1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.221

New insight on seismic soil-structure interaction: amplification of soil-generated high frequency motion on a kinematic pile

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Abstract

High frequency motion is typically observed in experimental works on seismic soil behaviour in centrifuge and in 1-g laboratory tests even if single harmonic sinusoidal input motions are imposed at base. Often these high frequencies are associated with the imperfections of the experimental setups, such as imprecise actuating systems or interaction between specimen and soil containers. On the other hand, the most up-to-date advanced numerical studies suggested that such higher frequencies can also be generated by soil due to its nonlinear behaviour.

This work presents results of a numerical study on seismic soil-structure interaction representative of a typical experimental setup. Two advanced soil constitutive models are used. In detail, the results show that soil generates higher harmonics of motion in free field for a single harmonic sinusoidal input motion applied at base. Further, the presence of higher harmonics of motion on a kinematic pile embedded in soil is amplified and can be thought as a potential example of a superharmonic resonance, i.e. a resonance of a structure with one of the soil-generated higher harmonics. The results of the numerical study are compared with the results of a relevant experimental work from the past in order to validate the findings of this paper. The explanation of the higher harmonics of motion generated by soil is also briefly drafted.

Finally, the importance of soil generated high frequency motion is briefly discussed, especially in the context of masonry old buildings, often of heritage significance, which are commonly damaged due to high frequency content of recent earthquakes recorded in Europe.

Key words: soil-structure interaction, numerical modelling, advanced soil constitutive modelling, kinematic piles, high frequency motion, masonry buildings

1 Introduction

The in-depth understanding of soil-structure interaction (SSI) under seismic loading conditions is of paramount importance for resilient society of the future. Numerous scientific studies have been carried out in recent years in order to develop the state-of-the-art knowledge on the subject of seismic SSI. Typically, two approaches are adopted to investigate seismic SSI. First of all, physical modelling, mostly at small scale (e.g. [1, 2]) but also at large scale (e.g. [3]) is considered as a reliable way of studying soil under seismic loading conditions. Alternatively to the physical modelling, advanced numerical studies (e.g. [4]), i.e. numerical studies where soil constitutive models account for soil cyclic behaviour, are adopted to predict the response of large boundary value problems. One of the problems encountered in experimental and numerical works is unexpected higher frequency motion, observed and computed even for perfect sine input motions applied at base of soil specimen. Typically, such higher frequency motion is attributed to difficulties with obtaining a perfect experimental setup [5] or with numerical noise [6]. Alternative explanation comes from the theory of wave propagation. [7] showed numerically that higher harmonics for monochromatic input motions are generated due to soil nonlinearity. Subsequently, [8] showed a comparison of numerical studies with experimental data and concluded that soil nonlinearity leads to higher harmonics observed in the spectral response for sinusoidal input motions. Finally, the most recent studies based on advanced numerical analysis and relevant comparisons with experimental data from the past attributed higher frequency motion observed in soil to be the result of unloading waves and soil-released elastic waves propagating in soil. The problem was initially approached and addressed in a wide context in [9]; where however, some misconceptions were still present. Later, the work was summarized in a more accurate way regarding the general effects of the propagation of soil unloading waves, soil elastic waves and their impact on structural response [10].
This paper presents a brief advanced numerical study of a group of piles under seismic loading conditions and validates this study against benchmark experimental work from the past. The results are shown in terms of horizontal accelerations at soil surface and pile top. Particular attention is given to higher frequency motion generated for single harmonic sine input motion applied at base. In detail, the results show how a kinematic pile is affected by soil-generated higher frequencies of motion. Subsequently, a brief discussion focuses on the importance of these findings especially in the context of the damage of old masonry buildings in recent earthquakes in Europe.

2 Methodology

This work is based mainly on the numerical studies shown in detail in [9] and comparison with an available example of experimental data from the past on shear stack tests on a group of piles [11]. Firstly, the experimental setup will be briefly presented in this section, and subsequently followed by more details on the conducted numerical studies.

