SEISMIC RESPONSE AND DESIGN OF PILE FOUNDATIONS

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Contents

Summary

This chapter presents a methodology for seismic design and performance assessment of reinforced concrete pile foundations. Under earthquake loading, the lateral force associated with the inertia of the superstructure may induce a large curvature demand in the pile with potential for damage or failure of the foundation. In foundations where yielding of piles cannot be avoided, the severity of local damage may however be controlled during design by limiting the curvature ductility demand in the potential plastic region. 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. An analytical model capable of assessing the stiffness, strength and ductility demand of laterally loaded piles is presented in this chapter. The model allows the severity of local damage to be assessed for a wide range of soil and pile properties. In order to guarantee satisfactory seismic performance of foundations, sufficient transverse reinforcement must be provided in the yielding region to ensure adequate structural ductility capacity and shear strength of the pile. The level of transverse reinforcement required by various design provisions and the available curvature ductility capacities are examined in this chapter. A simple yet acceptable approach for assessing the shear strength of reinforced concrete piles is also summarized. A procedure for seismic design of extended pile-shafts in bridge structures is developed using the analytical model presented. The design procedure follows the well-accepted approach of using a force-reduction factor to determine the lateral strength of the structure, and involves an iterative process to arrive at the required amount of longitudinal reinforcement. Finally, the versatility of the design

procedure and its suitability for seismic performance assessment are illustrated using two numerical examples of extended pile-shafts constructed in different soil sites.

1. General

Foundations consisting of drilled or cast-in-place concrete piles are widely employed in engineering practice to support structures on deep soil deposits. The primary functions of these piles include providing adequate support for the gravity loads arising from the self-weight of the structure, resisting the uplift and downward force from overturning and carrying the horizontal force induced by winds, waves or earthquakes. In the design of pile foundations under lateral loads, two types of boundary conditions are generally assumed at the pile-head. For piles embedded in a soft or medium soil, a rotational restraint is commonly applied at the pile-head resulting in increased lateral stiffness of the foundation. Such pile is referred as *fixed-head piles* in practice. Typical applications include building, bridge, or wharf foundations with a group of piles that are subsequently integrated using a heavily reinforced pile-cap, as shown in Figures 1(a), (b) and (c).

