IN-GROUND PLASTIC HINGE ANALYSIS FOR PILES USED IN MARINE OIL AND LNG
TERMINALS

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Masters of Science in Civil and Environmental Engineering

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ABSTRACT

In-Ground Plastic Hinge Analysis for Piles Used in Marine Oil and LNG Terminals

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The design and maintenance of Marine Oil and LNG Terminals is governed by the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) which is part of the 2010 Title 24 California Code of Regulations, Part 2, California Building Code, Chapter 31F: Marine Oil Terminals. The purpose of this thesis is to evaluate the current recommendations for the in-ground plastic hinge length and depth for piles in section 7 of MOTEMS for all typical soil properties and pile dimensions found in Marine Oil and LNG Terminals. The pile types considered in this analysis are 24-inch octagonal prestressed concrete piles and 24-, 36-, and 48-inch steel pipe piles in varying soil conditions.

Existing recommendations for plastic hinges are incomplete and inadequate. MOTEMS does not have any recommendations for plastic hinge depth, only length, nor does it have any recommendations for in-ground plastic hinge for steel piles. Recommendations for steel piles are however found in the Port of Long Beach Wharf Design Criteria (POLB), but the recommendations in both MOTEMS and POLB have shown to be inadequate for both steel and prestressed concrete piles. MOTEMS also proves to be adequate for Level 2 earthquakes but not for Level 1. The plastic hinge length for Level 1 is much longer than that for Level 2. So the MOTEMS recommendations for Level 1 lead to conservatively small displacement capacity. POLB recommendations are also adequate for Level 2 but not Level 1 for concrete and are

overly conservative for steel and therefore, not adequate for either level except in dense and medium sands during a Level 1 earthquake. POLB does not take into account different soil characteristics and has one value for all soils, which is inadequate for most cases.

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CHAPTER 1: INTRODUCTION

Marine oil and LNG terminals are a sensitive component of California's coastline. The current standard used for the engineering analysis of such terminals, the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) (MOTEMS, 2010), was developed by the California State Lands Commission as part of the Lempert-Keene-Seastrand Oil Prevention and Response Act of 1990. It was adopted as an enforceable part of the California Building Code, on February 6, 2006 (Eskijian, 2007). MOTEMS describes the seismic analysis procedure for two performance levels and specifies earthquake motions to be used in the analysis. Level 1 has a 72-year return period, based on the risk level, and should cause no or minor damage with little to no interruption in service. Level 2, on the other hand, has a 475-year return period with controlled inelastic behavior with repairable damage. This earthquake level results in temporary closure of service, which should be restorable within months. (Goel & Saeedy, 2012).

The MOTEMS recommendations for plastic hinge length were first presented in Priestly et al. (1996) based on the work by Budek et al. (1994) and then later published again by Budek et al. (2000). These recommendations provide in-ground plastic hinge length as a fraction of the pile diameter for normalized stiffness and height parameters (Figure 1a). Although not specified in MOTEMS, Priestley et al. (1996), and Budek et al. (1994) (2000) also make recommendations for in-ground plastic hinge depth. These recommendations are needed to ensure sufficient confinement in the plastic hinge region to avoid premature failure. Plastic hinge depth is also specified as a fraction of pile diameter for normalized stiffness and height parameters (Figure 1b).

FIGURE 1: RECOMMENDATIONS FOR (A) PLASTIC HINGE LENGTH AND (B) PLASTIC HINGE DEPTH

Engineers in the field have found evidence of deficiencies in MOTEMS pile design requirements. Priestley et al's recommendations were developed for a 6-ft diameter Cast-In-Drilled-Hole (CIDH) reinforced concrete pile that is commonly used in bridges in California (Budek, Benzoni, & Priestley, 1994). Also, the recommendations were developed based on the assumptions that (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. However, piles used in Marine Oil and LNG Terminals are much smaller in cross sectional area than the 6-ft CIDH reinforced concrete piles used by Budek et al. (1994). In fact most Marine Oil and LNG Terminals use 24-inch octagonal pre-stressed concrete piles. Also, the material strain limits in MOTEMS (Table 1) may differ significantly from those used by Budek et al. (1994). The MOTEMS specify concrete compression and tensile steel strains that differ for the two design levels and from the ultimate failure strain in confined concrete used by Budek et al. (1994). Finally the current practice uses nonlinear soil properties with lateral force-deformation relationships specified through p-y curves instead of an assumed linear increase with depth. Budek et al. (2000), also state

that since ultimate curvature depends on section details, axial load ratio, and lateral reinforcement ratio, the ductility capacity should be checked for pile details differing from the six-foot diameter pile used in their study. If marine structures are not engineered correctly, a major earthquake or other unexpected loads could lead to major disasters.

Seismic recommendations from MOTEMS have been referenced by other building codes, including the “National Earthquake Hazard Reduction Program.” They have become the approved methodology of the US military wharf and pier facilities in high seismic areas for seismic assessment (Eskijian, 2007). Furthermore, MOTEMS provisions have been used in projects in Washington state (Wray, Harn, & Jacob, 2007) (Klusmeyer & Harn, 2004) which were not originally under the MOTEMS jurisdiction.

