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Soil-pile interaction effects in wharf structures under lateral loads

Bilge Doran* and Aytuğ Seçkin[a]

Department of Civil Engineering, Yıldız Technical University, 34220 Esenler, İstanbul, Turkey

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Abstract. Wharfs are essential to shipping and support very large gravity loads on both a short-term and long-term basis which cause quite large seismic internal forces. Therefore, these structures are vulnerable to seismic activities. As they are supported on vertical and/or batter piles, soil-pile interaction effects under earthquake events have a great importance in seismic resistance which is not yet fully understood. Seismic design codes have become more stringent and suggest the use of new design methods, such as Performance Based Design principles. According to Turkish Code for Coastal and Port Structures (TCCS 2008), the interaction between soil and pile should somehow be considered in the nonlinear analysis in an accurate manner. This study aims to explore the lateral load carrying capacity of recently designed wharf structures considering soil-pile interaction effects for different soil conditions. For this purpose, nonlinear structure analysis according to TCCS (2008) has been performed comparing simplified and detailed modeling results.

Keywords: pile-wharf structures; nonlinear soil springs; equivalent length, pushover analysis

1. Introduction

Wharfs are important structures of shore transportation and generally supported on vertical or batter piles. Because of the pile-wharfs support very large gravity loads on their basis, the inertial forces produced by the seismic events can be quite large. Therefore, these structures are susceptible to seismic activities. A huge amount of pile-wharfs had been damaged after the past earthquake motions. For this reason, seismic response of these structures has gained popularity in recent years. Many researchers have investigated and discussed the design/evaluation philosophies of such structures under earthquake loadings (Chiou *et al.* 2011, Yüksel *et al*. 2003, Takakashi and Takemura 2005, Roeder *et al.* 2005, Vahdani *et al.* 2011, Boroschek *et al.* 2011, Siyahi *et al*. 2011, Doran *et al*. 2012, Doran *et al.* 2014).

Design/evaluation of pile wharf structures has recently been implemented in TCCS (2008). Two essential concepts are proposed; a) deformation-based and b) force-based design and evaluation. Force-based design methods are used in normal and simple structures while usage of the deformation-based design method shall be adopted for special and normal structures. Design and evaluation according to deformation-based concept involve optimization of the structural

*Corresponding author, Associate Professor, E-mail: doranbilge@gmail.com, doran@yildiz.edu.tr
[a]Msc., Civil Engineer, E-mail: aytugseckin@gmail.com

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elements of the dock or port in a nonlinear manner. In this context, the nonlinear behavior of soil and pile should somehow be considered in the analysis.

The structural behavior of pile-wharfs under earthquake excitation is greatly affected by the soil conditions. Asgarian *et al*. (2012) investigated the dynamic responses of a prototype jacket offshore platform experimentally and numerically considering the effect of soil-pile structure interaction. Cheng and Liu (2012) studied on the reliability of cable-stayed bridges. They proposed algorithm integrates the finite-element method considering soil-pile interaction. Generally, the effects of soil structure interactions on the dynamic characteristics of the pile wharf structures can be considered using two modeling techniques; detailed and simplified modeling. In detailed modeling technique, the nonlinear behavior of soil should be defined using nonlinear soil springs. As the computer programs develop so fast, it can be possible to model soil as a series of nonlinear spring elements that provide lateral restraint for the piles with the *p*-*y*, *Q*-*z* and *t*-*z* curves. In simplified modeling technique, piles assume to be fully restrained at an accepted distance below the mudline. For many years now, the soil-pile effects have been considered in the nonlinear analysis using fixed end piles with an equivalent length (equivalent fixed end). The main reason is that the lack of consistent nonlinear elements in some commercial structural software (Pardo and Fırat 2008). An equivalent pile length, L_{eq}, with assuming that the pile remains elastic with a flexural stiffness of *EI* and fixed against rotation at the top can be expressed as (TCCS-2008):

$$L_{eq.} = 1.4\sqrt[4]{\frac{EI}{k_h B}} \tag{1}$$

Here, B is the pile radius and k_h is lateral soil stiffness coefficient and can be defined as

