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Investigation of Dynamic Behavior of Piled Pier Structure

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Abstract: In regions with advanced global trading, sea-borne transportation is preferred. Currently, most of the transportation volume is transported by means of sea transportation. Therefore ports are an important aspect of the transportation network. In our country, studies about offshore structure design has been increasing in the recent 15 years. Primarily, technical approaches and durability for designing offshore structures were prominent. However, recently, performance continuity has been one of the primary concerns. During their service life, static and dynamic loading is applied to these structures. The system should be analysed under static and dynamic loading with accurate parameter selection for a proper behavior estimation of the structure under seismic activity. For this purpose, in order to study the dynamic behaviour of a pier structure, changes in the parameters have been examined. For parameters; 600, 800 and 1000 mm pile diameter, 4D and 8D placement gap has been considered. Analysis has been carried out using SAP2000 finite element model program. Limit displacement values and structural capacity of the structure have been determined using pushover analyses. Based on the determined limit values, dynamic condition performance is evaluated using time-history analysis The maximum base shear force values obtained in the pile system for the seismic data and ground condition defined in the displacement-controlled analyzes did not exceed the linear limit. When the pile system behavior was evaluated in terms of seismic performance, the ground provided sufficient rigidity to the pile system for 80 cm diameter and 4D pile spacing. As a result, in all models, it has been observed that the first deformation interacts with the foundation system on the pile and in the first one meter section where it comes into contact with the ground, buckling and plastic deformation begins in the piles and this height intensifies as the ratio of the pile embedded in the ground increases.

Keywords: Pier Structure, soil- structures interactions, pile foundations, dynamic analysis

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1. INTRODUCTION

The increasing needs of the countries and technological advancements have increased the demand for imports and exports. With it’s economic advantages, high volume transportation capacity, and reach to more regions, Seaborne transportation is preferred for the most volume on the globe. With the need for energy increasing worldwide, structures like; oil searching and extracting platforms, drilling platforms, wind and sun energy facilities, and mooring structures that are designed with the superstructure, substructure to carry the platform and the foundation are gaining importance day by day (Chandrasekaran., 2015; Zhang et al., 2017; Yan et al., 2018). For our country, being a peninsula, the need for modern ports and docks has become prominent. Carrier systems for offshore structures like single pile, multiple pile, and framework type systems that can be produced with different materials are subjected to; wind, wave, currents, seismic activity (Pérez-collazo et al., 2015; Randolph and Gourvenec, 2017). In addition, under wave, wind and seismic activity effects, these structures need to safely maintain their performance level. For offshore structure design, soil bearing capacity, subsidence criteria, and seismic resistance should be considered. Because Turkey is in a seismically active region, the investigation of seismic behaviour of the offshore structures is important. Generally, offshore structures prefer piled foundation design to safely transfer the superstructure and lateral loads, wind, wave, and mooring, to the soil.

For the vertical load from the platform that makes up the superstructure, it is possible to create substructure systems safely with simple mathematical approaches. However, a commonly accepted design model is unavailable for lateral loaded piles. One of the main reasons for this is that when such piles are subjected to displacement, they display a three-dimensional soil-structure interaction throughout their surface area (Zhang et al., 2017b).

In recent years, it was observed that damage occurred on most of the offshore structures is caused by instability of the seabed soil. In order to determine the design criteria and damage levels, the behaviour being affected by some parameters should be foreseen. Due to the nonhomogenous, nonlinear and anisotropic behaviour of soils, the system's complex sections, and the inertial and kinematical interaction of the structural elements with the soil, an analytical solution is generally impossible. Therefore, for such problems, numerical solutions are mostly preferred.

Kishida and Takwaki (2010), evaluated detailed seismic reactions for piled foundation systems with a three-dimensional finite element model. They observed that the seismic response of a piled foundation system is connected to the pile cap moment of inertia that is dependent on the kinematic effect.