TABLE 1: MOTEMS MATERIAL STRAIN LIMITS (TABLE 3107F2.5)

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

While most Marine Oil and LNG terminals use the typical 24-inch octagonal concrete pile, steel pipe piles are also occasionally used. However, MOTEMS does not provide recommendation for in-ground plastic hinge length for steel piles. As far as steel piles are concerned, MOTEMS merely states “The plastic hinge length depends on the section shape and the slope of the moment diagram in the vicinity of the plastic hinge” (MOTEMS, 2010).

The only recommendation currently available for in-ground plastic hinge length for steel piles is in the Port of Long Beach (POLB) Wharf Design Criteria (Lai, 2009). The POLB criteria were developed under the leadership of Chang Lei of the Port of Long Beach in collaboration with consultants from Moffat and Nichol, PBS&J, Earth Mechanics, Inc., and P2S Engineering (Lai, 2009). Instead of earthquake level 1 and level 2, POLB specifies Operating Level Earthquake (OLE) and Contingency Level Earthquake (CLE). An OLE is the equivalent to MOTEMS level 1 with the same 72-year return period and limited damages, and a CLE is equivalent to MOTEMS level 2 with the same 475-year return period and reparable damages. Thus for all future references, OLE and CLE will be referred to as Level 1 and Level 2, respectively.

This thesis describes the process and results from a plastic hinge analysis for a 24-inch octagonal concrete pile and 24-, 36-, and 48-inch steel pipe piles in six different soil conditions in order to find the plastic hinge length and depth for each case. The effects of earthquake levels, pile diameter, pile material, and soil properties will be examined. Once these have been determined they will be compared to the recommendations in MOTEMS and POLB. If the results prove to be different than what the current codes say, recommendations will be made on how to improve the code.

CHAPTER 2: BACKGROUND

Not much research is provided for steel piles used in offshore structures as they are less common than precast prestressed piles. Thus this chapter will focus on concrete piles.

Song, Chai, and Hale (2004) proposed an analytical model that relates the displacement ductility factor to the local curvature ductility demand for a fixed-head pile embedded in cohesive and cohesionless soils. They stated that the curvature ductility demand depends on the strength and stiffness of the soil pile system, as well as the location and length of the plastic hinges. By limiting the curvature in the plastic hinge, the ultimate limit state is assumed to be associated with a flexural failure. The curvature ductility demand in the pile, due to a certain imposed lateral displacement, must be properly assessed in order to control the damage due to the flexural yielding of the pile. Song, et al. also found that curvature demand in the yielding region of a pile is related to the equivalent plastic hinge length of the pile. However, they assumed that the plastic hinge length was only equal to one diameter length, which is much different than the recommendations in MOTEMS. Budek et al. (2004), on the other hand, showed that actual plastic hinge length was found to be significantly larger than this commonly assumed length of 1 diameter. Finally, Song et al. concluded that by limiting the curvature ductility demand in the plastic hinge region, the local damage in the piles can be controlled. The flexural strength of the pile and the ultimate pressure distribution of the soil are also needed to determine the ultimate lateral strength (Song, Chai, & Hale, 2004). Similar to Budek et al. (2004), they found that full flexural capacity of the system

can only be obtained through the formation of a subgrade hinge; this will be the only hinge in the case of a free-head pile.

Rather than using a concentrated plastic hinge method, like Song et al., Chiou, Yang, and Chen (2008) suggested adopting a distributed plastic hinge model to find where a pile yields. They stated that:

“Use of concentrated plastic hinge method in simulating the inelastic flexural behavior of piles gives unsatisfactory results because the location of maximum moment in piles may vary due to the effects of soil-structure interaction (Chiou, Yang, & Chen, 2008).”

There are two main difficulties in applying the concentrated plastic hinge method to the pile-soil system. The first is that due to a lack of sufficient experimental data, the moment vs. plastic-rotation of a pile is very difficult to obtain directly. This relationship is usually evaluated from theoretical analysis. The second issue is that the location of the plastic zone for a pile-soil system is difficult to be determined. The location of maximum moment (plastic hinge depth) varies with soil plasticity at increasing depth of the pile. Chiou et al. (2008) recommend using a distributive hinge model for cases where the hinge occurs along a member, which is the case in this experiment. Use of this model consists of many plastic hinges being inserted along the expected plastic zone of the member in question, instead of a single hinge for a specific plastic zone. Using the spacing of these hinges, the plastic hinge length can be determined. When the yield moment at a plastic hinge is exceeded, the plastic hinge yields and produces a plastic rotation. The actual plastic zone is determined by the range of these yielding hinges. The smaller hinges must be placed at spacing much smaller than the actual expected plastic hinge length. When the plastic hinge zone occurs in-ground the ultimate moment will occur at a particular depth of the pile with the plastic zone extending above and below the

point of ultimate moment. The range of the plastic zone increases as the difference between the ultimate and yield moments increase, but decreases as soil pressures increase.

