NONLINEAR PUSHOVER ANALYSIS OF PILE FOUNDATIONS

L. Handzhiyski\textsuperscript{1} and A. Dutta\textsuperscript{2}

ABSTRACT

In conventional design, the project geotechnical engineer typically calculates pile lateral capacity using pushover analysis with elastic stiffness for the pile cross-section and nonlinear lateral springs for the soil strata. Lateral capacity for a single pile is usually reported to the structural engineer at an arbitrary displacement of $\frac{1}{2}$ inch. Structural engineers use this capacity to determine the number of piles needed to resist base shear forces reduced to code specified levels as well as to design the pile sections. This methodology does not capture the actual foundation response in a seismic event and neither the geotechnical nor the structural engineer typically understands the ductility demands on the piles under design or MCE events.

This paper illustrates a performance-based approach in which nonlinear representation of piles allows a more realistic estimate of pile foundation performance under large earthquake demands. A tall reinforced concrete building supported by 850 precast prestressed reinforced concrete piles was used in this study. The model represented the pile cap using a grillage of line elements and piles using vertical spring supports to obtain the axial load at each pile. Pile cap rotations due to dishing effects caused by gravity loads were computed at every pile. A series of nonlinear individual pile pushover analyses were performed for 11 levels of axial load ranging from zero to 950 kips representing the range of gravity loads. Pile nonlinear moment-curvature relationship and soil nonlinearity were explicitly modeled. Analyses were then repeated with the pile preloaded with the maximum positive and maximum negative pile head rotation obtained from the pile cap resulting in a total of 33 pushover analyses.

The results of these analyses were used to calculate a pushover curve for each of the 850 piles in the foundation. Two-dimensional interpolation was performed for the lateral force at each pile using axial load and head rotation. The pushover curves obtained using this method were different

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in each of the four planar orthogonal directions as the sign of head rotations affected the response of each pile. The responses of the individual piles were then added to determine the total lateral response of the pile foundation in the positive and negative X and Y directions. Ultimately, the nonlinear pushover curve was implemented as a bidirectional nonlinear spring at the base of the building structural model to account for foundation flexibility and predict more realistic foundation demands.
Nonlinear Pushover Analysis of Pile Foundations

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ABSTRACT

In conventional design, the project geotechnical engineer typically calculates pile lateral capacity using pushover analysis with elastic stiffness for the pile cross-section and nonlinear lateral springs for the soil strata. Lateral capacity for a single pile is usually reported to the structural engineer at an arbitrary displacement of ½ inch. Structural engineers use this capacity to determine the number of piles needed to resist base shear forces reduced to code specified levels as well as to design the pile sections. This methodology does not capture the actual foundation response in a seismic event and neither the geotechnical nor the structural engineer typically understands the ductility demands on the piles under design or MCE events.

This paper illustrates a performance-based approach in which nonlinear representation of piles allows a more realistic estimate of pile foundation performance under large earthquake demands. A tall reinforced concrete building supported by 850 precast prestressed reinforced concrete piles was used in this study. The model represented the pile cap using a grillage of line elements and piles using vertical spring supports to obtain the axial load at each pile. Pile cap rotations due to dishing effects caused by gravity loads were computed at every pile. A series of nonlinear individual pile pushover analyses were performed for 11 levels of axial load ranging from zero to 950 kips representing the range of gravity loads. Pile nonlinear moment-curvature relationship and soil nonlinearity were explicitly modeled. Analyses were then repeated with the pile preloaded with the maximum positive and maximum negative pile head rotation obtained from the pile cap resulting in a total of 33 pushover analyses.

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Introduction

In conventional design, the project geotechnical engineer typically calculates pile lateral capacity using pushover analysis with elastic stiffness for the pile cross-section and nonlinear lateral springs representing the soil strata. Lateral capacity for a single pile is usually reported to the structural engineer at an arbitrary pile head displacement of ½ inch. Structural engineers then use this capacity to determine the number of piles needed to resist base shear forces reduced to code-

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specified levels. In reality, in the design event, the force demand on the foundations is likely to be somewhat higher than predicted as structural lateral force-resisting systems tend to exhibit overstrength. This can lead to higher displacements and changes in the behavior of the nonlinear soil springs that can cause different behavior of the pile.