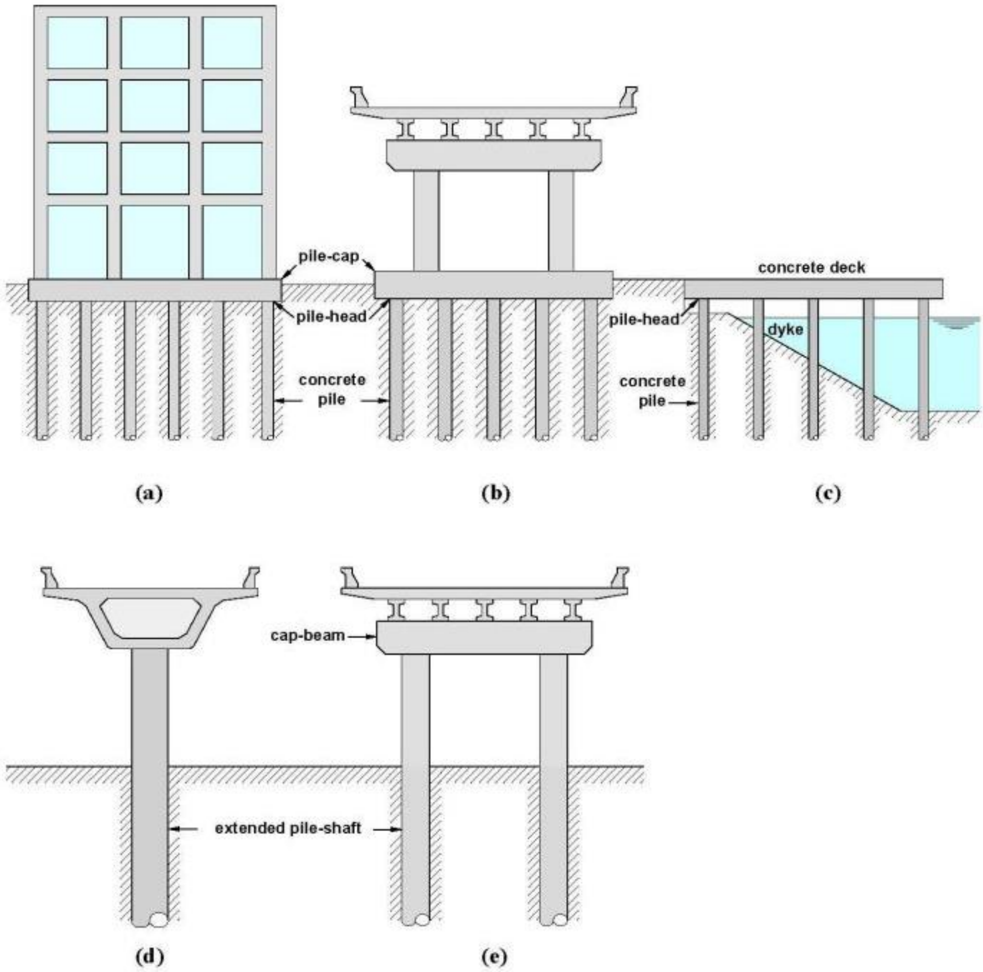

Figure 1. Various types of pile foundations: (a) group piles in a building foundation, (b) group piles in a bridge foundation, (c) group piles foundation in a wharf structure, (d) single-column bridge bent with extended pile-shaft, and (e) multi-column bridge bent with extended pile-shaft.

The rotational restraint, or so-called "fixity effect", is provided by fully anchoring the reinforcement into the pile-cap in order to develop the strength of the reinforcement. For the case where the soil at the construction site is stiff, however, a pin connection is commonly provided at the pile/pile-cap interface in order to reduce the moment demand at the pile-head. Such piles are normally referred as *pinned-head piles* in practice. The pin connection may be provided by placing an elastomeric pad on top of the pile with a few centrally located vertical rebars dowelling the pile to the pile-cap. Another type of pile foundation, which is commonly employed in bridge structures, is the single column and multi-column bridge bents in the so-called 'extended pile-shafts', as illustrated in Figures 1(d) and (e), respectively. The supporting columns are continued below the ground level as cast-in-drilled-hole piles of approximately the same diameter.

1.1. Objectives

Foundation systems must be recognized as an integral part of a building or bridge, capable of supporting gravity loads from the superstructure while maintaining dependable energy dissipation through carefully detailed regions of the structure in a severe seismic event. It must also be recognized that, under strong ground shaking, the lateral force associated with the inertia of the superstructure may induce a large bending moment in the piles in the case of deep foundations. The magnitude of the bending moment under a design-level earthquake can be sufficiently large to cause yielding of the pile, with potential for significant damage or failure of the foundation. Depending on the intensity of the ground motion, damage to pile foundations may include spalling and crushing of the concrete, buckling of the longitudinal reinforcement or fracture of the transverse reinforcement. Structures may suffer unacceptable level of tilting and residual deformation as a result of pile failure, significantly affecting the serviceability of the structure. Since yielding of the pile may be difficult to avoid under the design-level earthquake in high seismicity areas, post-yield performance of pile foundations, particularly the levels of global displacement and local inelastic deformation to be expected, becomes critically important and need to be carefully assessed. Without such an assessment, seismic response of pile foundations becomes uncertain and their satisfactory performance cannot be guaranteed. Moreover, when subjected to earthquake excitations, the response of pile supported structures is closely related to the properties of the surrounding soils. The interaction between the soil and pile imposes further design challenges. As practices move towards performance-based design, a simple approach capable of incorporating the nonlinearity of the soil and pile in the design process leading to an assurance of performance in the pile foundation will help to advance the state-of-the-art in earthquake engineering.

