Centrifuge modeling of the effects of earthquake amplitude on ground liquefaction and embankment response

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ABSTRACT: The objective of this study is to highlight the behavior of embankments constructed on liquefiable soil and subjected to earthquakes with different amplitudes. Two centrifuge models were performed to reproduce an embankment constructed on liquefiable soil subjected to dynamic excitation. The centrifuge models were prepared with clean sand (Hostun HN31) and instrumented (accelerometers, pressure sensors, and lasers). These models are excited with sinusoidal signals with different amplitudes: 0.1g and 0.2g. The impact of the amplitude on soil liquefaction was first examined by comparing the accelerations and pore pressures recorded during the tests. Different aspects were considered, including the location and extent of the liquefied zones, as well as the time required to initiate liquefaction. Additionally, the behavior of the embankment was investigated. The influence of the applied signal's amplitude on the model's deformation was also evaluated particularly focusing on vertical displacements such as embankment settlements and the uplift of the free ground surface.

1 INTRODUCTION

Earthquakes are one of the most devastating disasters in the world, as happened in 2023 in Morocco and Turkey (Santini et al. 2023). They can cause significant damages and give rise to phenomena such as liquefaction. Liquefaction can cause huge geotechnical damages like soil settlement and failure of big structures, as happened for the Koseli road embankment in Turkey in 2023.

It is essential to understand the effect of the liquefaction on the response of the big structures. Therefore, numerical simulations and centrifuge models have been carried out in recent decades to understand the response of an embankment constructed on liquefiable soil and subjected to earthquakes.

Adalier and Sharp (2004), Pramaditya and Fathani (2021) and Pourakbar et al. (2022) carried out centrifuge tests to investigate the response of the embankment constructed on liquefiable soil ground. Their findings revealed that liquefaction tends to occur beneath the ground surface near the toe of the embankment, while the soil beneath the embankment is less prone to liquefaction. Adalier et al. (1998) examined also the impact of liquefiable layer thickness and position on embankment behavior. Furthermore, Park et al. (2000), Okamura and Matsuo (2002), Li et al. (2021) Pramaditya and Fathani (2021), Pourakbar et al. (2022) and Gu et al. (2022) have highlighted the effects of liquefaction remediation on embankment response, considering different types of liquefaction reinforcement. Jafarian et al. (2017), Mehrzad et al. (2018) and Esmaeilpour et al. (2022) studied the effect of liquefaction on shallow foundations by varying the amplitude of the input signal. They reported that the extent of liquefaction and the displacement of the shallow foundation increase with the increasing amplitude of the input signal. Fioravante (2021) highlighted the effect of the characteristics of the input ground motion on a free-field centrifuge model by varying the arias intensity of the input signal. On the other hand, Rapti et al. (2018) performed numerical simulations to examine the effects of amplitude input signals on an embankment constructed on liquefiable soil. However, there is limited research on centrifuge models excited by varying only the signal amplitude.

The impact of amplitude on the liquefaction phenomenon and the response of an embankment constructed on liquefiable soil is presented in this article. Two comparable centrifuge models were subjected to sinusoidal signals with different amplitudes. The experimental results were analyzed in terms of accelerations, pore pressures, and displacement responses to highlight the effects of the amplitude of the input signals.

2 CENTRIFUGE MODEL

Two centrifuge tests were carried out at University Gustave Eiffel - Nantes Campus to study the effect of signal amplitude on the liquefaction response and the behaviour of an embankment. The centrifuge models were excited under 60 g using a 1D shaking table embedded in the swinging basket of the centrifuge

(Chazelas et al., 2008). In this part, the geometry, the preparation and the procedure of the centrifuge tests are presented.

