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Performance of Multi-Block Gravity Quay-Wall Subjected to Strong Earthquake Motions: Numerical Simulation of Centrifuge Test

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ABSTRACT

Gravity quay wall structures have repeatedly suffered substantial outward displacement and rotation even when subjected to moderate earthquake shaking. The dynamic response of gravity quay walls is strongly affected by non-linear soil behavior accompanied by development of excess pore pressures. Effective stress numerical analyses are conducted aiming to simulate a seismic centrifuge test of a multi-block gravity quay-wall, replica of a typical wall at Piraeus port in Greece subjected to two successive earthquakes with increasing intensity. Apart from predicting the experimental response, the study aims at shedding light to the mechanisms involved in the seismic performance of the multi-block gravity quay-walls, in terms of displacement, rotation, backfill settlement and block-sliding.

Keywords: quay-wall, seismic effective stress analysis, coupled flow dynamic response, FLAC

INTRODUCTION

Gravity quay wall structures have repeatedly suffered substantial outward displacement and rotation even when subjected to moderate earthquake shaking. . (e.g. Pitilakis and Moutsakis, 1989; Egan et al., 1992; Iai et al., 1994; Sugano and Iai, 1999; Inagaki et al., 1996; Tasiopoulou et al., 2013, 2014, 2015). The dynamic response of gravity quay walls is strongly affected by non-linear soil behaviour. Development of excess pore pressures and accumulation of shear and volumetric strains both at the retained and the foundation soil, produces shear strength degradation which may be accompanied by liquefaction. The above phenomena are further complicated when accounting for soil-structure interaction. The strong rocking of quay walls (due only to their inertial forces), when founded on a compliant foundation soil in combination with the one-sided action of earth pressures leads to the accumulation of horizontal displacement and rotation towards the seaside.

In this paper, the seismic response of a block-type gravity quay-wall is investigated by means of a coupled effective stress analysis considering pore water pressure build-up due to cyclic loading. The analysis is performed with the finite difference code FLAC via the use of the UBCSAND constitutive soil model (version 904aR) developed by Beaty and Byrne (1998). At first, a calibration procedure for the model parameters is applied involving fitting against published results from undrained cyclic simple shear tests. A comparison of calculated and measured centrifuge model response (Anastasopoulos et al, 2015) is then presented for two consecutive earthquake motions with increasing intensity, in terms of acceleration, displacement and pore-water pressure time histories. The analysis reproduces the measured response with satisfactory engineering accuracy.

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NUMERICAL MODELING

A dynamic centrifuge model test conducted at the University of Dundee centrifuge facility is examined. The model used a fine quartz based silica sand (HST 95) and simulated the response of a multi-block gravity quay wall made of aluminum alloy, as a replica of a typical wall at Piraeus port in Greece. The sand bed was formed into an ESB (equivalent shear beam) model container by carrying out air pluviation at a relative density of Dr = 80%. It was then saturated with water and subjected to an acceleration field of 60g. A sketch of the experimental setup (including the instrumentation layout) is illustrated in Figure 1. While in flight, a sequence of actual ground-acceleration records were applied at the base of the model as input motion. For more details on the experimental procedure the reader is referred to Anastasopoulos et al (2015).

In previous papers by the authors (Tasiopoulou et al., 2015 and Gerolymos et al., 2015), Class- A predictions for the first acceleration time history (a record from the ML = 5.9 L' Aquila 2009 Earthquake) were presented and compared with numerical predictions. In the present paper, results are also shown for a second earthquake motion, corresponding to Chavriata record from Cephalonia 2014 Earthquake, following the L'Aquila motion after a certain time interval where dissipation of excess pore pressures (consolidation) has occurred (see Figure 2).

