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A Review Study on Tapered Pile

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Abstract —*Tapered piles, which have greater top cross sections than bottom ones, have the potential for substantial cost advantages for static loading conditions. However, tapered piles have not often been considered a design option because of the lack of design tools and knowledge about the behaviour of these piles. The objectives of this study are to explore and better understand the operating characteristics of the axial response of tapered piles. Tapered piles represent a more equitable distribution of the pile material in several respects. In order to study their efficiency over piles of uniform section with the same material input, a three-dimensional finite element analysis is developed. This paper presents a review of the current practice and usage of the numerous types of pile in general construction. Information on this subject was obtained from a review of existing literature and from field experience. The paper reviews the purpose of pile foundations and the various factors involved in the selection of a type of pile.*

Keywords-*Tapered Pile, Kinematic Seismic Response*

I. INTRODUCTION

Pile foundations are used extensively to support both inland and offshore structures, including important structures such as nuclear power plants and oil-drilling platforms. Piles are usually loaded axially in compression to transfer structural loads to deeper competent soil layers. In some structures, like transmission towers and jetty structures, pile foundations resist uplift loads. Piles are also frequently used to support structures subjected to lateral forces and moments such as offshore structures, harbour structures high rise buildings and bridge abutments.

Piles are generally classified according to the pile material (timber, steel or concrete), the method of installation (driven, cast-in-place, bored, etc.), or are categorized in terms of the load transfer mechanism. (a) Friction piles: the load capacity depends mostly on the amount of frictional resistance developed at the interface between pile and soil. (b) End-bearing piles: the loading capacity relies primarily on the concentrated soil resistance at the pile tip for developing the resistance to axial load.

Different types of piles with different shapes such as circle, square or rectangle cross sections are used in practice. Piles are mostly used with straight-sided walls. Most of the design procedures and guidelines have been developed for straight-sided wall piles with little or no reference to tapered piles, although tapered piles have the potential for substantial cost advantages over straight-sided wall piles (Robinsky et al, 1964 and Rybnikov 1990). Tapered piles are not widely considered as a design option due to the lack of knowledge about their static and dynamic behaviour and the lack of appropriate design tools similar to those available for straight-sided wall piles.

If a friction pile subjected to a downward vertical load, have its sides parallel, the transfer of load to the surrounding soil is entirely by the shear at the interface. However, if such a pile is provided with a taper a part of the downward load is transferred by direct bearing on the sides over the area. This bearing results in an increased normal pressure when compared to the pile without taper, which consequently increases the frictional component of the hearing resistance. Tapered piles are therefore very effective in frictional soils such as sand. On the other hand, in clay, the difference between the capacities of prismatic and tapered piles will be marginal or nil, since the adhesion component of shearing resistance is independent of the normal pressure. On the side of tension, however, the advantage in compression is lost as can be realised from (in which the pile width is exaggerated by compressing its length), where heavy resistance is encountered in compression, but virtually no resistance in tension. A wedge which is difficult to drive in the face of increasing resistance, but easy to pull out, is another analogy for explaining the behaviour of a tapered pile.

Piles have been used to transfer structural loads to deeper competent soil layers, allowing construction in areas where the soil conditions near the ground surface are unfavourable. Piles can be loaded axially in tension or compression, or they can be subjected to horizontal forces. Different types of cylindrical piles of different shapes and materials are used in practice. Most of the design procedures and guidelines have been developed for cylindrical piles with little or no reference to tapered piles, although tapered piles have the potential for substantial cost advantages over cylindrical ones. Hence, tapered piles are not widely considered as a design option due to a lack of knowledge about their static and dynamic behaviour and the lack of appropriate design tools similar to those available for cylindrical piles. The last 3 decades have seen an increase in interest in tapered piles. Robinsky et al. (1964) investigated the effect of the shape and volume of piles installed in sand on their capacity. In this study, instrumented model cylindrical and tapered piles were driven into sand at different embedment depth to diameter ratios. These tests revealed that the intensity of unit load transfer through the pile walls changed continuously as the piles were advanced. Furthermore, tapered piles were found

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to be appreciably more efficient than straight-sided wall piles. Robinsky and Morrison(1964) studied the effect of pile taper on the displacement and compaction of cohesion- less soil adjacent to friction tapered piles. It was found that in relatively homogeneous cohesionless soils, a tapered pile with most of the load being carried by skin friction can support considerably greater loads than a straight-sided wall pile with a larger point. Rybnikov (1990) examined the bearing capacity of bored-cast-in-place tapered piles through a field experimental investigation. He suggested that the tapered piles that were investigated have a specific bearing capacity that exceeded the specific bearing capacity of straight cylindrical piles having the same length by 20–30%. Ladanyi and Guichaoua (1985) compared the response of tapered piles, straight wall piles, and corrugated piles in permafrost soils.