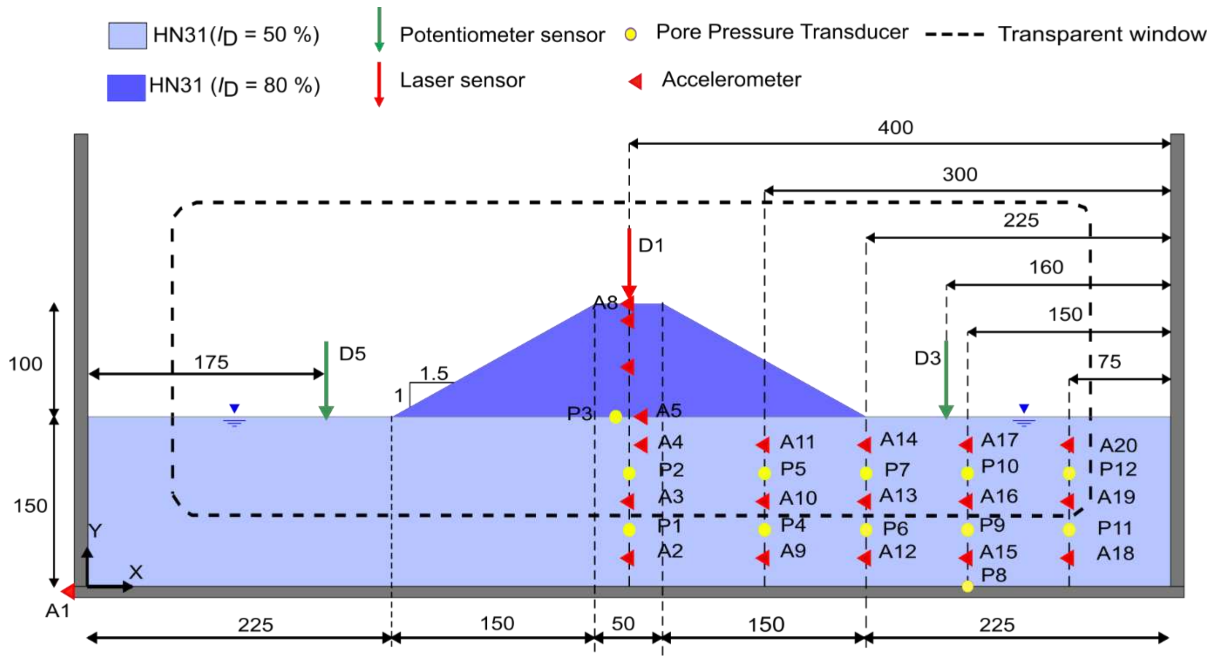

Figure 1. Centrifuge model at scale 1/60th (Dimensions in mm at the model scale)

2.1 Geometry

Fig.1 illustrates the geometry and dimensions of the reduced model (scale 1/60). The reduced model reproduces at prototype scale a 6m embankment, with a slope 1/1.5, constructed on a 9m liquefiable ground layer according to the scaling laws (Garnier et al., 2007).

2.2 Model preparation

The reduced model was prepared in a rigid container following specific steps. The followed steps and the effects of the rigid boundary of the container were discussed in Saade et al. (2023a, 2023b).

First, the liquefiable ground, characterized by a relative density equal to 50% ± 2%, was prepared with clean Hostun sand HN31 (Table 1) using under-compaction method (Ladd, 1974). Then, a flat layer, characterized by a relative density equal to 80% ± 1.5 % was air pluviated with the same clean Hostun sand HN31 using an automatic sand hooper. This pluviated layer was carefully trimmed using a vacuum cleaner to sculpt the desired geometry.

Table 1. Properties of clean Hostun sand HN31 (Benahmed et al.,2015 ; Gobbi et al.,2022)

Sand	D_{50} [mm]	e_{min}	e_{max}	G_s	ρ_{dmin} [g/cm^3]	ρ_{dmax} [g/cm^3]
HN31	0.35	0.656	1.049	2.65	1.33	1.6

The liquefiable ground was fully saturated at 1g in a vacuum chamber using viscous fluid to satisfy the diffusion and dynamic time scaling laws during centrifuge test (Garnier et al., 2007). The used viscous fluid had a viscosity 60 times higher than the water which and was prepared by mixing water with HPMC (HydroPropyl MethylCellulose) (Escoffier and Audrain, 2020). During the construction, the model was instrumented by different types of sensors: accelerometer, pore pressure transducer, laser and potentiometer, as presented in Fig.1.

2.3 Centrifuge test procedure

After the preparation process, the model was transported to the centrifuge and spun up to 60g. At 60g, the model was excited by a sinusoidal signal as presented in Fig.2. The input signal was characterized by a predominant frequency equal to 1.5Hz at prototype. For each test, a specific target amplitude signal (a_{max}) was adopted as presented in Table 2: 0.2g at prototype considered in this study as strong input and 0.1g at prototype considered as weak input.

Table 2. Characteristics of the centrifuge tests

Test Number	Input name	Target a_{max}
1	Weak input	0.1g
2	Strong input	0.2g

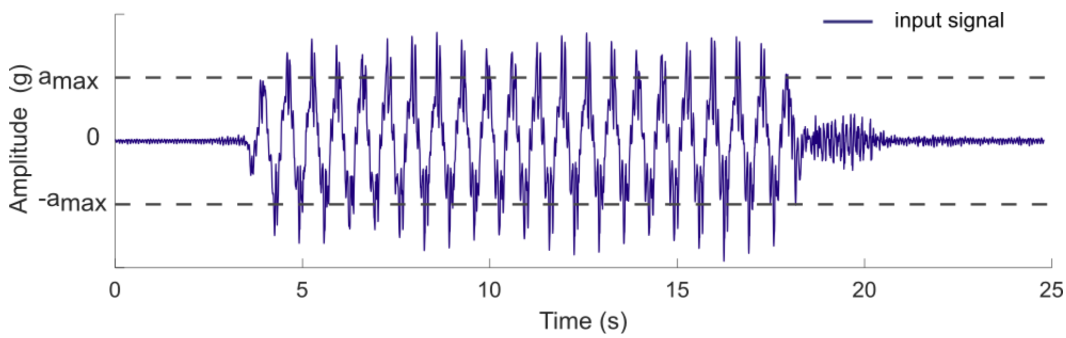

Figure 2. Input signal applied in the centrifuge test

3 EFFECT OF AMPLITUDE ON LIQUEFACTION RESPONSE

The influence of the amplitude of the input signal on the liquefaction response is presented in this section. The effect was examined through pore pressures and acceleration responses recorded during the centrifuge tests.