Yüksel and Orhan (2013), have given insights about seismic risks of port structures and consequent possible losses. Yasser (2012), have examined the effect of local and spherical scouring near the offshore structures and bridge footings on the behaviour of lateral loaded piles. Especially in sandy soil, spherical scouring has increased the pile lateral displacement and bending moments. Therefore, the lateral load-carrying capacity of the piles has decreased. Due to the pile-soil system having nonlinear responses, the effect of scouring has been detected to be more significant with higher lateral loads. Kadıoğlu (2015), modelled piled pier model located on İzmit gulf and performed nonlinear push analysis. By changing angles of the inclined steel piles and comparing them to vertical piles, observed while there is a 14-times difference between their displacements, there were 1,5 times axial force and 1,8 times bending moment differences. It is suggested that inclined and vertical piles should be investigated with nonlinear dynamic analysis in time-history. Topsoy (2016), observed that the base shear force of vertically placed lateral loaded piled pier structure is proportional with R coefficient. It has been mentioned that soil and wind loads are also effective on pile edge forces like seismic forces. Panchaland et al. (2018), have investigated the group behaviour of pile groups that have placement gaps between 2D-6D and different numbers of piles, under seismic loads. Through numerical and experimental analyses it was determined that axial force on the pile increased as the pile length increased. However, it was observed that for the increase in the pile length, shear force and bending moment have decreased for all different gap conditions. Studies in the literature have shown that numerical methods give results that are closer to reality rather than analytical and empirical methods. Therefore, this study has carried out pushover and time-history dynamic analyses of piled offshore structure. In the context of this study, three different pile diameters; 60, 80, 100 cm, and 4D-8D two placement gaps have been utilised.

2. MATERIAL AND METHOD

This study investigates the dynamic behavior of a pier structure with a foundation with circular steel piles. For this purpose, 6 numerical models are created. For the model creation, pile diameters and placement gaps have been considered parameters. DLH (2008) defined pile gaps based on pile diameter and stated that pile gaps can be accepted between 3D-8D. Pile gaps relative to pile diameters have been selected in 4D and 8D. Pile diameters and pile wall thicknesses are as follows: D600x12 mm, D800x12 mm and D1000x12 mm. While 3 pile diameters were selected, 1 pile wall thickness has been considered. Piles are modeled frame members. The steel tube section material grade is S275. Parameters that determine the pile placement is presented in Figure 1. Here; L refers to platform length, V refers to platform width, L1 and L2 refers to pile gaps in x direction, V1 and V2 refer to pile gaps in the y direction. Pile gaps determine the plan placement of the pier foundation. Created model namings and dimensional parameters are presented in Table 1.

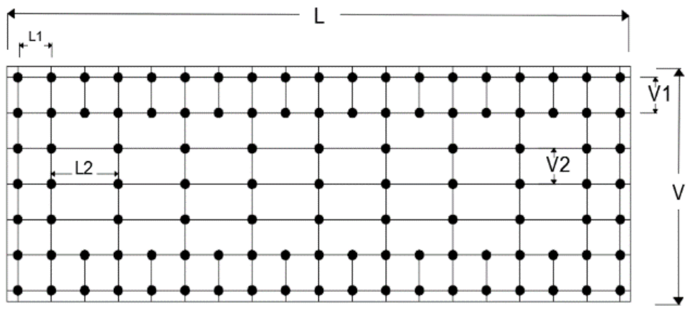


Figure 1. Plan placement of the piles used in numerical models

Pile count is varies throughout the models as can be seen in Table 1. In this context, M1 M2, M3, M4, M5 and M6 models have 128, 68, 99, 48,78 and 44 piles respectively. A pile cap that surrounds the piles from all directions with an 80 cm thick pile cap beam and 40 cm thick cap slab is defined and the superstructure is completed. The pile cap beam and slab are modelled shell element. Beam and slab material is defined as reinforced concrete. The concrete grade is selected C40 as indicated in the code (DLH, 2008). Pile lengths were assumed a constant value and accordingly with the inclined seabed, the buried depth has been defined as a parameter.

