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SIMPLIFIED SEISMIC ANALYSIS OF PILES IN MARINE OIL TERMINALS

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Abstract

The current seismic evaluation procedure of the piles in marine oil terminals includes monitoring material strains specified in the Marine Oil Terminal Engineering and Maintenance Standard (MOTEMS) during the nonlinear static pushover analysis to estimate the displacement capacity of piles. This paper presents closed-form formulas for estimating the displacement capacity of piles by utilizing a simple pile-deck connection system. The displacement capacity estimated from these formulas ensures that the material stain limits specified in the MOTEMS is not exceeded. These formulas are verified against results from the nonlinear finite-element analysis. Development of closed-form formulas enable better understanding of the various parameters that control the displacement capacity of piles: the curvature ductility capacity of the pile section and rotation ductility capacity of the connection at the selected seismic design level, and parameters β and η which define relative stiffness of the pile and the connection and relative strength of the connection and the pile, respectively. These formulas are intended to be used for preliminary design of piles or as a check on the results from the detailed nonlinear static pushover analysis procedure, with material strain control, specified in the MOTEMS.

Introduction

Marine oil terminals employ vertical piles to resist gravity loads as well as seismic loads. While the gravity load piles may be connected to the deck by a pin-connection, seismic load piles are typically connected to the deck by a partial-moment-connection. The connection is designed such that its moment capacity is smaller than the moment capacity of the pile. As a result, the yielding is expected to occur in the connection rather than the pile. The nonlinear behavior of piles with such partial-moment-connection to the deck slab may differ significantly from those of piles in which the connection is stronger than the pile and as a result yielding occurs in the pile and not the connection. This paper investigates seismic behavior of two types of piles commonly used in marine oil terminals with partial-moment-connection – hollow-steel piles connected to the deck by a concrete plug and dowels, and pre-stressed-concrete piles connected to the deck by dowels grouted into sleeves in the pile.

Figure 1a shows details of the typical connection between hollow-steel pile and concrete

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deck of marine oil terminals (Ferrito et al., 1999; Nezamian et al., 2006). In this connection, denoted as the concrete-plug connection, dowels are embedded in a concrete-plug at the top of the pile. The concrete-plug is held in place by shear rings at its top and bottom; the shear rings would prevent the concrete plug from slipping out (or popping-out) during lateral loads imposed by earthquakes. Others have proposed details in which the concrete-plug is held in place either by natural roughness of the inside surface of the steel shell or use of weld-metal laid on the inside of the steel shell in a continuous spiral in the connection region prior to placing the concrete plug (Ferritto et al., 1999). The dowels are then embedded in the concrete deck to provide sufficient development length. A small gap may or may not be provided between top of the pile and top of the concrete-plug. This concrete-plug connection in hollow-steel piles has been shown to provide remarkable ductility (Priestley and Park, 1984; Park et al., 1987).

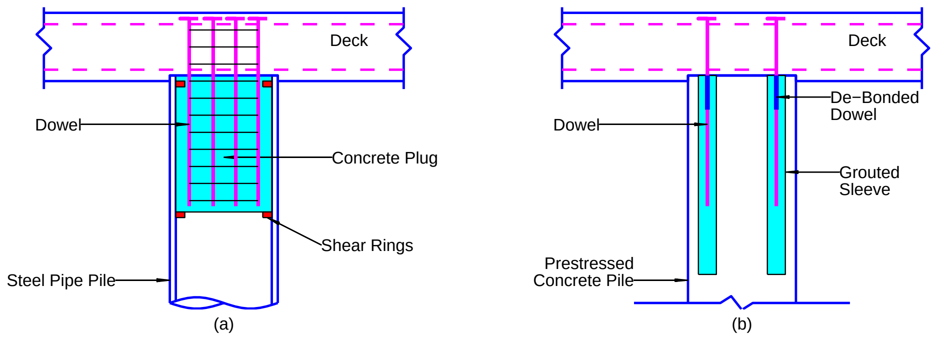

Figure 1. Partial-moment-connection of piles to the deck in marine oil terminals: (a) Concrete-plug connection for hollow-steel piles; and (b) Dowel-sleeve connection for pre-stressed-concrete pile.

