Proposal of a Model Setup for Verification of the Origin of High Frequency Motion in Soil

Piotr Kowalczyk

Abstract High frequency components of motion are typically measured in laboratory tests on shaking tables when investigating the dynamic response of soil subjected to harmonic excitation. The source of these high frequency components is often thought to be related to uncertainties of experimental setups. In contrast, a group of numerical and theoretical research works suggested potential physical explanations to high frequency components of motion as related to soil mechanical behavior including soil fluidization, cyclic mobility, pounding or unloading elastic waves. This paper presents a finite element numerical study of an example model setup designed to verify the origin of high frequency motion in soil as potentially related to the presence of soil elastic waves in the steady state response of nonlinear hysteretic soil. The soil is modelled with an advanced soil constitutive model within the general framework of hypoplasticity to account in a reliable manner for soil cyclic behavior. The results show that high frequency motion can be observed in the computations in free field and on a simple structure even though a simple harmonic sinusoidal input motion is introduced at the base of the model setup. It is shown that apparently this high frequency motion can be representative of soil elastic waves released in nonlinear hysteretic soil in the steady state response.

Keywords Finite element modelling · Soil-structure interaction · Hypoplasticity · High frequency · Elastic waves · Wave propagation

1 Introduction

High frequency motion is often registered in experimental works on soil dynamic behavior carried out in flexible soil containers placed on shaking tables and subjected to simplified sinusoidal input motions. Although often this high frequency motion

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is attributed to uncertainties of experimental setups, some attempts to recognize the source of the high frequency motion in the experimental works as related to physical phenomena were also made in the past. Different authors attributed the observed high frequency motion to various physical phenomena, for example, to soil fluidization [1], cyclic mobility in saturated soil [2] or pounding between soil and structure [3]. The most recent potential explanation to the experimental observations is the possibility of the release of soil unloading elastic waves in the steady state response of nonlinear hysteretic soil under harmonic excitation [4–7]. The author's previous works showed promising comparisons between advanced numerical studies and some benchmark experimental works supporting the idea of the presence of unloading elastic waves in the steady state response of soil. In fact, these findings may potentially explain why some experimentalists observe that their experimental tests were *destroyed* by elastic waves. On the other hand, one has to remind that experimental works are often aimed at studying complex boundary value problems and their setups include various structural elements, non-homogenous soil profiles or deal with saturated soil, all possibly inducing additional waves in the dynamic system. Moreover, the induced input motions may contain spurious high frequencies due to the imperfections of actuators. Finally, soil flexible containers tend to be rather small for the reasons of reduced experimental costs, however in such case the boundaries of the containers may more likely affect the measurements. Therefore, it appears that there is a need for a dedicated experiment to further advance the findings on soil unloading elastic waves, especially in regard to their impact on structures.

This paper presents a 2D finite element numerical analysis of an example model setup which could be considered as a *prefect experiment* for explicit verification of the existence of soil elastic waves potentially released in hysteretic soil in the steady state response. To this aim, homogenous dry soil is placed in a large flexible soil container and subjected to perfectly sinusoidal input motion of horizontal acceleration. The soil nonlinear behavior is accounted by an advanced soil constitutive model formulated in the framework of hypoplasticity to yield high-fidelity predictions. In addition, a small oscillator with its natural frequency close to the soil first natural frequency is placed in the middle of the soil container to allow further verification of the existence of soil elastic waves in the steady state response of soil.

2 Methodology

2.1 Numerical Model

The numerical model presented in this work is an example of a proposal of a *perfect experimental setup* where experimental uncertainties and imperfections are eliminated. To this aim, the flexible soil container in this work is assumed to be much

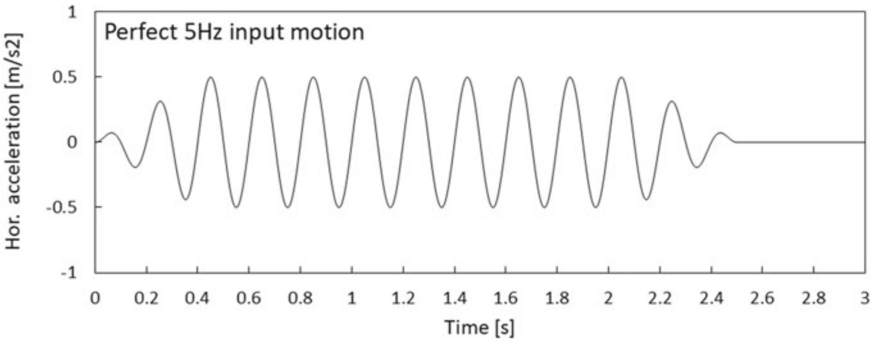


Fig. 1 Input motion of the driving frequency of 5 Hz introduced at the base of the soil specimen