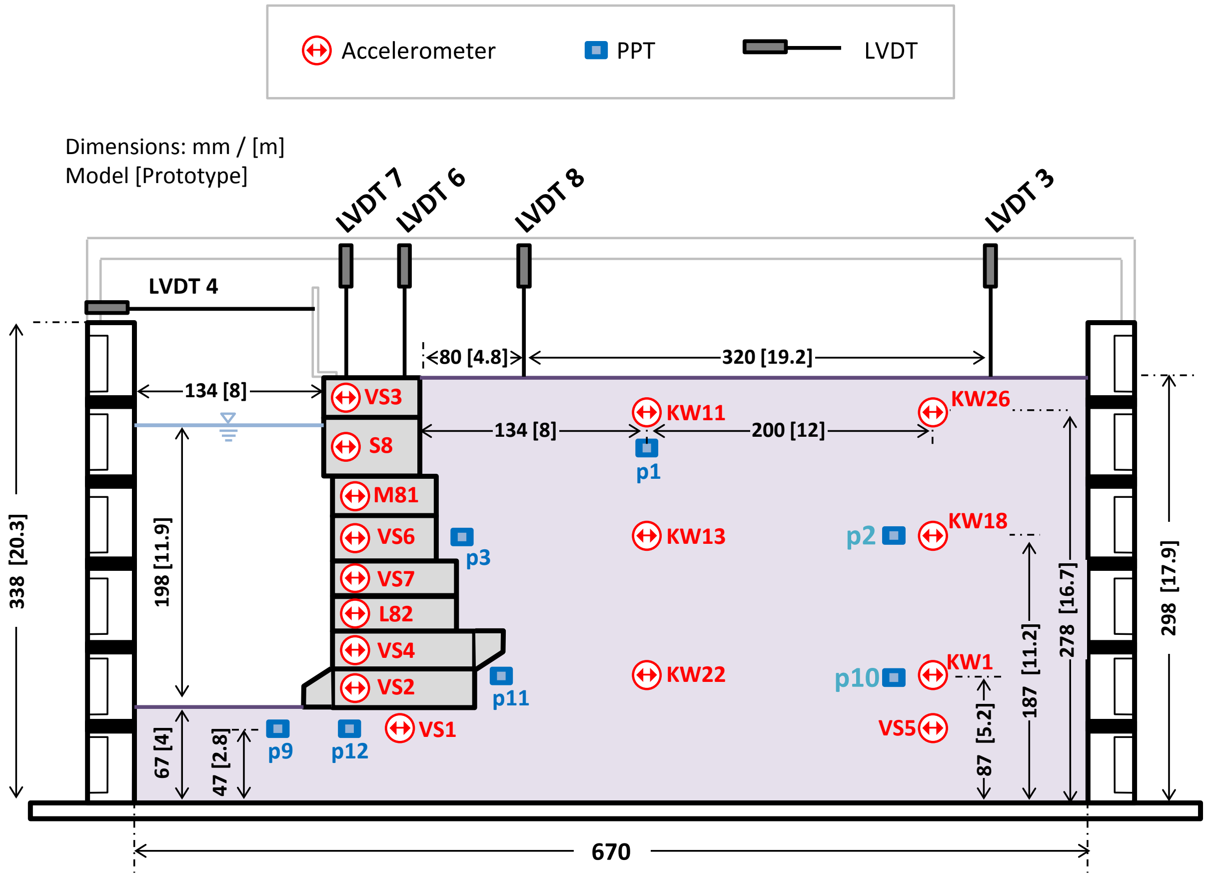

Figure 1. Centrifuge model setup and instrument locations

Numerical effective stress analysis of a section of the centrifuge model is performed in prototype scale with finite difference code FLAC. The finite difference mesh of the model, portrayed in Figure 3, involves a grid spacing of 0.5 m x 0.5 m. The coefficient of hydraulic permeability was estimated to k = 3 x 10^{-4} m/s (in prototype scale) and assumed to be constant throughout the analysis. The analysis is conducted taking into account for material (in the soil) and geometric (interface) nonlinearities. The aluminium alloy frames and rubber spacing layers of the ESB model container were also modelled in detail, assuming elastic behaviour. The contact conditions between the blocks of the quay wall as well as between the quay wall and the adjacent soil were modelled with special interface elements allowing for slippage and gapping via a Coulomb frictional law. The friction interface angles were assumed equal to 18^{o} between the blocks of the quay wall, 10^{o} and 14^{o} at the back and at the base of the wall, respectively, and 10^{o} for the inner vertical edges of the container. The waterfront was simulated through hydrostatic pressures applied to the front side of the wall, as well as the seabed. The input motion sequence in prototype scale, as shown in Figure 2, was applied to the base of the numerical models. UBCSAND constitutive model was used after calibration of its input parameters in order to capture experimental liquefaction resistances curves, illustated in Figure 3. For more details on the calibration procedure, the reader is referred to a previous paper by the authors (Tasiopoulou et al., 2015).

