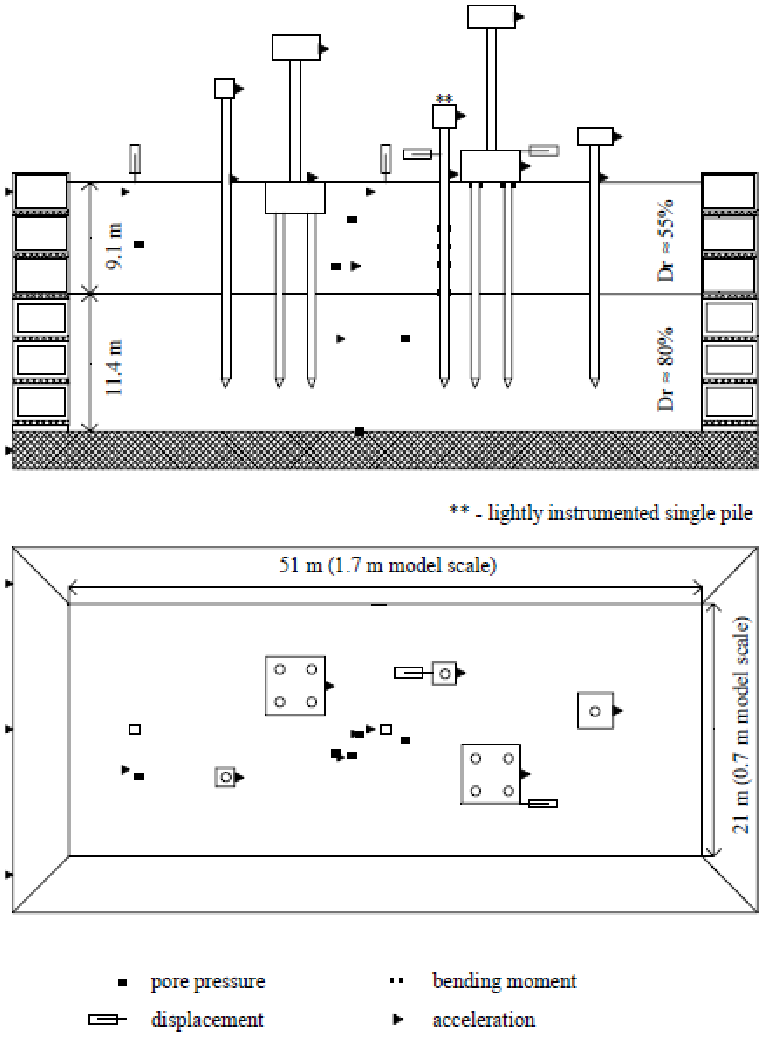


Fig. 1 - The cross-section view of the container in the centrifuge test [9]

Table 1 - An example of a table

	Model Units	Prototype Units
Material	6061-T6 Aluminium	
Young's modulus (GPa)	70	
Outside diameter (m)	0.0222	0.667
Wall thickness (mm)	2.4	72.4
Moment of inertia (m^4)	7.5x10-9	$6.1x10^{-3}$

2.1 Earthquake Record Used in The Study

The Kobe earthquake recorded on Harbour Island station at 79 m profundity was utilized within the centrifuge test of [9]. They consider modifying the initial record by duplicating the relocations with scalar products, coming about in 17 records called events (Event A to Event Q). In this ponder, Event F (amax=0.15g) and Event L (amax=0.24g) were chosen since the medium dense sand layer did not totally liquefy beneath these events. The maximum pore water pressure ratio (ru) values for Event F and Event L were detailed as 0.30 and 0.6, which were assumed to be distant sufficient from the liquefaction phenomenon. The acceleration-time history of the standard redressed and filtered movement with cutoff frequencies of 0.3 and 15 Hz and the reaction spectra for D=5% damping proportion were given in Fig. 2 and Fig. 3, separately [9].

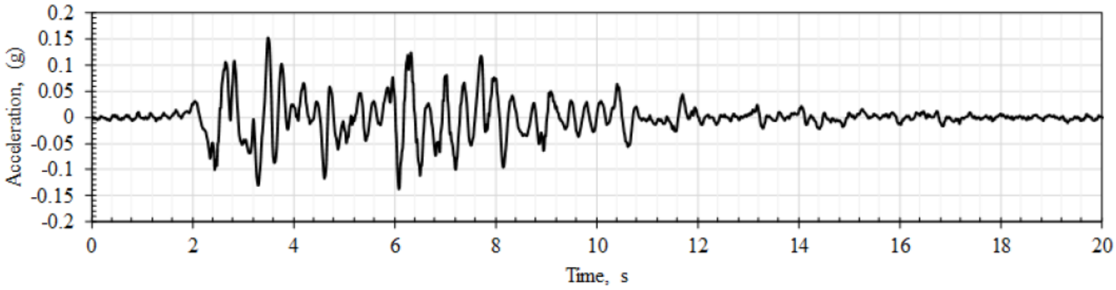


Fig. 2 - Kobe earthquake record scaled to 0.15g (Event F)