Budek, Priestley and Benzoni studied the effects of external confinement provided by soil on plastic hinge lengths (2004). They tested six different piles, varying the presence of external confinement and the levels of transverse reinforcement within the piles. They stated that modeling of pile response in most tests is complicated due to the difficulty of quantifying the soil-structure interaction. They found that the majority of pile tests that have been done have been on precast, prestressed piles, even though the seismic performance of these piles has been suspect. They found that the presence of external confinement played a significant role in enhancing the ductility by supporting the confinement in the pile from the transverse steel reinforcement. They also observed that in the confined piles, crack patterns observed indicated that curvature was developed significantly outside of the loading area. The cracks showed that a greater length of the pile shaft was mobilized in developing curvature to provide for the rotational demand. For the confined piles, they observed that high localized curvatures and cracking had developed at the same time as the flexural failure mechanism while new flexural cracking in the unconfined piles outside of the loading area ceased when spalling began, as this caused the curvature to be concentrated into the plastic hinge. They found that external confinement created much larger plastic hinge lengths than they had predicted. This was probably due to the external confinement from the soil preventing the development of high localized curvatures in the central part of the hinge. In contrast, the unconfined piles had plastic hinge lengths closer to the predicted values since they allowed for higher local

curvatures to develop just before failure. Finally they observed that when the external confinement is only provided immediately adjacent to the plastic hinge zone, and not in the plastic zone (as is the case when a very stiff soil layer is adjacent to a much softer one), the pile performance will be degraded.

Allotey and El Naggar (2008) also studied the effects of soil interaction with the pile including the effects that soil yielding, pile yielding, gapping, and soil cave-in have on the response of a pile foundation under lateral cyclic loading. They studied the response to these conditions in single piles in clay and in sand using a beam on a nonlinear Winkler foundation (BNWF) model, which is used due to the ease of its use. The BNWF model requires limited computational effort to satisfactorily account for nonlinearity in soil while still allowing for detailed structural modeling. They found that soil cave-in and recompression of the soil affect the response of soil-pile-structure interaction (SPSI) systems in 3 ways. The first is that it reduces the maximum bending moment of the pile. The second is that the point of maximum bending moment is moved closer to the ground surface. Finally, it increases the hysteretic demand of the soil-pile system. These affects were noted to be more pronounced when the soil cave-in occurred in the top section of the pile. This is possibly due to the soil cave-in increasing the effective confinement of the pile, enhancing the performance of the SPSI system. The soil cave-in also minimizes localized curvature and increases the effective length of the plastic hinge. They found that the concrete that spalled off also increased the effective soil-pile friction resistance and provided significant external confinement. The extra confinement provided in these damaged zones by the cave-in could contribute to the performance of the SPSI system.

Seismic analysis in MOTEMS requires that nonlinear static procedures be used to determine the seismic displacement capacity of piles in marine oil terminal structures. Displacement capacity of a pile can be defined as the “maximum displacement that can occur without exceeding material strain values” (Table 1) (Goel & Saeedy, 2012). Estimation of displacement capacity of the pile according to the MOTEMS procedure requires monitoring of material strains during the nonlinear static pushover analysis. The pile is typically modeled as a Winkler beam (linear-elastic beam-column elements connected at ends by nonlinear moment-rotation springs) (Figure 2), similar to that of Allotey and El Naggar. The soil-pile interaction is modeled with soil springs with increasing soil stiffness with depth. The rigid-perfectly-plastic moment-rotation relationship of the springs is computed from the moment-curvature relationship (Figure 3) and the estimated length of the plastic hinge. The limiting value of the plastic rotation in the hinge at a selected design level is defined as:

$$\theta_p = L_p (\phi_L - \phi_y) \quad (1)$$

Where:

θ_p = plastic rotation

Φ_L = maximum pile-section curvature without exceeding MOTEMS specified material strain limits

Φ_y = yield curvature (Figure 3a)

L_p = plastic hinge length

**FIGURE 2: COMPUTER MODELING OF PILES IN MARINE OIL AND LNG
TERMINALS (GOEL & SAEEDY, 2012)**

**FIGURE 3: PILE MOMENT-CURVATURE AND MOMENT-ROTATION
RELATIONSHIPS (GOEL & SAEEDY, 2012)**

CHAPTER 3: METHOD

3.1. ANALYTICAL APPROACH

To find the plastic hinge length and depth, the pile (Figure 4a) was modeled in OpenSees software developed at the Pacific Earthquake Engineering Research Center (McKenna & Fenves, 2001). The pile was modeled using a distributed-plasticity based nonlinear beam-column elements (Figure 4b) as per Goel & Saeedy (2012). Fiber-sections are used for the section properties of the nonlinear beam-column elements. Using OpenSees and Matlab, a nonlinear static pushover analysis is conducted while monitoring material strains and elemental bending moments. The displacement capacity of the pile, Δ_L , is defined as the maximum displacement at the top of the pile without exceeding selected material strain limits. Using the bi-linear idealization of the pushover curve (Figure 5), the yield displacement, Δ_y is identified. The yield displacement can also be defined as the deflection at the tip of the pile when it reaches yield curvature, ϕ_y . The bending moments are also monitored during analysis. The location of maximum bending moment below ground is where the plastic hinge is assumed to occur (D_p) (Figure 4c and d). The soil-springs (Figure 4b) are modeled using bi-linear material to capture the p-y curves. The spring stiffness is defined as the p-value times the tributary pile length for the node where the spring is attached. The pile above and below ground is modeled with distributed-plasticity elements.

