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# Retrofit of existing multi-block quay walls: centrifuge modeling

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**ABSTRACT:** Evidence from recent earthquakes has shown that quay walls are particularly vulnerable to seismic shaking. Being key components of commercial and passenger ports, their seismic damage may incur pronounced direct and indirect losses. To make things worse, the vast majority of ports in Europe's high-seismicity areas (e.g., Greece, Italy), were designed and constructed several decades ago, according to obsolete seismic codes. Such quay walls are typically composed of multiple blocks, resting on top of each other without substantial shear connection. A series of dynamic centrifuge model tests was carried out at the University of Dundee, using the Piraeus Port (Greece) as a case study, to investigate the seismic response of such quay walls and exploit retrofitting methods. The paper presents the physical modelling approach and presents a comparative evaluation of the proposed retrofitted system.

## 1 INTRODUCTION

Quay walls can be particularly vulnerable to earthquakes. Such structures are key components of commercial and passenger ports and of waterfront industrial facilities and terminals. Analysis of case studies from large magnitude historic events, such as the 1989 Loma Prieta earthquake in the USA and/or the 1995 Kobe earthquake in Japan, has demonstrated that failure of quay walls may have a vast impact on the long-term functionality of the port and thereby significantly affect the economy at a national or even international level. For example, the Industrial Container and Passenger Terminals of the Port of Kobe (Japan) have still not fully recovered from the indirect damage that was inflicted to them by the devastating 1995 Mw 7 earthquake. Today (21 years later), although the infrastructure has been fully restored (the direct damage is estimated to be of the order of \$10 billion), the Port is still struggling to overcome the indirect damage it sustained (which exceeded \$6 billion within only the first 9 months after the earthquake).

The seismic performance of single-block quay walls has been extensively studied analytically and experimentally. Analytical studies have focused on the development of sophisticated effective-stress constitutive models, capable of simulating pore-pressure build-up, liquefaction, and lateral spreading (Iai et al., 1998, Madabhushi & Zeng, 1998, Yang et al., 2001, Nozu et al., 2004, Berry & Madabhushi, 2007, Dakoulas & Gazetas, 2008, Alyamiet al.,

2009). A variety of experimental studies have been conducted, employing shaking table (Inagaki et al., 1996, Iai & Sugano, 2000] and centrifuge model testing (Zeng, 1998, Lee, 2005). The generation of excess pore pressures during seismic shaking has been shown to be a crucial factor. For example, Zeng (1998) showed that the generation of excess pore pressures in the surrounding soil leads to a complex behaviour that cannot be determined using conventional methods, such as the Mononobe-Okabe (Okabe, 1926, Mononobe & Matsuo, 1929) and Richard & Elms (1979) methods, which are based on Coulomb's limiting equilibrium method and Newmark's sliding block concept, respectively.

As with the current building stock, the vast majority of existing quay walls were designed and constructed several decades ago according to obsolete seismic codes. Typically composed of simply supported multiple blocks, such quay walls may be particularly vulnerable to strong seismic shaking. Pitilakis & Moutsakis (1989) studied numerically the performance of such a multi-block quay wall during the 1986 Kalamata  $M_s$  6.2 earthquake (Greece). However, in their study, the quay wall was simulated as a single block. Attempting to shed light on this interesting system through a more comprehensive simulation, Anastasopoulos et al (2015) studied the seismic response of a multi-block quay wall which resembles the relatively old port of Piraeus (Athens, Greece). They conducted dynamic centrifuge testing and concluded that even seismic motions of medium intensity, equivalent to code requirements, may in-

cur significantly large wall displacements practically leading to failure. Therefore, it was decided that investigation of a retrofitted system, which would aim to reduce the permanent displacements of the quay wall, would be worthwhile. Hence, a second set of centrifuge tests was carried out, which is the scope of this paper

## 2 DEFINITION OF THE STUDIED PROBLEM

As depicted in Figure 1, the studied quay wall consists of 8 concrete blocks, placed on top of each other without any shear connection. The actual quay wall has a height of 17.4 m, but because of restrictions related to the capacity of the centrifuge and the dimensions of the soil container, a slightly reduced (by roughly 20%) version was tested, having a total height of 13.86 m. The soil is uniform dense sand ( $D_r = 80\%$ ).