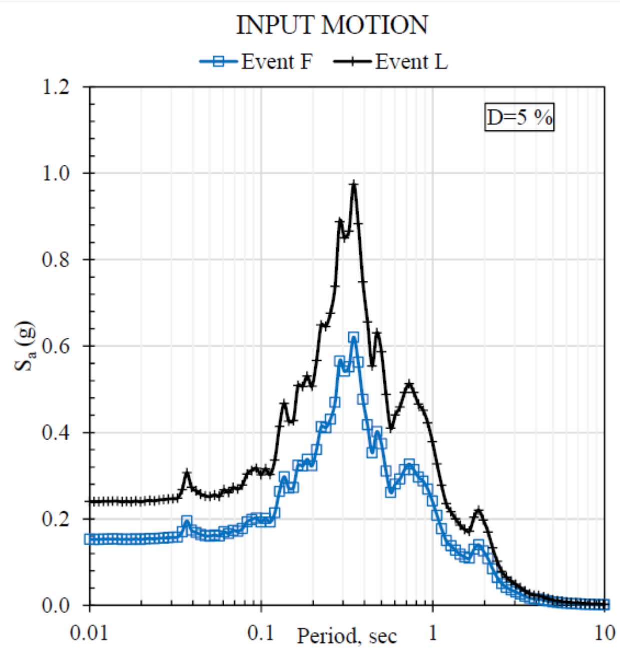


Fig. 3 - Response spectra of the Kobe earthquake records scaled to 0.15g and 0.24g (Event F and Event L)

2.2 Soil Properties

The soil properties of Nevada sand were considered by a few analysts [10], [11]. Small strain shear moduli values of Nevada sand at the reference effective stress of 100 kPa were reported as 28 MPa and 41 MPa for DR=55% and DR=80%, separately, by [12]. The proposal was utilized by [13], [14] in their confirmation investigations. In this study, as in [15], [16], the equation of [17] was adopted for the small strain shear modulus of the soil. The bulk modulus is calculated by elastic hypothesis utilizing the shear modulus calculated by Eq.1 and the Poisson's ratio which is expected as 0.3.

$$G_{max} = 21.7(K_2)_{max} p_a (\frac{\sigma'_m}{p_a})^{0.5} \quad (1)$$

The nonlinear stress-strain behavior of soils beneath dynamic loading can be taken into consideration by shear modulus reduction (G/Gmax) curves. In this study, the curves of [18] given in Figure 4 were expected.

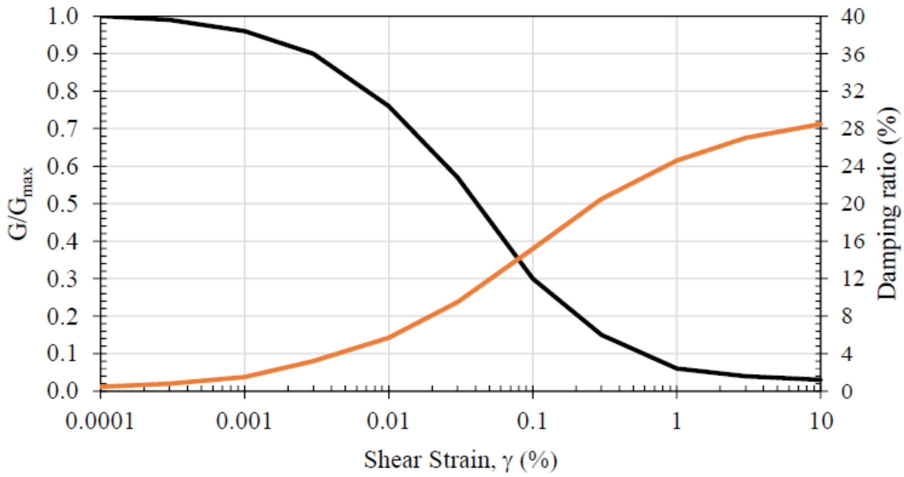


Fig. 4 - Shear modulus reduction and damping ratio curves for the sand layer [17]

3. Soil-Pile-Structure Interaction Analyses

In this study, dynamic soil-pile-structure interaction analyzes were performed in ACS SASSI and FLAC 3D. ACS SASSI (An Advanced Computational Software for 3D Dynamic Investigation Including Soil-Structure Interaction) is a soil-structure interaction program based on the finite element method working within the frequency domain. At the same time, FLAC 3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) gives the time-space analysis using the finite distinction approach. The most contrast between the two programs is that the fully nonlinear analysis can be executed in FLAC 3D, whereas the nonlinearity is considered with the iterative equivalent of the linear approach in SASSI. Within the equivalent linear approach (SASSI), the modulus decrease and the damping ratio variation with the shear strain must be specified since the iterative solution is implemented. In a fully nonlinear approach (FLAC 3D), the modulus lessening behavior is relegated to soil components utilizing a utilitarian frame, and the damping relation is administered through reloading/unloading (Masing rule) behavior.

