Raked Piles

Battered and Misunderstood

By Mark A. Moore

Raked-pile systems have fallen into disfavor in areas of high seismic activity. One possible reason could be the observed performance in past earthquakes, such as Loma Prieta in 1989 and Kobe in 1995. However, the raked-pile system's poor seismic performance may be attributed to the design rather than to the system itself. A poor design begins with the selection of an initial pile configuration, such as the one shown in *Figure 1*. This configuration was intended to develop a plastic hinge, a location where inelastic strain occurs, within the pile and not in the pile cap (the deck of the wharf in this example).

Figure 1: Too Frequently Occurring Raked Pile Configuration

Frequently, the raked-pile configuration is intended to provide only non-seismic lateral force-resistance. When seismic resistance is intended, a conventional strength-based design approach is used, reducing seismic forces by an "R" factor. Regardless of the design intent or approach, the configuration can be problematic because of the high forces generated within the pile cap, particularly where the piles are eccentric and there is not controllable inelastic behavior. For the configuration to form a mechanism, either the pile cap will yield or the pile will uplift. In either case, strength and displacements are difficult to predict. In configurations without eccentricity, there is still no apparent lateral force limit: axial forces in the pile increase, and with concurrent flexure, brittle compression and/or shear failure may be inevitable. Poor construction and inadequate reinforcement detailing have compounded the potential poor behavior of this system.

The design of a foundation usually considers sliding (lateral forces) and overturning (resulting in tension and compression on the piles) separately; however, sliding and overturning are coupled for the raked-pile system. This difference may cause confusion and thus a reluctance to specify raked-piles. Likewise, concerns of vertical settlement and potential lateral spreading in soft or liquefiable soils, possibly increasing the lateral forces and moments on battered piles, deters use of the raked-pile system.

Because of the apparent uncontrollable axial demand on the raked-pile system, there is a perception among structural engineers that a raked-pile foundation does not possess the necessary ductility needed for a large earthquake. In reality, understanding a system that couples the sliding and overturning, an engineer can design a high-performance, cost-effective found-ation system. The performance of the raked-pile system during a seismic event will exceed conventional foundation systems, making raked-piles ideal for hospitals, non-essential facilities and for use on seismic upgrade projects. This article provides a design methodology for the raked-pile system and illustrates two successful applications.

Code and Performance

In the recently adopted 2006 International Building Code, as with previous codes, the strength-based design procedure does not necessarily indicate performance level (SEAONC Blue Book, 1999). The current and future codes require that the design forces of the raked-pile system be multiplied by an over-strength factor, because of the perceived and observed poor performance of the system. Other foundation system designs are based on varying strength reduction factors, based on the lateral system used, that will result in rocking or sliding responses for some situations. (An empirically-derived R = 4.0 for foundation design is suggested as a placeholder and is consistent with the other R-values derivation process.) Therefore, to use the code design approach to make a performance comparison between any of these systems is not possible, and is a part of the code that needs improvement.

To justify the superior performance noted above, one must be aware that foundation deformation may govern the pattern and extent of damage to the superstructure. Additionally, although behavior may be ductile, structural systems that experience sliding or rocking typically exhibit strength and stiffness degradation. These systems are also subject to permanent deformations, have significant variation in their hysteric energy absorption capability and have some radiation damping characteristics. There is little consensus within the engineering community regarding the performance of foundation systems with inelastic behavior. The following performance assessment, therefore, is based on case-specific evaluations.

Consider Raked Piles from First Principles

The demand actions on the foundation, P (vertical force), M (overturning, which may be resolved by coupled vertical forces) and V (horizontal force), can be delivered from any lateral force-resisting system and will include some portion of dead and live loads. The vertical component (P_V) of pile load provides equilibrium to loads resulting from gravity and overturning of the superstructure. Total lateral resistance is from the horizontal component (V_{pile}) of pile load, and the lateral soil pressure against pile and pile cap, and the structural slab provide the lateral resistance (V_{other}).

