A SIMPLIFIED PROCEDURE FOR NONLINEAR ANALYSIS OF MARINE STRUCTURES

By

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ABSTRACT

This paper presents a simplified procedure for estimating seismic displacement capacity of piles typically used in marine oil terminals. The current procedure specified in the Marine Oil Terminal Engineering and maintenance Standard (MOTEMS) requires monitoring material strains during the nonlinear static pushover analysis. Monitoring material strains is not very convenient. Therefore, closed-form formulas have been developed for estimating the displacement capacity of piles typically used in marine oil terminals. Rooted in fundamentals of nonlinear analysis, these formulas were developed to ensure that the material stain limits specified in the MOTEMS are not exceeded while determining the displacement capacity of piles. These formulas are demonstrated to be very "accurate" by comparing results from these formulas against those from the nonlinear finite-element analysis. The formulas presented in this paper 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.

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, 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. 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 deck of marine oil terminals (Ferrito et al., 1999). 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 steel shell or use of weld-metal laid 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 has been shown to provide remarkable ductility (Priestley and Park, 1984; Park et al., 1987).

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.

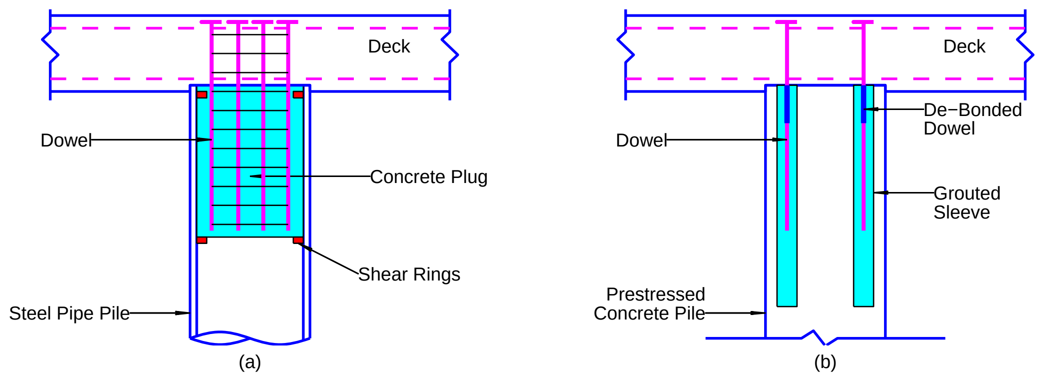

Figure 1. Partial-moment-connection of piles to the deck in marine oil terminals: (a) Concrete-plug connection for hollow-steel piles; and (b) Dowel-sleeve connection for pre-stressed-concrete pile.

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. The material strain limits in two types of piles addressed in this paper are summarized in Table 1.

Table 1. Material strain limits in the MOTEMS.

Pile Type	Material	Hinge Location	Level 1	Level 2
Pre-stressed-concrete	Steel	In-Ground	$\varepsilon_p \leq 0.005$ (Incremental)	$\varepsilon_p \leq 0.04$ (Total)
		Pile/Deck	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$
Hollow-steel	Steel	In-Ground	$\varepsilon_s \leq 0.008$	$\varepsilon_s \leq 0.025$
		Pile/Deck	$\varepsilon_s \leq 0.01$	$\varepsilon_s \leq 0.05$

Since the acceptance criteria in the MOTEMS is specified in terms of maximum permissible strains, design 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 directly monitoring of strains during seismic analysis.

In order to fill this need, this investigation proposes that the displacement capacity, instead of material strain limits, be used as the acceptance criteria for piles in marine oil terminals. Simple, closed-form formulas have been developed 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.

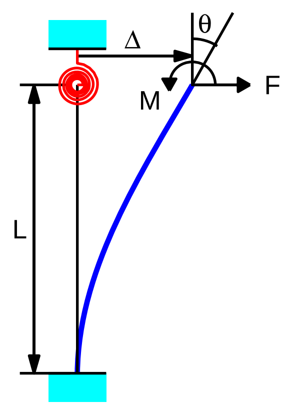

Figure 2. Simplified model of the pile with partial-moment-connection to the deck.