The eight blocks differ from one another in terms of height and width, and the sea level is 2 m below the ground surface. Compared to single-block quay walls, such structures may develop additional modes of failure. The deformation pattern of a single-block quay wall involves seaward displacement, vertical settlement and rotation around the base. In the case of multi-block quay walls, the lack of shear connection between the concrete blocks may also lead to relative displacements and rotations between the blocks. The latter can be detrimental, increasing the seismic vulnerability of the quay wall.

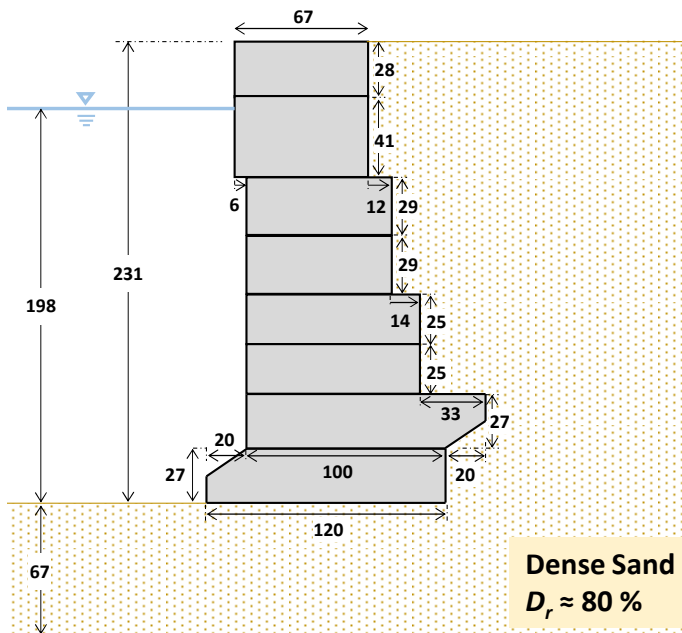
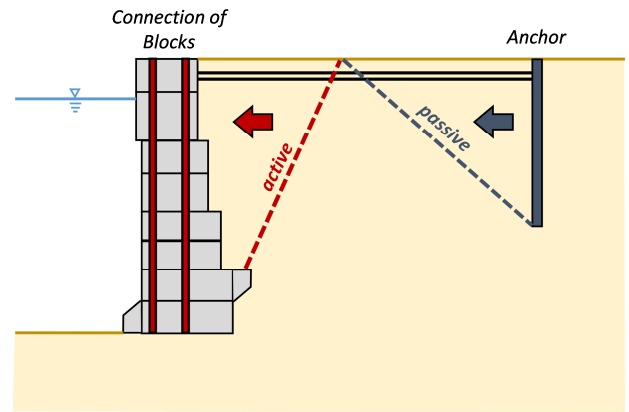
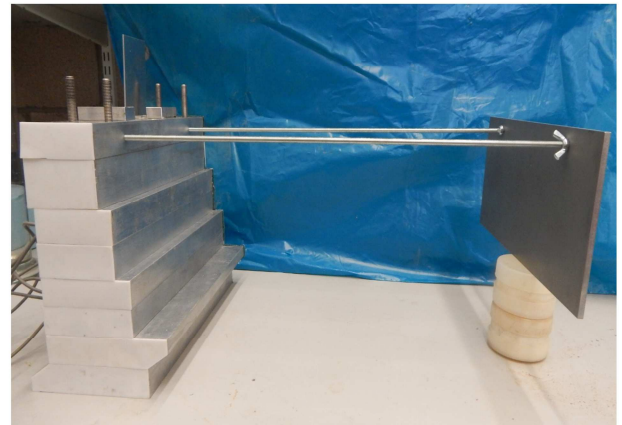


Figure 1. Geometry of the existing multi-block quay wall, Port of Piraeus (Athens, Greece). Dimensions are indicated in millimetres at model scale (1:60).

The proposed retrofit solution is schematically illustrated in Figure 2a. It suggests that the quay wall blocks be connected (this connection was in the experiment implemented with tie rods but could in reality consist of steel reinforced boreholes) and anchoring of the quay wall top at an appropriate distance (calculated with due consideration to the static active and passive failure wedges). The anchor was modelled using an aluminium plate of 5 mm thickness, yet the prototype may be considered as a relatively flexible sheet pile wall. The anchor plate was connected to the model wall through a pair of (M 5) tie rods and Figure 2b displays a photo of the retrofitted wall model.