$$k_h = 67\,\frac{C_u}{B} \text{ -with cohesion} \tag{2}$$

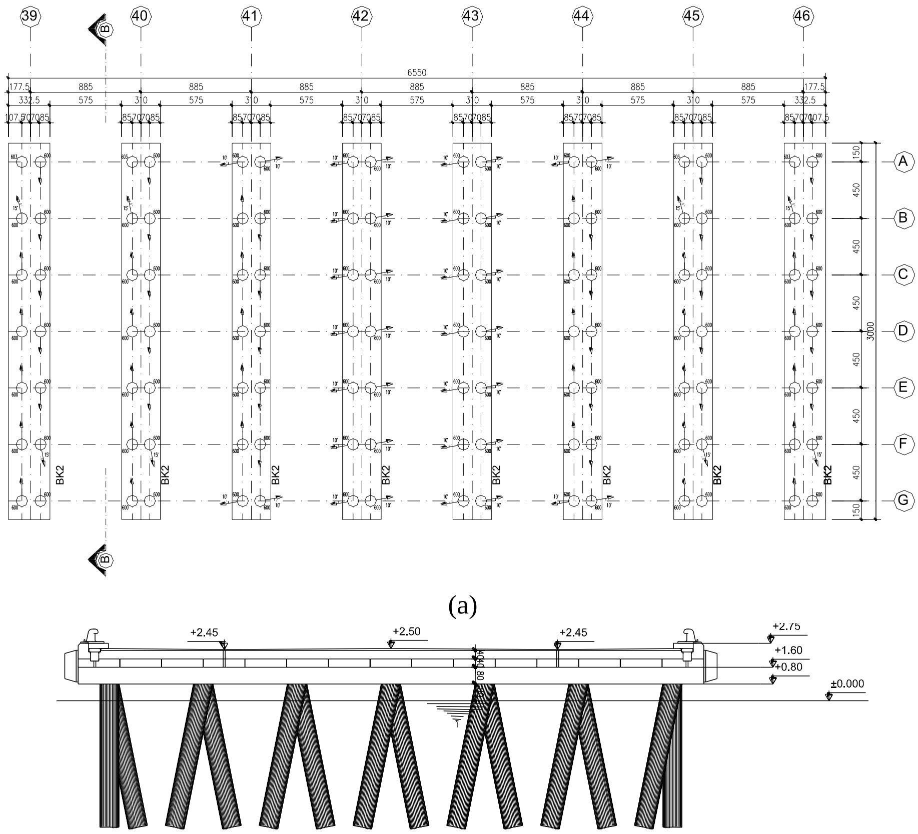
$$k_h = n_h\,\frac{z}{B} \text{ -without cohesion} \tag{3}$$

where, z is the depth, C_u is the undrained shear strength of soil and n_h is a coefficient.

This study presents three dimensional (3D) nonlinear finite element analyses (FEA) which have been performed using deformation-based design principles according to TCCS (2008) on recently designed pile wharf structures. In order to explore the soil-pile interactions, both detailed and simplified modeling techniques with different soil conditions “S_1” and “S_3” (Tables 1, 3) are considered. Besides, “S_2” soil condition (Table 2) which is weaker than “S_1” has also been considered for one of the structures and results have been discussed.

2. Structural data for recently designed pile-wharfs

The pile-wharfs (Figs. 1-2) located on the shores of Kocaeli and Iskenderun in Turkey, are numerically examined using 3D FEA according to TCCS (2008), in order to gain nonlinear soil-pile interaction effects. In the shore of Kocaeli, pile wharf structure (BW; batter pile-wharf) consisting six decks are 346 m in length and 30 m in width. Each deck is 65.5 m in length and 30 m in width and supported on reinforced concrete (R/C) and steel tube batter piles having a 0.911 m diameter. “BW” structure has 112 batter piles having length of 55 meters. The 28-day



(a)