larger than typically. For example, the size of the flexible soil container is assumed here to be 5 m long and 1 m high. The 5 m long soil container would allow reducing relatively the zone where the effects of boundary conditions and interaction between the container and the soil may occur, thus more reliable free field measurements could be obtained. The soil filling the container is dry sand, for example, Leighton Buzzard sand, fraction E. The assumed density is 1300 kg/m^3, with the initial void ratio of 0.9, and the initial K_0 condition of 0.5. Soil natural frequency in the soil container for such assumptions is around 24 Hz. Finally, example perfectly sinusoidal input motion of 5 Hz and a moderate amplitude of up to 0.05 g is introduced in a smooth manner as shown on Fig. 1.

In addition, a relatively small example structure made of aluminum is placed in the center of the soil container. To this aim, an oscillator consisting of 200 g mass fixed on the top of a 0.1 m high aluminum column of 3 × 12 mm section and placed on 0.1 m size foundation is assumed. The natural frequency of such oscillator assuming fixed base is 26 Hz, thus it lies closely to the soil natural frequency. In fact, such close match between the natural frequencies of the soil and the structure is intended. The oscillator in the proposed experiment can act as an additional measuring instrument which can identify the presence of soil elastic waves in the steady state response of soil. Namely, if such waves are released in soil, the oscillator will vibrate in the steady state response with its natural frequency in addition to the driving frequency of the input motion. On the other hand, if the elastic waves are not released in soil, the oscillator should vibrate only with a single frequency, the one of the input motion.

Note that no common procedure of filtering data with low-pass filters is proposed in order to avoid the possibility of removing physical phenomena from the results.

In general, the presented example model setup is such, in which typically encountered experimental uncertainties and imperfections, related to close boundaries, non-homogenous soil profiles or numerous structural elements, are minimized. Therefore, if carried out physically, one could expect unaffected response in free field and on the oscillator.

2.2 Constitutive Model

Hypoplastic sand model in the form developed by [8–10] and implementation available on *soilmodels.info* webpage [11] has been used in this work to ensure reliable soil mechanical response under seismic loading conditions and ease in replicating the numerical study by the interested Readers. The calibration of the model is practically the same as in the previous similar works of the author [4] with only slight modifications. The calibrated parameters with their descriptions are shown in Table 1.

Table 1 Model parameters for the hypoplastic sand model

	Parameter	Description	Value
Basic hypoplastictiy	φ_c	Critical friction angle	33.0
	h_s	Granular hardness [MPa]	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	4.0
	m_T	Stiffness multiplier after 90° change in strain path	2.0
	β_R	Control of rate of evolution of intergranular strain	0.8
	χ	Control on interpolation between elastic and hypoplastic response	0.5
	ϑ	Control on strain accumulation	5.0

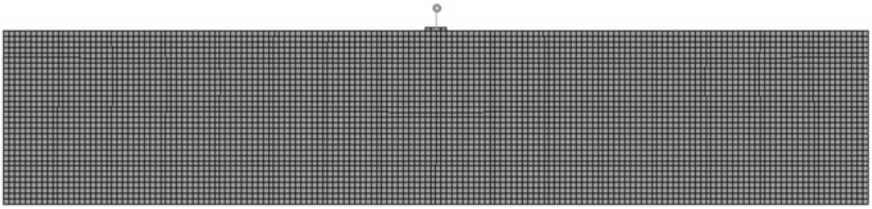


Fig. 2 Mesh discretization of the 2D finite element model

2.3 *Discretization and Boundary Conditions*

Abaqus finite element code [12] has been used to run the numerical model of the example experimental setup. The 2D mesh discretization is shown on Fig. 2. The size of a quadratic element of 0.05 m ensures reliable predictions for representing the problem of S-wave propagation.

The boundary conditions on the lateral sides comprise restricting corresponding nodes at the same height to have the same lateral displacement, i.e. to mimic the presence of a flexible soil container. Horizontal acceleration time history is introduced at the base.

The oscillator (i.e. the column and the foundation) are modelled with elastic material of properties of aluminum. Additional damping of 1% has been assumed for the elastic material of the oscillator.