(a)



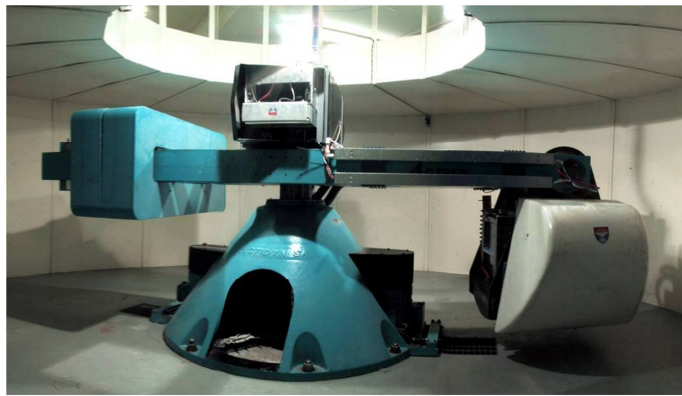
(b)

Figure 2. Retrofitted system: (a) schematic and (b) photo of the wall model and its connection to the anchor plate.

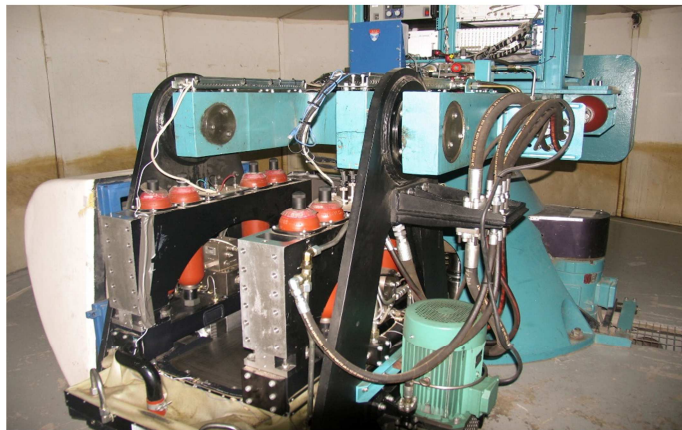
## 3 CENTRIFUGE MODELLING

A series of dynamic experiments on a 1:60 scaled-down physical model of the prototype quay wall were conducted using the University of Dundee geotechnical beam centrifuge and servo-hydraulic earthquake simulator. The centrifuge is an Actidyn C67-2 model (Fig. 3a), consisting of a 7m diameter rotating arm, equipped with a swinging platform that can carry a maximum payload of 1500 kg up to a maximum acceleration of 100 g. The earthquake

simulator (Fig. 3b) is an Actidyn Q67-2 mono-directional servo-hydraulic shaker with a payload capacity of 400kg, capable of reproducing a scaled earthquake motion within frequencies of 40 to 400Hz (0.4 to 4Hz prototype frequency at 100g or 0.8 to 8Hz at 50g). It is capable of simulating both artificial and real seismic motions of any waveform. In order to be within the frequency range of the earthquake simulator, the original seismic motions need to be band pass filtered. Then, a preliminary centrifuge test is carried out using a “dummy” physical model, in order to calibrate the motions and allow the repeatable and accurate reproduction of each one.



(a)



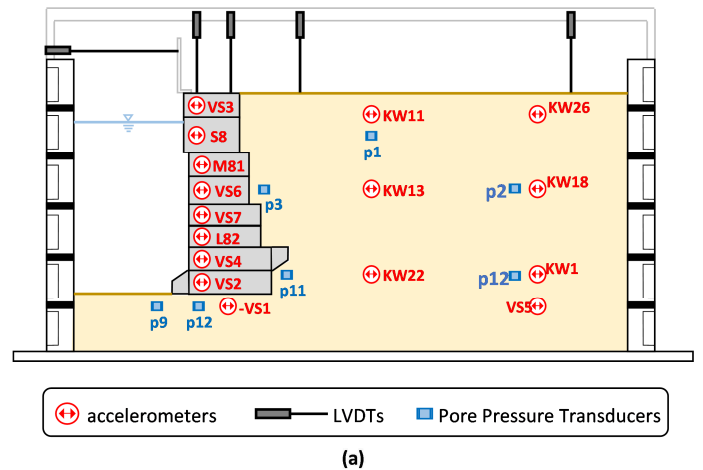
(b)

Figure 3. The University of Dundee centrifuge facility: (a) the beam centrifuge with (b) the earthquake simulator attached.