1.2. Observed Damage of Pile Foundations in Recent Seismic Events

Post earthquake observations in recent earthquakes have indicated that pile foundations are susceptible to severe damages due to the strong ground shaking. This section highlights selected cases of pile damage observed during past major earthquakes. As historical reports of damage of pile foundations can be readily found in many literatures, only recent earthquake events with significant pile damage are described. In particular, cases from the 1985 Mexico City Earthquake, 1989 Loma Prieta Earthquake, 1995

Hyogoken-Nambu (Kobe) Earthquake, and 1999 Izmit (Turkey) Earthquake are presented.

The epicenter of the 1985 Mexico City Earthquake (Mw = 8.0) was about 400 km from Mexico City. However, because most of Mexico City is built on soft clayey deposits with high water content, the intensity of the shaking was greatly amplified with a predominant period of approximately 2 seconds. This long period motion was particularly damaging for deep foundations at soft soil sites. For example, a 16-story reinforced concrete apartment building supported on 36 m long reinforced concrete piles suffered damage that was largely attributed to the lateral response of the foundation. An inspection after the earthquake revealed that several piles located at the corner or the edge of the foundation had been seriously damaged. The failure, which is shown in Figure 2(a), was mainly caused by crushing of the concrete as a result of the large flexural deformation induced at the pile-head. Despite the damage of the pile, no tilting of the apartment building was reported.

The 1989 Loma Prieta Earthquake (M_W = 6.9) caused considerable damage to several pile-supported bridges and port facilities. Most of the bridge foundation damages occurred at sites underlain by thick deposits of soft clayey soils. A classic example of the damage to pile-supported bridges was the Struve Slough Bridge located on Highway-1 near Watsonville, California, approximately 20 km from the epicenter of the earthquake. The bridge superstructure was reported to show evidence of large lateral displacement in the transverse direction, resulting in failure of some of the pile-extensions and dropping of the superstructure deck, which led to dramatic punching of the pile-extension through the collapsed roadway. Reported localized failure include concrete crushing, buckling of longitudinal reinforcement and fracture of transverse reinforcement. A view of the collapsed structure and the localized failure in the pile-extension are shown in Figures 2(b) and (c). Port facilities around San Francisco Bay also experienced serious pile damage. The square prestressed concrete piles at the 7th Street Terminal Complex at the Port of Oakland failed at their connection to the deck, as shown Figure 2 (d), primarily due to lateral spreading of the surrounding soil. The reinforced concrete piles at the Charles P Howard terminal were found to have failed in bending at the pile-head. In San Francisco, pile foundations supporting the Ferry Plaza Piers also experienced severe damage at the pile/pile-cap connection.

The 1995 Hyogoken-Nambu (Kobe) Earthquake (M_W = 6.8) was the most destructive earthquake to have struck Japan since the 1923 Great Kanto Earthquake. The event was unique in the sense that many types of damage were observed in the pile foundations. The most dramatic failure during the 1995 Kobe Earthquake was the collapse of an elevated section of the pile supported Hanshin Expressway. Although above-ground failure captured most of the news headlines, pile foundations of bridge piers along other sections of the Hanshin Expressway also suffered serious damage, including concrete crushing at the pile/pile-cap connections, cracks that concentrated at some depth below the ground level and shearing of piles at the interface of adjacent layers of soils. These damages were mainly induced by the high inertial force during the intense shaking. Post earthquake inspection of highway system near the Kobe area also revealed that damage to fixed-head concrete piles occurred not only near the pile-head but also at a lower depth of the pile, where the damage may have arisen from the second large bending moment or as a result of the lack of attention to details of the curtailment of reinforcement. Several piles also indicated that the damage at the transition between soil layers of large stiffness contrast. Numerous multi-story buildings supported on piles in alluvial fans also suffered severe damage during the 1995 Kobe Earthquake. Post-earthquake investigations indicated that pile foundation damage was due to the large superstructure inertial load. The failure mechanism included crushing of the concrete at the pile-head, as seen in Figure 2(e), as well as flexural-shear failure in the pile. Pile foundation for facilities at the Rokko and Port Islands experienced severe damage due to the large lateral ground displacement. Subsequent analyses indicated that piles were found to be under-designed resulting in large deformation demands from the earthquake. For example, Figure 2(f) shows a damaged pile that supported a low-rise building. The pile had only nominal amount of reinforcement and was therefore deemed inadequate for the lateral loads. The large seismic force also induced buckling of the main reinforcement.