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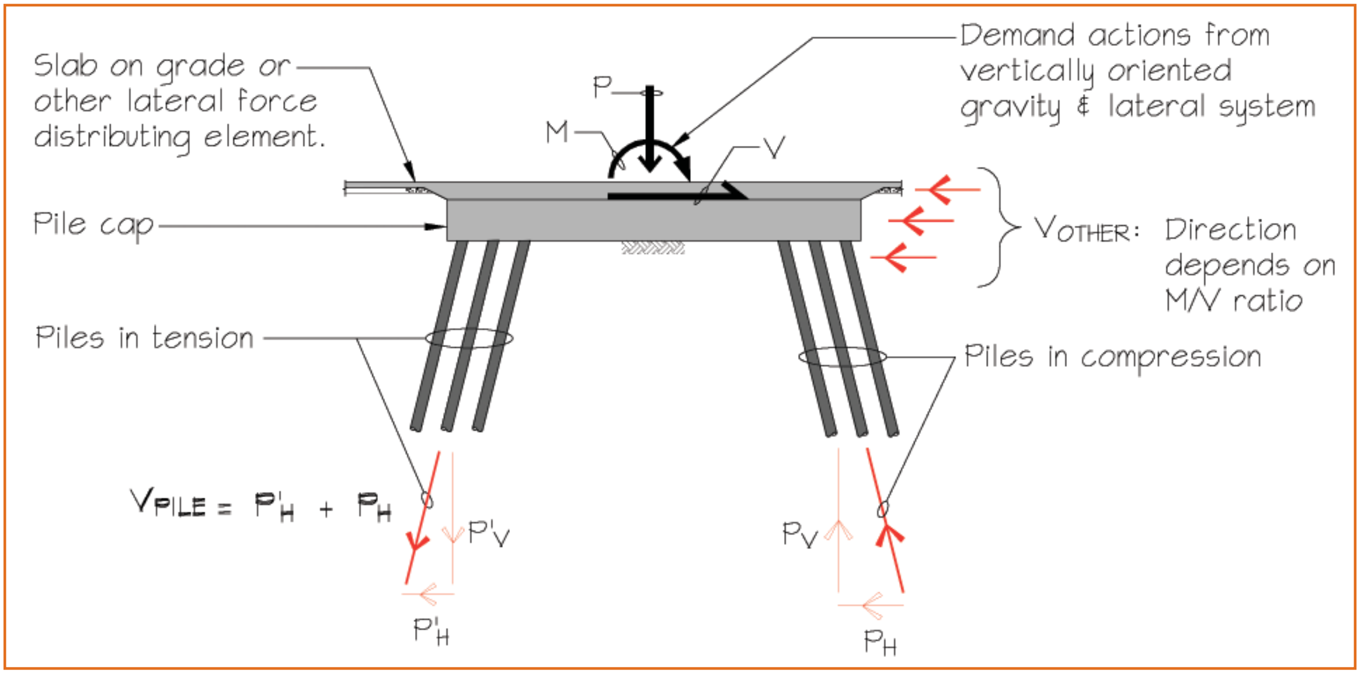

Figure 2: Raked Pile Configuration – Forms Reliable Mechanism

Although raked-piles are subjected to all three demand actions concurrently, to understand pile behavior, it is convenient to initially consider only P (vertical) and M (overturning) acting on the foundation. As with typical deep foundations, the axial load from overturning typically exceeds the dead and live gravity loads, resulting in pile tension. For simplicity, these loads are represented as a single force vector at each end of the pile cap, as shown in *Figure 2*. There is a horizontal component to the pile axial force, which opposes the applied load and depends on the pile inclination. The inclination of the pile dictates the magnitude of horizontal force; as the pile approaches vertical the horizontal force tends to zero, but as the pile approaches horizontal the lateral resistance becomes greater. By adjusting the pile angle, the designer is able to match all or part of the shear demand (V) induced by the earthquake. When determining pile inclination, the designer is encouraged to provide a steeper (more vertical) pile configuration. This recognizes that "other resistances" can be significant and it maintains foundation lateral displacement direction compatibility.