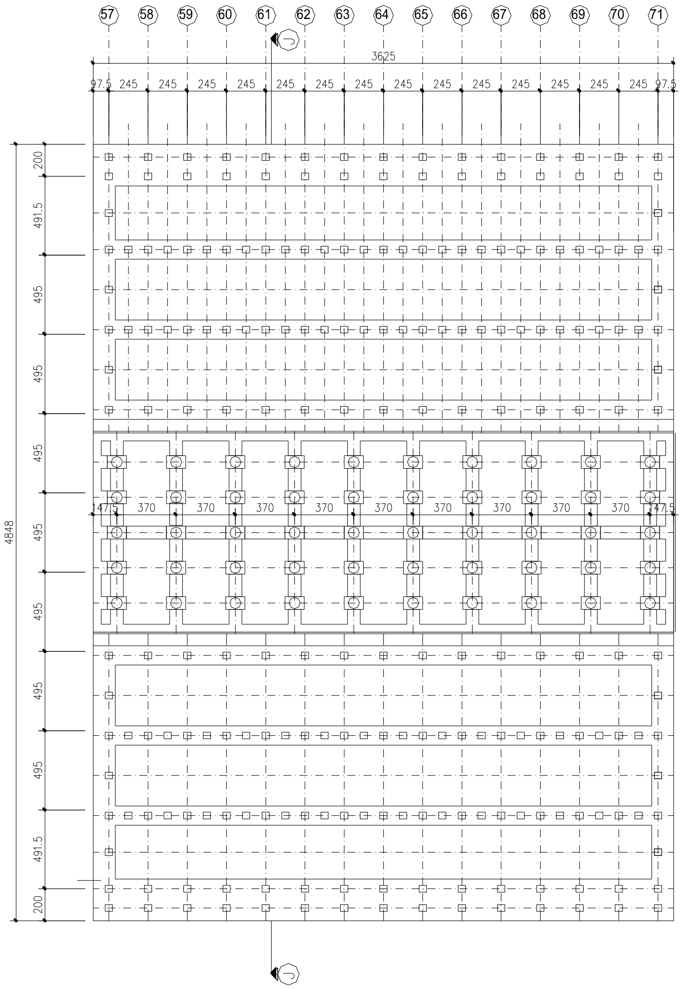
(b)

Fig. 1 “BW” structure (a) Plan view (b) Section (B-B)

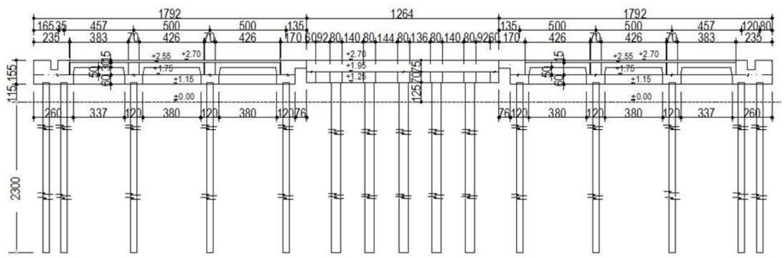
concrete compressive strength of 40 MPa for concrete, nominal yield strength of 420 MPa for reinforcing steel and nominal yield strength of 355 MPa for steel piles are used. In the shore of Iskenderun, the pile wharf structure (VW; vertical pile-wharf) supported on 0.46 m square and 0.70 m circular concrete vertical piles is 109 m in length and 48.45 m in width. “VW” structure involves three decks with 268 vertical piles and each deck is 36.25 m in length and 48.45 m in width. Total length of R/C piles is 24.25 m. The 28-day concrete compressive strength of 30 MPa for concrete and nominal yield strength of 420 MPa for reinforcing steel are used (Doran *et al.* 2014).

3. Soil profile description and geotechnical parameters

On the shore of Kocaeli, the main soil layers consist of Mesozoic, old rock formations. The sub grade of the region involves old permion sandstones. In this region, two different soil conditions (S_1: strong and S_2: weak) are considered (Fig. 3). On the shore of Iskenderun, the main soil layers include clastic fluvial and marine material consisting of Mesozoic limestones, ophiolitic rocks and Eocene limestones. The alluvial deposits can be distinguished as “old” and “new”. The recent ones



(a)



(b)

Fig. 2 “VW” structure (a) Plan view (b) Section (J-J) (Doran *et al.* 2014)

consist of very loose / loose / medium dense / dense sand, medium dense /dense sand / gravel and very stiff clay layers near the shore areas and very soft / medium stiff and stiff clay away from the shore (Doran *et al*. 2014). In this region, S_3 strong soil condition is considered (Fig. 4). Besides,