Between the consecutive input motions a certain time interval was used for the dissipation of the excess pore pressures which were developed during the first input motion (L'Aquila 2009). In order to reduce the computational time, the permeability of the backfill and the foundation soil was decreased during the dissipation time interval and it was later recovered to the appropriate value (k = 3 x 10^{-4} m/s) during the second motion (Chavriatta, 2014). No recalibration of the constitutive model was performed for the second following motion.

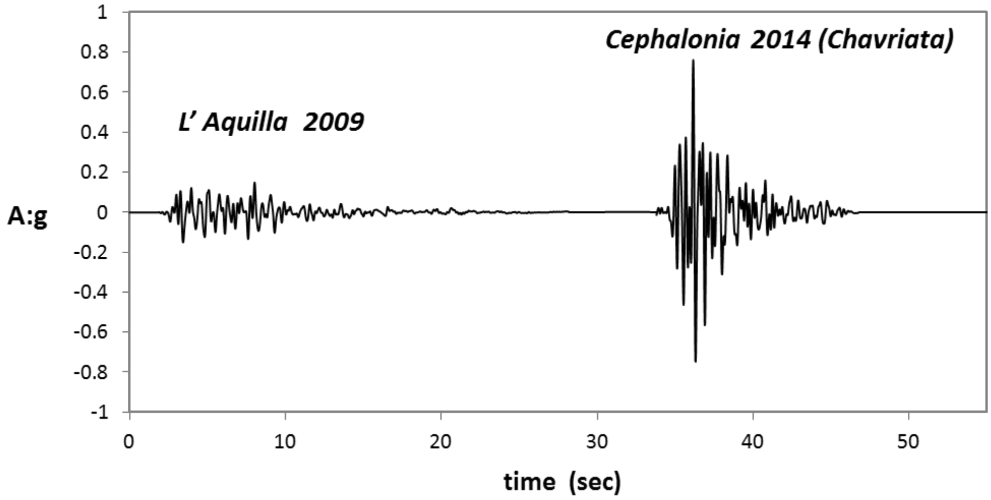

Figure 2. Acceleration time history of input motions applied at the base of the model