Moderate numerical damping has been introduced to the Hilbert-Hughes-Taylor integration scheme [13], with its parameters set to: $\alpha = -0.41421$, $\beta = 0.5$, $\gamma = 0.91421$, in order to remove very high frequency (i.e. much higher than those studied in this work) oscillations in the computed accelerations.

3 Results

The results present the occurrence of high frequency motion in free field and on the oscillator in the computed horizontal accelerations (Fig. 3) and in the horizontal relative lateral displacements (Fig. 4) even though perfectly sinusoidal input motion has been applied (Fig. 1). Figure 5 shows the spectral response of the computed accelerations as evaluated in the steady state part of the motion (i.e. from 0.8 to 2.0 s) and reveal increased presence of the harmonic 25 Hz representative of soil elastic waves. In particular, one can observe very strong presence of high frequency motion on the oscillator. Note also the presence of other harmonics in the spectral response (e.g. 15 Hz). These are believed to characterize a distorted sinusoidal wave

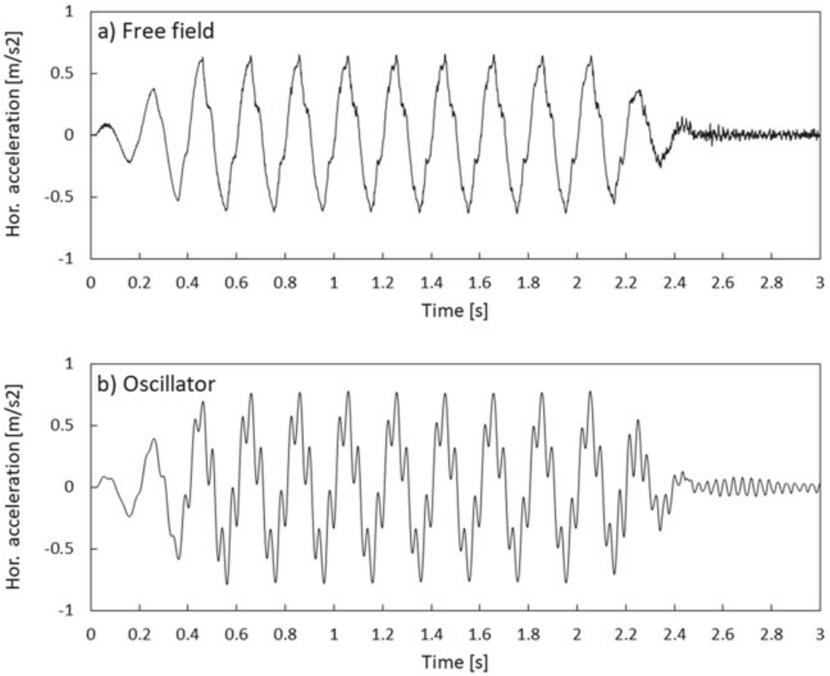


Fig. 3 Horizontal accelerations computed at the top of the soil in free field (**a**) and at the top of the oscillator (**b**)

as explained in the past, e.g. [14], and not representative of additional waves in the analyzed system.

Note that the presence of high frequency motion is the strongest in the steady state part of the motion, thus the presented effects can not be related to the transient response. In any case, any additional waves induced at the initiation of motion due to the transient response would be damped out as a result of material hysteretic damping (Fig. 6). On the other hand, apparently this damping is not sufficient to remove the high frequency motion (i.e. soil elastic waves) from the steady state response. Finally, note how high frequency motion remains in the *coda* part of the computations and is slowly damped out.