Figure 1b shows details of the connections between pre-stressed-concrete pile and concrete deck of marine oil terminals (Klusmeyer and Harn, 2004; Roeder et al., 2005; Restrepo et al., 2007; Wray et al., 2007). Pre-stressed-concrete piles typically have corrugated metal sleeves that are embedded in the concrete. These sleeves are located inside of the confined concrete core formed by the pre-stressing strands and confining steel. Once the pre-stressed-concrete pile has been driven to the desired depth, the dowels are grouted into the sleeves. If higher flexibility of the connection is desired, a small portion of the dowel at the top of the pile may be wrapped in Teflon to ensure de-bonding between the dowel and the grout. The dowels are then embedded in the concrete deck to provide sufficient development length. The development length of the dowel may be achieved either by outward bending of the dowel in the deck concrete or by using T-headed dowels (Roeder et al., 2005). However, the most commonly used dowel in marine oil terminals and other port facilities is the T-headed dowel as shown in Figure 1b (Restrepo et al., 2007). Note that Figure 1b shows only two outermost dowels; a typical connection may include several dowels but they are not shown here to preserve clarity in the figure.

Seismic design of marine oil terminals in California is governed by the Marine Oil Terminal Engineering and Maintenance Standard (MOTEMS) [Eskijian, 2007; MOTEMS, 2006]. The MOTEMS requires design of such facilities for two earthquake levels: Level 1 and Level 2. The return period of the design earthquake for each level depends on the risk level. For example, Level 1 and Level 2 design earthquakes for high risk terminals correspond to return periods of 72 and 475 years, respectively. The acceptance criteria for piles in the MOTEMS are specified in terms of maximum permissible material strains. The maximum permissible material strains depend on the earthquake level – Level 1 or Level 2 – and on location of the plastic hinge – pile-deck or in-ground.

Since the acceptance criteria in the MOTEMS is specified in terms of maximum permissible strains, evaluation of piles as per the MOTEMS provisions requires monitoring material strains during the seismic analysis. However, most commercially available structural analysis programs do not have the capability to directly monitor strains during seismic analysis. Therefore, there is a need to develop simplified acceptability criteria for piles in marine oil terminals that ensure that material strains do not exceed the values specified in the MOTEMS and yet do not require direct monitoring of strains during seismic analysis.

In order to fill this need, this paper presents simple, closed-form formulas to estimate the displacement capacity of piles with partial-moment-connection. Development of these formulas eliminates the need to monitor material strains during the pushover analysis. Furthermore, these formulas are shown to provide "accurate" estimate of the displacement capacity of piles.

The investigation reported in this paper presents simplified procedure for piles with partial-moment-connection. The investigation reported in this paper utilizes a commonly used simplifying assumption that the pile-soil-system may be represented by a simple model that is fixed at the base at a depth equal to depth-of-fixity below the mud line. The depth-to-fixity, which depends on the pile diameter and soil properties, is typically provided by the geotechnical engineer or estimated from charts available in standard textbooks on the subject (e.g., Priestley, et al., 1996) or from recommendations in several recent references (e.g., Chai, 2002). Further discussion on the subject is available elsewhere (Goel 2008) and is not included here for brevity.

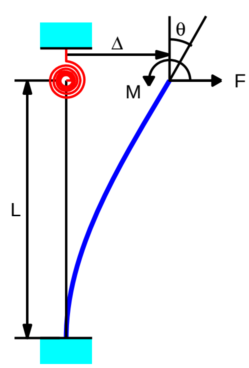

Figure 2. Simplified model of the pile with partial-moment-connection to the deck.

Simplified Model of Pile with Partial-Moment-Connection

A pile with partial-moment-connection to the deck may be idealized as a beam-column element fixed at the base and a rotational spring at the top (Figure 2). The length of the element is equal to the free-standing height of the pile plus the depth of fixity below the mud-line. The procedure to select the depth-of-fixity is available elsewhere (see Priestley at al., 1996; Chai, 2002). The rotational spring at the top of the pile represents the nonlinear behavior of the concrete-plug or the dowel-sleeve connection. Ignoring axial deformations in the pile, this system can be modeled with two displacement degrees-of-freedom: lateral displacement, Δ, and rotation, θ, at the top. When lateral force, F, is applied at the top of the pile, a moment, M, also develops at the top of the pile because of rotational resistance provided by the rotational spring representing the concrete-plug or the dowel-sleeve connection. Note that rotation in the rotational springs is equal to rotation at top of the pile. The nonlinear moment-rotation relationship of the connection between pile and the deck, developed based on the recommendation by a committee of the Coasts, Oceans, Ports, and Rivers Institute (COPRI) of the American Society of Civil Engineers (Harn, 2008), is typically idealized as an elastic-perfectly-plastic curve.