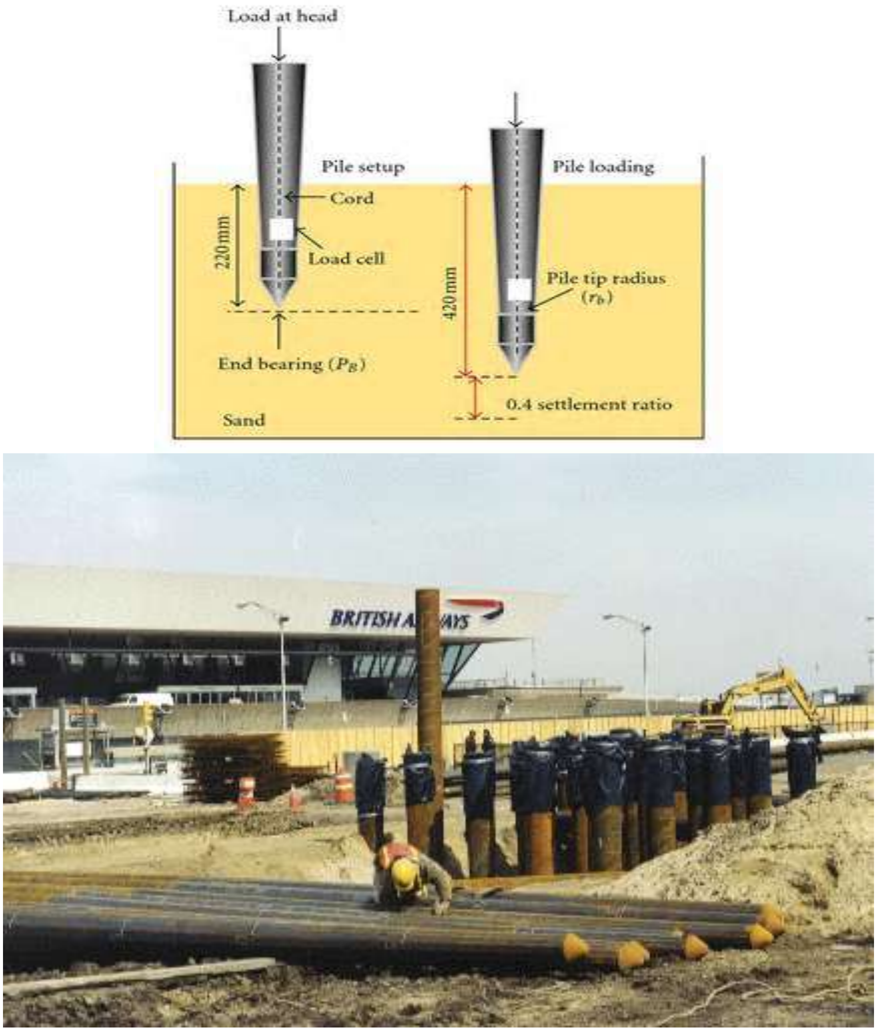

Figure 3.1 Tapered pile

A tapered pile actually represents a more equitable distribution of material in the pile than a uniform pile, in the frictional mode of resisting a compressive load and also in resisting a horizontal load at the top. If the friction generated on the pile surface is uniform or uniformly increasing with depth, the axial force diagram increases uniformly (triangular) or parabolically towards the top, respectively. In either case, a tapered pile with its cross section increasing towards the top makes for a more efficient utilisation of the pile material. In the same way, under a horizontal load at the top, the flexural effects of deformation, bending moment and shear force are maximum at the top and decreases in a periodic form very fast with depth. Hence from the point of view of bending also, a tapered pile represents a more optimum distribution of the pile material.