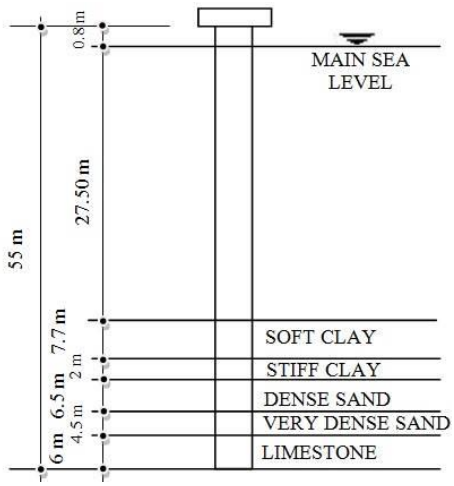


Fig. 3 "S_1" and "S_2" soil conditions

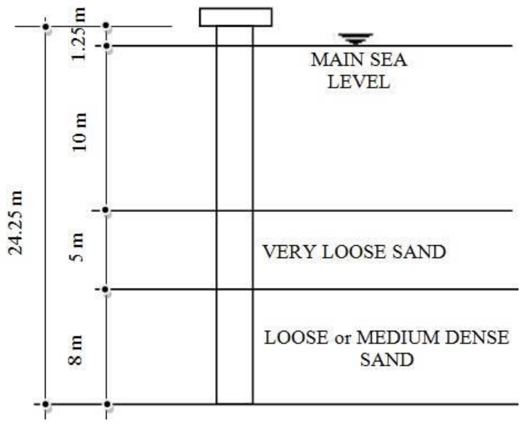


Fig. 4 "S_3" soil condition

Table 1 Geotechnical parameters for "S_1" soil condition

Soil condition	Layer thicknesses (m)	Cohesion (kN/m^2)	Internal friction angle
Soft clay	7.70	3.75	None
Stiff clay	2.00	53	None
Dense sand	6.50	None	36^o
Very dense sand	4.50	None	40^o
Limestone	6.00	250	None

Table 2 Geotechnical parameters for "S_2" soil condition

Soil condition	Layer thicknesses (m)	Cohesion (kN/m^2)	Internal friction angle
Soft clay	7.70	3.75	None
Stiff clay	2.00	3.75	None
Dense sand	6.50	0	15^o
Very dense sand	4.50	0	15^o
Limestone	6.00	12	None

Table 3 Geotechnical parameters for "S_3" soil condition

Soil condition	Layer thicknesses (m)	Internal friction angle
Very loose sand	5.00	28^o
Loose or medium- dense sand	8.00	32^o

for all soil conditions, layer thicknesses and geometrical parameters given in Tables 1-3 are chosen arbitrary for exploring the strong/weak soil effects. Furthermore, the layers under the wharfs are assumed to be horizontal and no risk of liquefaction is considered.

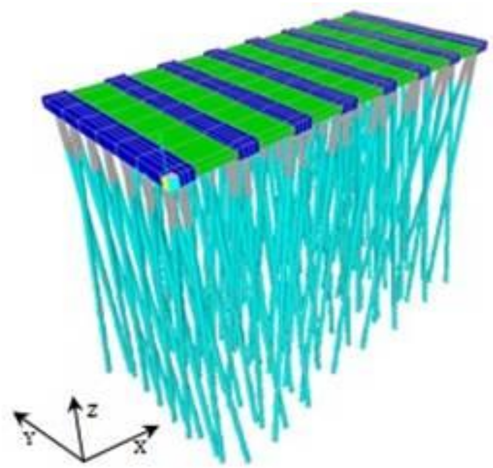


Fig. 5 Numerical model for “BW” structure

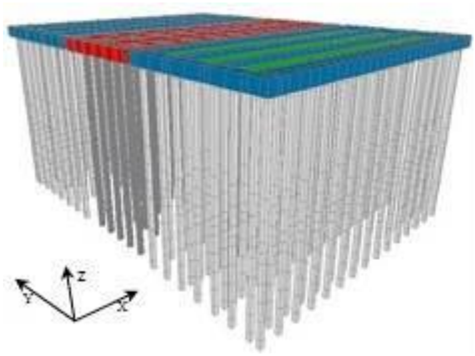


Fig. 6 Numerical model for “VW” structure

4. Numerical modeling and aspects for nonlinear static analysis

Nonlinear static analysis of wharf structures modeled both detailed and simplified techniques have been performed using a computer program (SAP 2000-ver.14.1). For this purpose, numerical models for “BW” and “VW” structures are constructed (Figs. 1- 2). In both modeling techniques, the piles are modeled using “Frame” elements capable of accounting for *P*-delta effects. Besides, “Link” elements along piles are used for reflecting nonlinear behavior of soil as mentioned in detailed modeling technique.

