Plastic Hinge Length and Depth for Piles in Marine Oil Terminals Including Nonlinear Soil Properties

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SUMMARY
This investigation examined the current recommendations for plastic-hinge length and depth for piles and soil properties typical of those in Marine Oil Terminals. It is found that the current recommendation for plastic-hinge length is adequate for Level 2 MOTEMS design but not for Level 1 MOTEMS design: the plastic-hinge length for Level 1 design is much longer than that provided by the current MOTEMS recommendation. Since shorter plastic-hinge length will lead to smaller displacement capacity, it appears that current MOTEMS plastic-hinge length recommendation will lead to conservatively small pile displacement capacity for Level 1 seismic design. The location of the plastic-hinge is found to be much deeper than predicted by current recommendation. Therefore, the confinement zone in piles needs to be extended to larger depth below ground than indicated by current recommendation.

Keywords: MOTEMS, Plastic Hinge Length, Depth of Plastic Hinge, Seismic Design, Seismic Piles

1. BACKGROUND AND OBJECTIVES

Seismic design of Marine Oil Terminals in California is governed by 2010 Title 24 California Code of Regulations, Part 2, California Building Code, Chapter 31F: Marine Oil Terminals, commonly known as the "Marine Oil Terminal Engineering and Maintenance Standard" (MOTEMS) (MOTEMS, 2010). The MOTEMS describe the acceptable methods of seismic analysis and provide the specific performance criteria for two levels of earthquake motions to be used in the seismic assessment. The return period of the design earthquake for each level depends on the risk level, which is a function of the oil susceptible to spillage at any given time. For example, Level 1 and Level 2 design earthquakes for high risk terminals correspond to return periods of 72 and 475 years, respectively. The performance goal for Level 1 earthquake is no or minor damage without interruption in service or with minor temporary interruption in service. The performance goal for Level 2 earthquake is controlled inelastic behavior with repairable damage resulting in temporary closure of service, restorable within months and the prevention of a major oil spill.

Table 1.1. Material strain limits in MOTEMS.

Component Strain	Level 1	Level 2
Maximum Concrete Compression Strain: Pile-Deck Hinge	$\varepsilon_c \le 0.004$	$\varepsilon_c \le 0.025$
Maximum Concrete Compression Strain: In-ground Hinge	$\varepsilon_c \le 0.004$	$\varepsilon_c \le 0.008$
Maximum Reinforcing Steel Tension Strain: Pile-Deck Hinge	$\varepsilon_s \le 0.01$	$\varepsilon_s \le 0.05$
Maximum Reinforcing Steel Tension Strain: In-Ground Hinge	$\varepsilon_s \le 0.01$	$\varepsilon_s \le 0.025$
Maximum Prestressing Steel Tension Strain: In-ground Hinge	$\varepsilon_p \le 0.005$ (Incremental)	$\varepsilon_p \le 0.025$ (Total)

The MOTEMS seismic analysis requires that the seismic displacement capacity of piles in marine oil terminal structures be determined using nonlinear static procedures. The displacement capacity of a pile is defined as the maximum displacement that can occur without exceeding material strain values

(Table 1.1) during the pushover analysis.

Estimation of displacement capacity of the pile according to the seismic provisions of the MOTEMS requires monitoring of material strains during the nonlinear static pushover analysis. Typically, the pile is modeled with linear-elastic beam-column elements that are connected at ends by nonlinear moment-rotation springs (Fig. 1.1). The nonlinear (rigid-perfectly-plastic) moment-rotation relationship of this spring (or hinge) is computed from the moment-curvature relationship (Fig. 1.2) and estimated length of the plastic hinge. The limiting value of the plastic-rotation, θ_P, in the hinge at a selected design level is defined as:

$$\theta_P = L_P\left(\Phi_L - \Phi_y\right) \tag{1.0}$$

in which Φ_L is maximum pile-section curvature without exceeding MOTEMS specified material strain limits, Φ_y is the yield curvature (Fig. 1.2a), and L_P is the plastic-hinge length. The in-ground plastic-hinge length in MOTEMS is estimated from relationship specified in Fig. 1.3a.

