A Comparison between the Dynamic Behaviour of Flexible Dual Row Walls Founded in Dry and Liquefiable Sands

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ABSTRACT

The 2011 Tōhoku earthquake and Tsunami event devastated large parts of the Japanese coastline, causing widespread damage to infrastructure and claiming many human lives. The dual row wall concept is potentially a robust and efficient sea wall design. However, loss of soil strength and stiffness from earthquake induced liquefaction is a prospective design concern. Evaluating the resilience of the dual row system to earthquake loading is a complicated soil-structure-interaction problem even when the walls are founded in dry ground. Further, soil liquefaction fundamentally changes the seismic wall and soil response. Centrifuge modelling provides an avenue to explore the dynamic behaviour. Dynamic testing of small scale centrifuge models of the dual row wall systems, founded in dry and liquefiable sands is detailed. Recorded wall and soil accelerations are considered and the impact of excess pore pressure generation on the shear stress transmission highlighted. Observable changes in the dynamic shear stress-strain behaviour of the soil rationalise the system responses. A modified approach to inferring the wall displacements from the accelerations and discrete displacement measurements is discussed. Consistency between the results is verified and the differing displacement modes obtained are considered in the context of the overall soil behaviour.

Key words: *Disaster Prevention, Tsunamis, Centrifuge Modelling,*

1. Introduction

1.1. Motivation for Study

The 2011 Tōhoku Earthquake and Tsunami event highlighted the importance of Civil Engineering in protecting coastal communities. In the face of increasingly extreme natural hazards, both practical solutions from industry and rigorous academic understanding is vital to form a globally resilient society.

The Dual Row Wall concept, which offers enhanced protection against earthquake induced Tsunamis, centres on implanting two parallel rows of sheet piles into an existing coastal levee. A soil infill is placed between the walls and the pile heads connected by tie rods. A schematic illustration is shown in **Fig. 1**. Further, the practical implementation of this system, as constructed by Giken Ltd. in Kochi Japan is also shown. The photos highlight the integration of the defence into the coastal scenery and urban infrastructure.

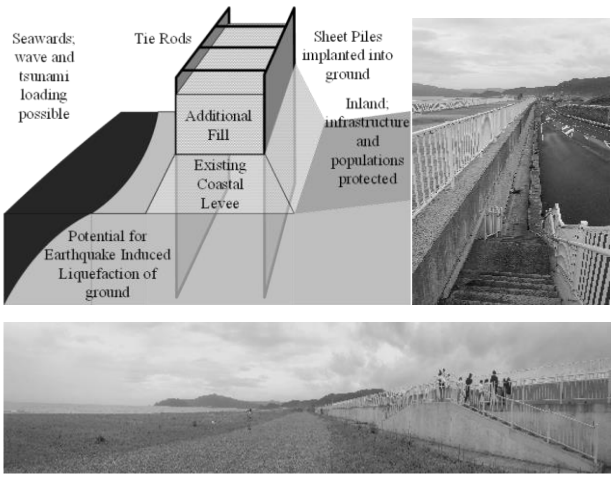

Fig. 1 Dual Row Retaining Wall Concept and photos of implementation by Giken Ltd. in Kochi, Japan

1.2. Objectives of Investigation

The lateral capacity of the dual row system arises from a combination of the strength and stiffness of both the structural elements and the soil infill. However, the evaluation of the dynamic performance of the system is crucial to adjudge the resilience of the dual row wall system to a combined earthquake and Tsunami event.

The dynamics of the soil structure interaction of the dual row wall system, even in dry sand, poses a significant academic challenge. There is also additional complexity added by founding these systems in saturated strata, particularly if earthquake induced liquefaction can occur.

In this work the results from two dynamic centrifuge tests are reviewed. The same dual row wall system is tested under two cases; firstly founded in a dry sand bed and secondly in a liquefiable deposit. An overview of the mechanisms developed, structural performance and key design considerations are compared and contrasted between tests. The unique academic challenges and considerations for practicing industry of this potential coastal defence are summarised.

2. Methodology

2.1. Centrifuge Modelling at the Schofield Centre

Similarity between the soil behaviours of the full sized dual row walls and the small scale models is achieved using a centrifuge to elevate the model stresses. The 10 m Turner beam centrifuge (Schofield, 1980) was used to apply an acceleration of 60 g at a point 1/3 the height of the dual row wall system. A high power Earthquake Actuator was used to impart the lateral shaking onto the model (Madabhushi *et al.* 1998 & 2012).