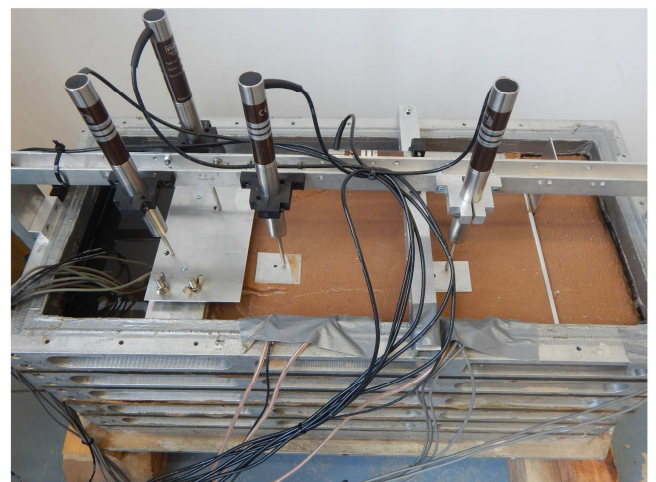
Thanks to the enhanced gravitational field applied, the use of centrifuge modelling allows realistic replication of the stress dependent soil behaviour in small scale, thus enabling the investigation of any relevant soil-structure interaction issues that obviously play a significant role in the quay wall’s performance. If a test is conducted in a  $1 : N$  scale, the centrifuge artificially increases the gravitational field by a factor of  $N$ , in order to increase the self-weight of the model and counterbalance the reduced stresses due to the small size. This way, the effective stresses within the scaled-down model will be the same to

those at corresponding points of the full-scale prototype soil. In order to achieve similitude, appropriate scaling laws have been developed [Schofield, 1981; Kutter, 1994]. These tests were conducted at a centrifugal acceleration of 60 g.

The physical model was prepared inside an equivalent shear beam (ESB) container with flexible walls, described by Bertalot et al. [2012], with internal dimensions of 670mm x 279mm x 338 mm (length x width x height). A schematic cross-section of the model set up with evident instrumentation is depicted in Figure 4a. The soil was prepared by air pluviation of dry fine to achieve a uniform relative density  $D_r \approx 80\%$ . The motion of each quay wall block was recorded using identical ADXL78 MEMS accelerometers. Additional accelerometers were buried inside the soil to measure accelerations at characteristic locations. Horizontal and vertical displacements at the top of the wall were recorded by LVDTs. Two more instruments were used to measure the settlement behind the quay wall. Pore pressure transducers were installed underneath and behind the quay wall, but also in the free field.



(a)



(b)

Figure 4. Model set-up and instrumentation: (a) schematic, and (b) photo of the model within the ESB container.



The model was subjected to a sequence of moderate to strong seismic excitations, including real records from Greece (Lefkada, 2003; Kefalonia, 2014), Italy (L'Aquila, 2009), the US (Northridge, 1994), and Japan (Kobe, 1995). Figure 5 illustrates the acceleration time-histories of the seismic motion sequence.

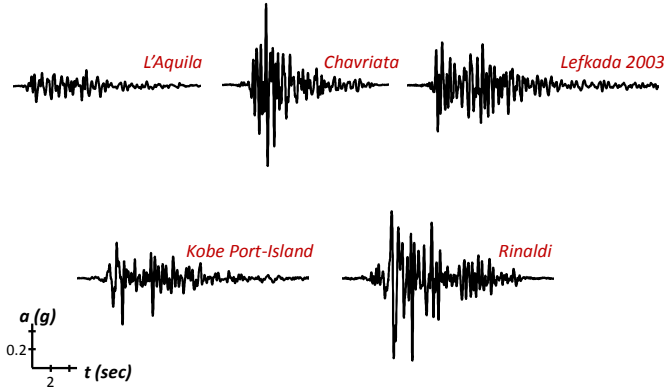


Figure 5. Seismic motions used in the centrifuge tests.

#### 4 PRESENTATION OF RESULTS

The following presentation of results focuses on the comparison between the responses of the two systems in order to evaluate the effectiveness of the proposed retrofit solution. Furthermore, due to space limitations, the results are shown here only for the first record of the seismic sequence: the AM043 record of the 2003 Mw 6.3 L'Aquila earthquake in Italy [Chiarabba et al., 2009]. More detailed presentation of results will be included in a future publication.