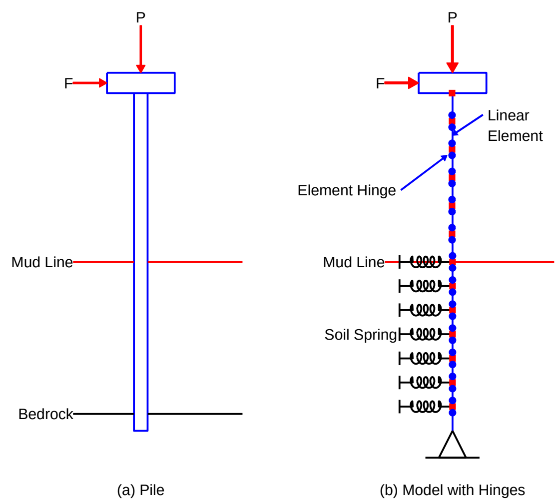

Figure 1.1. Computer modeling of piles in Marine Oil Terminals.

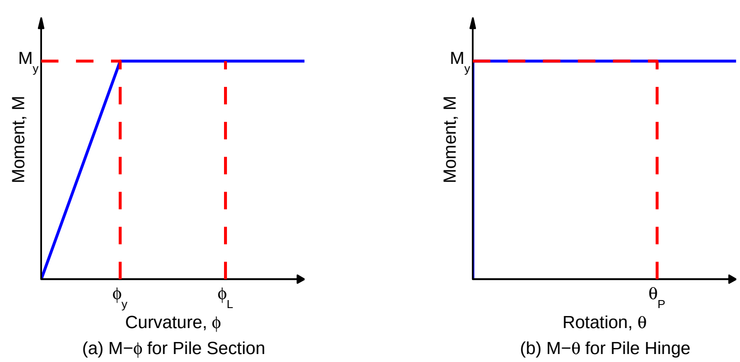

Figure 1.2. Pile moment-curvature and moment-rotation relationships.

The in-ground plastic-hinge recommendation was first presented in Priestley et al. (1996) based on the work reported by Budek et al. (1994) and later published by Budek et al. (2000). These recommendations provide in-ground plastic hinge length as a fraction of pile diameter for normalized stiffness and height parameters. The normalized stiffness parameter is defined as $KD^6 / D^* EI_e$ where

K is the subgrade modulus, D is the pile diameter, D^* is a reference diameter of 6 ft (1.83 m), and EI_e is the effective stiffness of the pile cracked section. The normalized height parameter is defined as H / D where H is the pile height from ground level to the aboveground point of contraflexure.

Although not directly specified in MOTEMS, Priestley et al. (1996) and Budek et al. (1994, 2000) also recommended depth of in-ground plastic-hinge (Fig. 1.3b). Location of the in-ground plastic-hinge is needed to ensure sufficient confinement in plastic-hinge region of the pile to avoid premature failure. Similar to the plastic hinge length, the depth of plastic-hinge is specified as a fraction of pile diameter for normalized stiffness and height parameters.

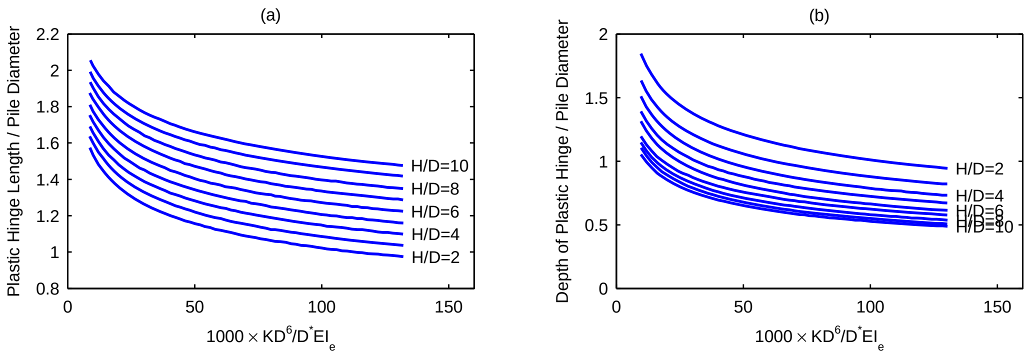

Figure 1.3. (a) MOTEMS recommendation for in-ground plastic hinge length (MOTEMS Figure 31F-7-4), and (b) Depth of in-ground plastic-hinge (Figure 5.31 in Priestley et al., 1996).