Table 1. Details of wall system at prototype scale

Variable	Value
Height (m)	12
Embedment Depth (m)	6
Wall Thickness (m)	0.18
Bending Stiffness (MNm^2 /m)	34
Tie Length (m)	6

Fig. 2 presents the cross sections of the two centrifuge tests discussed in this paper and indicates the relative density, I_d, of the soil. Test identifiers DF666 and SF666 are assigned to the dry and saturated tests respectively. The full prototype dimensions of the wall system used in both tests are furnished in **Table 1**. The results presented in this paper represent walls with flexural stiffness at the lower end of those which would be used practically. This was done to facilitate better understanding of the soil-structure interaction.

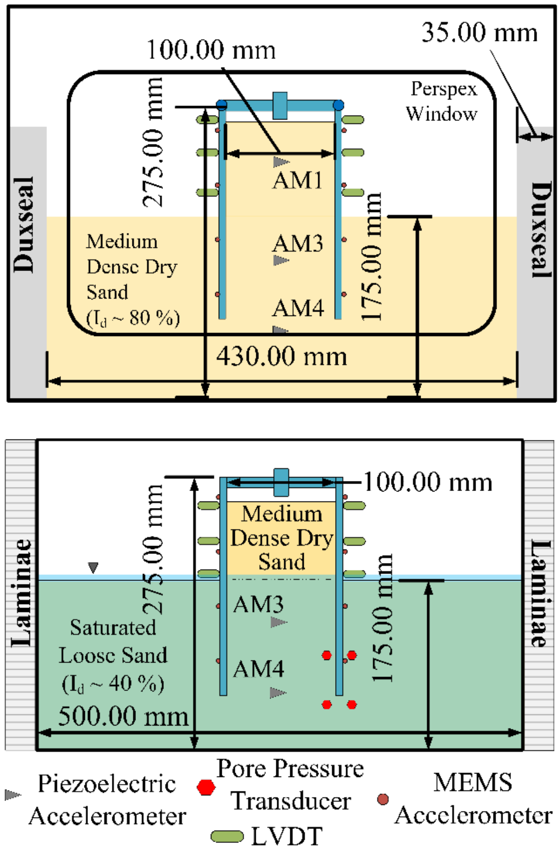

Fig. 2 Centrifuge cross sections of test DF666 *(top)* and SF666 *(bottom)*

2.2. Model Details, Preparation and Instrumentation

The complete model system was prepared at 1 g with S28 Hostun sand deposited in and around the dual row wall system using an automatic spot pluviator (Madabhushi *et al.* 2006). Test SF666 was flushed with CO_2 and saturated with 60 cSt fluid under vacuum with a controlled mass flux.

The installation of the wall systems at 1 g means the construction sequence is not well captured by the centrifuge models and the initial static conditions not readily comparable to the field. However, under moderate to large earthquake loading as the soil must tend to the same limit states the dynamic results from the centrifuge models become more analogous to the field case.

The instrumentation in the models shown in **Fig. 2** includes miniaturized sensors to register the soil and wall accelerations, pressures in the pore space and displacements of the walls.

It is also important to comment on the different model containers used. For the dry test a rigid container with a Perspex front was used to facilitate in-flight imaging of the model cross section. The use of Duxseal inserts can effectively minimise stress reflections from the boundaries (Campbell *et al.* 1991), especially for the limited lateral deformations generated in dry sand models. However, for SF666 where liquefaction was expected it was crucial to use a laminar box where the free laminae can deform equivalently to the enclosed material.

The following sections consider the results from the two tests described. Unless otherwise stated, the results will be given at the prototype scale and the sign convention that leftward displacements are positive is adopted. Heights are measured relative to the ground surface.

3. Results

3.1. Accelerations and Excess Pore Pressures

The accelerations transmitted through the soil are drastically altered by the presence of a liquefiable soil layer. **Fig. 3** shows the recorded accelerations in the soil infill between the walls of tests DF666 and SF666. For the dual row wall founded in dry soil, there is a clear amplification of the accelerations as they propagate vertically through the infill.