DISPLACEMENT CAPACITY OF PILE

A pile with partial-moment-connection to the deck may be idealized by a fixed-base column with 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-to-fixity below the mud-line. This length is selected as the length of a fixed-base cantilever that would have same lateral displacement at the pile top as the actual pile (see Priestley at al., 1996; Chai, 2002). 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; Chai and Hutchinson, 2002). The rotational spring at the top of the pile represents the nonlinear behavior of the concrete-plug or the dowel-sleeve connection. The procedure to develop the moment-rotation relationship of the rotational spring is available in a recent publication by Goel (2008).

For an idealized moment-rotation relationship of the partial-moment-connection given by Figure 3a and an idealized moment-curvature relationship of the pile section given by Figure 3b, the force-deformation behavior (or pushover curve) of the idealized pile-connection system (Figure 2) is a tri-linear relationship shown in Figure 6c. The displacement capacity of this system is given by

$$\Delta = \mu_\Delta \Delta_{y,C} \tag{1}$$

in which

$$\Delta_{y,C} = \frac{\theta_{y,\mathrm{C}} L \left(1+4\beta\right)}{6\beta} \tag{2}$$

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

$$\mu_{\Delta,C} = \begin{cases} \dfrac{1+4\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta \le \dfrac{\eta-1}{2\beta} \\ \dfrac{2-\eta+6\beta\mu_\theta}{1+4\beta} & \text{for } \mu_\theta > \dfrac{\eta-1}{2\beta} \end{cases} \tag{3}$$

Equation (3) 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

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

In Equations (2) to (4), $\beta = EI/k_\theta L$ (EI = initial slope of the pile section moment curvature relationship of Figure 3b; k_θ = initial elastic stiffness of the connection in Figure 3a; and L = length of the pile-connection system in Figure 2); $\eta = M_{y,P}/M_{y,C}$ ($M_{y,P}$ = yield moment of the pile section, and $M_{y,C}$ = yield moment of the connection); $\mu_\theta = \theta_L/\theta_{y,C}$ is the ductility of the connection (θ_L = the rotation in the rotational spring when the strain in outermost dowel of the connection just reaches the strain limit specified for a selected design level, and $\theta_{y,C}$ = the yield rotation); and $\mu_\phi = \phi_L/\phi_{y,P}$ is the curvature ductility of the pile section (ϕ_L = the curvature of the pile section when the material strain just reaches the strain limit specified for a selected design level, and $\phi_{y,P}$ = the yield curvature). In addition, ρ is the length of the plastic hinge in the pile as a fraction of its "effective" 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. The "effective" length of the pile is defined as the distance from the critical section of the plastic hinge to the point of contra-flexure. It is useful to note that the values of ρ suggested here are based on judgment; it may be appropriate to verify these values from experimental observations. A detailed derivation of the results of Equations (1) to (4) is presented in Goel (2008).