Figure 6 compares the performance of the two systems during the L'Aquila record in terms of the inertial loading imposed on the wall. This may be evaluated in view of the acceleration time-histories recorded at the top block (Fig. 6a) and at the bottom block (Fig. 6b) of the wall. It should be observed that there is no dramatic difference between the two quay wall systems response in terms of accelerations. Yet, the retrofitted wall suffers somewhat lower maximum inertial loads, as indicated by the peak block acceleration distribution with depth shown in Figure 6c.

Although the magnitude of inertial loading transmitted to a system during seismic excitation is always an important consideration, the performance of quay wall systems is reasonably better reflected in view of displacements rather than accelerations. Especially in such cases, where failure of facilities and lifelines supported upon the quay wall, (e.g. cranes, pipelines etc.) are of primary concern, it is essential to account for the magnitude of permanent wall displacements as well as the deformations of the back-fill soil. In this direction, Figure 7 comparatively

summarizes the displacement performance of the two quay wall systems.

Figure 7a plots the time-histories of the horizontal dislocation experienced at the top of the wall. It should be noted that this dislocation is the result of two components: (i) the translational movement and relative sliding between the blocks (a mechanism which governs the performance of the existing quay wall) and (ii) the rotational movement of the wall (important in the case of the retrofitted quay wall). The figure evidently indicates the superiority of the retrofitted quay wall, which has suffered less than half the residual dislocation caused at the existing wall by the end of L'Aquila record.

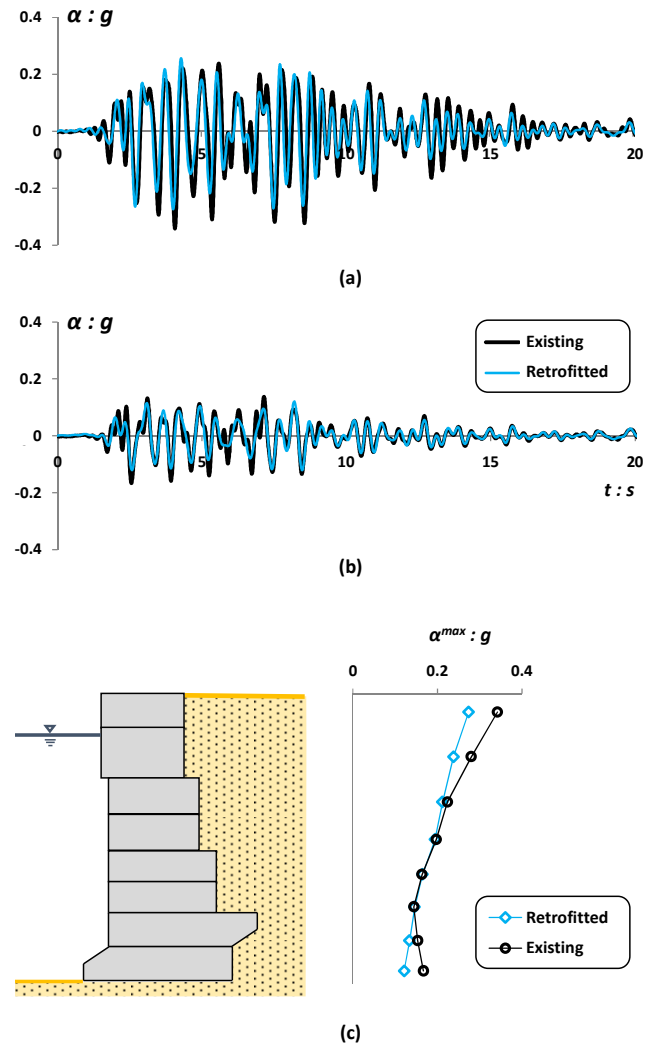


Figure 6. The response of the retrofitted wall in comparison to the response of the existing system during shaking with the L'Aquila record in terms of: acceleration time-histories recorded (a) at the top; (b) at the base of the wall, and (c) distribution of maximum acceleration with depth.

Comparison of wall rotation time-histories, shown in Figure 7b, highlights that rotational movement is important in the case of the retrofitted wall. This was, presumably, the expected result of connecting the blocks of the quay wall and thereby increasing its slenderness. The response of the exist-

ing quay wall, where the blocks are disconnected and free to slide, is characterized primarily by translational movement and much less by rotation.