FIGURE 4: ANALYTICAL APPROACH FOR ESTIMATING PLASTIC HINGE LENGTH AND DEPTH

FIGURE 5: BI-LINEAR IDEALIZATION OF PUSHOVER CURVE

After the pushover analysis is completed, a moment-curvature analysis is conducted while the material strains and curvature are monitored. The curvature, ϕ_L , is defined as the maximum curvature without exceeding material strains. The yield curvature, ϕ_y , is identified using a bi-linear idealization of the moment-curvature relationship (Figure 6).

FIGURE 6: BI-LINEAR IDEALIZATION OF MOMENT-CURVATURE CURVE

The plastic hinge rotation (θ_p) can be calculated by

$$\theta_p = \frac{(\Delta_L - \Delta_y)}{(L + D_p)} \quad (2)$$

Where :

Δ_L = displacement capacity

Δ_y = yield displacement

L = length of the pile from the mud-line to the point of contra-flexure
above ground (Figure 4d)

D_p = Plastic hinge depth

The plastic hinge length (L_p) can be calculated by

$$L_p = \frac{\theta_p}{\phi_L - \phi_y}$$

(3)

Where:

ϕ_L = maximum curvature

ϕ_y = yield curvature

This approach is similar to that used by Budek et al. (1994) in determining the plastic hinge length and depth recommendations in Priestley et al (1996).

3.2. SOIL TYPE CONSIDERED

There were 6 soil types considered, dense sand, medium sand, loose sand, stiff clay, medium clay, and soft clay (Table 2). The soil was modeled as springs below the mud line at the nodes of each beam-column element (Figure 4b). The nonlinear p-y curves, as well as upper and lower bound multipliers, were provided by Arumoli and Vartharaj (2010). The lateral force-deformation relationships of soil-springs below ground level are defined by the p-y curves. The upper-bound and lower-bound p-y curves were obtained by multiplying the p-values by 1.5 and 0.67 for upper and lower bound curves respectively, for all level-ground conditions. These bounds are intended to encompass all possible soil characteristics, since the values in Table 2 are average values.

TABLE 2: SOIL CONDITIONS CONSIDERED AND SUBGRADE MODULUS (TABLE 31F-7-4 OF MOTEMS)

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

3.3. PILE SECTIONS CONSIDERED

3.3.1. CONCRETE

The first step in the analysis was to run the program for concrete pile generally used in Marine Oil and LNG Terminals. The pile type a 24-inch diameter octagonal pre-stressed concrete pile (Figure 7a) in the various soil conditions. The cross section consisted of 16 pre-stressing tendons each with an area of 0.217 in², #11 wire spiral pitched at 2.5 in, and 3 in cover. The unconfined concrete compressive strength was selected as $f'_c = 6.5$ ksi and pre-stressing steel tendon yield strength, $f_y = 270$ ksi, and were pre-stressed to 70% of their yield stress. The pile was subjected to an axial load equal to 5% of its axial load capacity. The pile was free to deflect and rotate at the top. It extended to 80 ft below ground with heights above ground of 20 ft, 16 ft, 12 ft, 8 ft, and 4 ft corresponding to a pile height to pile diameter

ratio, H/D , of 10, 8, 6, 4, and 2 respectively. The same pile conditions were used by Goel & Saeedy (2012).

FIGURE 7: (A) PILE SECTION CONSIDERED, (B) MOMENT-CURVATURE RELATIONSHIP (GOEL & SAEEDY, 2012)

3.3.1.1 FORCE-BASED VS. DISPLACEMENT-BASED ELEMENTS

Two types of distributed plasticity models for beam-column elements are available in *OpenSees*: force-base elements and displacement-based elements (Neuenhofer & Filippou, 1997). Force-based elements are based on exact force interpolation functions. The solution error for force-based elements can be reduced either by increasing the number of integration points or increasing the element subdivision. Displacement-based elements on the other hand, are based on approximate displacement interpolation functions. *OpenSees* uses linear distribution of curvature over the element length. The solution error in using displacement-based elements can only be reduced by a

finer discretization, which requires higher computational effort to achieve comparable accuracy.

To Analyze which element type worked better between force-based (element type 1) and displacement-based (element type 2) elements, the results of both element types were compared for all soil conditions. The pile for each case was discretized with the same number of elements for both element types. Two integration points were used for both element types. As is seen in Figures 8, 9, and 10, the values for displacement, plastic hinge depth/diameter and plastic hinge length/diameter, respectively, are very close and the differences are negligible. However, the pile curvature diagrams for element type 2 (Figure 11c) showed discontinuities while the curvature diagram for element type 1 (Figure 12c) was smooth. The discontinuity is more pronounced in the yielding, or plastic hinge, region. This result is expected because the displacement interpolation function used in displacement-based elements lead to linear variation of curvature over the element length with no guarantee of identical curvatures at the intersection of two elements.

These results proved to be true for all soil types and heights and are shown in Appendix A. It is clear from Figures 8 to 10 that either type of element can be used in this assessment but the curvature profile obtained by using displacement-based elements may be unrealistic unless a very fine discretization is used. Since the results were so close and due to the

discontinuities in displacement-based elements, only force-based elements were used in all other analyses.