2.1 Experimental setup

The experimental example used in this paper for the validation purpose was carried out in a shear stack container on a shaking table at University of Bristol [12]. The shear stack is a box filled with soil which contains eight aluminium rings joined with rubber in between to provide flexibility for lateral soil movements under shaking motion (Fig. 1). The dimensions of the box are 120cm by 65cm in plan, and 80cm in depth. The experimental setup used in the comparison in this paper is shown on Fig. 2. In details, five piles were placed in a bi-layered soil profile consisting of two sand layers of Leighton Buzzard (LB) sand. The top layer consisted of LB sand, fraction E, whereas the bottom layer of a mixture of LB sands, fractions E and B. The details of the properties of LB sand are shown in Table 1 and of the soil profile in Table 2.
The input motion used in this study is a perfect sinusoidal input motion (25Hz) of a maximum amplitude of 0.077g. Note that the experimentally measured accelerations were filtered with a low-pass Butterworth filter (80Hz, 5th order).

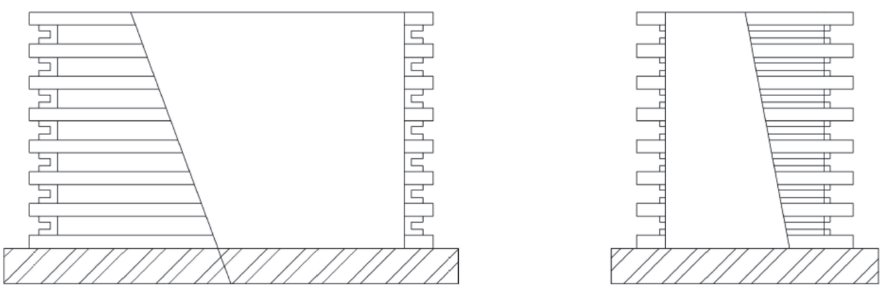

Figure 1. Sketch of a shear stack used in typical experimental works

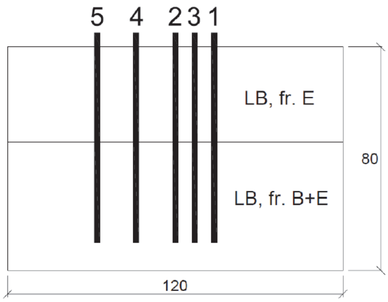

Figure 2. Geometry of experimental setup of shear stack tests on piles (dimensions in cm)

Table . Properties of Leighton Buzzard sand in experimental work [11]

Sand type	γ_s[kg/m^3]	D_{10}	D_{50}	e_{min}	e_{max}	Reference
LB, fr. E	2647	0.095	0.14	0.613	1.014	[13]
LB, fr. B+E	2647			0.289	0.614	[14]

Table 2. Sand properties within two soil layers in experimental work [11]

Layer	**Height** [m]	γ_s[kg/m3]	*e*	D_r [%]
LB, fr. E	0.34	1332	0.91	25
LB, fr. B+E	0.46	1800	0.48	41

2.2 Numerical model

Two advanced soil constitutive models are used in this work, namely the Severn-Trent (ST) sand model [15] and the hypoplastic (HP) sand model [16] in a version extended by [17] and [18]. The constitutive models have been calibrated for small strain behaviour in shear stack as advised by [19]. Note that both soil layers in the bi-layered soil profile have been modelled with the same set of parameters, with the only difference in the initial void ratio to account for different relative densities between both of the layers. Details of the soil constitutive features can be found in the cited references whereas details on the calibration were shown in [9], none are repeated here for brevity. For completeness, the input parameters of both of the models are shown in Appendix A.

The optimized mesh in the numerical studies is shown on Fig. 3. The quadratic element size of 0.05m was chosen for soil to ensure accurate representation of wave propagation in soil. Note that shear stack has not been modelled as typically its impact is considered negligible [19]. Tie connections between the soil side nodes were used to ensure periodic boundaries.