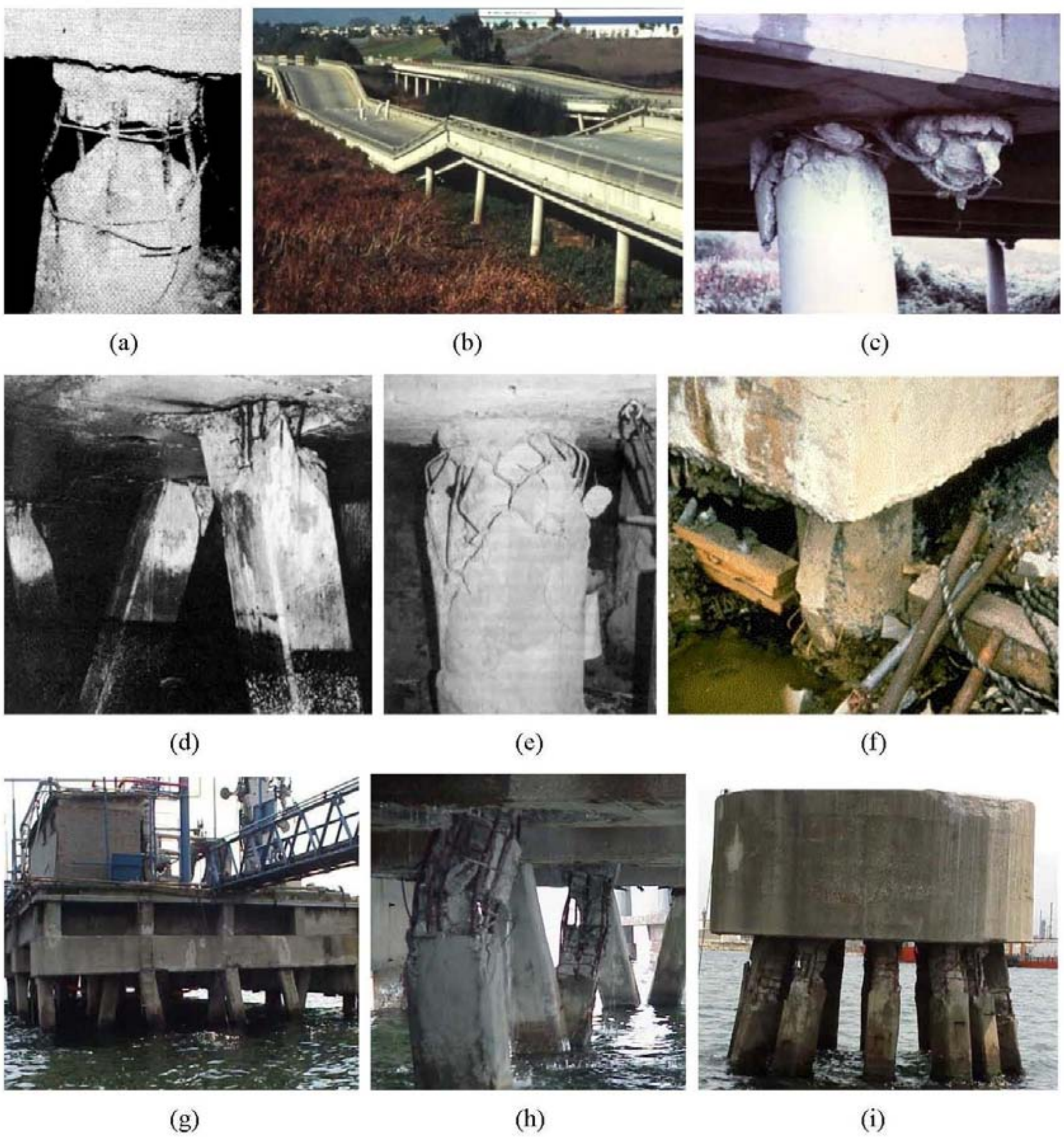

Figure 2. Observed pile damages in recent earthquakes

The 1999 Izmit Earthquake (M_W =7.6), which struck the Kocaeli area in the Northwest Turkey, was one of the most devastating earthquakes of the twentieth century. Damages to pile-supported structures primarily occurred in waterfront structures. For example, the pile foundation of the Petkim pier facility, as shown in Figure 2(g), suffered serious damage at the pile/pile-cap connections. It can be seen from Figure 2(h) that the battered piles were severely damaged with crushing of the concrete at the pile-head. Severe damage at the pile/pile-cap connection was also observed for dolphin structures, as seen in Figure 2(i). Signs of plastic hinge formation in the piles were evident.

1.3. Approaches for Modeling Laterally Loaded Piles

Lessons learned from recent earthquakes emphasize the need to carefully assess the post-yield performance of the pile foundation systems, particularly for structures located in moderate or severe seismic regions. Seismic performance of pile foundations is greatly dependent on the interaction between the pile and surrounding soil. Approaches commonly used in practice for modeling laterally loaded pile foundations, with the consideration of the soil-pile interaction effects, are illustrated in Figure 3. The uncoupled base-spring approach simplifies the pile foundation to a set of translational and rotational foundation springs located at the ground level. Under lateral loads, the response of pile foundations is idealized by the equivalent movement and rotation of the springs. The load-deformation relation of the springs, which may be non-linear, is defined using a push-over analysis of the soil-pile system. However, since the soil-pile system is replaced by foundation springs, the