**FIGURE 8: COMPARISON OF DISPLACEMENTS, BASED ON ELEMENT TYPES FOR
(A) LEVEL 1 (B) LEVEL 2**

FIGURE 9: COMPARISON OF DEPTHS OF PLASTIC HINGES, BASED ON ELEMENT TYPES FOR (A) LEVEL 1 (B) LEVEL 2

**FIGURE 10: COMPARISON OF LENGTHS OF PLASTIC HINGES, BASED ON
ELEMENT TYPES FOR (A) LEVEL 1 (B) LEVEL 2**

**FIGURE 11: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) PILE CURVATURE
FOR DISPLACEMENT BASED ELEMENTS IN DENSE SAND FOR A
HEIGHT/DIAMETER RATIO OF 10**

FIGURE 12: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) PILE CURVATURE FOR FORCE BASED ELEMENTS IN DENSE SAND FOR A HEIGHT/DIAMETER RATIO OF 10

3.3.2. STEEL

The analysis was repeated using steel piles and varying the diameters. Pile diameters of 24-, 36-, and 48-inches were used with pile thicknesses of 0.5-, 0.75-, and 1.0-inch respectively. Only force-based elements were used due to the discontinuities in the curvature diagram. The yield strength of the steel was 50 ksi. The heights were once again varied to make an H/D ratio of 2, 4, 6, 8, and 10 for all soil conditions and all other dimensions were kept constant.

CHAPTER 4: RESULTS AND ANALYSIS

4.1. COMPARISON OF EARTHQUAKE LEVELS

A comparison of the results for the different earthquake levels was the first step in the analysis. The results varied based on material type.

4.1.1. CONCRETE

For the concrete pile examined in this study, the Level 1 earthquake results in a much longer plastic hinge length than Level 2. The Level 2 earthquake is more damaging than Level 1 resulting in temporary closure while the Level 1 would produce little to no damage. The presented results indicate much longer plastic hinge length for a Level 1 earthquake than for a Level 2 earthquake for concrete piles.

When looking at the curvature distributions for Level 1 (Figure 13c) and Level 2 (Figure 14c), it is apparent that the rate of change of curvature for Level 1 is much smaller than that for Level 2. This implies that the curvature is more evenly distributed over a longer length of the pile for Level 1 compared to Level 2. This shows why the plastic hinge length for level 1 is longer than level 2.

Plastic hinge lengths also increase with looser soils and with increasing height to pile diameter ratios for both levels. This is due to the smaller subgrade modulus in looser soils, as will be discussed in section 4.3. Smaller soil stiffnesses lead to larger curvature, which, according to Budek et

al. (2000), lead to longer plastic hinges (Figure 15a). See Appendix B for a summary of all results.

The depth of the plastic hinge, on the other hand, is the same for Level 1 and Level 2 for all soil conditions and height to diameter ratios. The depth increases with decreasing soil stiffness and increasing height to diameter ratios (Figure 15b). See Appendix C for a summary of all results.

FIGURE 13: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) CURVATURE DISTRIBUTIONS FOR 24 INCH CONCRETE PILE IN DENSE SAND WITH $H/D=2$ AND LEVEL 1 EARTHQUAKE

FIGURE 14: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) CURVATURE DISTRIBUTIONS FOR 24 INCH CONCRETE PILE IN DENSE SAND WITH $H/D=2$ AND LEVEL 2 EARTHQUAKE

FIGURE 15: COMPARISON OF (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 24 INCH CONCRETE PILE FOR ALL SOIL TYPES AND H/D RATIOS

4.1.2. STEEL

Unlike the concrete pile response, plastic hinge lengths for level 2 for the steel piles ended up being larger than level 1, likely do to steel being more ductile than concrete. Steel can deflect much larger amounts than concrete before failing, leading to a larger plastic hinge length for the larger earthquake load. The concrete would start to crush much earlier than the steel would

yield. It is also seen in the curvatures in Figures 16c and 17c that the hinge length responds similarly to the curvature distributions as with concrete. The plastic hinge lengths did also react similarly in relation to changing soil stiffness and height to diameter ratios (Figures 18a, 19a, and 20a). The results were consistent for all three pile diameters examined. See Appendix B for a summary of all results.

The depths of the plastic hinges responded similarly to concrete and were equal for both level 1 and level 2 (Figures 18b, 19b, and 20b). See Appendix C for a summary of all results.

FIGURE 16: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) CURVATURE DISTRIBUTIONS FOR 24 INCH STEEL PILE IN DENSE SAND WITH H/D=2 AND LEVEL 1 EARTHQUAKE

FIGURE 17: (A) DEFLECTION, (B) BENDING MOMENT, AND (C) CURVATURE DISTRIBUTIONS FOR 24 INCH STEEL PILE IN DENSE SAND WITH H/D=2 AND LEVEL 2 EARTHQUAKE

FIGURE 18: COMPARISON OF (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 24 INCH STEEL FOR ALL SOIL TYPES AND H/D RATIOS

FIGURE 19: COMPARISON OF (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 36 INCH STEEL FOR ALL SOIL TYPES AND H/D RATIOS

FIGURE 20: COMPARISON OF (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 48 INCH STEEL FOR ALL SOIL TYPES AND H/D RATIOS

4.2. COMPARISON TO CODES

Results were compared with Port of Long Beach Warf Design Criteria (POLB) and MOTEMS requirements for length of the plastic hinge. Neither POLB nor MOTEMS have recommendations for the location of the hinge,

however, as MOTEMS was adapted from Priestly et al. the location of the hinge will be compared to Priestley's recommendations (1996).