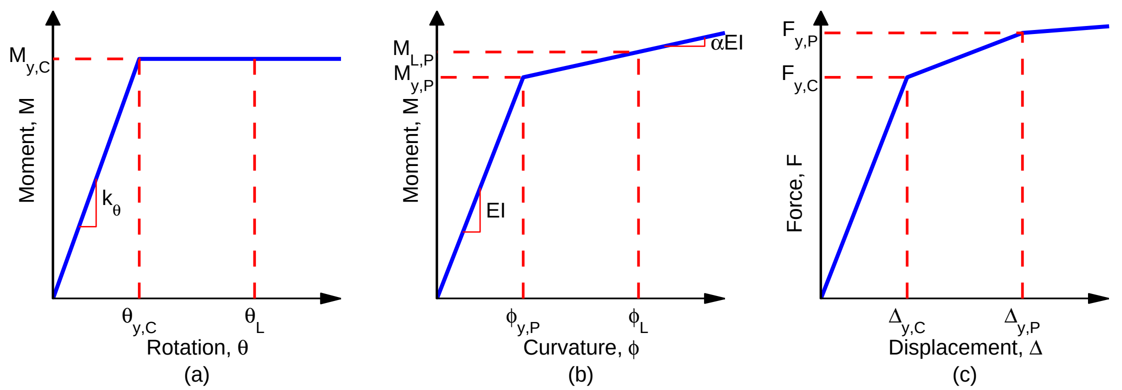

Figure 3. Idealized relationships: (a) Moment-rotation relationship of partial-moment-connection; (b) Moment-curvature relationship of the pile section; and (c) Force-deformation relationship of the pile system.

Step-by-Step Summary

Following is a step-by-steel summary of the procedure to compute displacement capacity of piles with partial-moment-connection:

1. Establish the axial load, P, on the pile.
2. Estimate the pile length based on equivalent-fixity assumption.
3. Select an appropriate design level – Level 1 or Level 2 – and establish various strain limits for the selected design level.
4. Develop the moment-rotation relationship of the partial-moment-connection (see Goel, 2008 for details).
5. Determine rotational stiffness, k_θ, yield moment, $M_{y,C}$, and yield rotation, $\theta_{y,C}$ of the connection from the moment-rotation relationship developed in Step 4.
6. Establish the rotation of the connection, θ_L, and corresponding connection rotational ductility capacity, $\mu_\theta = \theta_L / \theta_{y,C}$, when strain in the outer-most dowel of the connection reaches the strain limit established in Step 3 for the selected design level.
7. Conduct the moment-curvature analysis of the pile section and idealize the moment-curvature relationship by a bi-linear curve. For this analysis, apply the axial load on the pile prior to moment-curvature analysis.

8. Compute the effective, EI_e, and effective yield moment, $M_{y,P}$, from the pile moment-curvature relationship. Note that EI_e is equal to initial elastic slope and $M_{y,P}$ is the yield value of the moment of the idealized bi-linear moment-curvature relationship.
9. Estimate the yield curvature, $\phi_{y,P} = M_{y,P} / EI_e$.
10. Establish the curvature of the pile, ϕ_L, and corresponding section curvature ductility capacity, $\mu_\phi = \phi_L / \phi_{y,P}$, when material strain in the pile section reaches the strain limit established in Step 3 for the selected design level.
11. Select the value of ρ which defines the length of the plastic hinge as a fraction of the "effective" length of the pile.
12. Compute the dimensionless parameters: $\eta = M_{y,P} / M_{y,C}$, and $\beta = EI_e / k_\theta L$.
13. Compute the normalized value of the plastic hinge length: $L_P^* = (\rho\eta)/(1+\eta)$.
14. Compute the yield displacement which corresponds to first effective yielding in the connection as: $\Delta_{y,C} = \theta_{y,C} L (1+4\beta)/6\beta$
15. Compute the displacement ductility for yielding in the connection as $\mu_{\Delta,C} = (1+4\beta\mu_\theta)/(1+4\beta)$ if μ_θ computed in Step 6 is less than or equal to $(\eta-1)/2\beta$ otherwise $\mu_{\Delta,C} = (2-\eta+6\beta\mu_\theta)/(1+4\beta)$.
16. Compute displacement ductility for yielding in the pile as $\mu_{\Delta,P} = (2\eta-1)/(1+4\beta) + (6\eta L_p^*)(1-L_p^*/2)(\mu_\phi-1)/(1+4\beta)$
17. Establish the displacement ductility capacity as lower of the values computed in Steps 15 and 16.
18. Compute the displacement capacity of the pile as product of the yield displacement computed in Step14 and the displacement ductility capacity computed in Step 17.