Extensive studies involving both theoretical (by the finite element method) and experimental investigations on tapered piles with different geometrical shapes of cross section, such as square, circular and triangular, by Kurian and Srinivas (1995) have shown that for the same material input, he performance of the tapered pile is much superior in terms of both bearing capacity and settlement, to the corresponding piles of uniform cross section, under compressive axial load, in sand. In each case, piles in the displacement mode presented much better performance than replacement piles. A significant finding has been that triangular piles outperform the other shapes. These studies have been extended for horizontal loads, where tapered displacement piles again revealed their superiority, thanks to the more equitable distribution of pile material at the top where bending effects are the highest.

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II. ANALYSIS OF KINEMATIC SEISMIC RESPONSE OF TAPERED PILES

Piled foundations may be used to support various structures constructed in soft grounds, across rivers and valleys, or in shallow and deep water. Such deep foundations may be subjected to lateral seismic vibrations induced by earthquake. These vibrations cause lateral movements in the ground. These movements in parallel cause horizontal displacements in the pile and as a result in the structure supported by the pile. However, if the pile resists, the soil lateral movement, greater internal forces may be developed in the pile. It was formerly believed that during an earthquake, a pile may follow the ground movement in the lateral direction as shallow footings. As a result, greater lateral movement may be induced in the pile head. Such movement is applied to the supported structure. However, it has already been recognised that under some circumstances, the pile may not follow the ground lateral displacement. This may be useful from the viewpoint of less displacement induced to the structure. However, greater internal forces may be created in the pile. This may result in the pile failure and therefore attention must be paid at the time of designing the pile. Pile failure cases of this type have been reported in the literature (Moehle 1994; Mizuno 1987). Analyses of kinematic seismic behaviour of piles have been carried out in the last 20 years.
Further work is essential to perform on the topic since it is still interesting. In all of the above research work, the behaviour of cylindrical piles has been taken into account. This paper investigates the influence of earthquake horizontal loading on kinematic response of tapered piles.

III. ANALYSIS PROCEDURE

Some fundamental assumptions are required to be made to characterise the soil–pile system. The tapered pile is assumed to be vertical, rigid, of circular cross-section, and divided to a number of prismatic segments. The pile material is assumed to have elastic and linear load-deformation characteristics. The soil surrounding the pile is composed of a linear, hysteretic, continuum, homogenous, elastic material. The soil layer is assumed to have a constant Poison's ratio, mass density, elasticity modulus, and hysteretic damping. Harmonic shear waves, which are assumed to propagate vertically, cause the tapered pile–soil foundation system to vibrate in the lateral direction. The shear waves can create horizontal movements in the ground at all depth along the pile. The reaction of the soil to the pile lateral movement is modelled by considering continuously distributed linear springs kx and dashpots Cx. The former represents the soil stiffness and the latter models the energy loss due to radiation damping of waves and due to hysteretic energy dissipation.

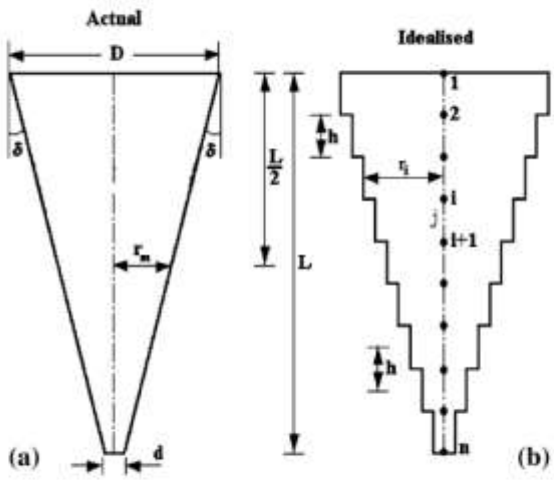

Figure 3.2 Idealisation of tapered pile; (a) real tapered pile; (b) idealised pile

3.1 Formulation

As mentioned above, the stiffness of the soil to the pile lateral displacement can be modelled using linear springs. The coefficient of the spring k_x was derived by simple expressions (Roesset and Angelides 1989) given by

$$K_s = 1.2\,E_s \qquad ...(3.1)$$

$$c_s = 6a_o^{-1/4}\rho_s V_s D + 2\beta_s k_s/\omega, \qquad ...(3.2)$$

where E_s is modulus of elasticity, V_s is shear wave velocity, β_s is damping ratio, ρ_s is mass density of the soil, ω is circular frequency, D is pile diameter, and a_o is dimensionless frequency. Subscript 's' denotes soil. The dimensionless frequency at each depth can be defined by

$$a_O = \omega D/V_s \qquad ...(3.3)$$

The diameter of the tapered pile and thus A_o vary continuously along the depth. However with the use of idealization shown in Fig. 3.1, for each cylindrical segment of the pile, D is kept constant. At an arbitrary time, the motion of the soil at the pile base in lateral direction u_g is assumed to be