By contrast, the propagation of accelerations in SF666 exhibits large attenuations relative to the input motion. By founding the dual row wall system in liquefiable ground the ability of the soil to transmit shear stresses has clearly been altered. The altered dynamic response of the soil may be attributed to the generation of excess pore pressures and thus a change in the material behaviour. With due care to the filtering parameters selected, the dynamic shear stresses and dynamic shear strains can be calculated from the recorded soil accelerations (Brennan *et al.* 2005). In the loops presented in this work, the lower and upper bandpass limits were 0.4 % and 90 % of the Nyquist frequency.

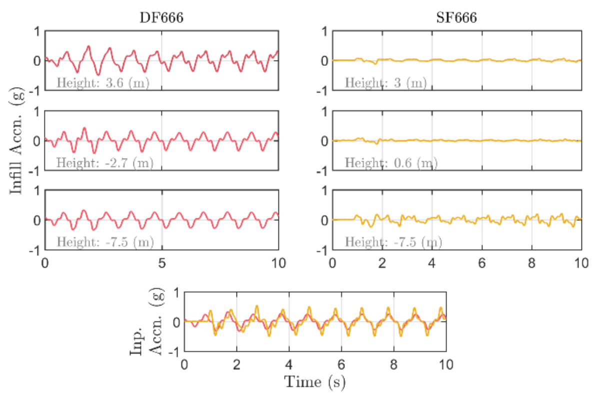

Fig. 3 Comparison of Infill Soil Accelerations between DF666 and SF666

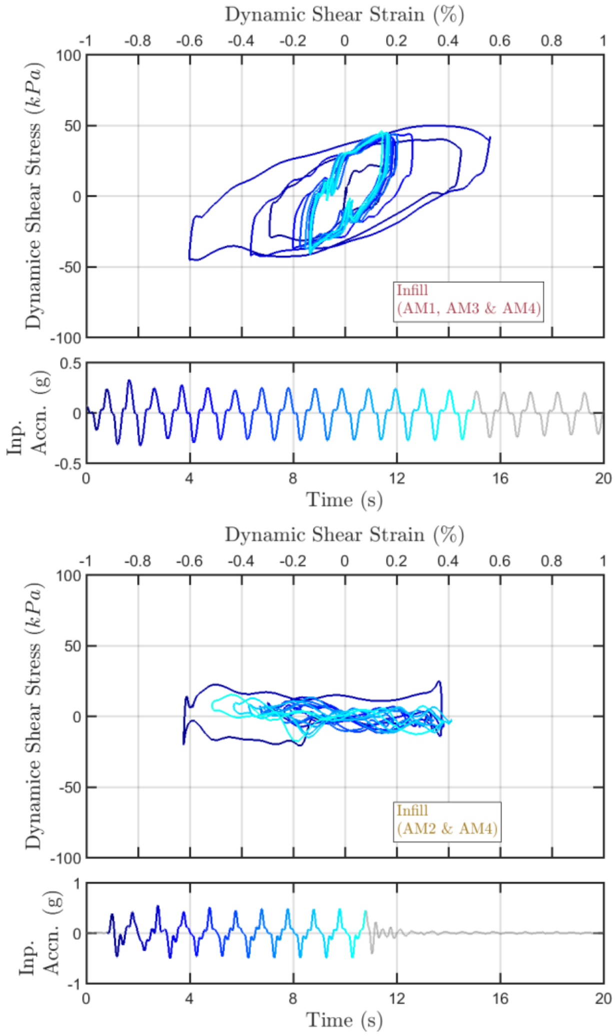

Fig. 4 Dynamic Shear Stress Strain Loops from the infill of DF666 *(top)* and SF666 *(bottom)*

Fig. 4 exemplifies the changes shown by **Fig. 3**. Continued cyclic loading actually results in a stiffening effect on the dry infill; the dynamic shear strains reducing dramatically by later cycles. This may be attributed to