There is a limit in the lateral force resistance provided by this pile configuration. The axial load and overturning actions are known, particularly when a capacity design is employed, limiting the pile axial force and, consequently, the pile's lateral capacity (V_{pile}). An imposed lateral-load greater than V_{pile} results in pile movement, which induces pile bending, not additional axial load as would be the customary perception. Although relying on the kinematics of a group of elements, this results in a well-understood, stable plastic mechanism.

To confirm the reliability of this mechanism, consider variations in demand on an optimal raked-pile foundation. This study acknowledges that seismic demand actions may be higher and vary in their proportions, such as the overturning moment to base shear (M/V) ratio. For higher demand actions, but with approximately the same M/V ratio, pile axial forces increase while the proportion of pile and other elements lateral resistance remains essentially unchanged. Note that when code-level forces without the over-strength factor Ω_o are used, as is the case with most foundation systems, actual imposed forces on the foundation are higher. A similar increase in actual pile forces would be realized with any deep foundation system.

Variations in the M/V ratio is more interesting in that, as the M/V ratio increases for the same pile group configuration, the pile axial load increases, resulting in greater foundation lateral resistance. The high M/V ratio results in higher lateral resistance from the piles, in fact, higher than the demand shear force. There is a tendency, therefore, for the pile cap to move in the opposite direction to the applied load. Conversely, a low M/V ratio results in the pile cap moving in the direction of applied load, as would traditionally be the case. Both directions of

Figure 3: Model of Laguna Honda Hospital

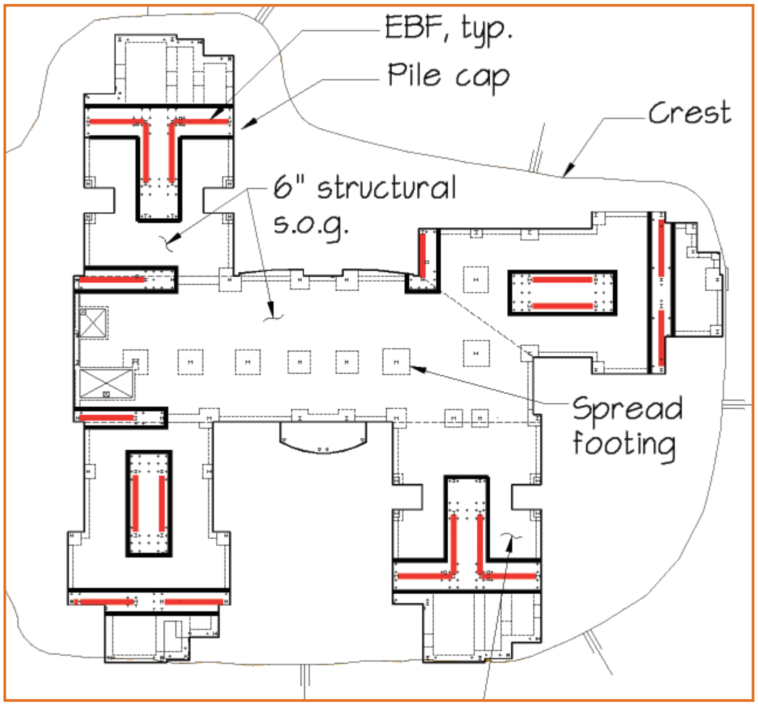

Figure 4: Structural Drawing Plan – Building Footprint and EBF locations

lateral movement are, however, acceptable and merely a result of pile flexural resistance and additional lateral resistance from soil pressure against the pile.

As with any pile type, proper detailing for post yield behavior at the pile head, and at other locations of curvature concentration, is needed for adequate performance.

Although beyond the scope of this article, it is worth noting that down-drag and liquefiable soil loads cause additional axial and flexural forces on the pile configurations, and should be included in the design.