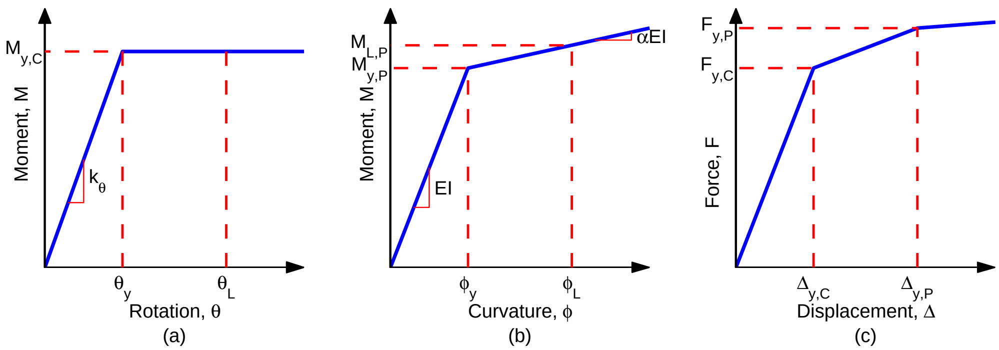

Figure 3. Idealized relationships: (a) Moment-rotation relationship of partial-moment-connection; (b) Moment-curvature relationship of the pile section; and (c) Force-deformation relationship of the pile system.

Presented next are the closed-form solution of the displacement capacity of this simplified model. For this purpose, let us consider an idealized moment-rotation relationship for the partial-moment-connection (Figure 3a) and idealized moment-curvature relationship of the pile section (Figure 3b). The rotational ductility capacity of the connection at specified design level is defined by

$$\mu_\theta = \frac{\theta_L}{\theta_y} \tag{1}$$

in which θ_L is the rotation in the rotational spring when the strain in outermost dowel of the partial-moment-connection just reaches the strain limit specified for a selected design level and θ_y is the yield rotation (Figure 3a). Similarly, the pile section curvature ductility capacity at a selected design level is defined as

$$\mu_\phi = \frac{\phi_L}{\phi_y} \tag{2}$$

where ϕ_L is the curvature of the pile section when the material strain just reaches the strain limit specified for a selected design level and ϕ_y is the curvature at effective yielding of the pile (Figure 3b). Finally, dimensionless constants, η and β are defined as

$$\eta = \frac{M_{y,P}}{M_{y,C}}; \quad \beta = \frac{EI}{k_\theta L} \tag{3}$$

in which $M_{y,P}$ is the pile yield moment, $M_{y,C}$ is the connection yield moment, EI the initial elastic slope of the idealized pile moment-curvature relationship, L is the pile length, and k_θ is the initial elastic stiffness of the partial-moment-connection.

The force-deformation behavior (or pushover curve) of a pile with fixed-base and rotational spring at the top may be idealized by a tri-linear relationship shown in Figure 3c. For piles with partial-moment-connection, the yield moment of the connection is typically selected to be smaller than yield moment of the pile section. For such condition, the first yielding in the pile-connection system would occur in the connection at lateral force and displacement equal to $F_{y,C}$ and $\Delta_{y,C}$, respectively. Since the pile has not yet reached its yield moment, the lateral force in the pile-connection system would continue to increase with displacement till yielding occurs in the pile at force and displacement equal to $F_{y,P}$ and $\Delta_{y,P}$, respectively. Subsequently, the lateral force in the pile system would increase with displacement only due to strain-hardening effects in the pile material.