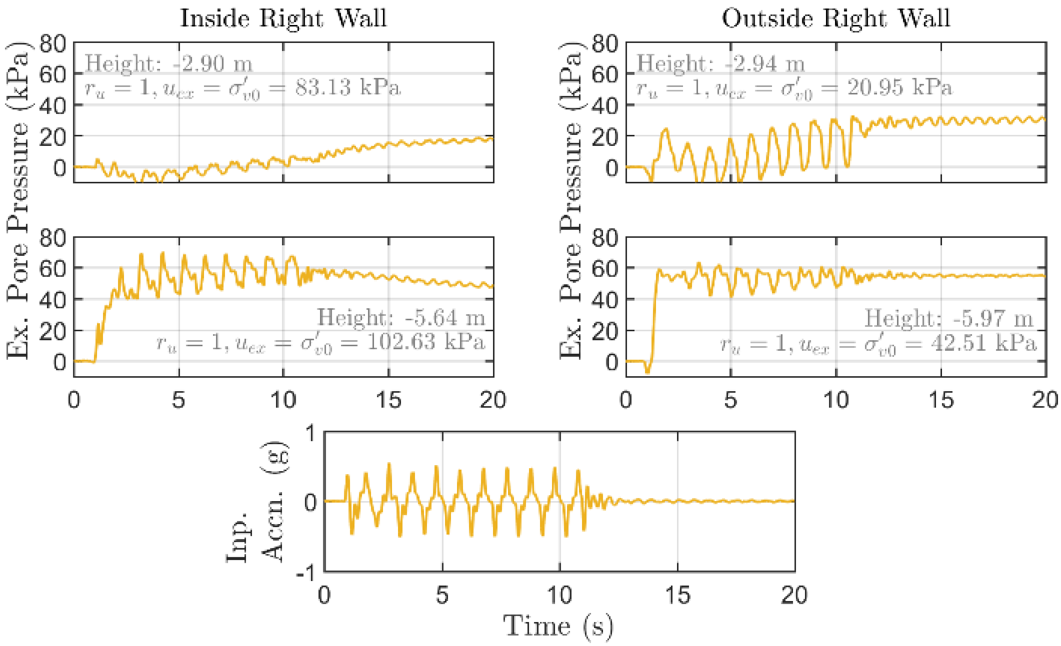

Fig. 5 Excess Pore Pressures generated around the right wall in test SF666

shear induced volumetric strains and the locking in of soil stresses under the prolonged earthquake motion (Madabhushi and Haigh, 2018).

For test SF666, **Fig. 4** shows the reduction of the dynamic shear stresses transmitted but also shows that comparable shear strains are developed. Though the liquefying soil softens considerably, the system is not completely isolated from the ground motion and a cycling in the dynamic response persists.

To gain further insight, the excess pore pressures developed inside and outside the right wall in tests SF666 are plotted in **Fig. 5**. The generation of large positive excess pore pressures leads to a corresponding drop in effective stresses and thus the ability of the soil to transmit the accelerations. However, there is considerable cycling of the excess pore pressures during the shaking which helps rationalise the complex dynamic behaviour of the soil shown in **Fig. 4**.

Fig. 5 additionally shows the excess pore pressure required for ‘full liquefaction’, based on the excess pore pressure ratio (r_u). The definition in **Eq. (1)** shows that full liquefaction, corresponding to r_u = 1, means the excess pore pressure (u_{excess}) is equal to the initial vertical stress (σ'_{v0}).

$$r_u = \frac{u_{excess}}{\sigma'_{v0}} \quad (1)$$

It is worth noting that the practical use of this definition with the dual row system is complicated by a number of factors. The initial vertical stress is calculated assuming a geostatic distribution caused by the soil’s self-weight. Broadly speaking, this correctly implies that the large overburden pressure in the infill increases the resilience of the soil between the walls to liquefaction. However, there is likely a bulb of increased vertical stresses below the dual wall system, as well as changes to the vertical stresses from the shear stresses applied by the walls, which should be accounted for.

Nevertheless, when comparing the values of the excess pore pressures in **Fig. 5** with the approximate values needed for full liquefaction a number of trends may be discerned; during the shaking the relative suction developed between the walls could help limit the wall displacements. Externally though the soil tries to liquefy, the co-seismic drops in excess pore pressure reveals that the soil will cyclically regain some strength and stiffness which could also help reduce the overall wall displacements.

Finally, **Fig. 7** offers a comparison of the accelerations measured along the height of a single wall from both tests. The disparity between the soil behaviour of the two tests manifests in quite different structural accelerations experienced by the walls.