Table 1. Pile Diameters and Gaps

Model Number	Pile Diameter (mm)	Pile Spacing	L (m)	L1 (m)	L2 (m)	V (m)	V1 (m)	V2 (m)	Pile Count
M1	D600	4D	59,60	2,4	4,8	21,2	2,4	4,8	128
M2	D600	8D	59,60	4,8	9,6	21,2	2,4	4,8	68
M3	D800	4D	59,60	3,2	6,4	21,2	3,2	3,2	99
M4	D800	8D	59,60	6,4	12,8	21,2	3,2	6,4	48
M5	D1000	4D	58,0	4,0	8,0	22,0	4,0	4,0	78
M6	D1000	8D	58,0	4,0	16,0	22,0	4,0	4,0	44

Soil layers the piles are connected to are considered medium-density sand on coarse clay. For the defined soil layers, all the piles within the 26m are located in medium-dense sand. Soil-structure-pile interaction is investigated in this study, pile behaviour is investigated using the lateral bedding coefficient method (Feng et all, 2017; Yeter et all, 2019). Pile-soil interaction is defined in the numerical models using the spring coefficient. For the calculation of the spring coefficient, cohesionless medium-dense sand parameters and parameters for calculating bedding coefficients are presented in Table 2 and Table 3.

Table 2. Design parameters for cohesionless soil (Polat, 2008).

Soil	**E_s (kN/m^2)**	**ϕ**	**Y_d (kN/m^3)**	**v**
Medium-dense Sand	30000	35°	19	0,3

E_s:Modulus of Elasticity (Young's modulus)

ϕ:Effective shear resistance angle

Y_d: Soil saturated weight per unit of volume

v= Poisson ratio.

In sands, lateral bedding coefficient is proportional with the depth. In these soils, Kh (bedding coefficient, kN/m3) value is calculated using Equation 1 (Polat, 2008).

$$Kh = nh*(z/B) \quad (1)$$

In equation 1, nh refers to a coefficient related to soil density, z is depth (m), and B is pile diameter (m).

Table 3. Nh Values in Cohesionless Soils (DLH 2008)

Soil Stiffness	**On YASS nh (kN/m^3)**	**Under YASS nh (kN/m^3)**
Loose	2200	1300
Medium Density	6600	4400
Density	18000	11000

For structures that extend to sea from the shore, buried depth is heterogeneous due to the inclined seabed (Erkan et all, 2014). Pile buried depth varies between 9-15 m in numerical models. Springs representing bedding coefficients are defined in every 1 m interval in the Sap2000 program (CSI, SAP 2000). In numerical models, pile systems are defined with spring coefficients that are lateral boundary conditions in the x and y.

Three-dimensional views from the numerical models of the pier structure modelled for 4D and 8D arrangement are presented in Figure 2. Plan arrangement is of relevance to pile diameters and placement gaps.