The displacement capacity of the pile with partial-moment-connection is defined as the maximum displacement at the top of the pile without material strains specified in the MOTEMS being exceeded either in the connection or the pile for a selected design level. This capacity can be expressed as

$$\Delta = \mu_\Delta \Delta_{y,C} \tag{4}$$

in which

$$\Delta_{y,C} = \frac{\theta_{y,C} L (1+4\beta)}{6\beta} \tag{5}$$

is the yield displacement which corresponds to first effective yielding in the connection (see Figure 3c), and μ_Δ is the displacement ductility capacity of the pile defined as lower of the displacement ductility capacity corresponding to yielding in the connection, $\mu_{\Delta,C}$ and the displacement ductility capacity corresponding to yielding in the pile, $\mu_{\Delta,P}$. The ductility $\mu_{\Delta,C}$ is given by

$$\mu_{\Delta,C} = \begin{cases} \dfrac{1+4\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta \le \dfrac{\eta-1}{2\beta} \\[2ex] \dfrac{2-\eta+6\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta > \dfrac{\eta-1}{2\beta} \end{cases} \tag{6}$$

Equation (6) provides the value of $\mu_{\Delta,C}$ for two cases: strain limits in the connection reaching the specified values prior to or after initiation of yielding in the pile. The ductility $\mu_{\Delta,P}$ is given by

$$\mu_{\Delta,P} = \frac{2\eta - 1}{1+4\beta} + \left(\frac{6\eta}{1+4\beta}\right)\left(\frac{\rho\eta}{1+\eta}\right)\left(1 - \frac{\rho\eta}{2(1+\eta)}\right)(\mu_\phi - 1) \tag{7}$$

in which ρ is the length of the plastic hinge in the pile as a fraction of its length. The recommended value is $\rho = 0.03$ for Level 1 design and $\rho = 0.075$ for Level 2 design of hollow-steel piles with concrete-plug connection; and $\rho = 0.05$ for both design levels of pre-stressed-concrete pile with dowel-sleeve connection. A detailed derivation of these equations is available in Goel (2009).

It is useful to note that the ρ values recommended in the preceding paragraph were selected by matching displacement capacity of pile from the proposed formulas with that from nonlinear finite element analysis for a single pile configuration. However, as will become apparent from results presented later in this paper, these values appear to be applicable for a wide range of pile parameters. Ideally, these values must be verified from experimental observations. However, experimental verification was not possible due to limited scope of this project.

Analytical Verification

The accuracy of the closed-form formulas presented in the preceding section is verified next by comparing design ductility capacity from nonlinear finite element analysis (NFEA) with that from Equations (4) to (7). Ideally, such verification should occur against experimental results. However, experimental verification was not possible due to limited scope of this project. Figures 4 and 5 present the results for a 61 cm diameter hollow-steel pile for seismic design level 1 and 2, respectively. The results are for two wall thicknesses, 1.27 cm and 2.54 cm; two values of pile axial load, $0.05Af_y$ and $0.1Af_y$; and two arrangement of dowels, 8 or 12, in the connection. The area of each dowel is 8.2 cm^2. The combination of these parameters is indicated on each figure. Similarly, Figures 6 and 7 present the results for pre-stressed-concrete pile for design levels 1 and 2, respectively. The selected pile is of 61 cm diameter with 16 pre-stressing strands. The area of each pre-stressing strand is equal to 1.4 cm^2, strength is 1884 MPa, and initial pre-stress in strands is equal to 70% of its strength. The confinement is provided by #11 spiral wire (area = 0.71 cm^2) with spacing equal to 6.3 cm. The dowel connection consists of 8 bars, each with an area equal to 3.9 cm^2. Four different values of de-bonded lengths (DL) – 0, 30, 61, and 91 cm – are selected.

The results from nonlinear finite element were generated, as noted previously, using *OpenSees* (McKenna and Fenves, 2001). The pile was modeled with the *nonlinearBeamColumn* element in OpenSees. The *nonlinearBeamColumn* element uses a force-based, distributed-plasticity approach with integration of section behavior over the member length. The pile was modeled with five elements, each with seven integration points. The section is defined with fibers of confined concrete, unconfined concrete, and steel reinforcing bars for reinforced-concrete piles and steel for hollow-steel piles. The nonlinear axial-flexural behavior of the element is determined by integration of the nonlinear stress-strain relationships of various fibers across the section, whereas linear behavior is assumed for shear and torsional. Further details of the material models and *nonlinearBeamColumn* element are available in McKenna and Fenves (2001). As mentioned previously, the nonlinear moment-rotation relationship of the connection between pile and the deck was developed based on the recommendation by a committee of the Coasts, Oceans, Ports, and Rivers Institute (COPRI) of the American Society of Civil Engineers (Harn, 2008); details of this model are available in Goel (2008).