For DF666, both the wall and soil system experience

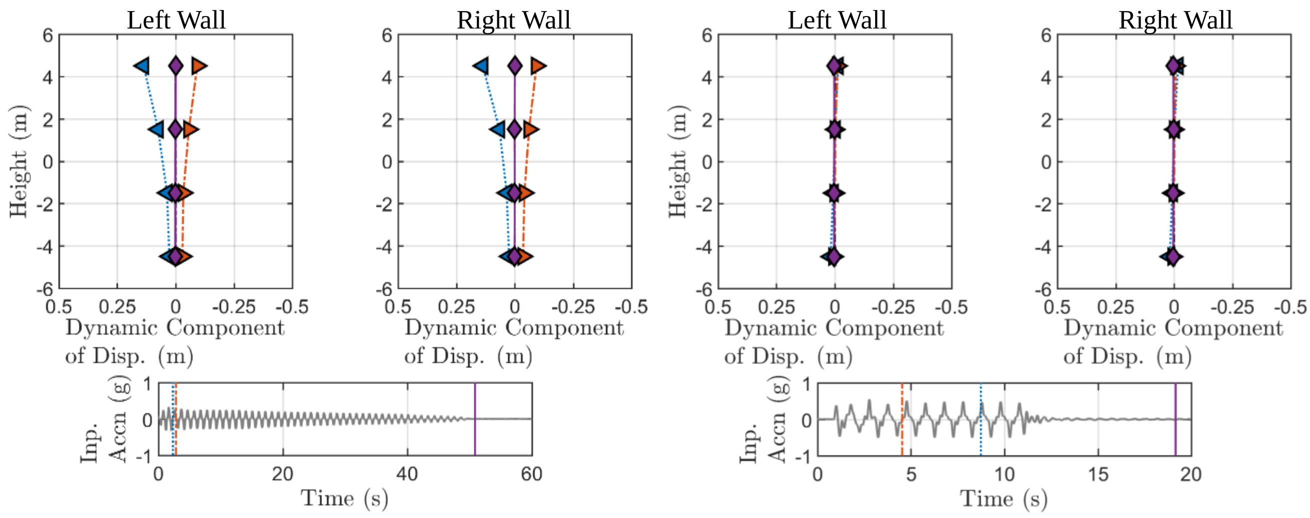

Fig. 6 Calculating Dynamic Displacements from Left and Right Wall Accelerations for DF666 (left) and SF666 (right)

amplified vibrations with height. Considering the wall and soil accelerations together suggests that the system dynamically displaces in a 'cantilever' type mode when founded in dry sand. Further, the appearance of vibrations at double the driving frequency gives some clues as to the role of the tie rod in enforcing symmetric deformations at the heads of both walls.

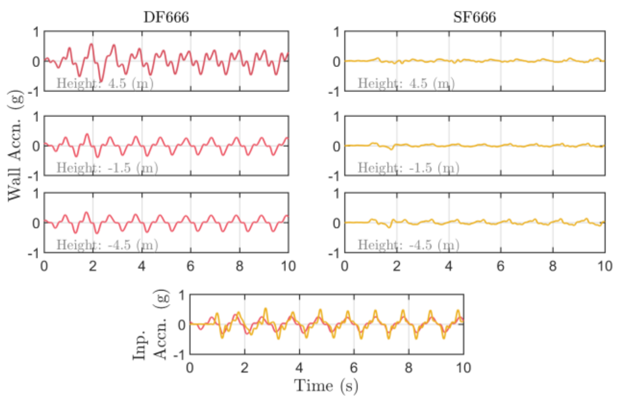

Fig. 7 Comparison of Wall Accelerations between DF666 and SF666

From the results of SF666 the partial isolation of the wall from the ground accelerations is highlighted. The soil was softened and moderate dynamic shear strains inferred. However, the subtly of the co-seismic excess pore pressure variation could have large implications for the dynamic displacements that actually accrue, which are now considered.

3.2. Wall Displacement

It is clearly desirable to obtain the total wall displacement to ascertain the performance of the dual wall systems. If model containers with Perspex windows can be used digital imaging techniques are often the most reliable and direct way to obtain the total static and dynamic deformations. However, when this method is not available, such as in test SF666, less direct methods must be pursued. The use of a combination of wall acceleration measurements from MEMS and individual displacement measurements from LVDTs is now detailed.

The wall accelerations can be double integrated with respect to time to obtain the temporal displacement variations. However, this process can introduce drifts in to the integrated signal which are not physically justifiable i.e. non-zero velocities at the end of the shaking event. To remove these, a 'high-pass' filter can be applied to the signals obtained from the integration. This will leave only the dynamic component of the measured displacements, with the removed components being a combination of physically real permanent displacements and unphysical integration drifts.

In **Fig. 6** the dynamic component of the displacements inferred from the wall acceleration measurements in DF666 and SF666 are illustrated. The dynamic distributions shown are at opposite instants of applied acceleration. Further, it is confirmed that the dynamic displacement after the shaking ceases is zero.

