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Liquefaction mitigation using secant piles wall under a large water tank

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Two-dimensional and three-dimensional numerical models were developed to evaluate the effectiveness of a foundation perimeter wall on the mitigation of the effects of liquefaction in a 64 m diameter, reinforced-concrete water tank. The seismic response of the tank was evaluated in terms of differential settlements induced by an actual earthquake recording by comparing the situations with and without a mitigation strategy consisting of 20 m-long, 1 m-diameter secant piles wall. Although the mitigation strategy did not significantly reduce the liquefaction-induced settlements, it enforced a relatively homogeneous distribution of these settlements, leading to less structural damage.

1. Introduction

The February 27, 2010 M_w 8.8 Chile earthquake caused significant damage to ports, bridges and artificial landfills severely affecting the economy of the country. In many cases, the infrastructure damage was associated with earthquake-induced liquefaction. The main objective of this paper is to numerically investigate the effectiveness of a proposed solution to mitigate the effects of liquefaction on an industrial facility. This facility was built on reclaimed land, and it was severely damaged during the Maule earthquake.

The solution investigated consists on the installation of a rigid pile-ring beneath a large water tank. The original idea was first proposed by [18] to constrain the soft soil under a tank by a sheet pile-ring embedded into the hard underlying soil. Later, [20] evaluated the sheet pile-ring countermeasure for tank sites through three-dimensional two-phase nonlinear finite element analysis. They concluded that the use of a sheet pile-ring reduces the excess pore water pressures generated in the soil below and around the tank, and it remarkably reduces the settlements of the tank during large earthquakes. Subsequently, [2] conducted a centrifuge-testing program to assess the earthquake performance of mitigation techniques for a liquefiable foundation under an existing embankment. Among the investigated techniques, they considered a sheet-pile enclosure. They concluded that the sheet pile enclosure prevented lateral spreading of the liquefied foundation, and it virtually preserved the embankment's integrity with a reduced uniform settlement. Additionally, they observed that liquefaction within the contained foundation creates a base isolation mechanism reducing dynamic shear excitation. Afterwards, the same authors [9,6,1] conducted computational simulations of their centrifuge tests. The comparison between computational and experimental results showed the importance of post-liquefaction dilative soil behavior on the dynamic response and deformation characteristics of the studied systems, as well as the capabilities and limitations of the numerical modeling procedure. Regarding the use of rigid inclusions instead of sheet-piles, [10] presents a numerical investigation of a mitigation case consisting on a cement grouted containment enclosure adjacent to a foundation. Their results shows that this kind of liquefaction countermeasure does not prevent the excess pore-water pressure generation, but it reduces liquefaction induced deformations. In [8], on the basis of centrifuge testing of a stiff containment wall around a structure, the authors concluded that this kind of walls could reduce structural settlements by up to 55%. More recently, [12] investigated, by centrifuge testing, the performance of rigid containment walls as a liquefaction remediation method. Using a simple frame structure, founded on a deep layer of liquefiable sand, they tested the effectiveness of containment walls around the base of the structure, extending through the full depth of the liquefiable layer and also to partial depth. According to their results, rigid containment walls can be very effective in reducing structural settlements primarily by preventing lateral movement of the foundation sand. Additionally, they showed that the role of the walls permeability may also be important. Reduction in structural settlement was found when the walls did not extend through the full depth of the liquefiable layer, as long as the depth of the walls is larger than the

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depth of the free-field liquefaction. They also showed that the accelerations of the structure do not increase, provided there is no rigid, structural connection between the structure and the containment walls.

According to the literature review, there are several investigations proving the effectiveness of rigid containment walls as a liquefaction countermeasure. Based on this information, a numerical study was conducted to assess how the installation of rigid impermeable barriers (secant piles wall) might impact the effects of liquefaction on a 64 m diameter, reinforced-concrete water tank that was severely damaged after the February 27, 2010 M_w 8.8 Chile earthquake. The paper is organized as follows, in Section 2 we describe the case studied, the observed damages and the available field data. In Section 3, we present the numerical models developed to assess the effect of the secant piles wall. Section 4 shows the results of the numerical models, and a discussion on the effectiveness of the studied liquefaction countermeasure.

2. Case study

The wastewater treatment plant was located on the eastern side of an industrial project area. Its plan dimensions were, approximately, 100 m $\times$ 200 m, and it had an elevation of $+6.5$ m above mean sea level (Fig. 1a). The primary clarifier, the aeration tank, and the secondary clarifier were located one after the other going from SW to NE (Fig. 1b). As Fig. 1a and b show, a small lagoon, used to collect rainwater, was located $\sim$ 25 m to the NE of the secondary clarifier, and it had a maximum depth of about 5 m relative to the treatment plant platform.

The treatment plant was built on reclaimed land, consisting mainly on sandy soils that were deposited to level the area where some natural ponds and banks existed. Ground water level can be observed at a depth of about 3.5 m. Given the potential seismic hazard that these medium dense to loose sandy deposits had, it was decided to use dynamic compaction to densify the soils. A 25 ton mass was freely released from a height of 25 m, with a theoretical depth of influence of $1/2\sqrt{25 \times 25} = 12.5$ m, covering the whole area of the plant with a minimum over width of 10 m. Vibratory rollers were used to compact the bearing soils.