In addition to the lateral shear capacity, the geotechnical engineer provides displacements, bending moments, and shears at multiple points along the depth of the pile as shown in Fig. 1. Structural engineers use these demands to design the pile cross sections. During an earthquake, as the superstructure exhibits overstrength and causes larger displacements in the piles, these demands would increase and can potentially cause yielding and plastic hinging in the piles. In the case of high axial loads on some piles this can lead to significant softening of foundations due to P-delta effects which is not captured by the linear representation of the pile in the geotechnical model. Therefore, this methodology, which is the current state of practice, does not capture the actual foundation response in a seismic event and neither the geotechnical nor the structural engineer typically understands the ductility demands on the piles under design or MCE events.

![Figure 1. Example of a lateral displacement and bending moment profiles of a pile provided by a geotechnical engineer.](image)

This paper illustrates an alternative, performance-based approach, in which nonlinear representation of piles in the structural analysis model allows a more realistic estimate of pile foundation performance under large earthquake demands. A tall reinforced concrete building supported by 850 precast prestressed reinforced concrete piles was used in this study.

**Description of the Study Building’s Structural Systems**

The building subject to this study is a 58-story reinforced concrete structure. The lateral force-resisting system consists of a central reinforced concrete core with outriggers in one direction and reinforced concrete moment frames in both directions around the building perimeter. The concrete core and moment frame columns also serve as the gravity load-supporting system for the building. The building has a single-story basement. All vertical structural elements are connected at the
foundation level through a common pile cap that covers the entire footprint of the building.

**Structural Analysis Model**

The structure was modeled in Perform-3d [1]. The pile cap was represented by a grillage of FEMA beam line elements with shear hinges that have properties based on the flexural and shear strength of each section. The line elements have a spacing of 5 feet in each direction and each element represents a 5-foot-wide section of the pile cap. The piles were modeled at each joint of the 5-foot grid using inelastic bar elements with axial-only trilinear behavior with varying strength across the site based on a geotechnical investigation and analysis performed by the project geotechnical engineer. A pile cap plan from the Perform-3d model is shown in Fig. 2. At some column locations it was necessary to modify the grid spacing in order to model the columns at their exact location.

The model was analyzed with a pinned base under expected gravity loads to obtain the axial compressive loads at the piles and the deformed shape of the pile cap. Nodal rotations were recorded at all joints in the pile cap and were used to obtain the head rotations of the piles about the X and Y axes of the model. It should be noted that the rotational stiffness of the pile heads was ignored in this analysis which led to deformed shape of the pile cap that is not completely accurate. The results of the analysis showed that pile axial loads ranged from 0 to 950 kips and the maximum head rotation was 1.09%.

Head rotation was considered as an important aspect of the study. In a typical pile pushover analysis piles often form their first hinge at their connection with the pile cap. A pile preloaded with rotation at the top would therefore have a different force-deformation relationship from that of a straight pile. A schematic sketch of the deformed shape of the pile under pushover and dishing is shown in Fig. 3.

![Figure 2. Pile cap plan from the Perform-3d model.](image)
Pile Pushover Analyses

850 pairs of axial load and head rotation in the X and Y direction were obtained as a result from the gravity analysis in Perform-3d [1]. In order to construct a composite pushover curve for the entire building, pushover curves had to be computed for each pile. In order to avoid building 850 analytical models, analysis was done at representative gravity load and head rotation magnitudes and the results were used to calculate the pushover curve of every pile using 3-dimensional interpolation. Lateral load was interpolated based on lateral displacement, head rotation, and axial load.