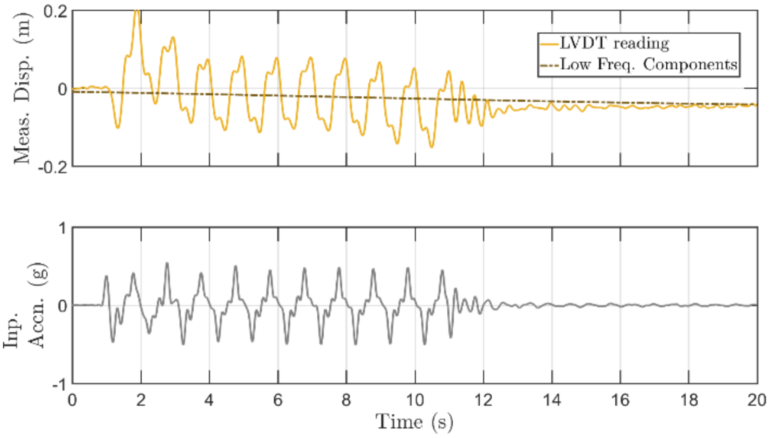

Fig. 8 Illustration of obtaining an estimate of permanent relative displacement from a LVDT signal

For test DF666 the results confirm that the dual row wall founded in dry sand vibrates in a 'cantilever' type mode as suggested earlier. It is thus evident that the wall founded in dry soil will develop flexural bending during the shaking. However, the results also imply that the wall toes dynamically displace. The lack of full fixity from the soil would reduce the dynamic bending moments induced. By contrast to the dry results, the distributions from SF666 reveals very small dynamic displacements are generated during the shaking which also implies the dynamic bending moments generated will be small.

From a structural design outlook, the failure of the wall system in bending might not be critical. This is particularly likely if the systems are founded in liquefiable soil, whereas the total co-seismic and post-seismic displacements may be of greater concern. The LVDTs measure the total lateral displacement of the walls but at only a few discrete locations above the ground level. Further, the dynamic response of these instruments is inferior to the MEMS.

The wall displacements obtained from the LVDTs can be subjected to a 'low-pass' filter to give an indication of the permanent displacement developed co-seismically. It was required to zero the values with respect to those before the earthquake so the displacements calculated must be described as the relative permanent displacements. Further, the small error which can arise when using horizontal LVDTs which are fixed relative to the moving laminae (Aversa *et al.* 2015) was ignored. **Fig. 8** illustrates the decomposition of an LVDT trace from test SF666 in this manner. The time variation of the filtered signal can be interpreted as an estimate of the wall displacement that would persist if the shaking was stopped at that instant.

It is therefore proposed that a combination of the recorded accelerations and LVDT readings can produce more accurate estimates of the total wall displacements. Overall, the permanent components from the LVDT and dynamic component from the MEMS can be combined to give an estimate of the 'total relative displacement' of the walls.

Fig. 9 shows the results of the entire process for both tests DF666 and SF666 at two instants during the applied ground motion and the final configuration after the shaking ceases. The cantilever vibration mode is the dominant source of displacement in DF666. However, following the end of the motion the walls return to a relatively upright position, though with a small amount of permanent toe displacements and curvature locked in. Further, accounting for the permanent wall displacements shows that the final toe displacements imply relative outward displacement, which is physically reasonable as the infill settles downwards and outwards.

By comparison, the displacement mode from SF666 implies moderate toe displacements and much less curvature is developed. The importance of accounting for the total wall displacement in this test is exemplified. Though between the tests the wall systems have the same structural stiffness, relative to the liquefying and thus softening soil in SF666 the system is able to behave more rigidly.