4.2.1. MOTEMS

MOTEMS makes recommendations for in-ground plastic hinges for concrete piles but not for steel piles, so comparison is possible for concrete piles only. The results from MOTEMS were taken from figure 31F-7-4 in MOTEMS which gives the plastic hinge length/pile diameter as a function of $KD^6/D*EI$ and H/D (MOTEMS, 2010) and was developed by Priestley et al which was adapted from figure 8 in Budek et al. (Budek, Benzoni, & Priestley, 1994). Figure 21a presents the length of in-ground plastic hinge for the pile in question for all six soil types and MOTEMS seismic design levels. It also includes the in-ground plastic hinge lengths estimated from the current MOTEMS recommendations for comparison. These results make it clear that the plastic-hinge length differs for both MOTEMS seismic design levels.

This study suggests that the MOTEMS recommendation for Level 2 earthquake design is accurate for most soil types. This is seen in the very similar values from the results obtained in this study and from MOTEMS recommendations. Since shorter plastic hinge lengths will lead to smaller displacement capacity, it appears that current MOTEMS recommendations for in-ground plastic hinge length will lead to conservative pile displacement capacity and thus should be acceptable for level 2.

There is, however, a large variance between MOTEMS results and the results found in this study for level 1. Since the shorter plastic hinge length will lead to smaller displacement capacity, the MOTEMS recommendations are overly conservative compared to the results found in this study.

The results shown in Figure 21a also present another short-coming of current analytical procedure. Structural modeling software typically only needs a single value for plastic hinge length, which is selected as the value recommended by MOTEMS. The displacement capacities of piles for level 1 and level 2 are estimated by the moment-rotation relationship developed based on this plastic hinge length. The results displayed in Figure 21a clearly show that this approach will lead to adequate displacement capacity for level 2 but will result in an overly conservative displacement capacity for level 1. Therefore separate recommendations for plastic hinge length should be made for level 1 and level 2 in order to not over design for level 1.

It is also helpful to note that the current MOTEMS recommendations for plastic hinge length were computed at failure compression strain by Priestley et al. (1996). These material strain levels are appropriate for MOTEMS level 2 but not for level 1. The material strains are much lower for level 1 (Table 1). Due to this, it is not surprising that the plastic hinge lengths found in this study differs so much from the current MOTEMS recommendations.

FIGURE 21: COMPARISON TO (A) MOTEMS AND (B) BUDEK ET AL FOR 24 INCH CONCRETE PILE

4.2.2. BUDEK, BENZONI, AND PRIESTLEY

The results from Budek, Benzoni and Priestley were based off of figure 6 in their study (1994). It is developed similarly to figure 31F-7-4 in MOTEMS except that it gives the depth of the plastic hinge instead of the length.

Figure 21b above presents depth in in-ground plastic hinge for two MOTEMS seismic design levels along with the current value recommended

by Priestley et al (1996). The recommendations from Budek are not adequate for any soil conditions or height to diameter ratio and are much shallower than what was determined in this investigation. Budek et al. recommendations lead to below ground depths of between 1D and 2D while this study showed actual depths to be between 2D and 8D depend on soil type and H/D ratio. Unlike the plastic hinge length, the plastic hinge depth is independent of the MOTEMS seismic design level.

4.2.3. PORT OF LONG BEACH

The recommendations in POLB for in-ground plastic hinges were taken from Table 4-2 for both steel and concrete. POLB states that all in-ground plastic hinges should be two times as long as the pile diameter, with no reference to the soil conditions or pile materials (Lai, 2009). Just like in MOTEMS there are also no specifications for different earthquake levels. As stated previously, POLB uses OLE and CLE which are equivalent to MOTEMS level 1 and level 2 earthquakes respectively, thus the results still refer to level 1 and level 2 instead of OLE and CLE.

This study demonstrates that the POLB recommendations are not suitable for most cases. Like MOTEMS they were accurate for concrete piles with a level 2 earthquake. When looking at all of the values individually as shown in Figure 22, the values from POLB are nowhere close to the values found in experimentation for steel except for in level 1 dense and medium sands or for concrete level 1.

FIGURE 22: COMPARISON TO PORT OF LONG BEACH FOR (A) 24 INCH CONCRETE (B) 24 INCH STEEL (C) 36 INCH STEEL AND (D) 48 INCH STEEL PILES

4.2.3.1. CONCRETE

Figure 22a presents the length of in-ground plastic hinge for the concrete pile in question for all six soil types and POLB seismic design levels. It also includes the in-ground plastic hinge lengths recommended by POLB (2 times the diameter) for comparison. These results make it clear that the plastic hinge length is not the same for both design levels.