Figures 7c and 7d compare the responses in terms of settlements. It is important to note that, although the retrofitted system appears to experience somewhat greater settlement than the original wall (this being associated with its rotational movement and the partial formation of bearing capacity failure mechanisms at its base) the performance of the retrofitted system is advantageous in terms of the wall displacement relative to the backfill soil. This parameter  $\Delta w$  (see schematic of Figure 7), which is the difference between the settlement of the wall and the settlement of the soil near the wall, is in fact a much more illustrative measure of the distress experienced by the structures and lifelines supported on the wall.

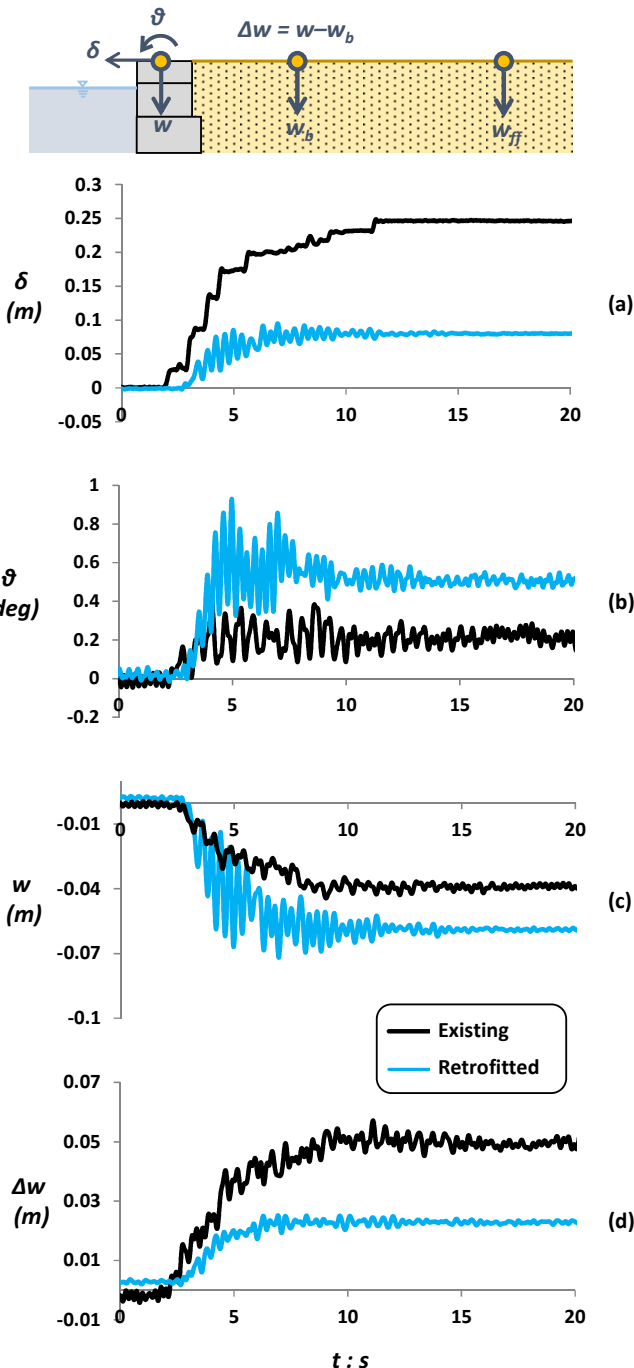


Figure 7. The response of the retrofitted wall in comparison to the response of the existing system during shaking with the L'Aquila record in terms of: (a) horizontal wall dislocation; (b) wall rotation; (c) settlement; and (d) settlement relevant to the settlement of the backfill soil.

## 5 CONCLUSIONS

A centrifuge model test series was carried out to comparatively evaluate the seismic performance of an old quay wall, which closely resembles the geometry of the port of Piraeus in Greece, with a proposed retrofitted wall. The results may be summarized as follows:

- The retrofitted scheme notably reduces the inertial loading transmitted to the wall.
- It experiences significantly reduced horizontal displacements.
- Despite showing relatively amplified rotational movement and settlement, it appears superior when wall settlements are considered in relation to the settlement of the soil behind the wall, the latter being a more illustrative index of seismic damage. Note also that rotations may be remediated through thorough design of the anchoring system.

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