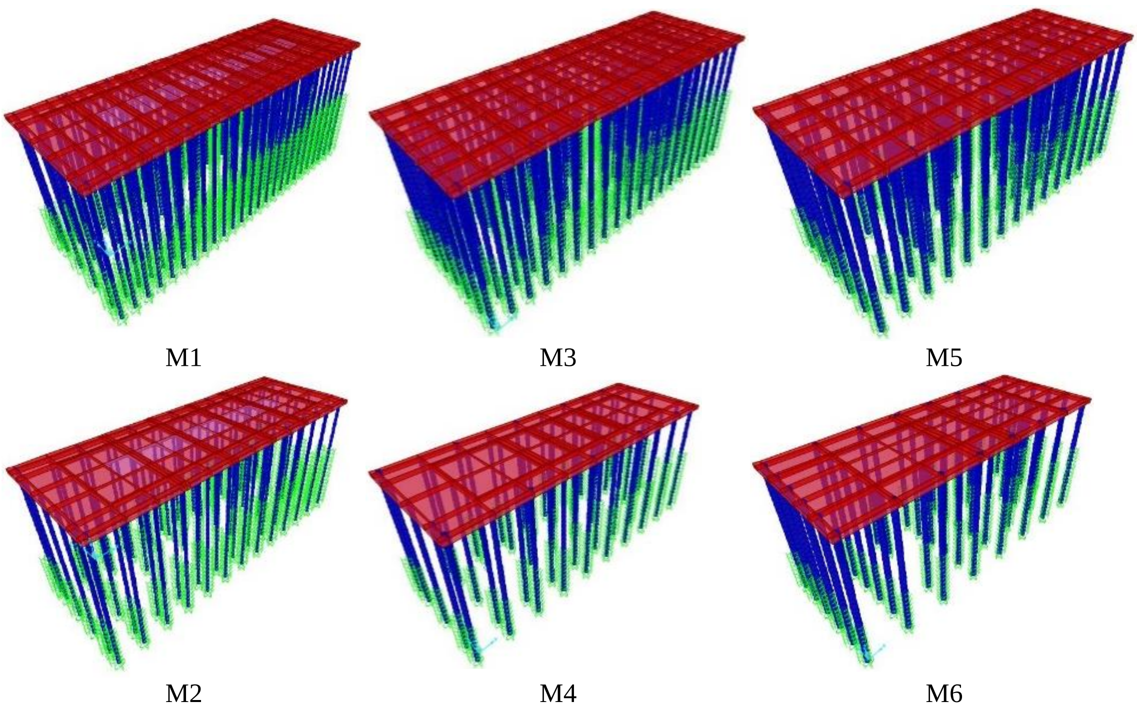


Figure 2. General views of the numerical models

Structural capacity is displayed by a pushover curve. In the study, displacement-controlled pushover analysis is carried out. In nonlinear pushover analysis, nonlinear material behaviour, plastic hinges, plastic rotation, distributed plastic behaviour model, strain values, performance point and structure performance is calculated automatically. For this performance analysis, "hinge" definitions are made on the piles. Internal forces caused by the affecting loads and section properties have determined the hinges. Therefore, columns are analyzed for "PMM" shear force and moment.

After performing a nonlinear static pushover analysis of the structure under dead weight, earthquake input for DD1 seismic condition is defined for X direction in the Sap2000 program under the time history tab. For a new analysis, nonlinear time history analysis is defined with Add New Loadcase. Kocaeli earthquake record is presented in Figure 3. In the figure, x axis refers to time while y axis refers to acceleration and x direction earthquake record is given with DDX.

Previously, pushover analysis was completed and hinges were defined. For nonlinear analysis, direct iteration method and initial condition have been selected. Spring coefficients that were used for soil representation are also used in the time history dynamic analysis.

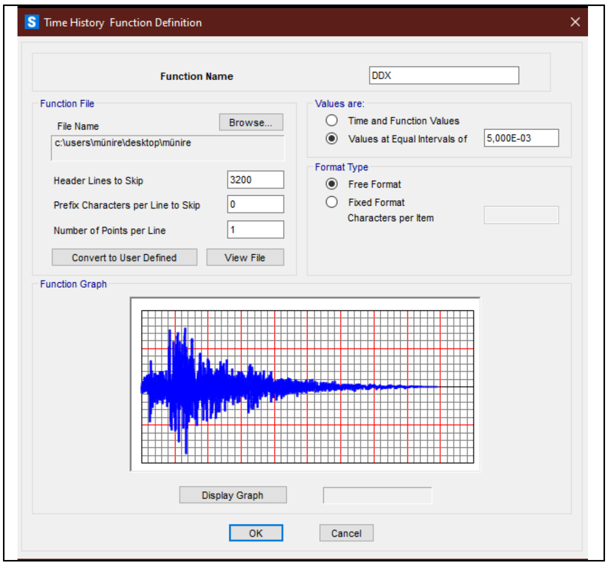
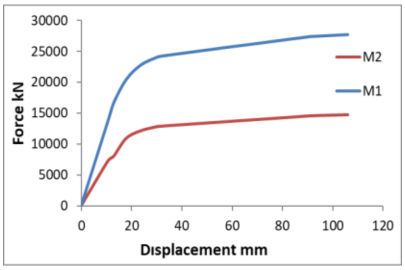


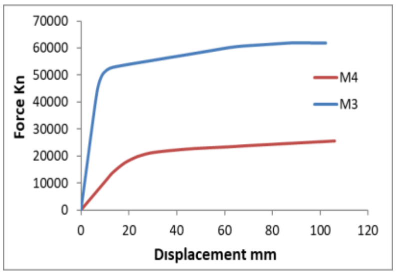
Figure 3. Earthquake record visual

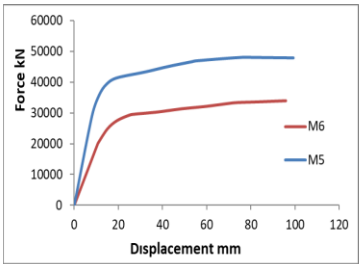
3. DISCUSSION AND CONCLUSIONS

In this study, a performance analysis of a pile foundation system used in a pier-type offshore structure has been carried out. In this context, 600 mm, 800 mm 1000 mm diameter piles for 4D and 8D arrangement plan are numerically analysed. From the numerical analysis, seismic performance of the models under lateral load is obtained. Analyses are carried out using Sap2000 V.22 finite element model program.