In numerical simulations, following criteria are established for the purpose of evaluating process (TCCS-2008):

a. Pile wharf structure has been classified as a “normal structure”.
b. Rigid diaphragm behavior is assumed for wharf deck system.
c. Plastic hinges are only allowed to occur along the pile length, not in the deck or cap beams and plastic hinge lengths at the pile cap/slab connection and below the ground level are taken as equal to $0.044f_yd_b$; where f_y and d_b are the yield stress of steel in “MPa” and reinforcement bar diameter in “mm”, respectively.
d. P-delta effects are considered.
e. For the idealization of nonlinear behavior of piles under combined bending and axial loads, plastic hinge theory has been used.
f. Linearized yielding surfaces are used for defining nonlinear behavior of steel and reinforced concrete sections (Fig. 7).
g. Strain hardening is neglected in defining moment-rotation relationships (Fig. 8).
h. Soil-pile interaction will be considered with nonlinear soil springs in detailed modeling technique. For this purpose, nonlinear axial load transfer (t-z) curves representing the load transfer along the sides of the pile, tip load-displacement (Q-z) curves at the pile tips representing the end bearing resistance, and lateral soil resistance deflection (p-y) curves to represent the lateral resistance of the soil near the surface in two horizontal orthogonal directions are constructed (API, 2000). As an example, some of these curves in linearized form are given in Figs. 9-14 for “BW” and “VW” structures.