The plastic-hinge length and depth recommendations in Fig. 1.3 were developed for a 6-ft (1.83 m) diameter Cast-In-Drilled-Hole (CIDH) reinforced concrete piles that are used in bridges in California (Budek et al., 1994, 2000). Furthermore, these recommendations utilized following assumptions: (1) plastic-hinge length was evaluated at ultimate failure strain in confined concrete; (2) soil was assumed to be linear elastic; and (3) subgrade modulus was assumed to increase linearly with depth below ground.

It is clear from the discussion so far that the in-ground plastic-hinge length and depth recommendations in Fig. 1.3 were not developed specifically for piles used in Marine Oil Terminals. First, piles used in Marine Oil Terminals are of much smaller cross-sectional dimensions than 6-ft (1.83 m) CIDH reinforced concrete pile used in the study by Budek et al. (1994, 2000). For example, new Marine Oil Terminals typically use 24-inch (0.61 m) octagonal pre-stressed concrete piles. Second, material strain limits in MOTEMS may differ significantly from those used by Budek et al. (1994, 2000). For example, MOTEMS specify concrete compression and tensile steel strains (Table 1.1) which differ for the two design levels and also differ from the ultimate failure strain in confined concrete used by Budek et al. (1994, 2000). Finally, the current practice uses nonlinear soil properties with lateral force-deformation relationship specified through p-y curves.

Therefore, the primary objective of this investigation is to develop recommendations for in-ground plastic hinge length for piles and soil properties that are typically used in seismic design of Marine Oil Terminals. Another objective is to develop recommendation for depth of the in-ground plastic-hinge.

2. ANALYTOCAL APPROACH

In order to estimate the plastic-hinge length and depth, the pile (Fig. 2.1a) is modeled using a distributed-plasticity based nonlinear beam-column elements (Fig. 2.1b) using *OpenSees* software developed at the Pacific Earthquake Engineering Research Center (McKenna and Fenves, 2001). The section properties of the nonlinear beam-column elements are specified by a fiber-section. A nonlinear static pushover analysis of this model is conducted and material strains are monitored during the pushover analysis. The pile displacement capacity, Δ_L, is defined as the maximum displacement that can occur at top of the pile without exceeding selected material strain limits. The pushover curve is idealized as a bi-linear curve (Fig. 2.2a) and the yield displacement, Δ_y, is identified. Alternatively, the yield displacement can be defined as the deflection at top of the pile when the pile section reaches yield curvature Φ_y (Budek et al., 1994). Element bending moments are also monitored during the pushover analysis and the location of maximum bending moment below ground is identified as D_p (Fig. 2.1c).

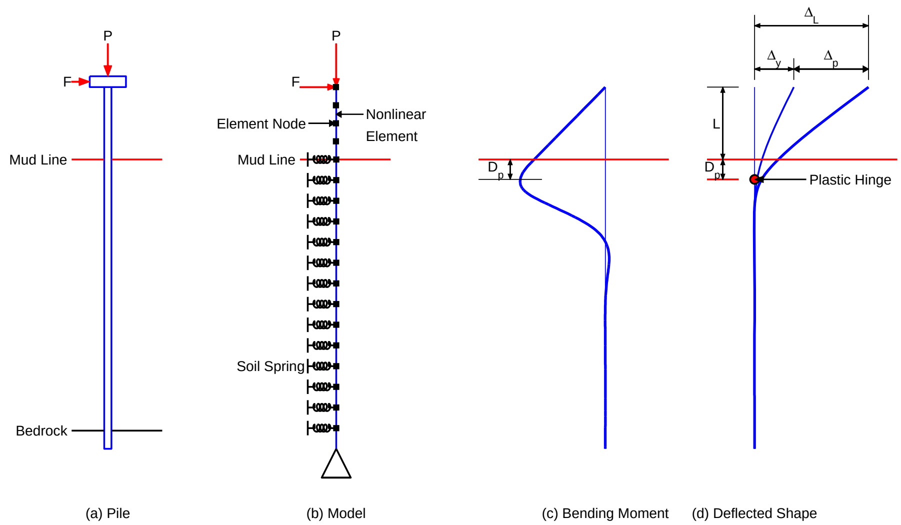

Figure 2.1. Analytical approach for estimating plastic hinge length and depth.

Next, a moment-curvature analysis of the pile section is conducted. Material strains are monitored during this analysis and curvature, Φ_L, is defined as the maximum curvature without exceeding selected material strain. The moment-curvature relationship is idealized as a bi-linear curve (Fig. 2.2b) and yield curvature, Φ_y, is identified.

