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Experimental study of remediation measures of anchored sheet pile quay walls using soil compaction

Ashraf Zekri [a,*], Abbas Ghalandarzadeh [b,1], Pooyan Ghasemi [b,2], Mohammad Hossain Aminfar [a,3]

[a] *Department of Civil Engineering, University of Tabriz, Iran*
[b] *School of Civil Engineering, University College of Engineering, University of Tehran, Iran*

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ABSTRACT

The seismic performance of quay walls was determined to be highly dependent on liquefaction. The dynamic response of anchored sheet pile quay walls that are embedded in liquefaction-susceptible soil was investigated using shaking table modeling. Extensive damage to the retaining system was attributed to the soil liquefaction near the embedded section. The lateral displacements of the walls due to liquefaction were accompanied by large seaward displacements of anchors; they consequently reduced the tensile forces of the tie rods. A remediation method that involves the compaction of weak areas was experimentally evaluated. The effectiveness of the soil improvement in zones adjacent to the embedded section and/or the area in front of the anchors was assessed based on recorded dynamic responses. The implemented countermeasures considerably reduced the deformations of the wall and the anchors. The foundation improvements influenced the failure mode. Densification in front of the anchors limited the seaward displacements of the anchors, which increased the tensile forces in the tie rods.

1. Introduction

Sheet pile wall structures consist of single sheet piles that are connected by interlocks and are driven, casted or installed in the soil. The sheet piles, which provide flexural and buckling rigidity, are used to sustain horizontal earth and water pressures. They can also transfer vertical loads to the soil (Mazurkiewicz, 2003). The wall is supported at the lower part by embedment in competent soil. To enhance the stability of high walls, the upper section is fixed by anchorage systems that consist of tie rods and anchors. This type of sheet pile wall is referred to as an anchored sheet pile wall. By utilizing anchored sheet pile walls, considerable high elevations of soil and/or water, which are not practically supported by gravity walls, have been retained throughout the world. The most valuable application of these walls comprises quay walls in coastal areas.

In static conditions, the performance of these walls may be evaluated by analyzing the applied earth/water pressure, the anchorage force and the superstructure load (Das, 2011). However, from the viewpoint of dynamic behavior, many unknown issues require detailed investigation. Extensive research has been performed by utilizing numerical and experimental methods and case studies. Depending on structural and geotechnical conditions, the modes of failure during earthquakes may be classified into three main groups. Any form of failure of the anchors, which causes overturning of the wall, is considered to be the "deformation/failure at anchor" mode. The second mode of failure is attributed to inadequate stiffness of the wall or failure of the tie rods. Structural problems are the primary reasons for the proliferation of these modes. Schematics of these modes are presented in Fig. 1 (a) and (b). However, in situations in which the foundation soil does not provide sufficient support for the embedded section, significant damage can occur due to outward "escape" of the wall root. This mode is referred to as "failure at embedment" (PIANC, 2001).

The performances of 110anchored quay walls in Japan were evaluated (Kitajima and Uwabe, 1979; Uwabe, 1983). Based on these valuable data, a statistical method was introduced to estimate the damage level to anchored quay walls during an earthquake as a function of the "effective anchor index" and the

* Correspondence to: Permanent address: No. 51, Rajaii St., Najati St., 22 Bahman Ave., Postal code 5183938516, 4th floor, Tabriz, Iran. Tel.: +98 9143067835; fax: +98 4114442895.
E-mail addresses: ashrafzekri@gmail.com (A. Zekri), aghaland@ut.ac.ir (A. Ghalandarzadeh), Pooyan_pta@yahoo.com (P. Ghasemi), aminfar@tabrizu.ac.ir (M.H. Aminfar).
[1] School of Civil Engineering, University of Tehran, Engelab Ave., Tehran, Iran. Tel.: +98 2166462616, +98 9123590814; fax: +98 2166403808.
[2] . Present address: No. 83rd Section, Ashrafi St., North Amirabad, Tehran, Iran. Tel.: +98 9183640471.
[3] 2nd floor, Department of Civil Engineering, University of Tabriz, 29 Bahman Sq., Azadi Ave., Tabriz, Iran. Tel.: +98 9143112813.

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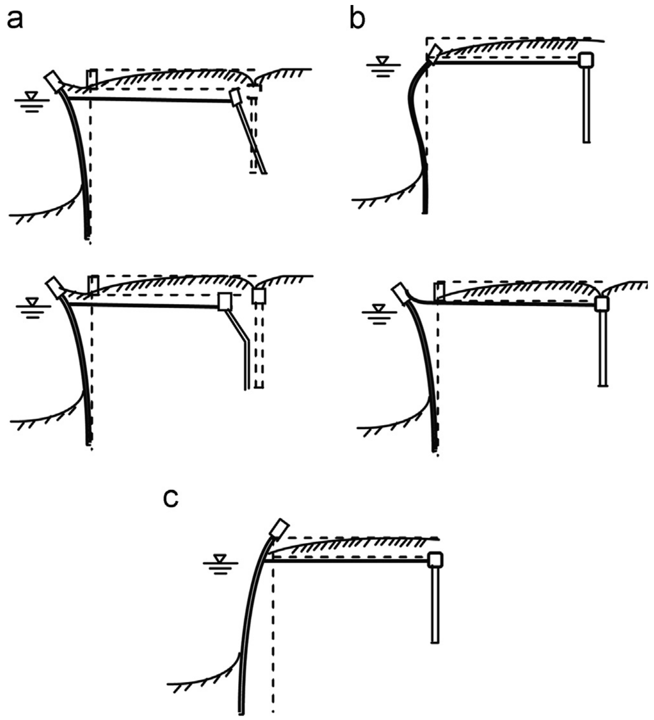

Fig. 1. Modes of failure for a sheet pile quay wall, (a) Deformation/failure at anchor, (b) Failure at sheet pile wall/tie-rod and (c) Failure at embedment (PIANC, 2001).