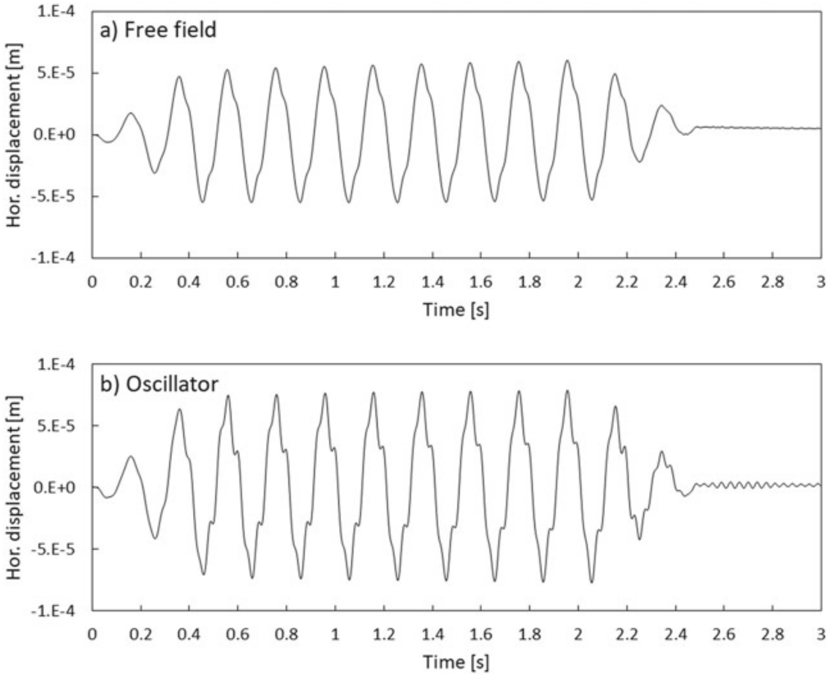
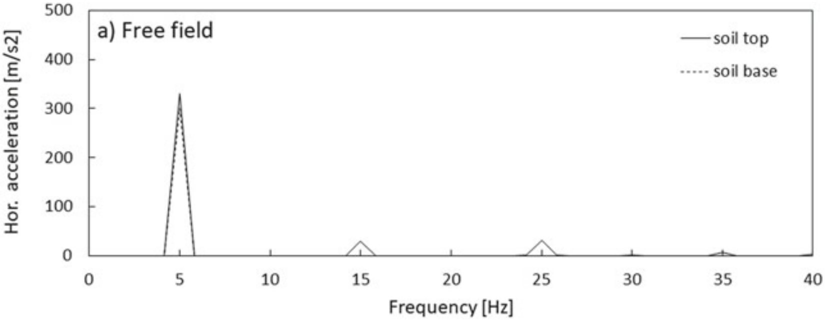


Fig. 4 Horizontal displacements computed at the top of the soil in free field (**a**) and at the top of the oscillator (**b**)

4 Summary

The numerical study in this work showed a proposal of an example model setup for the verification of the origin of high frequency motion often observed in soil specimens tested under sinusoidal input motions. The computed results indicated that soil elastic waves can be found in the steady state response of the soil and the structure. Further studies should involve experimental verification of these findings, for example, by physical modelling of the example model setup proposed in this work.



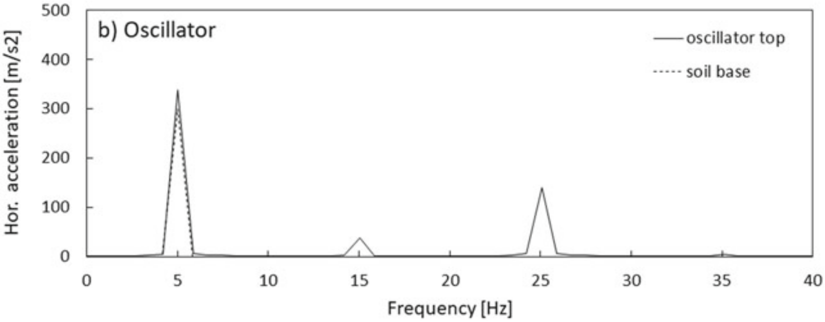


Fig. 5 Spectral response evaluated in the steady state response of the computed accelerations at the top of the soil in free field (**a**) and at the top of the oscillator (**b**)

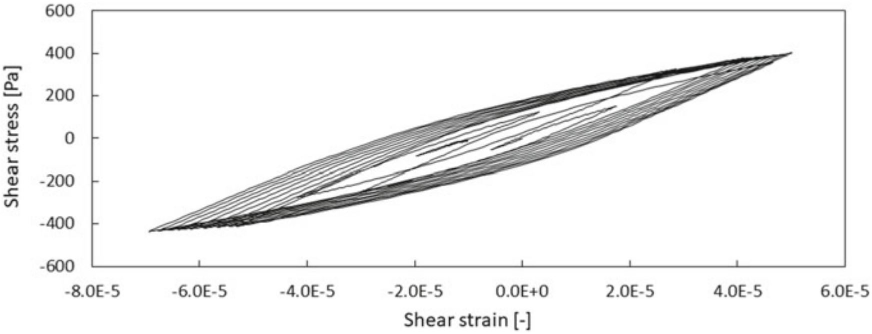


Fig. 6 Shear stress versus shear strain response computed at the mid-depth of the soil

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