For the performance evaluation of the piles, axial force, moment and shear force reactions are used. In this context, plastic hinges are defined on the piles at PM2M3 (Axial force, Moment in 2 direction, Moment in 3 direction), V2 (2-direction shear force) and V3 (3-direction shear force), and load-displacement graphs are obtained from the analysis. In the definition, 2 and 3 directions refer to horizontal directions. Load-displacement graphs of the models are given separately based on the diameters in Figure 4.







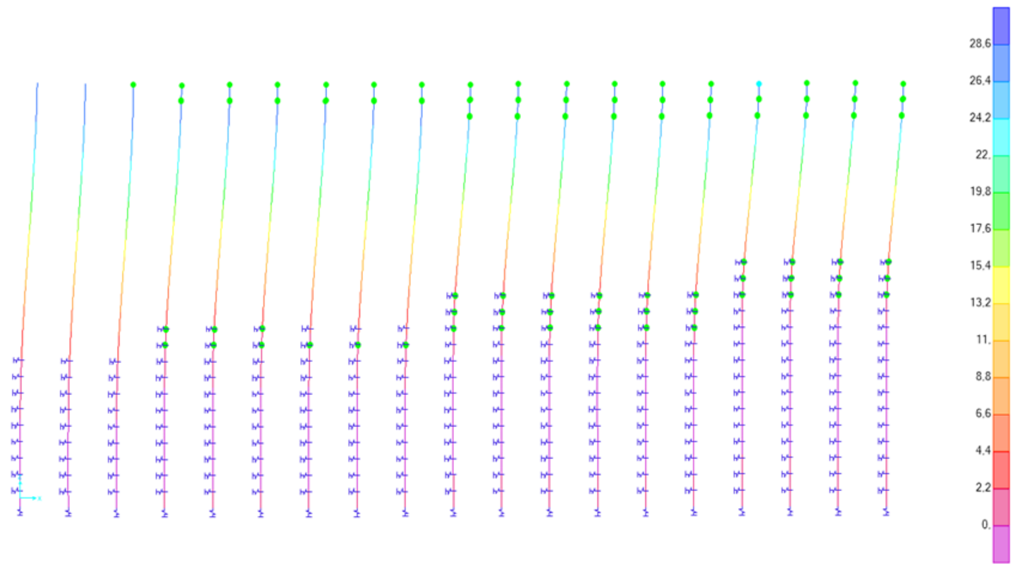
a) **b)** **c)**

Figure 4. Performance comparison of 4D and 8D arrangements a) 600 mm pile system behaviour, b) 800 mm pile system behaviour, c) 1000 mm pile system behaviour