A series of nonlinear individual pile pushover analyses were performed for 11 levels of axial load ranging from zero to 950 kips representing the range of gravity loads. Analyses were then repeated with the pile preloaded with the maximum positive and maximum negative pile head rotation obtained from the pile cap resulting in a total of 33 pushover analyses.

All piles had the same 14-inch square concrete cross section with 8 ½-inch prestressing strands. In the upper 7 feet of the pile additional 4 #9 bars were added to increase flexural strength. In the top 2.5 feet additional 4 #9 grouted dowels were added to strengthen the connection to the pile cap. This resulted in three different pile cross sections.

Each of the pile cross sections was modeled in XTRACT [2]. The square cross sections were approximated conservatively as circular since the piles have chamfered corners and circular reinforcing arrangement. As a simplification, variations in pile vertical loads due to overturning demands and vertical ground motions as well as biaxial flexural strength interaction effects were not considered in the moment-curvature analysis. Doing so would require implementation of each pile in the superstructure model and was not considered practical for the scope of this research.

P-M interaction curves are shown for the three sections in Fig. 4. Unidirectional moment-curvature analyses were performed for each section under the 11 levels of axial load. A representative moment-curvature relationship is shown in Fig. 5. The XTRACT [2] moment-curvature output was then used to define hinge properties in the nonlinear SAP2000 [3] model of the pile.
In addition to defining the nonlinear behavior of the pile cross section, soil nonlinear p-y spring properties were developed from an LPile [4] model of the ground conditions at the site considering lateral group effects. These values were used to define nonlinear spring properties in SAP2000 [3] (Fig. 6). Near the top of the pile, soil springs were spaced at 2 feet. Near the bottom, a 4-foot spacing was used since this part of the pile would exhibit very limited deformations. Hinge properties with the moment-curvature relationships calculated in XTRACT [2] were defined at each location where the pile cross section reinforcement changes.
The SAP2000 [3] model included P-delta effects which were observed to have a significant effect on pile lateral behavior adding a large negative stiffness at high axial load. The results from the 33 pushover analyses are shown in Fig. 7. As expected, pile head rotation preload causes shear in the piles and affects the ductility of the section. Under high axial loads pile failure occurs relatively early as expected due to concrete crushing combined with negative flexural stiffness due to P-delta effects.
Composite Pushover Curve and Analysis Implementation

Four composite pushover curves were developed by adding the individual pile pushover curves in the positive and negative X and Y directions as shown in Fig. 8. The results were relatively similar and it was deemed appropriate to represent the behavior in all four directions using the same backbone curve.

From the pushover curve it can be observed that the foundation does not have much overstrength beyond the pile design displacement of ½ inch. The current state-of-practice procedure can therefore result in unconservative foundation designs.

The nonlinear backbone was defined in Perform-3d [1] as a V2-V3 hinge. A rigid diaphragm was assigned at the pile cap level. The diaphragm was connected to the single lateral support node using a rigid column which had the V2-V3 hinge property assigned to it. In order to maintain stability under torsional loads, all nodes at the pile cap were assigned an in-plane rotational restraint. If torsional nonlinear foundation behavior needs to be captured, lateral springs would need to be modeled at every pile as pile degradation due to displacement would depend on the distance from the pile group center of rigidity.

The Perform-3d [1] model with the shear hinge was used to assess foundation displacement demands and confirm stability of the structure under MCE.
Figure 8. Composite pushover curve and Perform-3d V2-V3 hinge definition.

**Conclusions**

This paper demonstrates an alternative performance-based approach to pile foundation design and evaluation. The method presented herein allows for an understanding of foundation displacement demands and the effect of pile P-delta on the lateral strength of a building’s foundation. Both of these parameters are not considered in the current conventional approach to designing pile foundations. In the individual pile pushover analyses it was observed that P-delta can significantly affect the ductility of piles with large compressive loads when cross section nonlinearity was considered in addition to soil behavior. The current approach to designing pile foundations was found to be potentially unconservative as it does not warrant significant overstrength at displacements greater than the ½ inch design displacement.

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