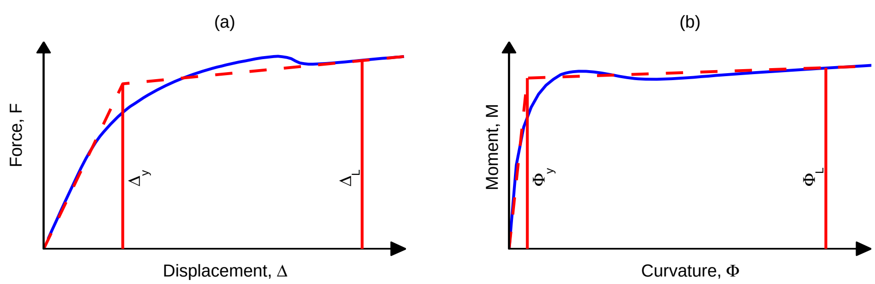

Figure 2.2. (a) Pushover curve and its bilinear idealization, and (b) Moment-curvature curve and its bilinear idealization.

The plastic hinge is assumed to occur at the location D_p of maximum bending moment below ground (Fig. 2.1d). The plastic rotation is computed as:

$$\theta_P = \frac{(\Delta_L - \Delta_y)}{(L + D_p)} \tag{2.1}$$

and plastic hinge length as

$$L_P = \frac{\theta_P}{\Phi_L - \Phi_y} \tag{2.2}$$

In Eq. (2.1), L is the length of the pile from ground-level (or mud line) to point of contra-flexure above ground; L is equal to the cantilever height above ground-level for the example shown in Fig. 2.1. The approach described here is similar to that used by Budek et al. (1994) in arriving at the plastic hinge length and plastic hinge depth recommendations in Priestley at al. (1996).

3. SOIL TYPES CONSIDERED

The soil types considered are dense sand, medium sand, loose sand, stiff clay, medium clay, and soft clay (Table 3.1). The lateral force-deformation relationships of soil-springs below ground level are defined with nonlinear p-y curves which were provided by Arumoli and Vartharaj (2010) for 24-inch (0.61 m) pile-diameter. The subgrade modulus values reported in Table 3.1 are taken from Table 31F-7-4 of MOTEMS.

Table 3.1. Soil types considered and subgrade modulus.

MOTEM Site Class	Shear Wave Velocity	Stand Penetration Resistance	Undrained Shear Strength	Soil Type	Subgrade Modulus, K
Sand (API sand)					
D. Dense soil	600-1200 ft/s 183-366 m/s	15 to 50		Dense Sand	275 pcf 43200 kN/m^3
				Medium Sand	90 pcf 14138 kN/m^3
E. Loose soil	< 600 ft/s < 183 m/s	< 15		Loose Sand	25 pcf 3927 kN/m^3
Clay (Matlock)					
D. Dense soil	600-1200 ft/s 183-366 m/s		1000-2000 psf 48-96 kN/m^2	Stiff Clay	500 pcf 78544 kN/m^3
E. Loose soil	< 600 ft/s < 183 m/s		< 1000 psf < 48 kN/m^2	Medium Clay	100 pcf 15709 kN/m^3
				Soft Clay	20 pcf 3142 kN/m^3

4. VERIFICATION OF ANALYTICAL APPROACH

As mentioned previously, the plastic hinge length and depth recommendations were developed for a 6-ft (1.83 m) diameter Cast-In-Drilled-Hole (CIDH) reinforced concrete piles commonly used in bridges in California at the time (Budek et al., 1994, 2000). The original study used simple modeling for capturing nonlinear behavior of pile element: stiffness of each element was softened after initial yielding based on the slope of the moment-curvature at the selected stage (Budek et al., 1994). Analyses in the current study were conducted using *OpenSees* software developed at the Pacific Earthquake Engineering Research Center (McKenna and Fenves, 2001). This software is capable of modeling pile elements with distributed-plasticity elements with pile sections modeled as fiber section consisting of un-confined concrete, confined concrete, and steel fibers. Clearly, the analytical approach used by Budek et al. (1994) differs from that used in the current study. Therefore, it is useful to verify if the results from the analytical approach in the current study match those from Budek et al. (1994).