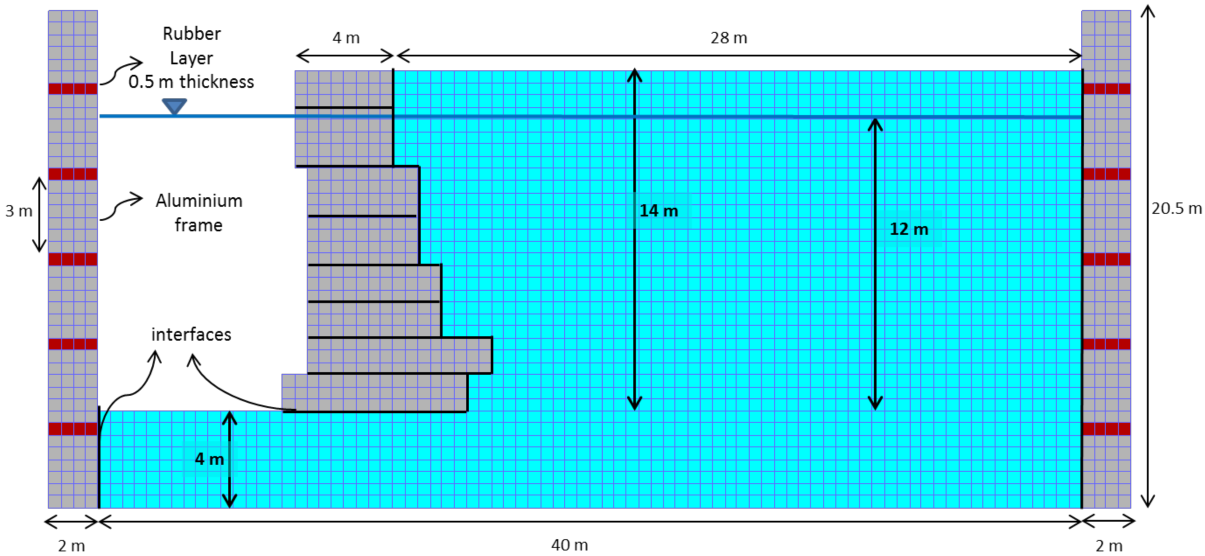

Figure 3. Numerical model in FLAC

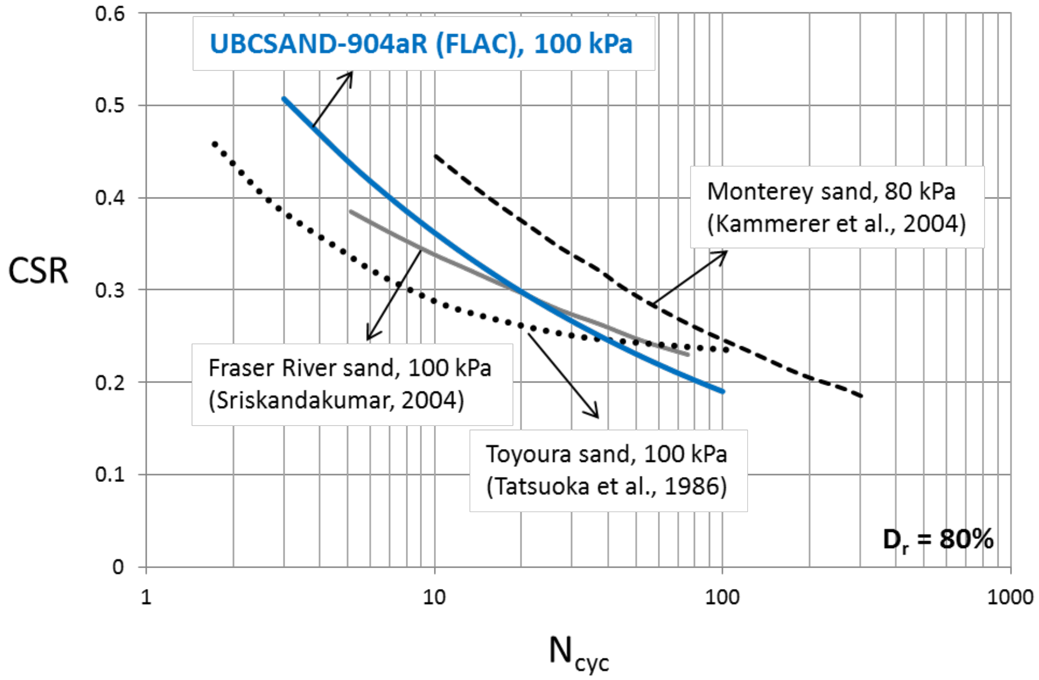

Figure 4. Comparison between predicted and experimental liquefaction resistance curves in undrained cyclic simple shear testing for D_r = 80%.

RESULTS & CONCULSIONS

Indicative predicted and measured performance response, in terms of outward quay-wall horizontal displacement and backfill settlement, is illustrated in Figures 5 and 6. It may be seen that, in general, both the magnitude and the pattern of all time histories are in reasonable agreement for both consecutive earthquake motions. However, numerical analysis predicted larger outward quay-wall displacement, accompanied by consequent larger backfill settlement, than the centrifuge experiment. A possible cause for this discrepancy may be attributed to the densification of the backfill and foundation soil after the first motion. Despite the need for further sensitivity numerical analyses, the fact that the present numerical predictions for two consecutive input motions without recalibration of the constitutive model, is promising and exhibits reliability both to the numerical modeling at hand and the centrifuge experiments.