"embedment participation index" (PIANC, 2001). Previously, Uwabe (1983) had proposed experimental relations to evaluate the maximum horizontal displacement and the settlement of anchored quay walls. McCullough and Dickenson (1998) investigated the effects of backfill improvement on the lateral displacement of these walls by utilizing the "effective stress analysis" numerical method.

In addition to the numerous complicated features of the dynamic behaviors of anchored quay walls, an extreme danger has been recognized in coastal regions, "liquefaction". The term liquefaction has been used to describe a number of related but different phenomena that are observed in loose, saturated soils (Kramer, 1996).

Observations after previous earthquakes have proven that the seismic performance of sheet pile quay walls is highly dependent on liquefaction occurrence. For instance, the quay wall of Ohama no. 2 at Akita Port experienced significant damage during the Nihonkai–Chubu Earthquake of 1983, with a peak ground surface acceleration (PGA) of 0.24g due to the liquefaction of backfill; however, a similar sheet pile quay wall of Ohama no.1 experienced no damage. No signs of liquefaction were evident on this quay wall. Extensive damage to wall no. 6 in the Benten district in Hakidate Port, Japan during the Hokkaido–Nansei-Oki earthquake in 1993, with a PGA of 0.12g, was induced by liquefaction of the backfill and foundation soil. The total height of this sheet pile quay wall was 16.30 m. Approximately 6 m of the wall was embedded in liquefaction-susceptible soil with a standard penetration test (SPT) value less than 20. Despite the relatively small acceleration, the wall displaced approximately 5.2 m horizontally and 1.6 m vertically. A tilt of 15° was estimated (PIANC, 2001).

Studies of the liquefaction effect on anchored quay walls have been performed using numerical methods and physical modeling. In the numerical field, the main challenge is the development of an adequate constitutive model to simulate liquefiable soil behavior. In physical modeling, however, researchers attempt to directly observe the response of the retaining wall and the liquefiable soil using full-scale tests in the field or via centrifuge apparatus and small-scale tests via shake table equipment.

A full-scale test by controlled blast induced liquefaction was conducted in 2001 at the Port of Tokachi on Hokkaido Island, Japan. The focus of this experiment was the dynamic behavior of full-scale steel sheet pile quay walls and the difference between those walls, which correspond to seismic coefficients of 0.15 and 0.00. The test results revealed the progress of the deformation behavior of the full-scale quay wall in the process of liquefaction; the liquefaction in backfill caused a reduction in the horizontal bearing capacity of anchor piles and the deformation of the quay walls. Therefore, the difference between quay walls with and without seismic design in this test was not substantial with regard to displacement because the anchor piles became ineffective due to liquefaction (Kohama et al., 2004).

To realistically model liquefaction and the lateral spreading of saturated sand deposits behind sheet piles and the consequent deformation and translation of neighboring pile foundations, the largest laminar box in the world ($12\ \text{m} \times 3.5\ \text{m} \times\ 6\ \text{m}$) was employed and a series of shake table tests were conducted at the National Research Institute for Earth Science and Disaster Prevention in Japan. In these nearly full-scale tests, a group of four concrete piles were modeled behind steel sheet piles. After a few cycles of loading and unloading, the test results revealed that pore water pressure in saturated and relatively loose backfill increased with a consequent loss of effective stress in the lateral spread of the liquefied sand. The tendency toward minimal potential energy in the liquefied soil caused deformation in the sheet pile and resulted in bending moments and lateral deformation of the piles. The post-liquefaction behavior of the liquefied sand as observed during real earthquakes, particularly during the 1964 Niigata earthquake, was also modeled. The delayed lateral displacement of the sheet pile began a few minutes after the end of the input shake (Sato et al., 2004).

The effect of the liquefiable layer extension in the backfill area was examined by utilizing shaking table tests on small-scale models of anchored flexible quay walls. When the backfill and the foundation soil were loose, the model wall experienced a large movement. Neither the embedded part of the wall nor the anchorage system was able to resist a large displacement of the wall. By increasing the thickness of the surface dense layer, the wall movement reasonably decreased. This finding may suggest that any improvement applied to the backfill soil should be sufficiently deep. Otherwise, it will not reduce or prevent failure of the quay wall (Ghalandarzadeh and Akbari-Paydar, 2007). Subsequent to the knowledge of the liquefaction mechanism, extensive research has commenced to develop mitigation methods against this hazard for existing and planned structures. Remediation measures are generally adopted to achieve one or both of the following objectives:(i) reduce the liquefaction potential of the soil and(ii) increase the stability of structural elements in the event of liquefaction occurrence.

Some published studies suggest the efficiency of well-known soil compaction (Kumar, 2001), soil grouting (Boulanger and Hayden, 1995), the addition of water drainage paths (Andrus and Chung, 1995; Madhav and Arlekar, 2008) the driving of displacement piles (Day, 2002). Recently, sheet-pile enclosures (Adalier et al., 2004), sandbag confinements (Yoshida et al., 2008), and displacement reducer elements (Mostafavi Moghadam et al., 2009) were physically modeled and proposed as successful liquefaction countermeasures for several structures. The fundamental concepts of remediation measures are discussed by Towhata (2008), and a comprehensive review of the field performances of several mitigation methods has been presented by (Hausler and Sitar, 2001).

Soil compaction is a predominant mitigation method that is based on the reduction of liquefaction potential. In addition to