The POLB values seem to be adequate for level 2 in concrete for most soil conditions, but not for level 1, similar to MOTEMS. This is seen

in the similar values from the results obtained in this study and from POLB recommendations. The results for POLB are slightly conservative however, but should still be acceptable for level 2.

Like in MOTEMS there is a much larger difference in level 1 for concrete, since a shorter plastic hinge length means smaller displacement capacities. This shows that the POLB produces overly conservative values for level 1.

Overall the POLB recommendations for concrete are very similar to those in MOTEMS and should also be changed to have different values for each earthquake levels.

4.2.3.2. STEEL

Figure 22b, c, and d present the length of in-ground plastic hinge for the steel piles in question for all six soil types and POLB seismic design levels. It also includes the in-ground plastic hinge lengths recommended by POLB (2 times the diameter) for comparison. These results show that the plastic hinge length differs for both design levels.

For level 1, the POLB recommendations are not very accurate and overly conservative for all soil types except for dense and medium sands. For these soils the recommendations are only slightly conservative. Thus the POLB recommendations should be amended to take into account the different soils.

For level 2, on the other hand, the POLB recommendations are overly conservative for any listed soil. Thus the different outcomes suggest

the need for separate recommendations for level 1 and level 2. Like for MOTEMS, there should also be a separation of different soil conditions. As is seen above, the differences get much more pronounced as the soil stiffness decreases, particularly in the clays. While sands seem to be slightly closer in value, the differences in the clays are much higher and need their own recommendations.

4.3. COMPARISON OF SOIL CONDITIONS

The effects of different soil conditions were examined carefully in this study. As stated earlier, Allotey and El Naggar (2008) and Budek et al. (2004) both observed the effects that soil confinement and cave-in have on the pile response. Soil cave-in increases the confinement effects on the pile, enhancing the internal transverse reinforcement. This leads to more evenly distributed curvatures in the plastic hinge zone, which leads to longer plastic hinge lengths.

One part that was not talked about previously was the effect of upper and lower bounds, for the p-y curves, on the results. As was stated earlier in section 3.2 on the soil types considered, the p-y curves and upper and lower bound multipliers were supplied by Arumoli and Vartharaj (2010). Also as stated earlier, the plastic hinge length and depth increases with decreasing soil stiffness. Budek et al. (2000) observed that larger curvatures could be expected in relatively softer soils, resulting in longer hinge lengths. The lower bound increases most of these values while the upper bound decreases them. Figures 23, 24, 25, and 26 show the results of the analyses which compared the upper and lower bounds to the nominal values.

The lower bound decreases the soil stiffness by 33% which would explain the increase in plastic hinge lengths and depths based on observations by Budek et al. (2000). The decreased soil stiffness allows for larger curvatures, which means longer plastic hinge lengths.

The upper bound, on the other hand, increases the soil stiffness by 50%, leading to decreased plastic hinge lengths and depths. The increased soil stiffness leads to smaller curvatures which mean smaller plastic hinge lengths.

FIGURE 23: COMPARISON OF BOUNDS TO NOMINAL VALUES FOR (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 24 INCH CONCRETE PILE

FIGURE 24: COMPARISON OF BOUNDS TO NOMINAL VALUES FOR (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 24 INCH STEEL PILE

FIGURE 25: COMPARISON OF BOUNDS TO NOMINAL VALUES FOR (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 36 INCH STEEL PILE

FIGURE 26: COMPARISON OF BOUNDS TO NOMINAL VALUES FOR (A) PLASTIC HINGE LENGTH/PILE DIAMETER AND (B) DEPTH OF PLASTIC HINGE/PILE DIAMETER FOR 48 INCH STEEL PILE

CHAPTER 5: CONCLUSION

This investigation examined the current recommendations for plastic hinge length and depth for piles and soil properties typical of those in Marine Oil and LNG Terminals. For this purpose, 24-inch octagonal pre-stressed concrete and 24-, 36-, and 48-inch steel piles supported in six different soil types; dense sand, medium sand, loose sand, stiff clay, medium clay, and soft clays; were analyzed. Nonlinear behavior for both pile and soil were considered and MOTEMS specified strain levels were used to compute the pile capacity and then compared to recommendations in MOTEMS and POLB. All analyses in this study were conducted using *OpenSees* software developed at the Pacific Earthquake Engineering Research Center.

The MOTEMS recommendation for plastic-hinge length is adequate for level 2 MOTEMS design but not for level 1. The recommended plastic hinge length for level 1 is much longer than that provided by the current MOTEMS recommendations. As shorter plastic hinge length leads to smaller displacement capacity, current MOTEMS plastic hinge length recommendations will lead to conservatively small pile displacement capacity for level 1 seismic design. The location of the plastic hinge in piles also needs to be extended to larger depth below ground than indicated by current recommendation. MOTEMS should also include recommendations for location of plastic hinge, not just the length. MOTEMS should also include information for plastic hinge length and location for steel piles.

The Port of Long Beach recommendations for plastic hinge length is adequate for level 2 (CLE) for concrete but not for level 1 (OLE). The plastic hinge length for level 1

is much longer than that provided by the current POLB recommendations producing conservatively small displacement capacity.