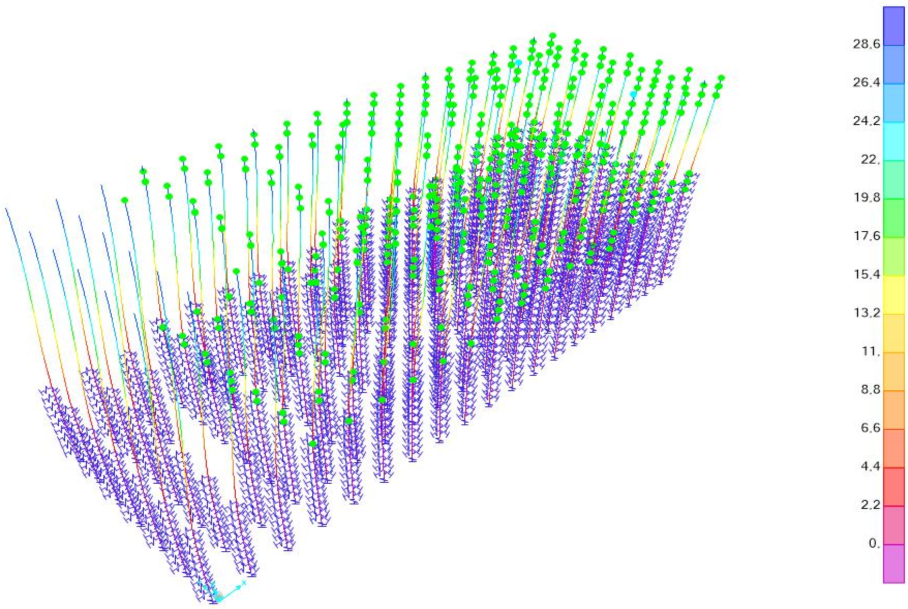
Capacity curves obtained from the analysis results are a results of pile behaviour integrated in the system. In this context, all the systems having sufficient stiffness and ductility can be seen. From the figure, it can be deduced that the 800 mm diameter condition has the highest performance level. For different pile gap conditions, 600 mm and 800 mm diameter models resulted with high efficiency. Performance levels of 600 mm diameter for 4D arrangement is approximately 2,5 times compared to 8D arrangement. The performance levels for 800 mm diameter for 4D to 8D conditions is approximately 3 times. For 1000 mm diameter, this value is approximately 1,25 times. M3 model, the model with 800 mm diameter and 4D arrangement, has given the most effective result from performance points for linear limit and 100 mm displacement mark.

For all pile diameters, in 4D arrangement models M1, M3 and M5, nonlinear dynamic analysis is carried out using scaled accelerogram data. In order to determine if the

displacements in the x direction has exceeded the linear limit, firstly, a nonlinear pushover analysis is carried out. Capacity curves given in Figure 4 shows linear and nonlinear limit (failure) conditions. The deformed condition for the M3 model is presented in Figure 5. From the figures, it can be seen that the plastic deformations have begun with the buckling level. The first deformation has occurred at the interaction zone of the upper foundation, piles and the soil and in the first metre of the piles, buckling and plastic deformation started. Plastic deformations are detected to be higher in places where the pile-soil interaction is higher, piles with more buried depth (i.e. places of the pier closer to shore). Springs representing the soil around the pile and hinge points are shown in the 3 dimensional visual of the pier structure (Figure 5). In addition, plastic deformations on the section and 3 dimensional visuals are presented for displacement.



a)



b)

Figure 5. Displacement scale visual of deformed pier a) Pier section, b)3D Visual

The base shear force and displacement graph obtained from the dynamic analysis results are presented in Figure 6.

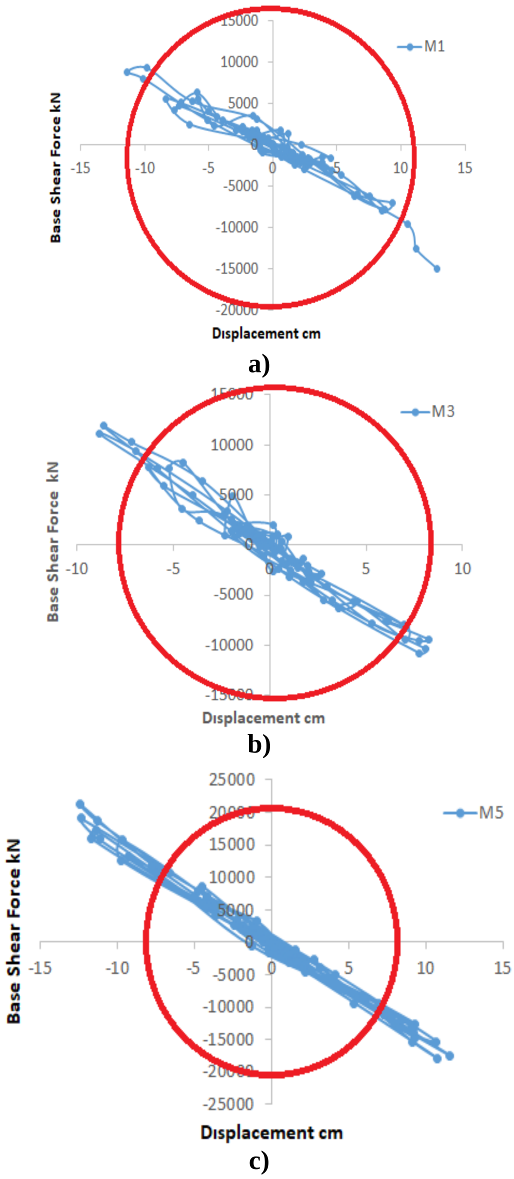


Figure 6. Time history nonlinear analysis graph a) 600 mm Diameter 4D arrangement, b) 800 mm diameter 4D arrangement, c) 1000 mm diameter 4D arrangement