3.1 ACS SASSI Model

The numerical model for frequency domain analysis was made in ACS SASSI. The soil domain was modeled using eight noded brick elements. The work of the finite element show was made in ANSYS, and it was exported to ACS SASSI. The restrain for the least estimate of mesh elements within the vertical direction is one-tenth of the wavelength ($\Delta z<\lambda/10$) and 1m height is sufficient to permit the wave propagation through the soil domain accurately. Since the numerical model ought to simulate the centrifuge test, the bottom boundary of the model must be fixed. Viscous dashpots are applied to the lateral boundaries of the show to anticipate the waves from reflecting into the demonstration. Since the model simulates the shaking table within the centrifuge test, the input movement was characterized at the bottom boundary of the model. The pile and structure were characterized by utilizing the structural beam element, and the material properties given in Table 1 were doled out to the beams. Nodal mass (45 tons) was alloted to the top node of the beam. The made mesh comprises 1869 hubs and 1520 solid elements, as appeared in Fig. 5.

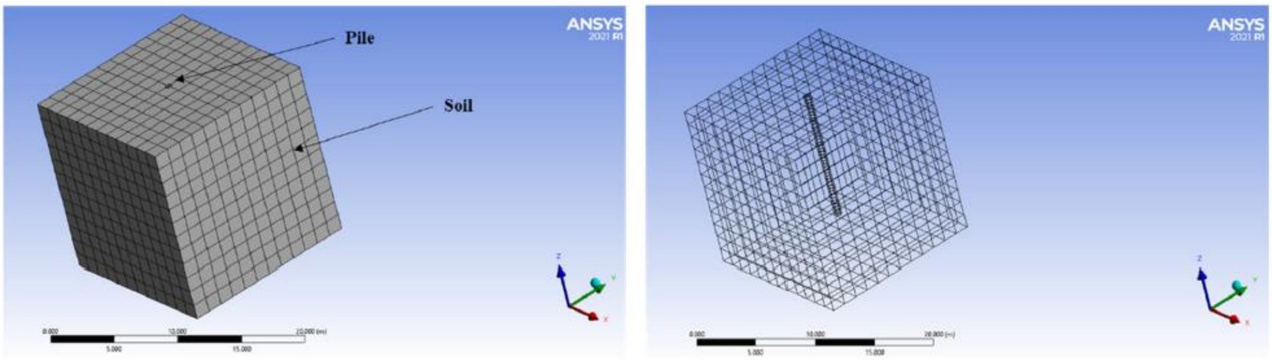


Fig. 5 - The finite element mesh made in ANSYS and traded to ACS SASSI

3.2 FLAC 3D Model

The numerical model for the time domain investigation was made in FLAC 3D. The soil was modeled by brick elements, whereas the pile and structure were made utilizing structural beam elements as within the ACS SASSI model. The bottom boundary of the show was fixed, and the free-field command was conjured for the lateral boundaries to retain the outward waves (FLAC 3D manual). Elastic material properties were allowed to solid zones, and the nonlinearity of the soil was taken into consideration by utilizing the hysteretic damping approach. Indeed in case, the program includes more advanced built-in constitutive models, the straightforward elastic model with the hysteretic damping approach was preferred to be steady with the SASSI model. The shear modulus decrease curve of [19] was received, and the Masing's unloading-reloading run the show governs the material damping behavior.

The minimum value for the shear modulus reduction was set to 0.05. Something else, the damping ratio would be overestimated at large strains. In addition to the hysteretic damping, a small amount of Rayleigh damping (0.2%) at the center frequency of 3Hz was applied to solids to channel the high-frequency component of the motion. The elastic model was utilized for the pile and superstructure, expecting that the bending moments and the coming about stresses are too low to consider the structural members' material nonlinearity. Not at all like the numerical model made in SASSI, radially graded mesh was not preferred since the FLAC 3D program utilizes the finite difference approach and the method requires as uniform mesh as conceivable. The numerical framework made in FLAC 3D with 35750 gridpoints and 28600 zones and it is shown in Fig. 6.

4. Discussion and Results

Dynamic soil-pile-structure interaction analyses were performed in SASSI and FLAC 3D, and the acceleration time histories at the ground surface and the superstructure are compared with the centrifuge test comes about as shown in Figures 9 and 10. The acceleration reaction spectra (ARS) for the damping ratio of D=5% are displayed in Fig. 7 and Fig. 8. The top accelerations, ghostly accelerations, and the overwhelming period values gotten from the analysis results are given in Table 2.