Recommendations for steel piles are not adequate for either level 1 or level 2 other than for dense and medium sands in level 1. All others produce conservatively small recommendations. POLB recommendations are incomplete because they do not take into account the soil conditions and only have a flat rate for all soils. POLB recommendations are also incomplete as they do not include recommendations for the location of the plastic hinge, just the length.

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APPENDIX A: COMPARISON OF ELEMENT TYPES

Dense sand

H/D=10

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=8$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=6

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=4

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=2

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

Medium sand

H/D=10

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=8

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=6$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=4$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=2$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

Loose sand

$H/D=10$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=8$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=6

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=4

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=2$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=10

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=8

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=6

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=4$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=2

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

Medium Clay

H/D=10

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=8

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=6$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

$H/D=4$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=2

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

Soft Clay

$H/D=10$

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=8

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=6

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=4

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

H/D=2

Level 1

Element 1

Element 2

Level 2

Element 1

Element 2

APPENDIX B: SUMMARY OF PLASTIC HINGE LENGTH/DIAMETER

24-inch Concrete Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	1.9	2.6	2.3	2.8	2.6	3.2	4.3	4.7	5.5	6.1	8.5	9.7
4	2.4	2.9	2.3	3.3	2.5	3.3	4.2	4.8	5.2	6.1	8.5	9.9
6	2.1	3.0	2.4	3.3	2.8	3.7	3.8	4.9	4.8	6.2	7.9	9.7
8	2.5	3.3	2.8	3.6	2.5	4.0	3.6	5.4	4.6	6.4	7.7	9.6
10	2.4	3.8	2.5	4.0	2.7	4.1	3.7	5.1	4.8	6.3	7.2	9.6

24-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	2.2	2.9	2.4	3.2	3.0	3.5	3.5	4.5	4.6	5.9	7.3	9.1
4	2.8	3.2	2.7	3.6	2.7	4.1	3.4	4.6	4.4	6.0	7.4	8.7
6	2.3	3.6	2.6	3.9	3.1	4.1	3.4	5.1	4.4	5.7	7.0	8.6
8	2.6	3.6	3.1	4.0	3.0	4.6	3.5	4.7	4.7	5.9	6.4	8.7
10	2.9	3.9	2.9	4.5	3.0	4.7	3.3	5.1	4.2	6.2	6.2	8.3

36-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	2.2	3.2	2.3	3.2	2.5	3.2	3.8	4.6	4.9	5.7	8.3	9.5
4	2.1	3.0	2.6	3.2	2.6	4.0	3.7	4.7	4.8	5.8	7.7	9.1
6	2.5	3.3	2.4	3.9	2.5	3.8	4.0	4.8	4.9	6.0	7.3	9.0
8	2.3	3.6	2.5	3.8	3.3	4.0	3.5	5.0	4.5	6.2	7.0	8.9
10	2.5	3.5	2.9	3.9	2.8	4.4	3.8	5.0	4.5	6.2	6.9	9.0

48-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	1.9	2.6	2.3	2.8	2.6	3.2	4.3	4.7	5.5	6.1	8.5	9.7
4	2.4	2.9	2.3	3.3	2.5	3.3	4.2	4.8	5.2	6.1	8.5	9.9
6	2.1	3.0	2.4	3.3	2.8	3.7	3.8	4.9	4.8	6.2	7.9	9.7
8	2.5	3.3	2.8	3.6	2.5	4.0	3.6	5.4	4.6	6.4	7.7	9.6
10	2.4	3.8	2.5	4.0	2.7	4.1	3.7	5.1	4.8	6.3	7.2	9.6

APPENDIX C: SUMMARY OF PLASTIC HINGE DEPTH/DIAMETER

24-inch Concrete Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	4	4	5	5	5	5	4	4	6	6	8	8
4	3	3	4	4	5	5	3	3	5	5	7	7
6	3	3	4	4	4	4	3	3	4	4	7	7
8	3	3	3	3	4	4	2	2	3	3	6	6
10	2	2	3	3	4	4	2	2	3	3	5	5

24-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	5	5	6	6	7	7	6	6	8	8	12	12
4	4	4	5	5	6	6	5	5	7	7	10	10
6	4	4	5	5	6	6	4	4	6	6	9	9
8	4	4	5	5	5	5	4	4	5	5	9	9
10	3	3	4	4	5	5	3	3	5	5	8	8

36-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	4	4	5	5	6	6	6	6	8	8	12	12
4	4	4	5	5	5	5	5	5	7	7	11	11
6	3	3	4	4	5	5	4	4	6	6	10	10
8	3	3	4	4	4	4	4	4	6	6	9	9
10	3	3	4	4	4	4	3	3	5	5	8	8

48-inch Steel Pile

	Dense Sand		Medium Sand		Loose Sand		Stiff Clay		Medium Clay		Soft Clay	
H/D	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
2	4	4	5	5	5	5	6	6	8	8	13	13
4	3	3	4	4	5	5	5	5	7	7	11	11
6	3	3	4	4	4	4	5	5	7	7	10	10
8	3	3	3	3	4	4	4	4	6	6	9	9
10	2	2	3	3	4	4	4	4	5	5	9	9

APPENDIX D: SUMMARY OF COMPUTER PROGRAM CODE