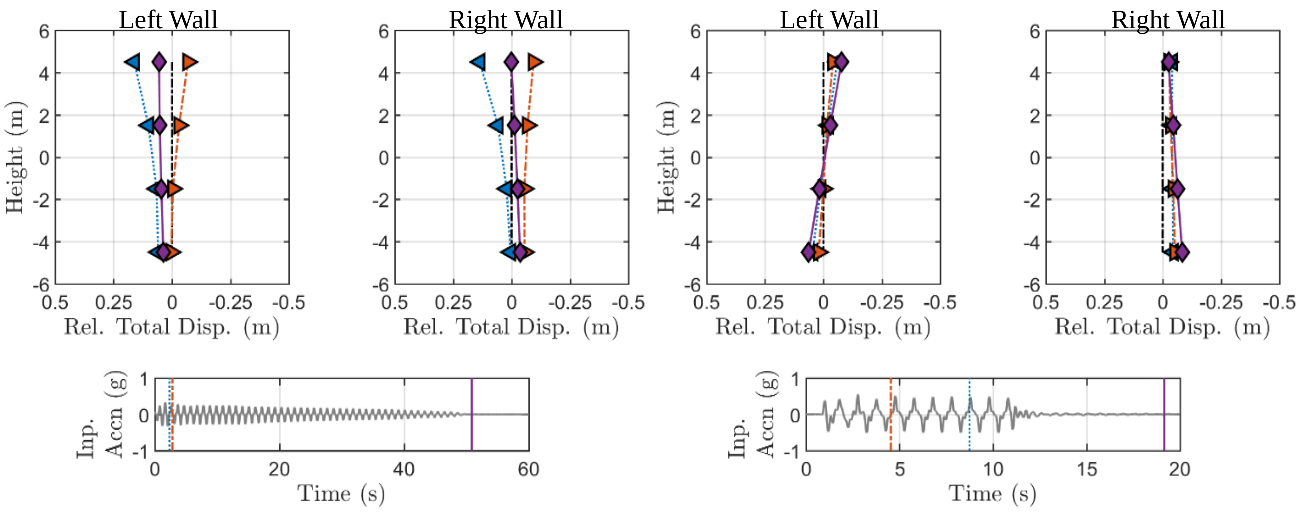

Fig. 9 Calculating Relative Displacements from Left and Right Wall Accelerations for DF666 *(left)* and SF666 *(right)*

Nevertheless, the overall magnitude of displacements for the saturated system are perhaps smaller than expected, particularly when it is remembered that the system was subjected to prolonged large magnitude shaking. A toe displacement of 0.2 m on a 12 m wall corresponds to less than a 1° rotation. The complexity of the soil behaviour, particularly the cycling of excess pore pressures and suction developed between the walls as a result of the shear induced dilation, can limit the total horizontal deformations that are accrued.

However, there is also the potential for vertical settlement of the dual row wall system when founded on liquefiable soils. To obtain an estimate of this, pore pressure transducers were affixed to the dual row wall system. The change of hydrostatic pore pressure before and after the ground motion can then be used to back calculate an estimate of the induced settlement of the wall system. For test SF666, the earthquake motion discussed resulted in an overall vertical settlement of 0.38 m. The impact of the model dimensions and particularly the proximity to the base of the container could have a bearing on the vertical settlement observed. Nevertheless, the liquefying system has some in-built resilience against vertical settlement as the overburden pressure from the infill reduces the extent of liquefaction, as witnessed by the excess pore pressures studied early. Practically, the potential impact of vertical settlement on the ultimate Tsunami load that could be withstood should be borne in mind.

4. Concluding remarks

A combined effort from the academic community and industrial practice is required to engineer a safer, economical and more environmentally friendly future. In particular, there is a growing need to protect coastal populations from earthquake-induced tsunamis. The construction of dual row walls represents a complex but potentially lifesaving application of press-in engineering.

In this work, a comparison between the dynamic performance of the dual row wall system founded in medium-dense dry sand versus a looser, liquefiable soil deposit is considered.

The two dynamic centrifuge tests conducted reveal interesting differences between the seismic responses of the two relatively flexible systems. These could have large implications for the practical design of the dual wall system in the field.

Accelerations obtained from the walls and the soil infill show that significant amplifications of the ground motion can occur. A combination of the dynamic component of the integrated wall acceleration data with boundary conditions provided by the static component of the discrete displacement measurements was used to infer the total displacement mode. For the dry wall a ‘cantilever’ type vibration was observed, though the system developed very little permanent displacements. The insight offered by the dynamic shear stress-strain loops show continued cycling results in a stiffening of the soil infill - which may be attributed to a combination of the shear induced volumetric strains and 'locked-in' soil stresses – and can explain the resilience of such systems.

When founding the dual row wall system in a liquefiable soil there is a greater tendency for toe displacement of the walls and the excess pore pressure generation leads to observable drops in the stiffness of the soil. However, the accumulation of wall displacement is restricted by the complicated shear induced cycling of excess pore pressures. In this regard, the performance of the flexible dual row wall system founded completely in a liquefiable ground is also shown to be quite resilient to large cyclic ground motions.

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