simplified uncoupled base-spring approach cannot be used to assess the local damage along the pile nor the post-yield response of the soil-pile system. Another commonly used approach assumes that the soil-pile system can be replaced by an equivalent cantilever that is fully restrained against lateral translation and rotation at some elevation below the ground level with the surrounding soil removed. The equivalent depth-to-fixity depends on the relative stiffness between the pile and soil. Such an approach adds flexibility to the structure system in an attempt to account for the influence of the soil and piles. However, it is important to note that for piles subjected to lateral loads, the maximum in-ground bending moment does not occur at the equivalent depth-to-fixity, but at a depth above the fixed-base of the equivalent cantilever. Therefore, the equivalent cantilever model is more applicable in the assessment for the elastic response of pile foundations. A more comprehensive approach for modeling laterally loaded soil-pile systems follows the “beam on Winkler foundation” concept. The pile is replaced by a nonlinear flexural member, while the resistance of the soil is modeled by a series of closely spaced *p-y* spring elements. In this case, ‘ *p* ’ represents the lateral soil reaction per unit length, and ‘ *y* ’ represents the lateral displacement of the pile. In current practice, various nonlinear *p-y* curves have been proposed for the load-displacement relations of different types of soils, e.g. cohesive soils vs. cohesionless soils, or different loading conditions, e.g. monotonic loading vs. cyclic loading. The beam on Winkler foundation model offers a rather handy approach to model laterally loaded soil-pile systems without major sacrifice of the essential nonlinear features of the pile and soil.