Case Studies

The following two case studies have different performance goals, but they share the same basic design principles described above for raked-pile foundation systems.

Laguna Honda Hospital – New Hospital (Under Construction)
JV Architects:
Anshen+Allen Architects
Gordon H. Chong and Partners

As a new hospital, it must provide health care services following a major seismic event. Thus, the design is under the Office of Statewide Health Planning and Development (OSHPD) jurisdiction, which adopted, with modifications, the California Building Code (part of the California Code of Regulations, Title 24). The modified code is intended to provide an Immediate Occupancy performance level for the Design Basis Earthquake.

There are five main buildings of varying heights and plan configurations to be built on the site. The buildings are either situated atop one of the two hills (the tops of which have been removed to just accommodate the building footprint) or span the valley between the hills. Three of the buildings (the tallest, in the foreground of *Figure 3*) provide mostly skilled nursing facilities to the elderly. The structural system is lightweight concrete on steel deck as the floor system, which is supported by steel beams and columns. The lateral force-resisting system consists of steel-braced eccentric frames (EBF). The steep hillsides, the close proximity of the buildings footprint and EBF to the hill crest, and the soil conditions required deep foundations with high lateral strength and stiffness. After considering drilled piers, Tubex™ Piles, and driven piles, vertical and raked micropiles were selected, which required an Alternate Means of Conformance application and review process through OSHPD. To our knowledge, this was the first California hospital facility to use micropiles and/or raked-piles.

The design criteria for the foundations required that the foundations develop the strength of the EBF system, including at the soil-structure interface. To control "wagging" of the wings, EBFs were located at the wing ends, which are near the crest of the hills (see *Figure 4*).

The typical frame and foundation elevation, shown in *Figure 5*, uses a 4H:1V raked-pile system. A more inclined 2H:1V orientation was considered, but inspecting the demand and capacities vectors on a foundation plan, it was determined that the 4H:1V battered piles afforded sufficient lateral capacity for the building's structural system seismic (real) forces. This was personally gratifying to satisfy equilibrium at realistic force levels, and to be assured that the inelastic action would form in the EBF links of the superstructure as intended.

All of the foundations with raked-piles have displacement direction compatibility with the other footings; they move in the conventional lateral direction. Calculations show that the raked-pile system will arrest lateral forces without significant lateral movement (less than ½-inch), or significant loading of the soil at the crest. This displacement performance is superior to a conventional system in that the slope stabil-

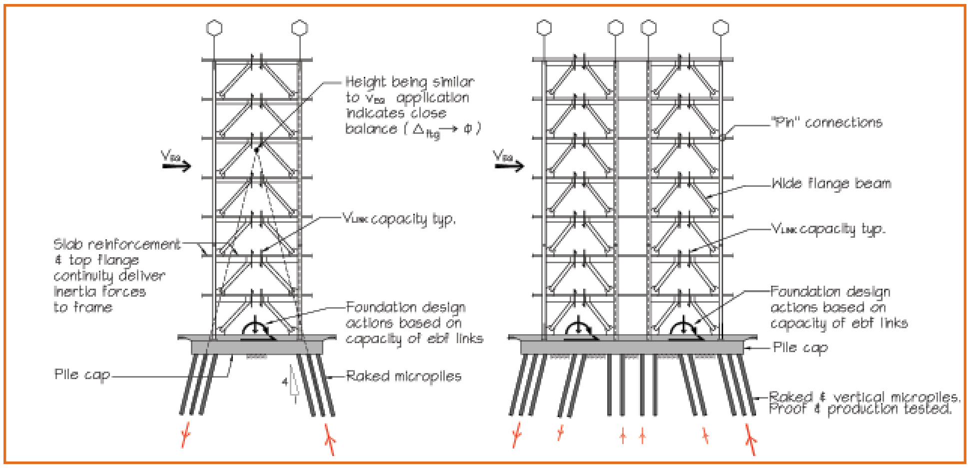

Figure 5: Structural Drawing Elevation – EBF and Foundation

ity issue is surmounted and controlling the "wagging" action mitigates damage to the superstructure's diaphragm during the seismic event.