The example pile used in this study is a CIDH pile with depth of 80 ft (24.4 m) below ground and height of 60 ft (18.23 m) above ground (Fig. 4.1a). The pile section was selected as a 6 ft (1.83 m) diameter circular section with 36-#14 Grade 60 bars (D43, 415 MPa), #6 Grade 60 spiral (D19, 415 MPa) pitched at 4.33 in (110 mm), and a 2 in (50.4 mm) cover (Fig. 4.2a). The concrete strength is selected as $f_c^{'} = 4$ ksi (27.6 MPa). The pile was assumed to carry an axial load of $0.1 f_c^{'} A_g$ where A_g is the total cross-sectional area of the pile. The theoretical moment-curvature relationship of this pile section is shown in Fig. 4.2b. The selected pile section is similar to that used in Budek et al. (2000) and corresponds to pile-height to pile-diameter ratio, $H/D = 10$. The limiting value of the section curvature (required in Eq. 2.2) was selected to be that corresponding to confined concrete strain of 0.01866 which equals the ultimate compression strain of the confined concrete in the selected pile section.

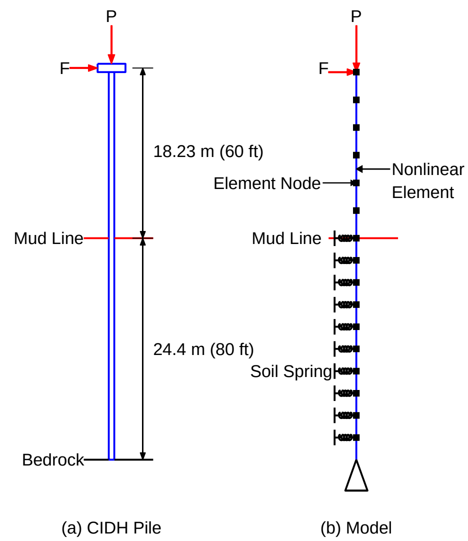

Figure 4.1. Example pile used in the verification study (a) CIDH pile and (2) Analytical model.

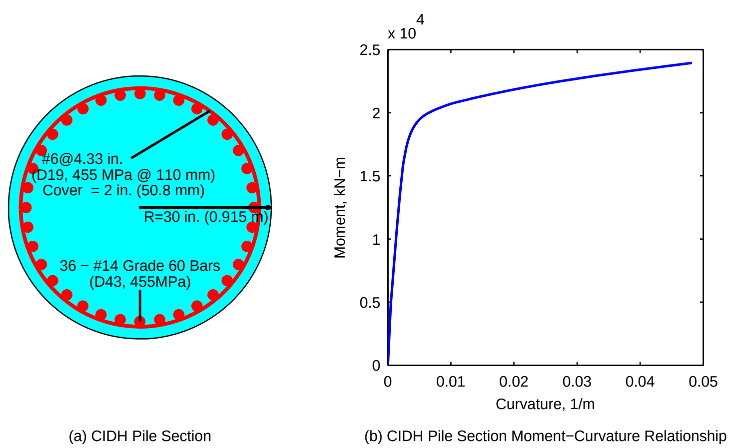

Figure 4.2. Example pile used in the verification study: (a) Pile section, and (b) Moment-curvature relationship.

The pile was discretized with displacement-based nonlinear beam-column elements (Fig. 4.1b). The soil below ground was modeled with discrete springs attached to element nodes. As in Budek et al. (1994, 2000), the soil was assumed to be linear with its stiffness increasing linearly with depth. The stiffness, k_i, of each linear soil spring was assumed to be given by:

$$k_i = z_i L_i K \tag{4.1}$$

in which z_i is the depth of the node below ground at which the spring is attached, L_i is the node's tributary length, and K is the subgrade reaction modulus of the soil. The subgrade modulus values selected in this verification study include those listed in Table 3.1 for six different soil types.