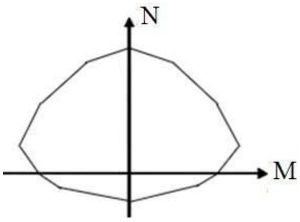


Fig. 7 Axial force - moment relationship for R/C sections

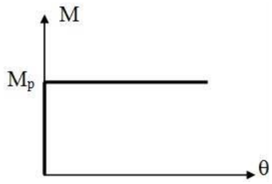


Fig. 8 Yield surface and moment-rotation relationship

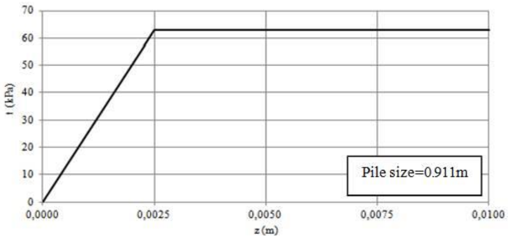


Fig. 9 Linearized *t-z* curve

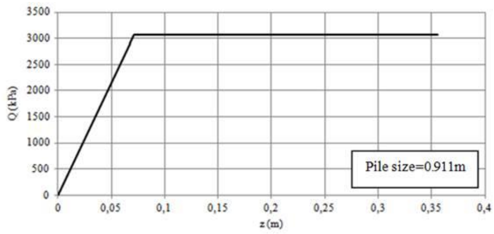


Fig. 10 Linearized *Q-z* curve

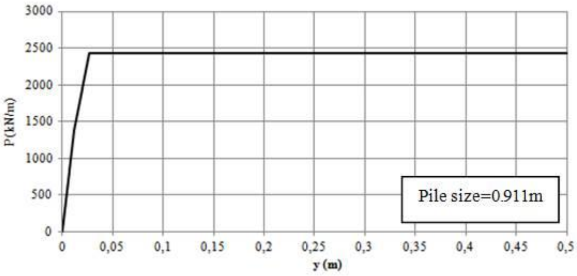


Fig. 11 Linearized *p-y* curve

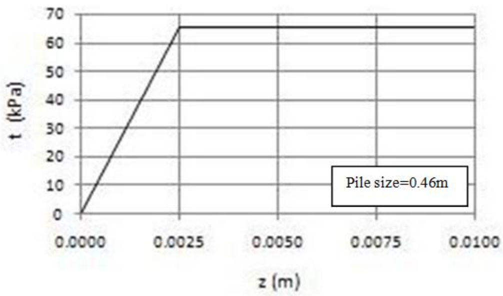


Fig. 12 Linearized *t-z* curve

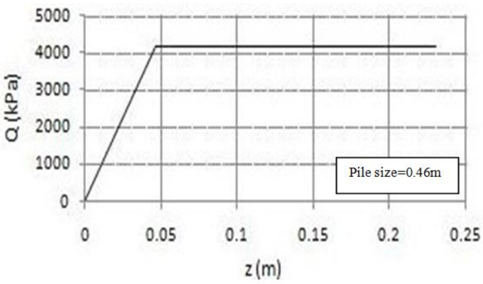


Fig. 13 Linearized *Q-z* curve

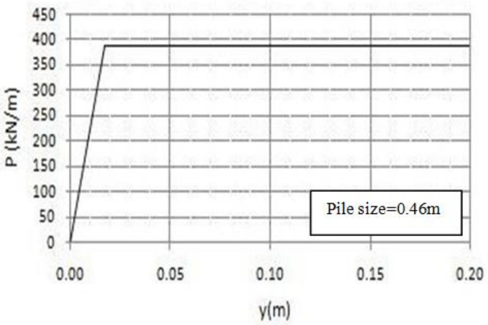


Fig. 14 Linearized *p-y* curve

5. Nonlinear static analysis of pile-wharfs

Nonlinear static analysis (pushover analysis) under constant gravity loads and monotonically increasing lateral forces during an earthquake until a target displacement is reached is generally carried out as an effective tool for performance based design. In this concept, the lateral force is incrementally increased in accordance with a predefined load pattern based on mode shapes for the loading direction under consideration. At each load increment, the plastic hinge rotations, base reactions and maximum displacements are calculated. The major outcome of a pushover analysis is the capacity curve (Pushover curve) which shows the base reaction vs. the maximum displacement relationship and represents the overall lateral load carrying capacity of the structure. Therefore, in order to obtain strength-lateral load bearing capacities of "BW" and "VW" structures, pushover analysis have been performed considering both detailed and simplified modeling techniques using SAP 2000-ver.14.1. In the pushover analysis, the magnitude of static lateral force is increased until the wharf is no longer stable. Pushover curves for both directions for each deck with piles having nonlinear springs (detailed modeling) and equivalent pile length (simplified modeling) have been given in Figs. 15-20 respectively.