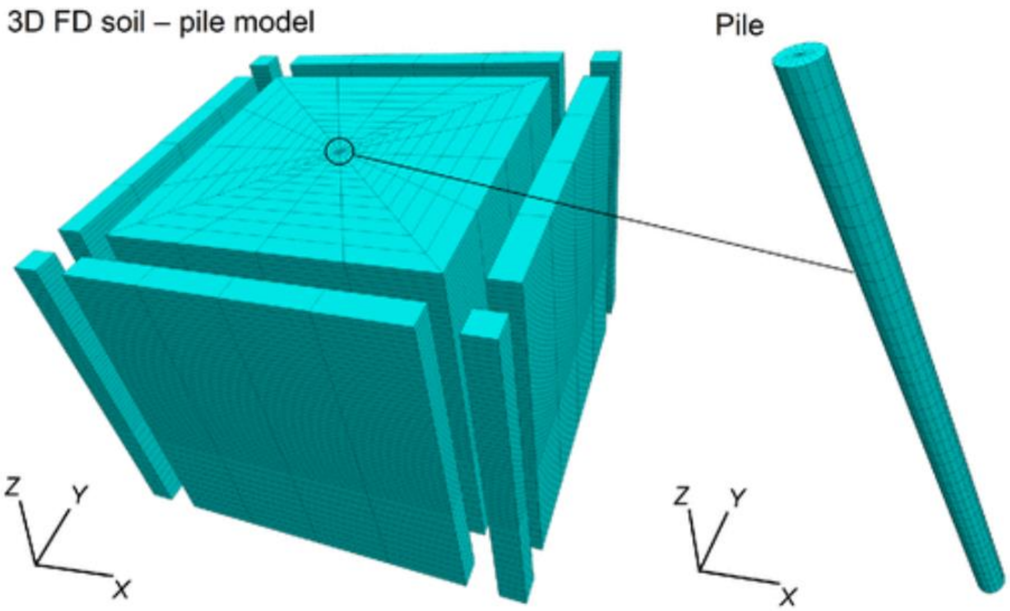


Fig. 6 - The numerical model created in FLAC 3D

Agreeing to the results, ARS at the ground surface for Event F was captured by both SASSI and FLAC 3D. The peak accelerations at the surface and the superstructure of Event L were found to be exceptionally near to the centrifuge test in SASSI. In any case, the unearthly accelerations and predominant periods are to some degree distinctive which can be observed by the phase difference within the acceleration-time history. FLAC 3D investigations appear that the peak accelerations are somewhat less than the test results, but the peak ghastly accelerations and overwhelming periods are very near to the test results. As the amplitude of the input movement increment (a_{max} from 0.15g to 0.24g), the acceleration responses diminish in FLAC 3D due to the higher damping ratios which are controlled by the masing rule. Although the crest accelerations in SASSI were closer to the test results, the ghastly accelerations and the predominant periods were almost the same within the FLAC 3D and centrifuge test.

Table 2 - The comparison of peak accelerations (PA), spectral accelerations (PSA), and predominant periods (Tp)

		Centrifuge	SASSI	FLAC 3D
Event F (0.15g) (Ground surface)	**PA (g)**	0.24	0.28	0.22
	PSA (g)	1.24	1.08	0.98
	Tp (s)	0.35	0.50	0.33
Event F (0.15g) (Structure)	**PA (g)**	0.82	0.76	0.63
	PSA (g)	3.07	3.85	2.72
	Tp (s)	0.95	0.71	0.94
Event L (0.24g) (Ground surface)	**PA (g)**	0.41	0.41	0.27
	PSA (g)	1.80	1.36	1.18
	Tp (s)	0.35	0.76	0.36
Event L (0.24g) (Structure)	**PA (g)**	1.26	1.38	0.99
	PSA (g)	4.46	6.87	4.36
	Tp (s)	1.10	0.76	1.00