Finally, the computed horizontal accelerations are shown after using an 80Hz filter (5th order) for the sake of consistency with the experimental results.

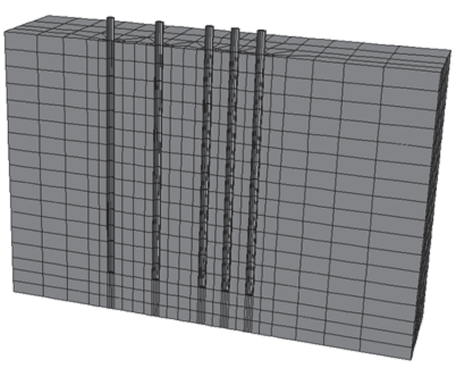

Figure 3. 3D mesh discretization chosen for numerical studies

3 Results

Fig. 4 shows a comparison of the measured and computed horizontal accelerations in free field, i.e. in soil far away from the piles, thus not affected by waves reflected from the piles. First of all, it can be observed that the acceleration amplitude and phase shift in free field is very well captured by both of the models. Secondly, wave distortion from a perfect sine shape applied at the soil base can be clearly seen in the experiments and in the computed accelerations at soil surface. Such distorted sine wave results in higher harmonics (i.e. 75 Hz and 125 Hz) of motion present in spectral response (not shown here for brevity).

Fig. 5 shows a comparison of the measured and computed horizontal accelerations on the top of a kinematic pile (pile no. 3 on Fig. 2). Similarly to the free field, the constitutive models predict quite precisely the acceleration amplitude at the top of the pile. In addition, the amplification of higher frequency motion can also be clearly seen on the pile when comparing with the free field response. Although the exact pattern of higher frequency motion from the experiment is not captured accurately in the numerical studies, Fig. 6 shows similarities between the numerical and experimental comparisons in terms of the evaluated spectral responses.

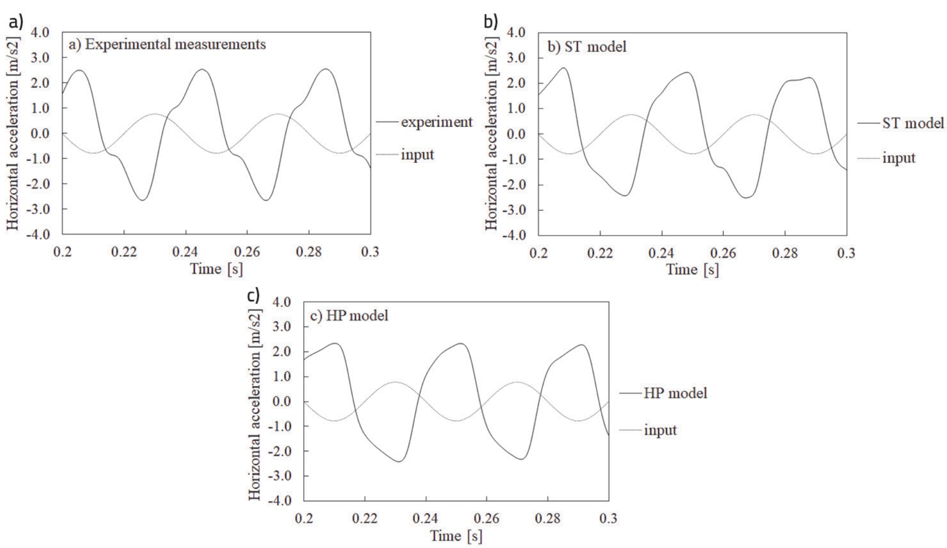

Figure 4. Horizontal accelerations in free field: a) measured in the experiment, b) computed by the ST model, c) computed by the HP model