Fig. 4.3 compares plastic hinge length and depth from the analytical approach used in this study with the values estimated from recommendations (Fig. 1.3) developed by Priestley et al. (1996). The presented results indicate that the analytical approach used in this study leads to plastic-hinge length that is essentially identical to the value estimated from the recommendation (Fig. 1.3a) by Priestley et al. (1996) for six selected soil types (Fig. 4.3a). The analytical approach in this study, however, leads to slightly lower depth of plastic-hinge location compared to the recommendation (Fig. 1.3b) by Priestley et al. (1996) for six selected soil types (Fig. 4.3b). The difference in plastic-hinge depth from the two studies is minimal for medium sand, loose sand, medium clay, and soft clay and may be considered negligible for most practical applications. For dense sand and stiff clay, however, the difference is significant. The large discrepancy for these two soil types appears to be because of errors in extrapolation of plastic-hinge depth value (Fig. 1.3b). It is useful to point out that $1000 \times KD^6 / D^* EI_e = 211$ for dense sand and 384 for stiff clay, both of which are outside the range of $1000 \times KD^6 / D^* EI_e$ in Fig. 1.3b. In this study, the plastic-hinge depths for both dense sand and stiff clay were assumed to be those corresponding to the highest value of $1000 \times KD^6 / D^* EI_e$ in Fig. 1.3b, which leads to larger depths compared to the values if the results in Fig. 1.3b were available for $1000 \times KD^6 / D^* EI_e = 211$ for dense sand and 384 for stiff clay; note that plastic-hinge depth for $H/D = 10$ tends to decrease with increasing values of $1000 \times KD^6 / D^* EI_e$ even after the highest range of $1000 \times KD^6 / D^* EI_e$ in Fig. 1.3b.

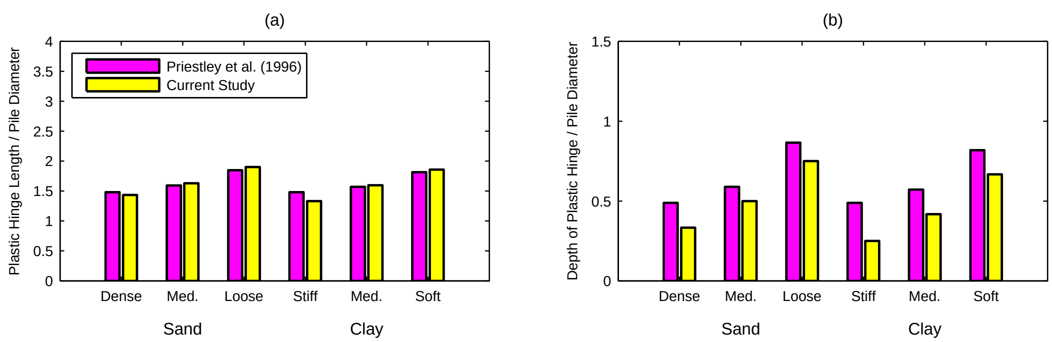

Figure 4.3. Comparison of results from Priestley et al. (1996) and current study: (a) Plastic hinge length, and (b) depth of plastic hinge.

The results presented so far indicate that the analytical approach used in this investigation leads to plastic-hinge length values which are similar to and plastic-hinge depth values which are sufficiently close to those from the recommendations of Priestly et al. (1996). This is found to be valid for the pile section and soil assumptions used in Priestley et al. (1996) as well as Budek et al. (1994, 2000). Therefore, it is concluded that the analytical procedure used in this study is compatible with that used in earlier studies (Budek et al., 1994, 2000). Any differences noted in later part of this study are due to different pile sections, and/or soil assumptions, and/or material strain limits.

5. PLASTIC HINGE LENGTH AND DEPTH FOR PRE-STRESSED CONCRETE PILES

5.1 Pile Section Considered

The plastic-hinge length and depth recommendation in this study are developed for a typical 24-inch (0.61 m) octagonal pre-stressed concrete pile (Figure 5.1a) used in typical Marine Oil Terminals. The material properties of the pile are selected as: unconfined concrete compressive strength $f_c' = 6.5$ ksi

(44.8 MPa) and pre-stressing steel tendon yield strength, f_y = 270 ksi (1860 MPa). The pile section consists of 16 pre-stressing tendons each with area of 0.217 in^2 (140 mm^2), #11 wire spiral pitched at 2.5 in (63.5 mm), and 3 in (76.2 mm) cover. The steel tendons are pre-stressed to 70% of their yield stress. The pile supports an axial load equal to 5% of its axial load capacity. The pile is considered to be free to deflect horizontally and free to rotate at its top. The pile depth below ground level (or mud line) is fixed at 80 ft (24.4 m). The pile height above ground level is varied between 20 ft (6.1 m) and 4ft (1.22 m) which correspond to pile height to pile diameter ratio, H/D, between 10 and 2. The pile section moment-curvature relationship is shown in Figure 5.1b.

5.2 Analytical Modeling

As mentioned previously, the pile and the soil springs are modeled in *OpenSees* (McKenna and Fenves, 2001). The soil springs are modeled using bi-linear material to capture p-y curves. The pile above- and below-ground is modeled with distributed-plasticity elements.