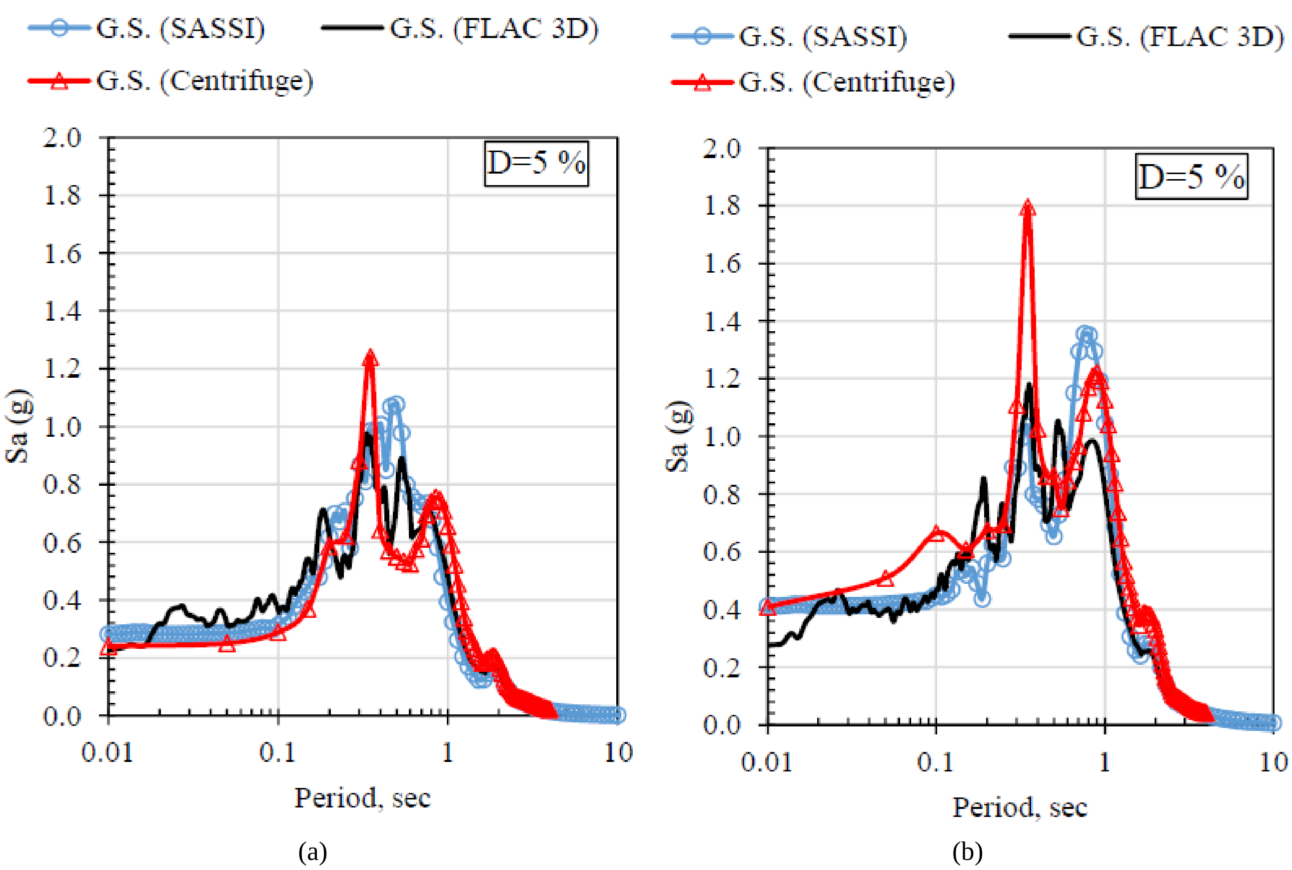
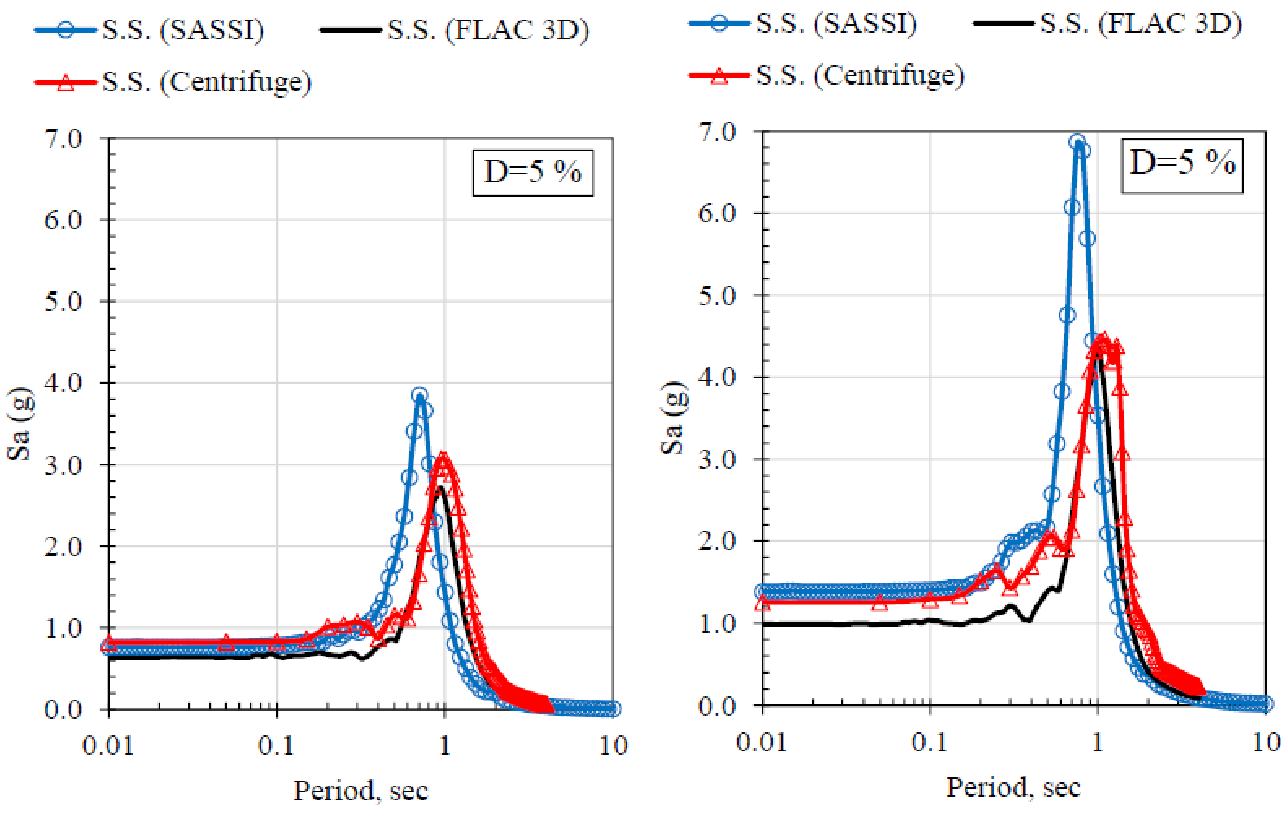
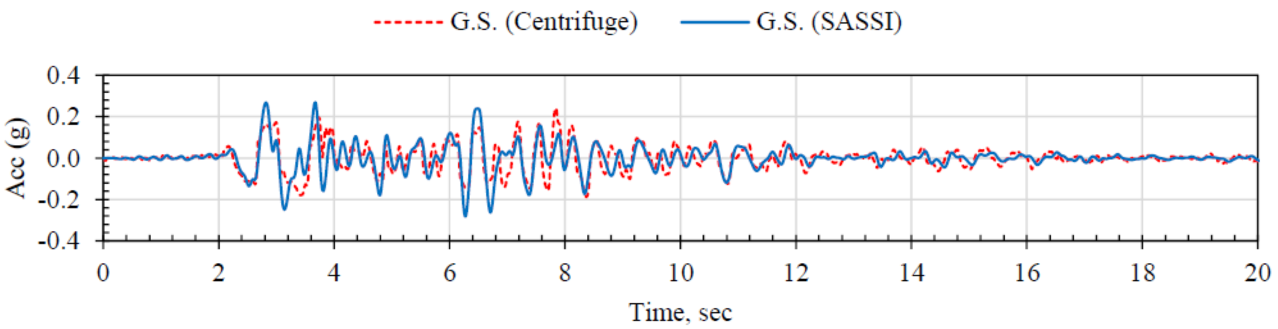