The M_w 8.8 February 27, 2010, earthquake and tsunami caused major damage to the secondary clarifier and partial damage to the aeration tank. Post-earthquake topographic measurements of the aeration tank showed overall settlements of less than 15 cm, except for the NE area where settlements of 37 cm were measured. In the secondary clarifier, settlements reached 75 cm. In the structures located in the SW area, where no major damage was observed, settlements ranged from 4 cm to 13 cm. Fig. 2 shows a detail of the post-earthquake settlements that were measured. Each measured point is indicated by a black triangle along with the corresponding settlement in millimeters.

In addition to the vertical settlements, lateral displacements were also observed. The secondary clarifier moved to the NW and it deformed. The center of the secondary clarifier moved around 130 cm with respect to the center of the aeration tank. In the SW-NE direction, the secondary clarifier stretched around 15 cm, and in the SE-NW direction it shortened around 3 cm. As a consequence of the relative lateral displacement between the secondary clarifier and the aeration tank, a 1.2 m-diameter metallic pipe that connected both structures got broken at the exit of the tank. The fluid that leaked out the broken pipe eroded the soil underneath the aeration tank.

No damage was observed along the perimeter walls nor along the perimeter footings. However, some cracks were observed in the interior walls of the aeration tank, mainly due to the differential displacement between this structure and the top pipes that connected it to the secondary clarifier. Also, some gaps at the joints of the base slabs at both tanks were observed. Some cracks on the base slab of the secondary clarifier were also detected, where the central column experimented some tilting. According to the plant's personnel, the aeration tank remained sealed after the earthquake (i.e., no leaks were observed).

A post-earthquake geotechnical investigation was conducted to assess the condition of the foundation soils. A total of nine borings were performed: four of them inside the aeration tank (borings T_1 to T_4), four inside the secondary clarifier (borings T_6 to T_9), and one (T_5) between the two tanks. Fig. 2 shows the locations of these borings with black dots, where no gaps between the base slabs and the foundation soils could be observed. Unfortunately, a detailed description of the soil properties was only available for boring T_9 (Table 1). This boring is not located on the aeration tank area, but it is close enough to provide valuable information of the expected properties of the soil below the studied tank. According to this data, below a shallow layer with a large proportion of silt the following 10 m are mainly poorly graded clean sands. Below this layer, the proportion of silt increases gradually, as well as the blow count. These properties suggest a high liquefaction potential of the upper layer of loose and clean sand. Fig. 3 shows the measured SPT versus depth profiles of the borings inside the aeration tank, while Fig. 4 shows the Cyclic Stress (CSR) and the Cyclic Resistance (CRR) ratios, as detailed in [19], considering a PGA of 0.4 g. This last figure shows that, after the earthquake, the sandy deposits under the aeration tank were denser

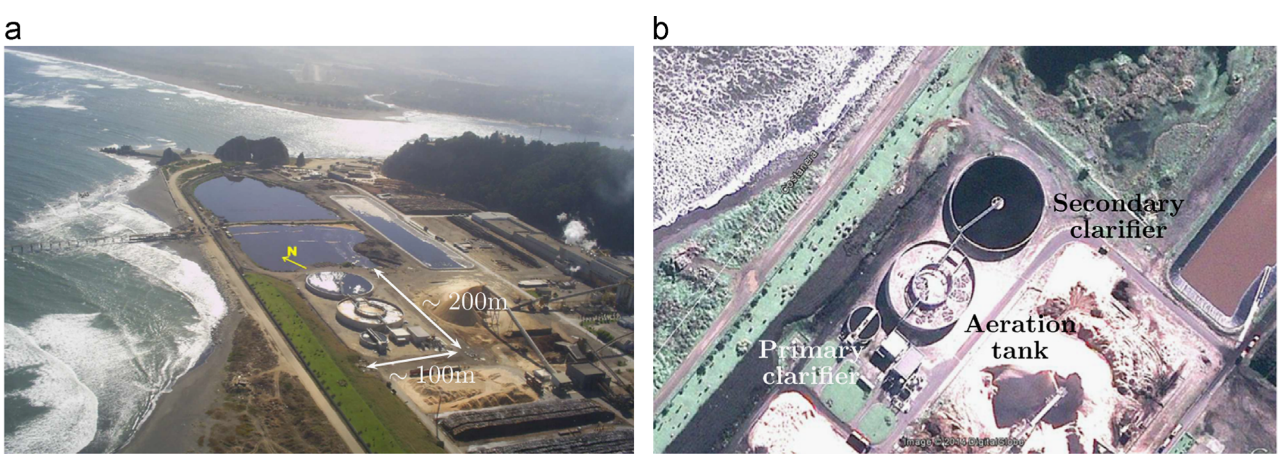

Fig. 1. Wasterwater treatment plant located on a reclaimed land. (a) Overview of the wastewater treatment plant. (b) Google Earth^{TM} image of the wastewater treatment plant (July 22, 2009).