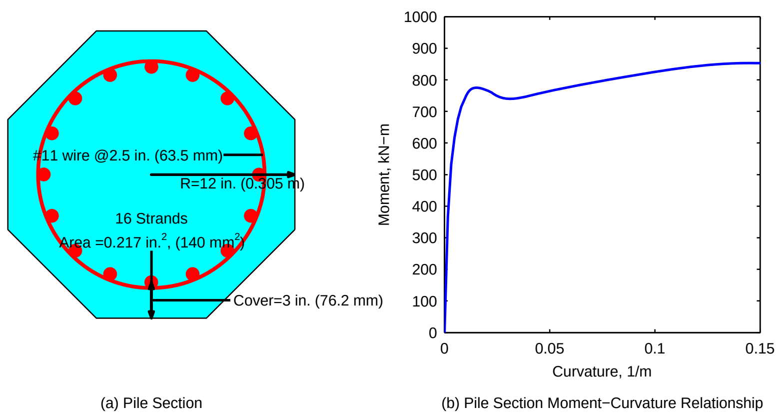

Figure 5.1. Pre-stressed reinforced-concrete pile considered: (a) Pile section, and (b) Moment-curvature relationship.

5.3 Plastic Hinge Length and Depth

Fig. 5.2a presents length of in-ground plastic hinge for the selected pile, six soil types, and two MOTEMS seismic design levels. Also included is the in-ground plastic hinge length estimated from current MOTEMS recommendations (Fig. 1.3a). It is clear from these results that the plastic-hinge length differs for two MOTEMS seismic design levels. In particular, the plastic-hinge length for Level 1 is longer than that for Level 2. The larger plastic-hinge length for level 1 is due to more gradual curvature distribution over the pile length for level 1 than for level 2.

The MOTEM recommended plastic-hinge length appears to be adequate for level 2 design for most soil types as apparent from very similar values from the results obtained in this study and from MOTEMS recommendation. The results in this investigation lead to slightly longer values of plastic-hinge length compared to the MOTEMS recommendation for soft clays. Since shorter plastic-hinge length will lead to smaller displacement capacity, it appears that current MOTEMS in-ground plastic-hinge length recommendation will lead to conservative (lower) pile displacement capacity for soft clays and thus should be acceptable.

The MOTEMS recommended plastic-hinge lengths for level 1 are much smaller than the values found in this investigation. Since shorter plastic-hinge length will lead to smaller displacement capacity, it appears that current MOTEMS in-ground plastic-hinge length recommendation will lead to overly conservative (lower) pile displacement capacity for all soil types.

The results presented in Fig. 5.2a also highlight another short-coming of current analytical procedure. Typically, a single value of plastic-hinge length is specified in structural modeling software; this value is selected as that recommended by MOTEMS. The moment-rotation relationship developed based on this plastic-hinge length is used to estimate displacement capacities of pile for both level 1 and level 2. The results of Fig. 5.2a clearly indicate that this approach will lead to adequate displacement capacity for level 2 but will result in overly conservative (lower) displacement capacity estimate for level 1. Therefore, two separate values of plastic-hinge lengths should be specified for the two MOTEMS design levels.

It is also useful to point out that the current MOTEMS recommendations for plastic-hinge length, first presented in Priestley et al. (1996) and originally reported in Budek et al. (1994, 2000), were computed at failure compression strain in the confined concrete. Clearly, such material strain levels are appropriate for MOTEMS level 2 but not for MOTEMS level 1 for which the material strains are much lower (Table 1.1). Therefore, it is not surprising that the plastic-hinge length found in this investigation differs from that from current MOTEMS recommendations, especially for Level1 seismic design.