Fig. 7 - Comparison of the response spectra at the ground surface for (a) Event F (a_{max}=0.15g) and; (b) Event L (a_{max}=0.24g)

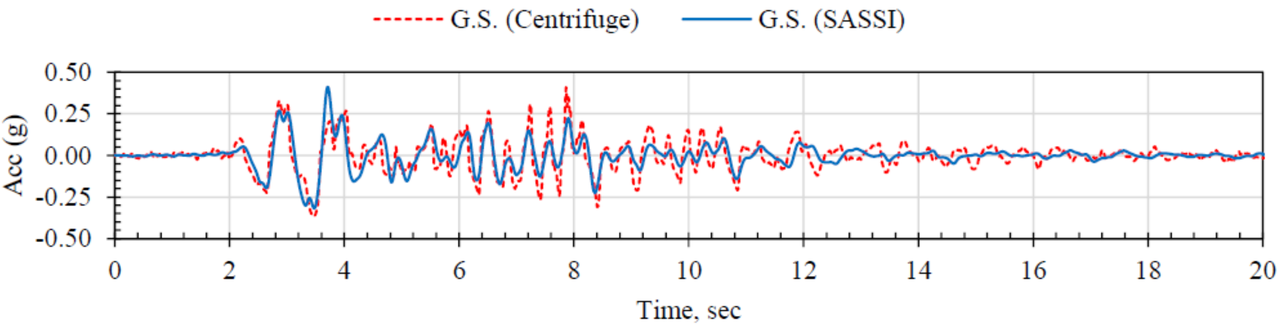


(a) (b)