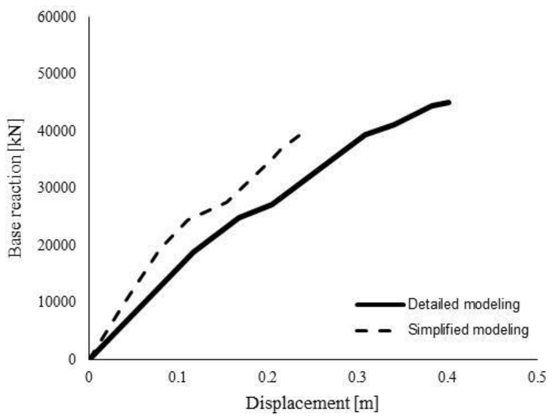


Fig. 15 Pushover curve in X-axis of "BW" structure for "S_1" soil condition

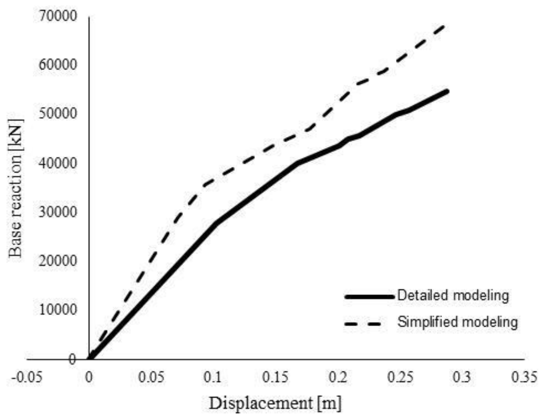


Fig. 16 Pushover curve in Y-axis of "BW" structure for "S_1" soil condition

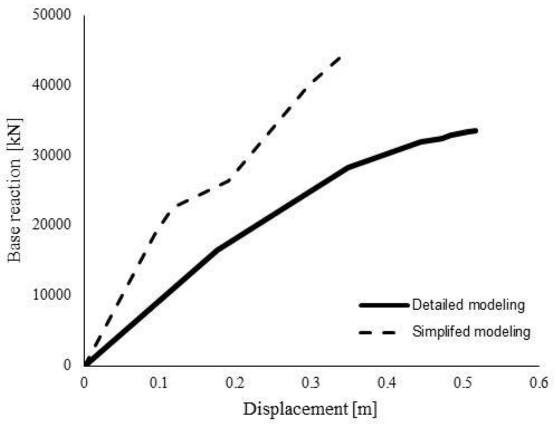


Fig. 17 Pushover curve in X-axis of "BW" structure for "S_2" soil condition

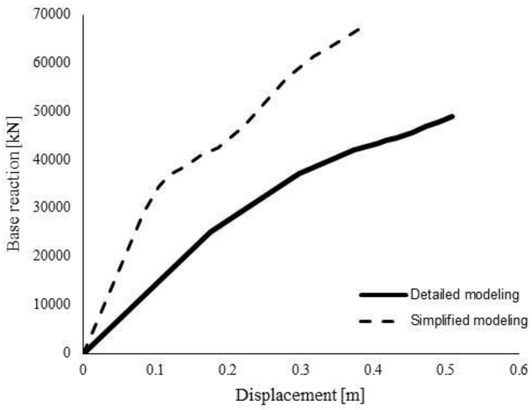


Fig. 18 Pushover curve in Y-axis of "BW" structure for "S_2" soil condition

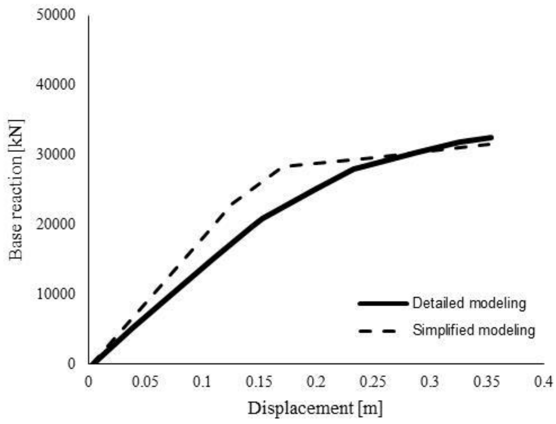


Fig. 19 Pushover curve in X-axis of "VW" structure for "S_3" soil condition

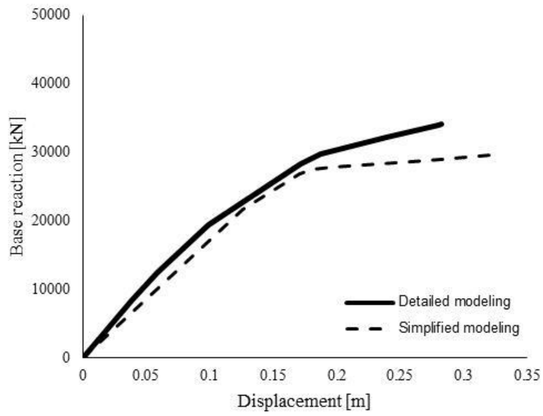


Fig. 20 Pushover curve in Y-axis of "VW" structure for "S_3" soil condition

In Figs. 15-16, lateral load capacities and lateral displacements evaluated by simplified and detailed finite element modeling for "S_1" soil condition are quite same except for the initial lateral stiffness. It can be said that using the simplified modeling technique as an alternative to detailed modeling technique leads to underestimation of the base reaction by 11 % in X-X direction and overestimation by 25 % in Y-Y direction for strong soil (S_1). However, there is large difference for "S_2" soil condition (Figs. 17-18). Overestimation of the base reaction by 30 % has been occurred in both directions for weak soil (S_2). Moreover, in Figs. 19-20, lateral load capacities and lateral displacements evaluated by simplified and detailed finite element modeling for "S_3" soil condition are just same together with the initial lateral stiffness for both directions.

6. Conclusions

A nonlinear static analysis of a recently designed wharf structures have been performed by application of deformation-based design principles according to TCCS (2008) with different modeling techniques to explore the soil-pile interaction in an accurate manner. For this purpose, in the light of the above modeling techniques, overall lateral load carrying capacity curves obtained from the pushover analysis are drawn for different soil conditions. Analysis results indicate that using such simplification in numerical modeling process (simplified modeling technique) gives very similar results as compared to the detailed modeling technique for strong soil conditions. However, the displacement demands for weak soil conditions have been observed to exceed the ones obtained from the detailed modeling technique. This is expected because the simplified method based on points of fixity for the piles does not take into account the energy dissipation at the supporting soil through lateral displacement reversals. Hence, the simplified modeling technique presented in this study is suggested as a reasonable method to be used in the design of wharves supported on strong soil.

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