ANALTYICAL EVALUATION OF CLOSED-FORM FORMULAS

The accuracy of the closed-form formulas presented in the preceding section is evaluated next by comparing design ductility capacity from nonlinear finite element analysis (NFEA) with that from Equations (3) and (4). Note that the results presented are higher of the ductility values due to hinging in the pile and the connection. The ductility capacity from the NFEA was computed from nonlinear static pushover analysis of the pile-connection system by ensuring that the material strains did not exceed the limits specified in the MOTEMS. The finite element model was developed in computer program OPENSEES (McKenna and Fenves, 2001) with the pile modeled by a nonlinear beam-column element with fiber section and rotational spring modeled by a bilinear moment-rotation spring. Additional details of the model are available in Goel (2008).

The presented results in Figures 4 to 7 indicate that the closed-form formulas developed in this investigation provide highly 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. Additional results presented in Goel (2008) also confirm this observation.

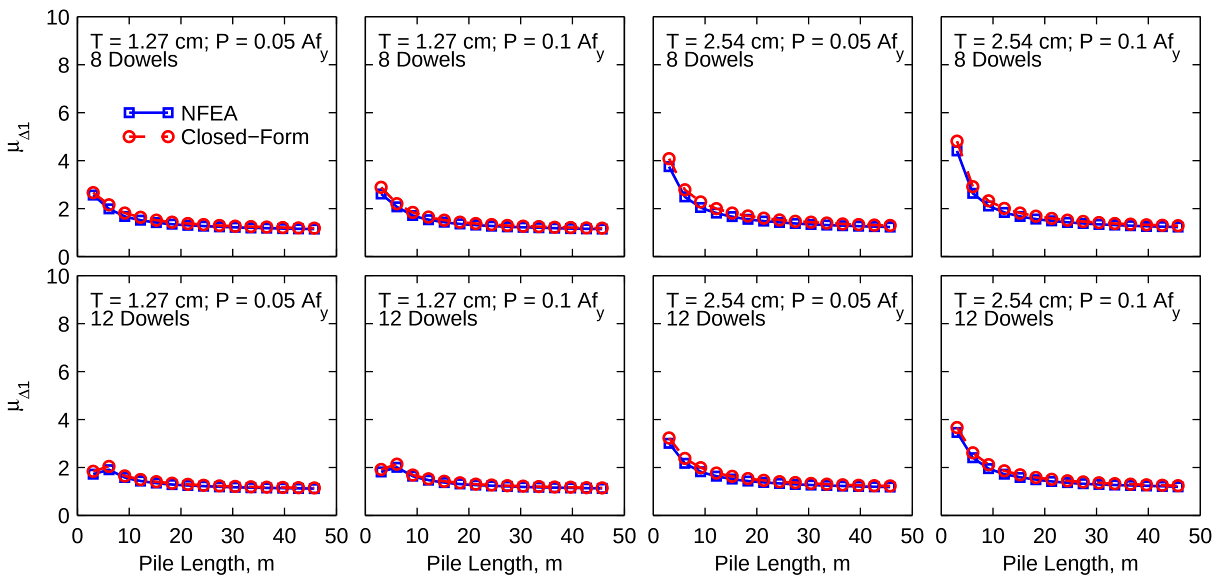

Figure 4. Displacement ductility capacity of hollow-steel pile at design Level 1.

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.