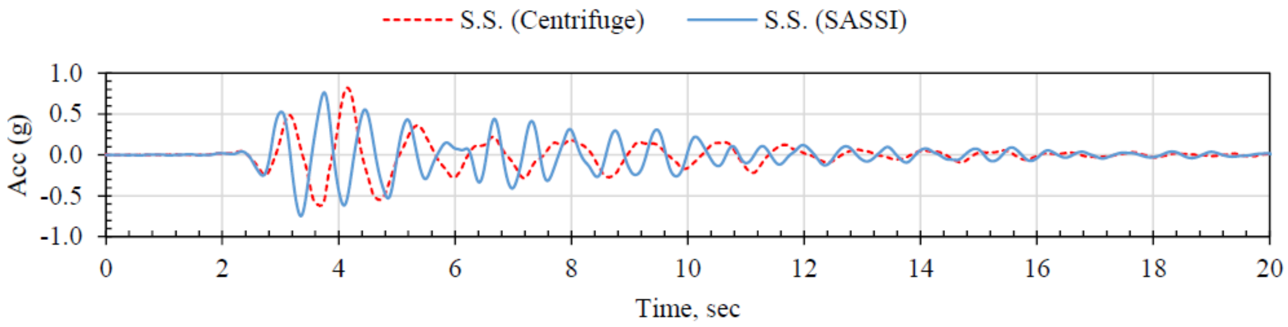
Fig. 8 - Comparison of the response spectra at TH for (a) Event F (a_{max}=0.15g) and; (b) Event L (a_{max}=0.24g)



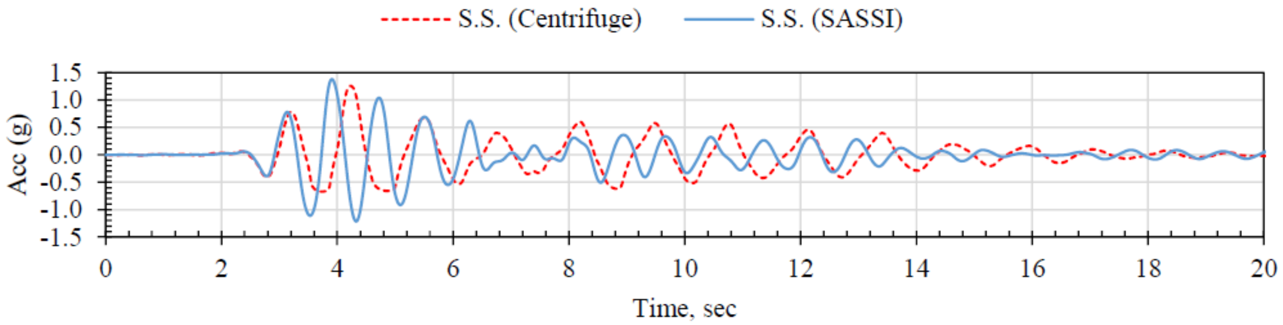
(a)



(b)

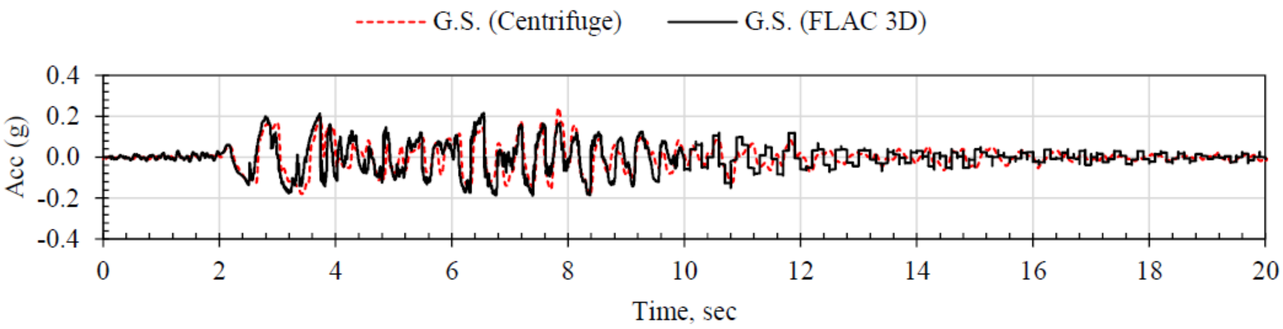


(c)

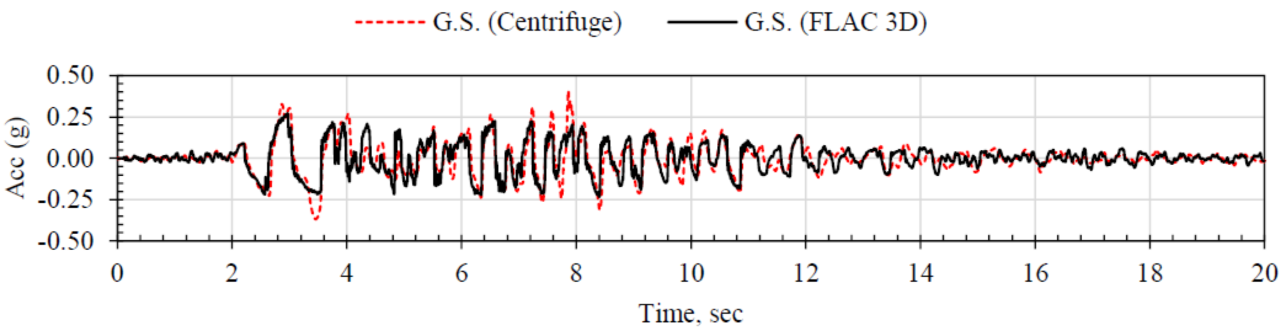


(d)