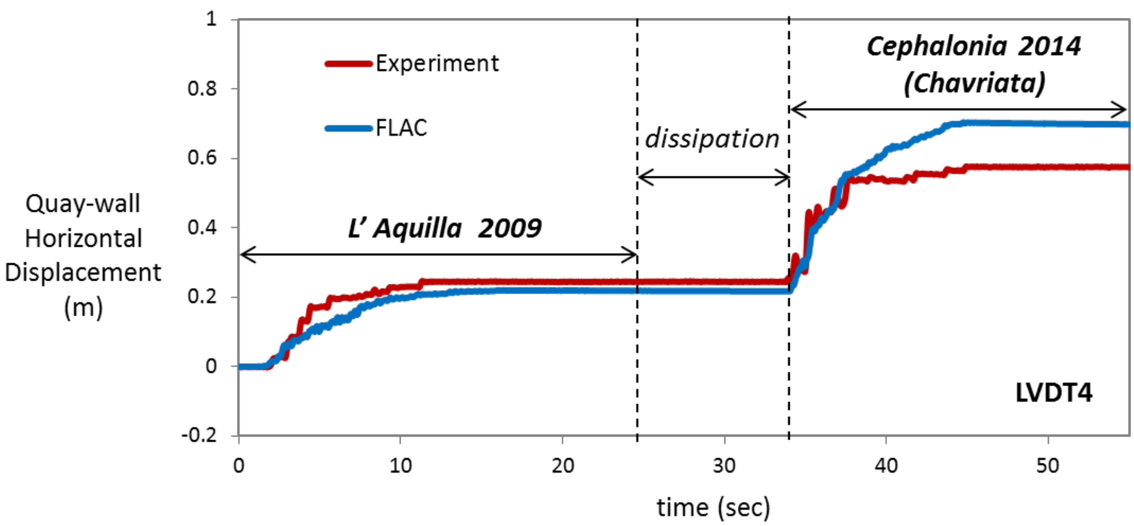

Figure 5. Predicted quay-wall outward horizontal displacement at top (location LVDT4 in Figure 1).

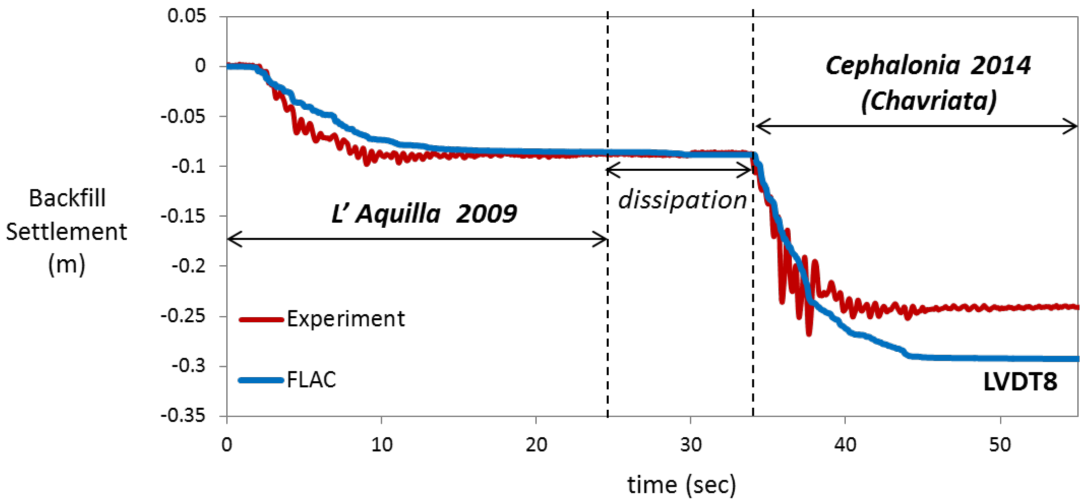

Figure 6. Predicted settlement of the backfill at location LVDT3 in Figure 1.

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