3.1 Pore pressure response

Fig.3 shows the distribution of the maximum excess pore pressure ratio reached in the two centrifuge models during weak and strong input. This representation allows the identification of the liquified zones during the different inputs. During both inputs, the full liquefaction did not happen under the embankment, where the excess pore pressure remained below 50% of the initial effective vertical stress, which agrees with Koga and Matsuo (1990).

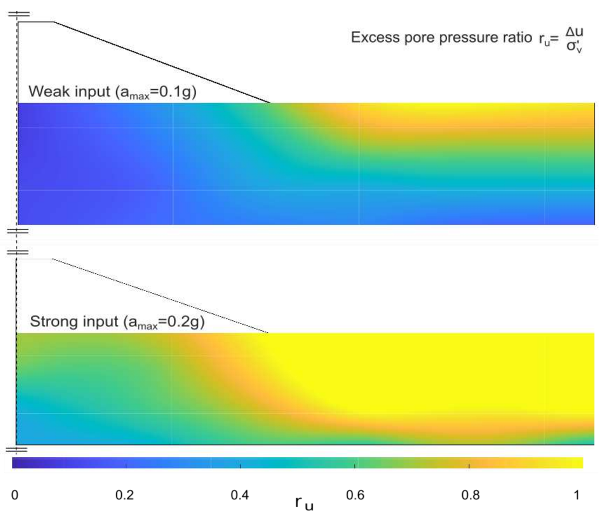

Figure 3. Distribution of maximum pore pressure ratio during weak input (0.1g) and strong input (0.2g).

However, the liquefaction happened under free ground surface where the excess pore pressure ratio reached 100% of the initial vertical stress (yellow zones in Fig.3). During weak input, the liquefied zone reached a shallow depth of up to 3 m, while during strong input, the liquefied zone developed and extended more intensively, reaching the position under the toes of the embankment and a depth of up to 6 m. Therefore, the extent of liquefaction depends on the amplitude of dynamic excitations. These observations are in accordance with what was observed and reported by Jafarian et al. (2017) and Mehrzad et al. (2018).

3.2 Acceleration response

The effect of amplitude was also evaluated through the acceleration response recorded during centrifuge tests. In this part, a time-frequency analysis was adopted to analyze the effect of the amplitude by using the Stockwell spectrograms (Kramer et al., 2016) of the acceleration at the positions A18 and A20 under free ground surface as presented in Fig.4.

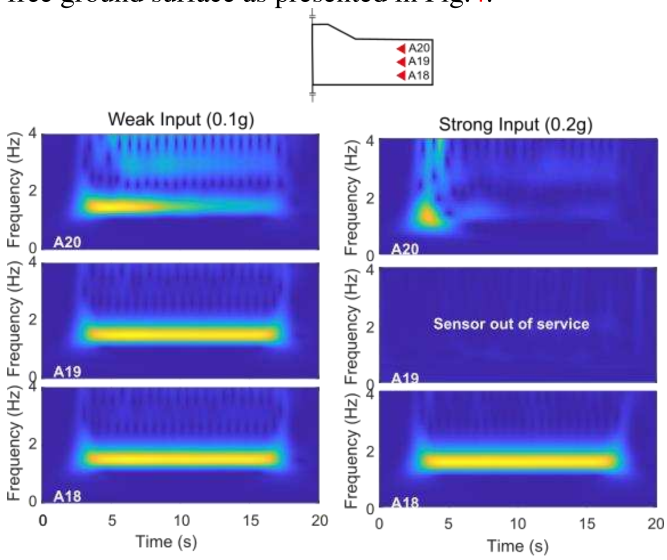

Figure 4. Stockwell representation of the accelerations recorded under free ground surface during strong (0.2g) and weak (0.1g) inputs.