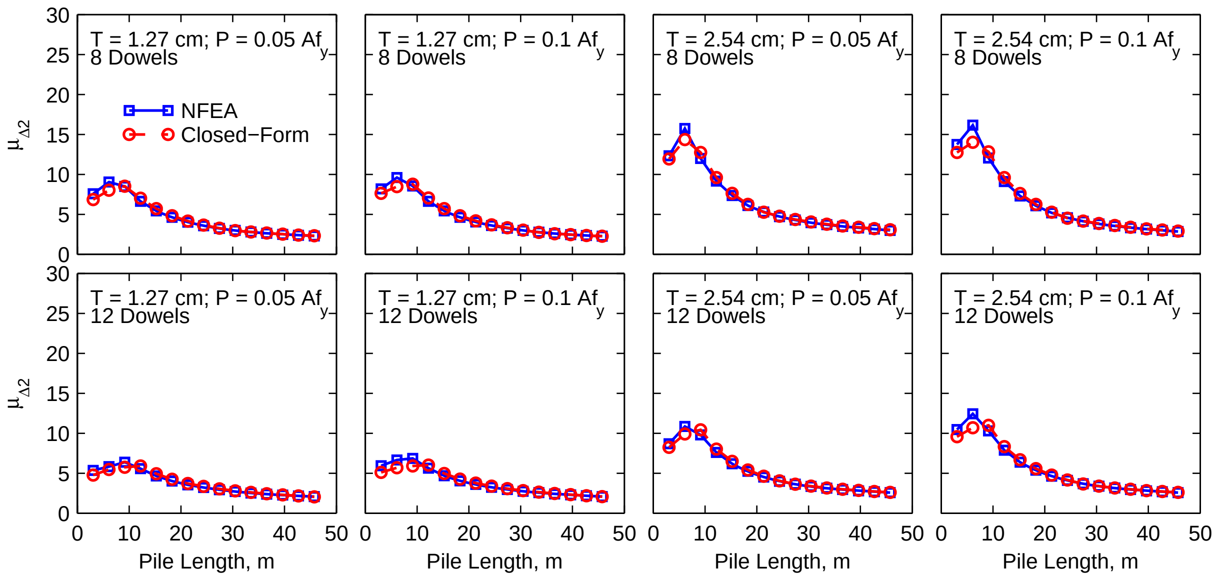

Figure 5. Displacement ductility capacity of hollow-steel pile at design Level 2.

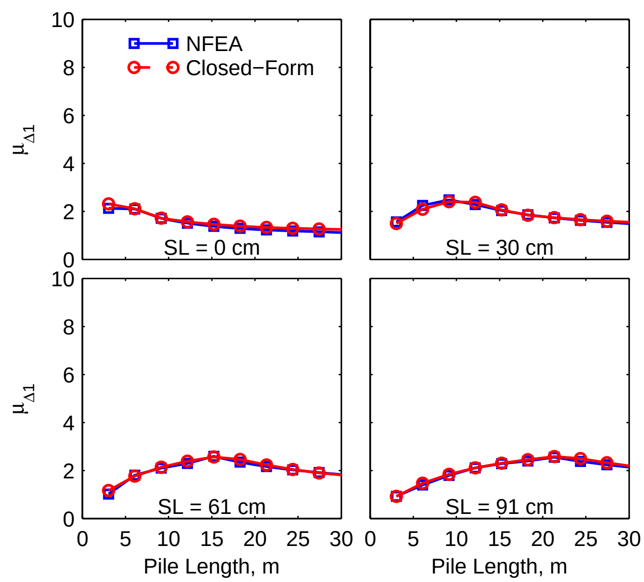

Figure 6. Displacement ductility capacity of pre-stressed-concrete pile at design Level 1.

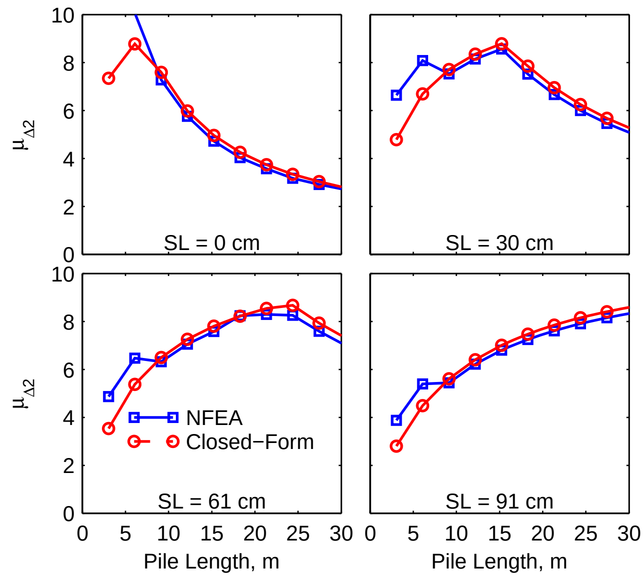

Figure 7. Displacement ductility capacity of pre-stressed-concrete pile at design Level 2.