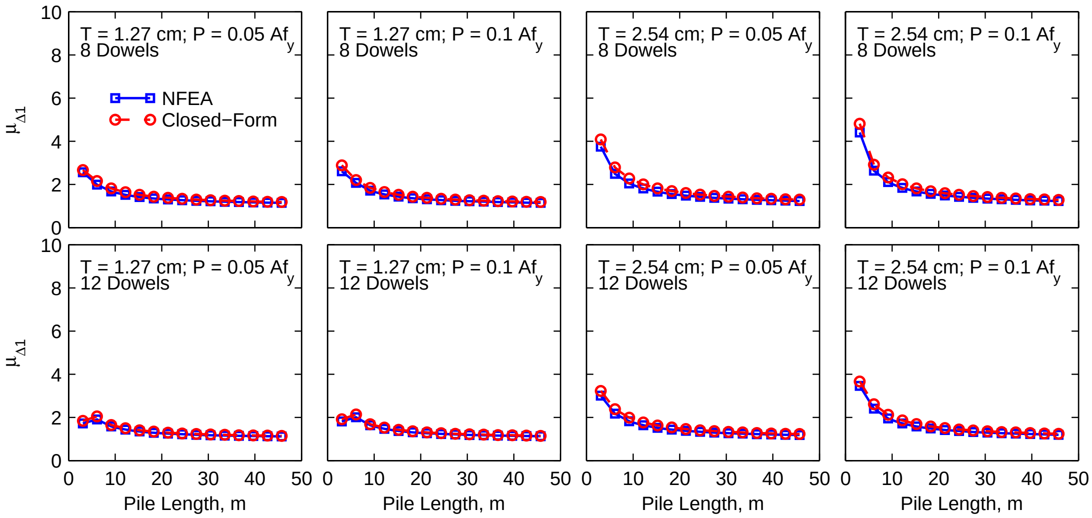

Figure 4. Displacement ductility capacity of hollow-steel pile with concrete-plug connection for design Level 1.

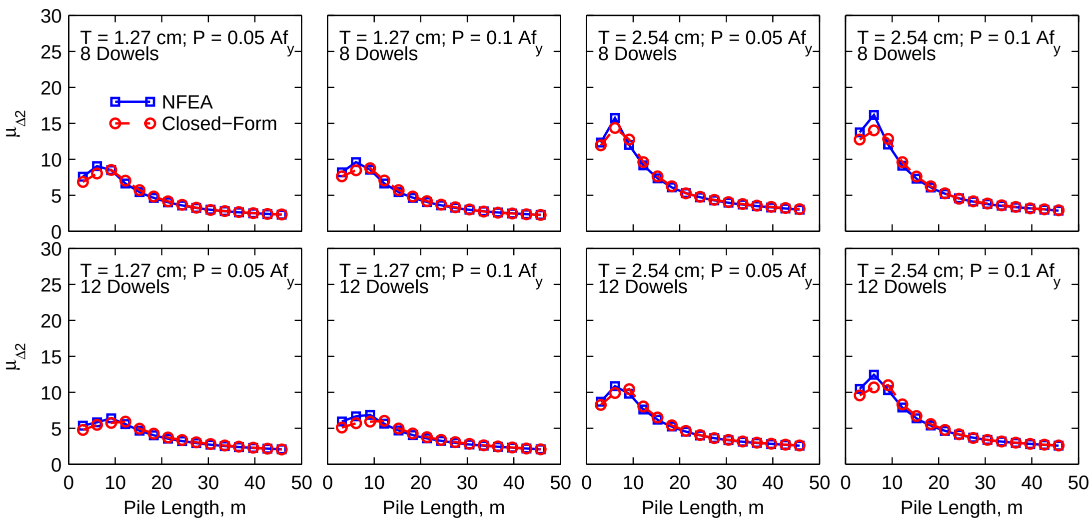

Figure 5. Displacement ductility capacity of hollow-steel pile with concrete-plug connection for design Level 2.

The presented results in Figures 4 to 7 indicate that the closed-form formulas presented in this investigation provide “accurate” estimate of displacement ductility capacity of hollow-steel piles with concrete-plug connection (Figures 4 and 5) as well as for pre-stressed-concrete piles with dowel-sleeve connection (Figures 6 and 7). This becomes apparent from essentially identical curves for the displacement ductility obtained from the closed-form formulas and the nonlinear finite element analysis. For very-short pre-stressed-concrete piles, the closed-form formulas provide values of the displacement ductility capacity that is lower than the values from the nonlinear finite element analysis for the MOTEMS seismic design Level 2 (Figure 7). However, the estimate of the displacement ductility from the closed-form formulas is a lower-bound, and hence conservative, estimate.