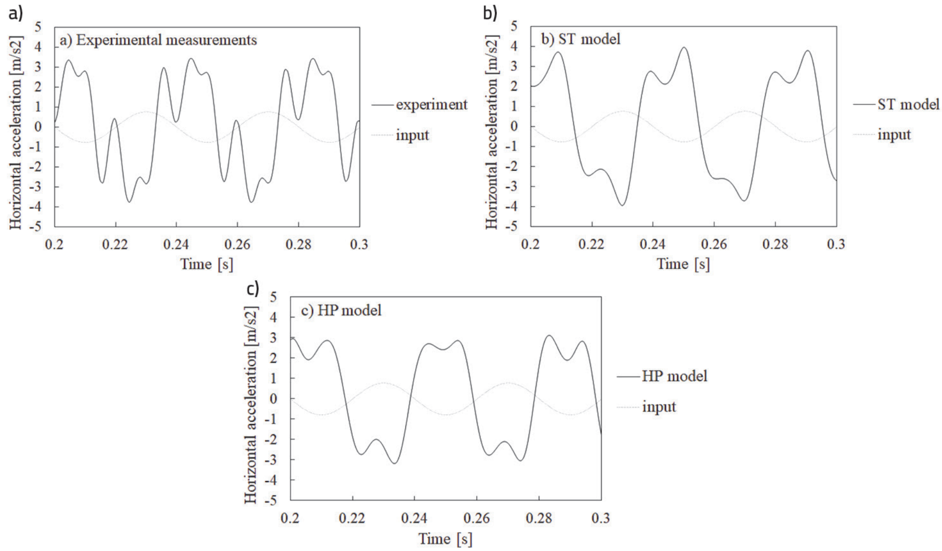

Figure 5. Horizontal accelerations at the top of the pile no.3: a) measured in the experiment, b) computed by the ST model, c) computed by the HP model

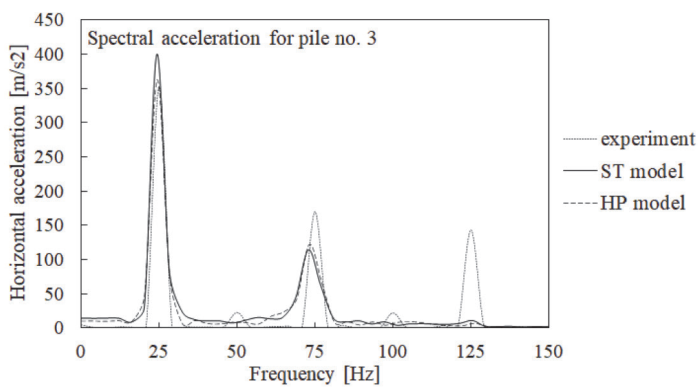

Figure 6. The spectral response for the measured and computed accelerations at the top of the pile no. 3

4 Discussion and summary

The origin of the observed high frequency motion in the shear stack studies was initially approached in a wide context, including s-wave and p-wave propagation, scaled earthquake input motions, seismic SSI and saturated soil response, in the previous work of the author [9]. Subsequently, the soil-generated higher frequency motion was shown to be attributed to: unloading waves and soil-released elastic waves [10]. Generally saying, it is soil highly nonlinear behaviour which results in the observed higher frequency motion. The higher frequency motion in soil has been of very little appreciation before, as typically soil is considered as a medium which filters out higher frequencies. However, based on the current findings, higher frequency motion can apparently be generated in soil and should be a subject of more detailed investigation in the future. Higher frequency motion has also been shown on the pile head in this study. Therefore, the kinematic piles, such as studied in this work in shear stack, can be treated as additional measuring instruments, i.e. elastic inclusions, which allow picking up and amplifying higher frequency motion generated in soil. The amplified higher frequency motion on the pile is a proof of the effects of unloading waves and released elastic waves in soil which introduce additional elastic waves on structural elements. In case of piles, the propagation of higher frequency waves in soil causes a relatively small elastic bending strain to 'travel' along the pile. This elastic bending strain is the reason of the high frequency motion shown in the computed accelerations on the piles. Such behaviour of piles can also be considered as a potential example of superharmonic resonance [20], i.e. resonance of a structure with higher frequency motion generated by the system, in this case, soil. Indeed, the kinematic piles in the shear stack tests behave as oscillators in their top parts thus can also be thought as representative of a structure.