Seismic Retrofit of McHenry Library, UC Santa Cruz, California (Construction not started)

The building is a cast-in-place reinforced concrete structure built in the mid 1960's that was expanded in the mid 1970's. The building is rectangular-shaped in plan and consists of a waffle slab floor construction, with shear walls serving as the primary lateral force-resisting system. The building is on large-diameter piers with very limited confinement or shear reinforcement (#3 spirals at a 16" pitch). The building is located on a sloping site, resulting in a height of five stories at one end and three stories (including a basement) at the other end. See *Figure 6* for the exterior elevation.

The project goal is to strengthen the building to a level consistent with the University's "GOOD" seismic performance rating (DSA rating IV). The equivalent seismic performance level is life-safety during a major (rare) seismic event. This performance is described in FEMA 273/356 and the "rare" event corresponds to the Basic Safety Earthquake 1 (BSE-1), defined as a level of ground shaking with a 10% chance of exceedance in 50 years.

Because the original construction used few walls and they are of lightly reinforced concrete, the building is heavy and relatively weak under lateral forces. Further, the building is located in a region of high seismicity with a peak spectral response acceleration of 1.0g at 5% damping.

The seismic upgrade to this building includes the addition of new shear walls to compensate for the insufficient strength and reliability of the existing system. However, adding new concrete shear walls concentrates lateral load to only a few locations, mainly at the building ends, overstressing the existing foundation system. The several inches of lateral foundation movement predicted for the modified structural system would overstress the shear-critical existing drilled piers and exceed their inelastic deformation capacity, compromising their vertical load carrying capability as well as overstressing the first floor interior gravity load resisting columns. The location of the shear walls, at the ends of the building, limits the degree of load transfer to other foundations, as often is the case with existing slabs on grade, which are lightly reinforced and nominally 5-inch thick.

After evaluating the need for, and the means to provide, lateral resistance at the foundation level, a raked-pile system was selected as the foundation solution. As with many seismic retrofit projects, and particularly because of the need to batter the piles, micropiles have been proposed for this foundation.

Arresting the lateral displacements provides reliability of the vertical-load-carrying capability of the existing drilled piers and the gravity-load-resisting columns. While the former is transparent, the latter may not be. The columns, located in the basement, are prone to concentrated inter-story displacement, should lateral resistance at the end walls foundations not be provided. While some inelastic deformation of these columns is possible, to have all of the inelastic deformation concentrated at a single floor would reduce the reliability of the columns to maintain their vertical load carrying capability.

Understanding that a raked-pile system utilizes coupling of the lateral and overturning actions, it was clear that the foundation and new wall would need to be isolated from the existing structure.