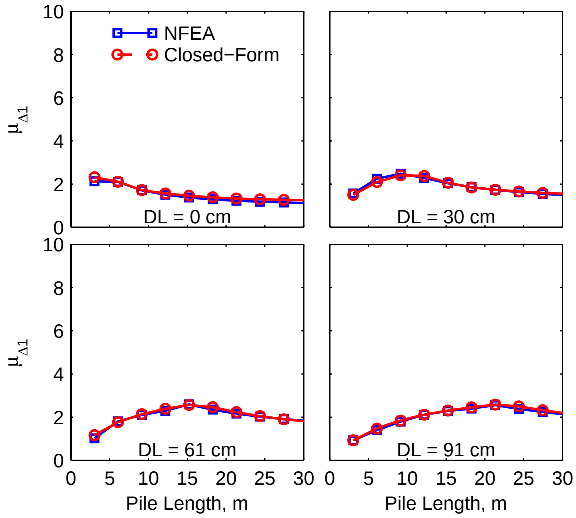

Figure 6. Displacement ductility capacity of pre-stressed-concrete pile with dowel connection for design Level 1.

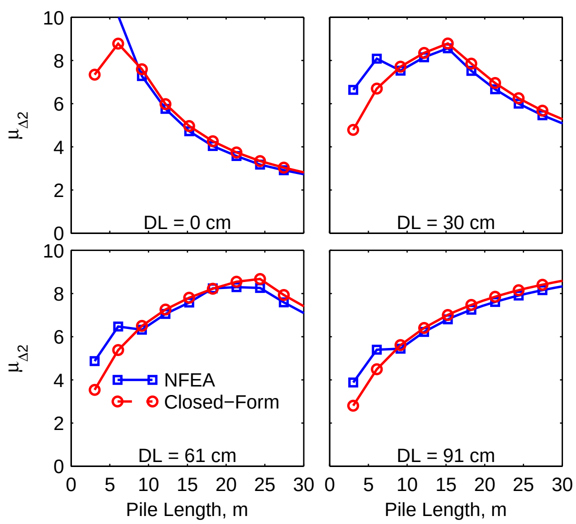

Figure 7. Displacement ductility capacity of pre-stressed-concrete pile with dowel connection for design Level 2.

The results presented so far indicate that the simplified pile-connection system utilized to develop the closed-form formulas for the displacement ductility capacity of the piles with partial-moment-connection provides very "good" estimate of the displacement ductility capacity.

These formulas utilize the curvature ductility capacity of the pile section and rotation ductility capacity of the connection, along with the parameter β which depends on the relative stiffness of the pile and the connection and the parameter η which depends on the relative strength of the connection and the pile. This information is readily available from the pile section moment-curvature analysis and connection moment-rotation analysis. The implementation of the closed-form formulas can be further simplified by developing design charts for commonly used piles section details and connection details thus eliminating the need for pile section moment-curvature analysis and the connection moment-rotation analysis.

Conclusions

This paper presents closed-form formulas for estimating the displacement capacity of piles typically used in the marine oil terminals. The displacement capacity estimated from these formulas ensures that the material stain limits specified in the MOTEMS is not exceeded. Development of these formulas enables better understanding of the various parameters that control the displacement capacity of piles which can be used be designers for achieving optimal design. These formulas are intended to be used for preliminary design of piles or as a check on the results from the detailed nonlinear static pushover analysis procedure, with material strain control, specified in the MOTEMS.

The formulas developed in this investigation utilize the curvature ductility capacity of the pile section and rotation ductility capacity of the connection at the selected seismic design level in the MOTEMS, along with the parameter β which depends on the relative stiffness of the pile and the connection and the parameter η which depends on the relative strength of the connection and the pile. This information is readily available from the pile section moment-curvature analysis and connection moment-rotation analysis. The implementation of the closed-form formulas can be further simplified by developing design charts for commonly used piles section details and connection details thus eliminating the need for pile section moment-curvature analysis and the connection moment-rotation analysis.

It must be noted that the formulas developed in this investigation has only been verified against results from nonlinear finite element analysis. Ideally, such verification should occur against experimental results. However, experimental verification was not possible due to limited scope of this project but such an evaluation is recommended for future work.

Acknowledgment

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