Fig. 9 - Acceleration time histories obtained in SASSI for Event F (a) ground surface; (b) superstructure and for Event L; (c) ground surface; (d) superstructure



(a)



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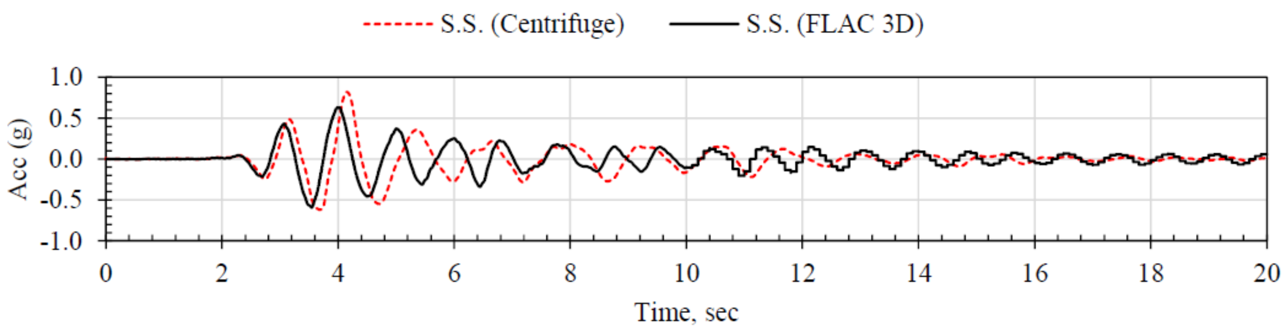
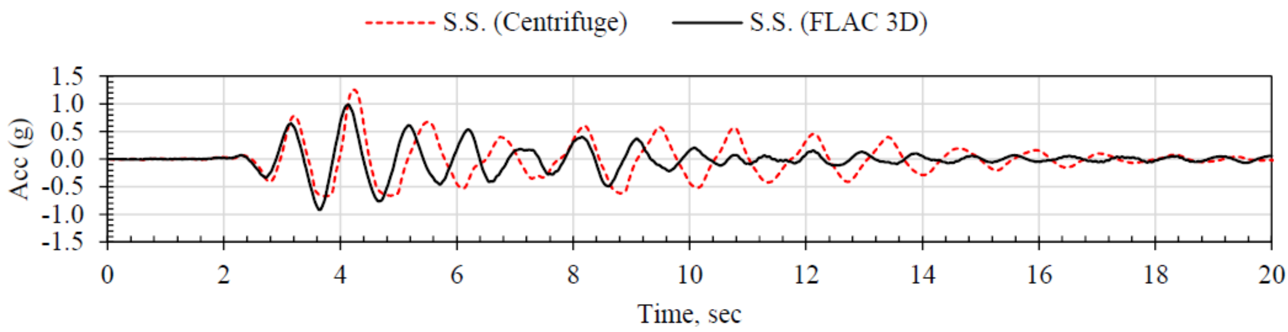


(c)



(d)

Fig. 10 - Acceleration time histories obtained in FLAC 3D for Event F (a) ground surface; (b) superstructure and for Event L; (c) ground surface; (d) superstructure

5. Conclusions

In this consideration, the single pile model within the centrifuge test of [20] was created in FLAC 3D and SASSI, and the dynamic soil-pile-structure interaction analyses were performed within the time domain and frequency domain, respectively. Kobe earthquake record was utilized within the analyses and the maximum increasing speeds of the motions were 0.15g and 0.24g. The acceleration time histories and reaction spectra on the ground surface and superstructure were compared with the test results. Concurring with the results gotten from the SASSI, the peak accelerations both at the ground surface and the superstructure are sensibly close to the centrifuge test results. However, the spectral accelerations at the superstructure are somewhat more prominent, and the transcendent period is less than the centrifuge test. The contrast within the results gets to be more articulated as the acceleration adequacy of input motion increments from 0.15g (Event F) to 0.24g (Event L). The FLAC 3D results demonstrate that the peak accelerations of the ground surface and the superstructure are belittled, but the period at the top spectral accelerations have around risen to the test results, which appears the accuracy of the numerical model parameters. The reason for the low top accelerations can be ascribed to the profoundly damped movement due to the Masing criteria for reloading/unloading behaviour.

Acknowledgement

The authors wish to express their gratitude to Department of Civil Engineering, Qom University of Technology for its support.

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