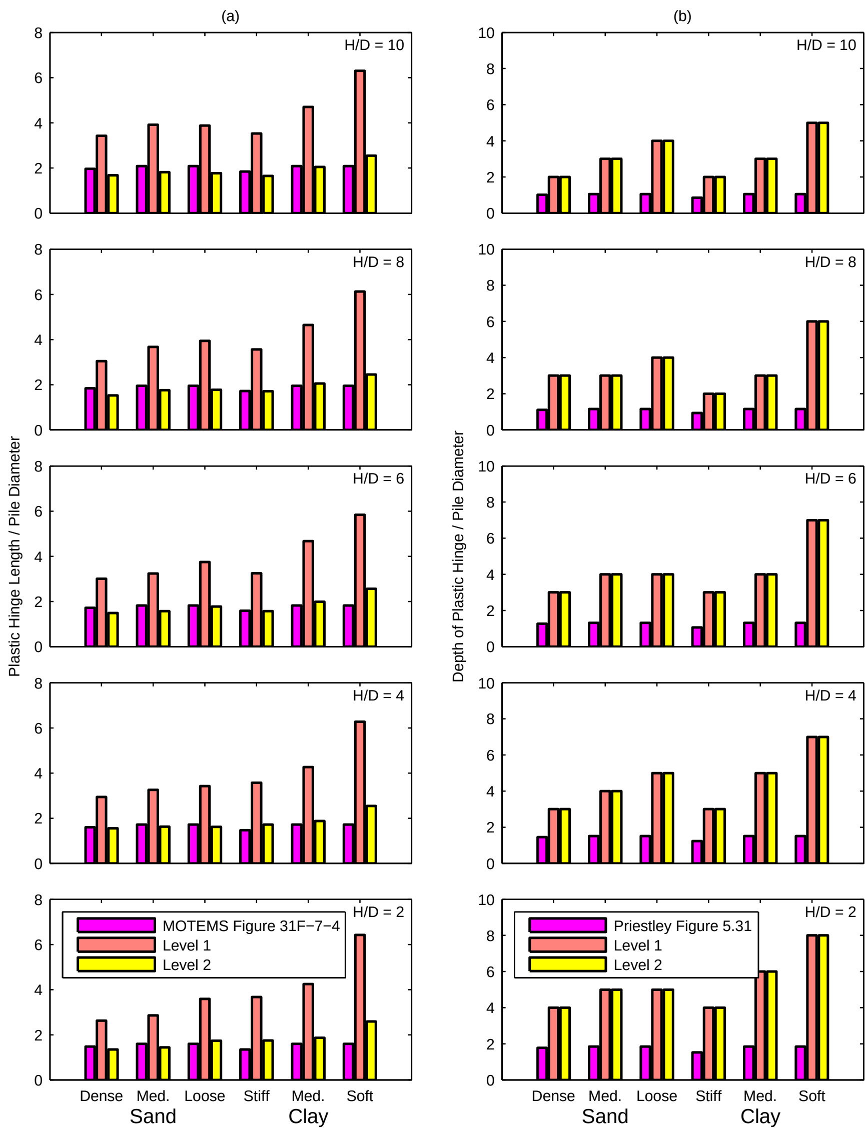

Figure 5.2. (a) In-ground plastic-hinge length and (b) depth for piles in Marine Oil Terminals.

Figure 5.2b presents depth of in-ground plastic hinge for two MOTEMS seismic design levels along with the current value recommended by Priestley et al. (1996). It is apparent that current recommendation lead to depth of plastic-hinge that is much shallower than that determined in this investigation. While the current recommendations lead to depth of plastic-hinge below ground to be approximately 1D for selected pile type, this study indicates depth varying from 2D to 7D depending on the soil type. Unlike plastic-hinge length, the depth of plastic-hinge below ground is independent of the MOTEMS seismic design level.

6. CONCLUSIONS

This investigation examined the current recommendations for plastic-hinge length and depth for piles and soil properties typical of those in Marine Oil Terminals. For this purpose, 24-inch (0.61 m) octagonal pre-stressed concrete piles supported in six different soil types – dense sand, medium sand, loose sand, stiff clay, medium clay, and soft clay – were analyzed. Nonlinear behavior for both pile and soil were considered and MOTEMS specified strain levels were used to compute the pile capacity. All analyses in this study were conducted using *OpenSees* software developed at the Pacific Earthquake Engineering Research Center.

It is found that the current recommendation for plastic-hinge length is adequate for Level 2 MOTEMS design but not for Level 1 MOTEMS design: the plastic-hinge length for Level 1 design is much longer than that provided by the current MOTEMS recommendation. Since shorter plastic-hinge length will lead to smaller displacement capacity, it appears that current MOTEMS plastic-hinge length recommendation will lead to conservatively small pile displacement capacity for Level 1 seismic design. The location of the plastic-hinge is found to be much deeper than predicted by current recommendation. Therefore, the confinement zone in piles needs to be extended to larger depth below ground than indicated by current recommendation.

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