CONCLUSION

In this investigation, closed-form formulas are presented 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. These formulas are demonstrated to be very "accurate" by comparing results from these formulas against those from the nonlinear finite-element analysis.

It must be noted that the formulas developed in this investigation have been verified against results from nonlinear finite element analysis. It would be useful to verify this procedure against experimental results as well.

ACKNOWLDEGMENT

This research investigation is supported by the California State Lands Commission (CSLC) under Contract No. C2005-051 with Martin Eskijian as the project manager. This support is gratefully acknowledged.

REFERENCES

Chai, Y.H. (2002). "Flexural strength and ductility of extended pile-shafts. I: Analytical model," *Journal of Structural Engineering*, 128(5):586-594.

Chai, Y.H. and Hutchinson, T.C. (2002). "Flexural strength and ductility of extended pile-shafts. II: Experimental study," *Journal of Structural Engineering*, 128(5):595-602.

Eskijian, M. (2007). "Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS)," *Proceedings of 2007 Structures Congress*, ASCE, Long Beach, CA.

Ferritto, J., Deckenson, S., Priestley, N., Werner, S. and Taylor, C. (1999). Seismic criteria for California marine oil terminals, *Technical Report No. TR-2103-SHR*, Naval Facilities

Engineering Service Center, Shore Facilities Department, Structures Division, Port Hueneme, CA.

Goel R.K. (2008). “Simplified procedures for seismic analysis and design of piers and wharves in marine oil and LNG terminals,” Draft *Report No. CP/SEAM-08/01*, California Polytechnic State University, San Luis Obispo, CA

Klusmeyer, L. and Harn, R. (2004). “Displacement-based seismic design of large naval pier.” *Proceedings of PORTS 2004*, Houston, TX, May 23-26.

McKenna, F. and Fenves, G. (2001). *The OpenSees Command Language Manual: version 1.2*, Pacific Earthquake Engineering Center, University of California, Berkeley. <http://opensees.berkeley.edu>

MOTEMS (2006). *Marine Oil Terminal Engineering and Maintenance Standards*, Chapter 31F (Marine Oil Terminals), Title 24, California Code of Regulations, Part 2, California Building Code, Published by the California State Lands Commission, Long Beach, CA. <http://www.slc.ca.gov/Division_pages/MFD/MOTEMS.html>

Park, R.J.T., Priestly, M.J.N., and Berrill, J.B. (1987). Seismic performance of steel-encased concrete piles. *Report No. 87-5*, Department of Civil Engineering, University of Canterbury, N.Z.

Priestley, M.J.N. and Park, R. (1984). Strength and ductility of bridge substructures. *Report No. 84-20*, Department of Civil Engineering, University of Canterbury, N.Z.

Priestley, M.J.N, Seible, F. and Calvi, G.M. (1996). *Seismic Design and Retrofit of Bridges*. John Wiley and Sons, Inc. New York.

Restrepo, J.I, Yin, P., Jaradat, O., and Weismair, M. (2007). “Performance of new pile-deck connections under earthquakes,” *Proceedings of 2007 Structures Congress*, ASCE, Long Beach, CA.

Roeder, C.W., Graff, R., Sonderstrom, J., and Yoo, J.H. (2005). “Seismic performance of pile-wharf connections.” *Journal of Structural Engineering*, 131(3):428-437.

Wray, M., Harn, R., and Jacob, J. (2007). “Port of Everett rail/barge transfer facility seismic design Everett, Washington.” *Proceedings of PORTS 2007*, San Diego, CA, March 25-28.