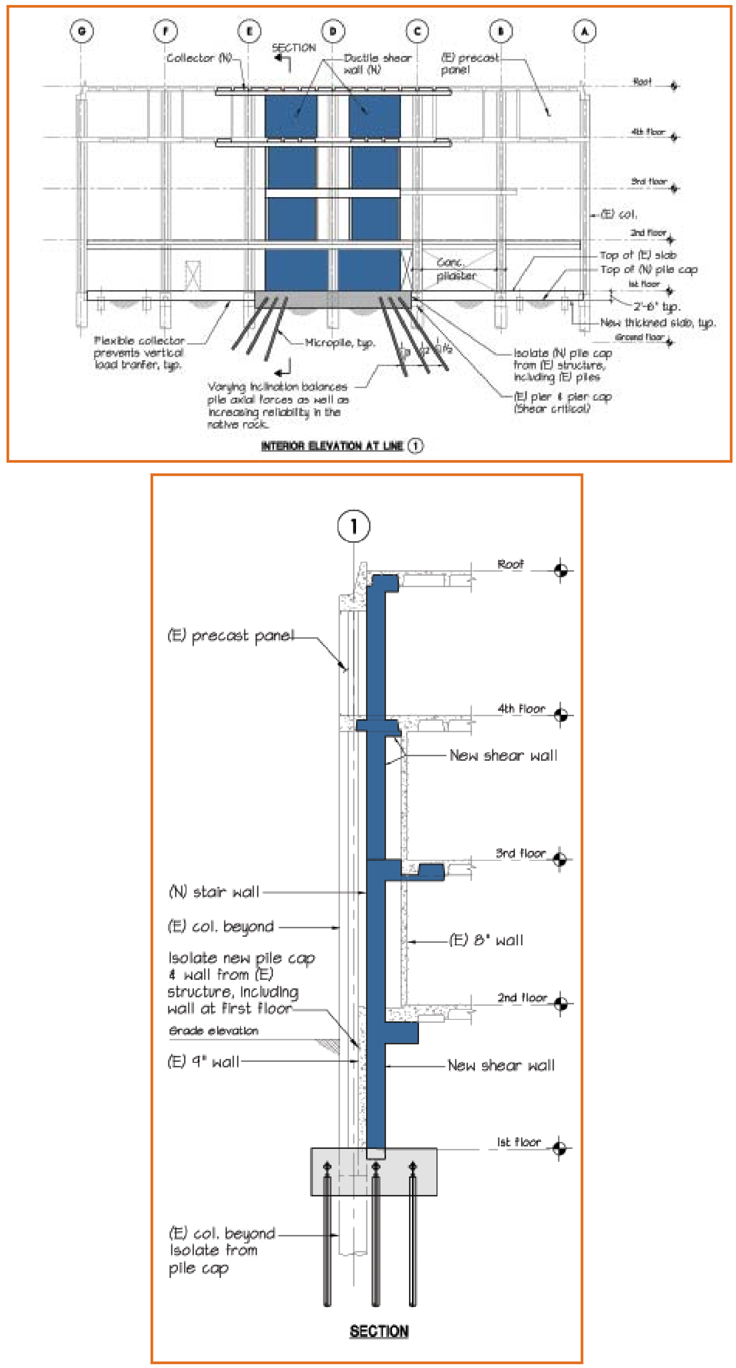

Figure 6: McHenry Library End Wall Elevation and Section

That is to say, if the lateral resistance benefits of a raked-pile system were to be harnessed, the overturning forces, compression, and tension axial forces need to be delivered to the raked-piles, not the stiffer existing piles. To accomplish this, an isolation joint is provided between the new and existing construction, except at the base. At the base there is a need to transfer the lateral force from the raked-pile to the existing structure, hence a tie/strut is required for this action. This is achieved while maintaining the no vertical-load transfer by the flexible link, as shown in *Figure 7*.

Conclusions

Unless raked piles are designed for unreduced (elastic-level) seismic forces, or there is consideration of developing an inelastic mechanism, compression and/or shear failure is likely to occur resulting from lateral movement, rotation and axial overload of the piles. This combined with a lack of understanding of the coupled sliding-overturning system has led to the decline of the use of raked-piles in seismically active areas.

Codes lack performance consistency between the various lateral systems and their foundations, and are in dire need of a holistic overhaul of their strength-based approach. Consequently, the codes cannot be used to assess system performance. Instead, an understanding of the building's entire lateral system is required, as shown in the two case studies which demonstrate instances where raked-piles can provide superior performance over conventional deep and shallow foundation systems.

Well-designed raked piles provide a ductile system that is far superior to conventional shallow and deep foundation systems for arresting lateral and overturning forces and displacements. This advantage is primarily due to the fact that they couple sliding and overturning forces, which, in turn, leads to better understood lateral system behavior, and, if applied correctly, superior performance.

Once the basic kinematics is understood (i.e. knowing which pile configurations form a stable plastic mechanism) raked-piles can be a very useful tool for the designer – piles can then be battered but not misunderstood.▪

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Foundation during construction (Photo Courtesy of Michelle Gale)