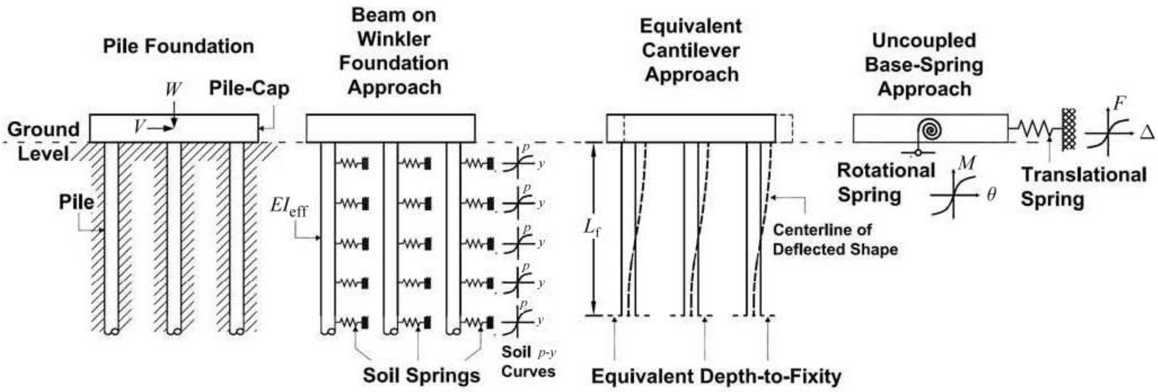

Figure 3. Various approaches for modeling laterally loaded pile foundations

1.4. Current Design Philosophy

The methodology for seismic design of pile foundations has undergone significant changes in recent years. Traditionally, foundation systems of most bridge structures are strategically designed to remain elastic when subjected to seismic loads. The approach is intended to avoid the difficulty of the post-earthquake inspection and the high cost associated with repairing the foundation if damage or failure occurs. In this case, pile foundation is designed on the basis of elastic response of the piles even under severe seismic demands. This design principle is particularly relevant in seismic design of bridge foundations consisting of group piles, as illustrated in Figure 1(b). By following a capacity design principle, an elastic response of the foundation can be ensured by increasing the strength of the foundation above that of the bridge columns so that plastic hinges develop in the column instead of the foundation. In essence, the design process focuses on the overall strength of the foundation and the force distributed to piles in the group. Assessments of the pile deformation and the potential failure are not routinely included in the design process. In the case of buildings, the pile foundations are traditionally designed for seismic forces using the same force reduction factor as the building superstructure. This methodology implies that yielding of piles can also occur under a strong seismic excitation. However, since most building codes typically do not limit the lateral displacement of the foundation, damage in the foundation system under the design-level earthquakes could be more severe than the superstructure when soft or collapsible soils exist at the building site.

The international earthquake engineering community recognizes the importance of properly designed foundation systems and has mobilized with a concerted effort to develop performance-oriented design process for pile foundations. The underlying philosophy of performance-based seismic design relies on the determination of an optimum strength or deformation of the structure to achieve a set of specified performance requirements, for example requirements that limit the damage level, given different seismic intensities at the site. In current seismic design provisions, the pile is designed according to the Seismic Design Category designated for the construction site. Besides the lateral force demand, the overall displacement and local deformation of the pile must be considered in the design process. Regions associated with potential inelastic deformation need to be carefully detailed to ensure a ductile response of the pile.

Despite the presence of soil, proportioning and detailing of piles may follow the ductile design of reinforced concrete columns where transverse reinforcement is used to provide an adequate structural ductility capacity and shear strength of the pile. Since pile foundations belong to a class of substructures where inelastic deformation could possibly occur in areas that are not readily accessible for visual inspection, a more stringent limit is generally placed on the ductility demand in order to minimize the severity of structural damage. Such type of structure is designated as "*Limited Ductility Structures*" by Applied Technology Council (ATC) in the US practice. More specifically, a smaller design ductility factor is implicitly adopted to control flexural yielding and hence damage of the pile. A similar approach has been adopted for seismic design of bridge foundations in New Zealand. For plastic hinges expected at a depth less than 2 m below the ground level but not below the mean water level, the design displacement ductility factor μ_Δ, which will be defined later, is limited to $\mu_\Delta < 4$. For plastic hinges expected at a depth greater than 2 m below the ground level or below the mean water level, the design displacement ductility factor μ_Δ is reduced to $\mu_\Delta < 3$.

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