For the static pushover results, the red circle represents the linear capacity of the structure in the x direction and is presented in Figure 6. Base shear force and displacements are examined and for the accelerogram, with this capacity considered, most of the system remaining in the linear zone can be seen. 600 mm diameter piled system flexibility is higher. Therefore displacement capacity and the linear limit value were higher than other two diameters.

When the load is applied, it will not be distributed equally on the pile system. For the pile group consideration, pile group carrying capacity can be determined with a reduction factor. Depending on their position in the group, load-carrying capacity differs (Walsh, 2005). Piles on the front end meet the forces first and bear the most of it, the stresses caused by this and the stress entrance zones overlapping soften the soil in the zone. The Softening effect on the soil decreases the loads piles can carry. This effect is applied to the piles depending on their position on the plan, thus a reduction coefficient was used. Therefore, piles are placed in 4D spacing, while piles in the inner regions are placed in 8D spacing. It was detected that pile buried depth differentiates the buckling length. Buckling length is related to pile slenderness. To restrain this parameter, either pile buckling length should be decreased or pile diameter should be increased. With the pile diameter increase, the system can tolerate the slenderness. 600 mm diameter pile has a more wavy behaviour while 800 mm and 1000 mm piles pose a more integrated behaviour. Deviation in the displacement behaviour of the piles are related to their buried depths. If the pile buried depths were the same, it would be expected from load-displacement curves from the linear behaviour to shift within the same boundaries. However, this structure is a pier and the effect of the natural slope formation by the shore results with piles that have different effective lengths. Therefore, piles in the system have different capacity and displacement values. For this reason, the damping of the building system behaviour was not formed by a cyclic effect in the same line but by a wavy displacement.

4. RESULTS

In this study; a performance evaluation of a piled pier foundation system with different pile diameters and pile spacings is carried out. Used pile diameters are; 600 mm, 800 mm and 1000 mm. Used pile spacings are, 4D and 8D. In total 6 models are created. Dimensional parameters of the numerical models are determined by pile diameters and analysed using Sap 2000 finite element model program. In the program, pushover analysis is carried out and capacity curves are obtained. After, nonlinear time history analysis using a scaled seismogram data is carried out. Obtained values are presented comparatively.

In this context;

- From the capacity curves, it was detected that all of the models have sufficient stiffness and ductility.
- From the 600,800 ve 1000 mm diameter conditions, the highest performance level was obtained from 800 mm diameter with a 4D spacing condition, which is the model M3.
- For the defined earthquake model and soil properties, pile system maximum base shear force values have not exceeded the linear limit. For 800 mm diameter and 4D arrangement, soil has provided sufficient stiffness for piled system behaviour under seismic effect,
- It was detected that plastic deformations on the piles have started with the buckling level. The first deformation has occurred at the interaction zone of the upper foundation, piles and the soil and in the first metre of the piles and this height concentrates as the buried depth of the pile increases
- Dynamic behaviour of the pier structure is affected by slenderness and correspondingly buckling shape change. As the pile diameter increases, system stiffness and load-carrying capacity of the system also increases accordingly.

- Buried depths of the piles varying has affected the buckling length of the piles, therefore 600 mm, 800 mm and 1000 mm diameter systems have shown different behaviour.

Ethics Committee Approval
N/A

Peer-review
Externally peer-reviewed.

Author Contributions
Conceptualization, Investigation, Material and Methodology, Supervision, Visualization, Writing-Original Draft, Writing-review & Editing ;M.F.. Other: All authors have read and agreed to the published version of manuscript.

Conflict of Interest
The authors have no conflicts of interest to declare.

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