This representation allows the evaluation of the liquefaction initiation by identifying the time at which it occurred (Özener et al., 2020; Manandhar et al.,2021). At a deeper position under the free ground surface (A18) where no liquefaction was observed, the

dominant frequency content remained constant throughout both inputs.
However, at the shallower position (A20), high-frequency components first appeared and then vanished rapidly, which indicates the initiation of liquefaction. In the case of the model subjected to strong input, time-frequency analysis revealed that liquefaction occurred at approximately 5 s when the predominant frequency disappeared. While, during the weak input, the liquefaction took more time to be initiated and was triggered after around 8 s. These observations reveal that the signal amplitude not only affects the extent of the liquefied zones but also affects the time required to initiate the liquefaction in the ground layer as also observed by Jafarian et al. (2017).

4 EFFECT OF AMPLITUDE ON EMBANKMENT DEFORMATION

The influence of the amplitude of the input signal on the embankment response is studied in this section through the deformation pattern and the vertical displacement recorded during the tests.
As reported by Saade et al. (2023a) and shown in Fig.5(a), during the strong input, the embankment was subjected to an important crest settlement followed by a lateral displacement of the embankment toes which can lead to a heave in the free ground surface. Fig.5(b) and 5(c) show the comparison between the models subjected to weak and strong inputs in terms of, respectively, crest settlements and vertical displacements of the free ground surface recorded during tests. A high crest settlement of around 0.7m was observed during strong input, while a smaller settlement was recorded during the weak input. The amplitude of the signal highly affects the crest settlement. The embankment settled 12% of its height with an amplitude of 0.2g and approximately 2% of its height with an amplitude of 0.1g. The fact that embankment crest settlement increases with the increasing amplitude of the input signal aligns with the observations made by Esmaeilpour et al. (2022) regarding the shallow foundations.
The vertical displacement observed at the free ground surface gives insights into the lateral displacement of the embankment toes. A heaving of 0.04 m at the free ground surface was observed with strong input, while a small settlement was recorded during the weak input. These observations indicate that the lateral displacement of the embankment toes is also limited with weak input. In addition, it should be noted that the observed small settlement does not exclude the possibility of the lateral displacement of the embankment toes taking into account that the rigid boundary of the container and the self-weight of the potentiometer at 60g can increase the settlement and at the same time limit the heaving during centrifuge tests.

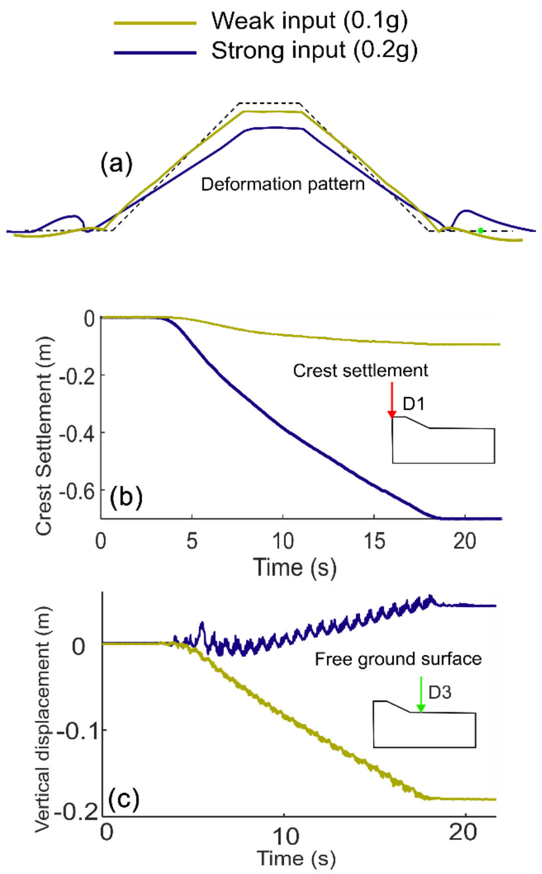

Figure 5. Embankment response during strong and weak input: (a) deformation pattern, (b) crest settlement, and (b) vertical displacement of free ground surface.

5 CONCLUSION

In this study, two centrifuge tests were conducted to study the effect of amplitude signals on the liquefaction phenomenon and the response of an embankment constructed on liquefiable soil. Two amplitude signals were adopted: a high amplitude for strong input and a small amplitude for weak one. Based on the experimental results, the following conclusions can be drawn:

- During the strong and the weak signal, the liquefaction happened under the free ground surface at shallower positions, observed with the excessive pore pressure reached. On the contrary, liquefaction did not occur at deeper positions and under the embankment.
- During weak input, the liquified zones were limited to shallower depths, not exceeding 3 meters. While, during strong input, these zones were largely extended, propagating to deeper positions (6 meters) and under the embankment toes.

- The liquefaction initiation time was 8 seconds during the weak input signal. This initiation time is longer compared to the model subjected to strong input, where it occurred in 5 seconds.
- The deformation pattern of the embankment was characterized by crest settlement followed by lateral displacement of the toes despite the amplitude signals. This deformation is less pronounced during the weak signal, characterized by 2% crest settlement, compared to the model subjected to a strong signal, which had 12% crest settlement.

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