In general, the soil-generated higher frequency motion amplified at pile tops should be of increased interest and deserves more attention. It is interesting to ponder that such effects could also take place in real earthquakes and affect real structures. Note that old buildings are often those that suffer severe damages during earthquakes and are characterized dynamically by relatively higher natural frequencies thus can be detrimentally affected by seismic higher frequency content. It is reminded that many of these buildings are of heritage value. For example, churches of historical significance were severely damaged in the recent earthquakes in Italy (Norcia, Amatrice) and Croatia (Zagreb). Therefore, vulnerable masonry architecture should deserve particular attention in regards to the possibility of being damaged by soil-generated higher frequency seismic motion.

Acknowledgments

The research presented herein was initiated under the XP-Resilience project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 721816.

The author would want to thank Prof. Alessandro Gajo for the provision of the numerical tools, advice and support during the PhD research of the author where the work on higher frequency motion generated in soil originates from.

The author would like to acknowledge the provision of the examples of experimental data by Maria Giovanna Durante and Prof. Luigi di Sarno, and thank Maria Giovanna Durante for brief but fruitful email exchange on experimental nuances.

The author would also like to thank Dr Andrew Brennan and Prof. Jonathan Knappett for inspiring conversations on protection of heritage vulnerable structures in seismic zones.

Appendix A

This appendix presents the sets of input model parameters chosen for the ST model (Table A1) and for the HP model (Table A2) in the presented numerical study.

Table A1 Input parameters for the ST model

Parameter	Description	Value
ν_Δ	Intercept for critical-state line in ν-ln p plane at p=1Pa	2.194
Δ	Slope of critical-state line in ν-ln p plane	0.0267
ϕ_{cv}	Critical-state angle of friction	33°
m	Parameter controlling deviatoric section of yield surface	0.8
k	Link between changes in state parameter and current size of yield surface	3.5
A	Multiplier in the flow rule	0.75
k_d	State parameter contribution in flow rule	1.3
B_{min}	Parameter controlling hyperbolic stiffness relationship	0.0005
B_{max}	Parameter controlling hyperbolic stiffness relationship	0.002
α	Exponent controlling hyperbolic stiffness relationship	1.6
R_R	Size of the yield surface with respect to the strength surface	0.02/0.01*
E_R	Fraction of G_0 used in the computations	1.0
*slightly larger yield surface has been assumed in the top soil layer to avoid numerical problems at soil surface		

Table A2. Input parameters for the HP model

	Parameter	Description	Value
Basic hypoplastictiy	ϕ_c	Critical friction angle	33.0
	h_s	Granular hardness	2500
	n	Stiffness exponent ruling pressure-sensitivity	0.42
	e_{d0}	Limiting minimum void ratio at p'=0 kPa	0.613
	e_{c0}	Limiting void ratio at p'=0 kPa	1.01
	e_{i0}	Limiting maximum void ratio at p'=0 kPa	1.21
	α	Exponent linking peak stress with critical stress	0.13
	β	Stiffness exponent scaling barotropy factor	0.8
Intergranular strain concept	R	Elastic range	0.00004
	m_R	Stiffness multiplier	5.0
	m_T	Stiffness multiplier after 90° change in strain path	2.0
	β_R	Control of rate of evolution of intergranular strain	0.3
	χ	Control on interpolation between elastic and hypoplastic response	0.5
	ϑ	Control on strain accumulation	5.0

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