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$$u_g = U_g e^{i\omega t} \quad ...(3.4)$$

where U_g is the amplitude of motion of the base soil. The free-field horizontal movement u_f can also be assumed to follow a variation as

$$u_f = U_f e^{i\omega t} \quad ...(3.5)$$

where U_f the motion amplitude and can be determined using the theory of one-dimensional wave propagation (Roesset and Angelides 1989) with appropriate boundary conditions. These conditions are zero shear stresses at the ground surface and displacement at the pile base equal to the induced soil displacement U_g. For the assumed linear hysteretic damping for the soil, the total free-field lateral displacement at depth Z from the ground surface can be given by

$$u_f(Z) = \frac{U_g}{\cos\left(\frac{\omega}{V_s^*}L\right)} \cos\left(\frac{\omega}{V_s^*}Z\right) e^{i\omega t} \quad ...(3.6)$$

Where $V_s^* = V_s\sqrt{1+2\beta_s i}$ and L is the pile length.

The pile deflection at any time in terms of the amplitude of the pile motion can be described by

$$u_p = U_p e^{i\omega t} \quad ... (3.7)$$

The equilibrium equation for steady state vibration of an arbitrary pile segment (j th segment between i and i+1 in Fig. 1b) in the horizontal direction can be given by

$$E_p I_p \frac{d^4 U_p}{dz^4} + m_p \omega^2 U_p - (k_x + ic_x\omega)(U_f - U_p) = 0 \quad ...(3.8)$$

where E_p is modulus of elasticity, I_p is moment of inertia, and mp is the mass of unit length of the pile. The subscript p denotes pile. It should be remembered that in Eq. (8), it is assumed that the soil–pile response of a pile segment embedded in a soil layer is identical to that of an infinite rigid pile undergoing a uniform displacement of the same magnitude in a homogeneous medium with the same properties as the soil of that layer. This essential assumption has also been used else- where for laterally loaded piles under harmonic vibration (Novak and Aboul-Ella 1978). Substituting Eq. (6) into Eq. (8) gives

$$E_p I_p \frac{d^4 U_p}{dz^4} + (k_x + ic_x\omega - m_p\omega^2) U_p = (k_x + ic_x\omega) U_g \frac{\cos(\beta Z)}{\cos(\beta L)} \quad ...(3.9)$$

where z represents depth from the top of the pile segment and can be correlated to Z, and d is termed wave number given by $\delta = \omega / V_s^*$.

The total solution of Eq. (9) for uniform piles, which consists of the homogeneous and particular parts, was given elsewhere (Makris and Gazetas 1992; Kavvadas and Gazetas 1993). For jth seg- ment of the tapered pile, the total solution is:

$$U_p(z) = e^{\lambda z}[A\cos(\lambda z) + B\sin(\lambda z)] + e^{-\lambda z}[C\cos(\lambda z) + D\sin(\lambda z)] + U_g \Gamma \frac{\cos(\beta Z)}{\cos(\beta L)}, \quad ...(3.10)$$

where A, B, C, and D are constants pertinent to homogeneous solution and can be determined from appropriate boundary conditions. Parameters $\lambda$and Γ are given, respectively, by

$$\lambda = \left[\frac{k_x + ic_x\omega - m_p\omega^2}{4E_p I_p}\right]^{1/4} \quad ...(3.11)$$

$$\Gamma = \frac{k_x + ic_x\omega}{E_p I_p \beta^4 + k_x + ic_x\omega - m_p\omega^2}. \quad ...(3.12)$$

Equation (3.10) may be solved by 1-D finite element method or segment by segment method (SSM) developed by the author for the analysis of cylindrical piles (Ghazavi 2002) and tapered piles (Ghazavi et al. 2003) vibrating vertically. In a laterally loaded uniform pile, rotation, h, shear force, H, and bending moment, M, at each point along the depth can be correlated to appropriated derivatives of U_p in Eq. (3.10) as follows:

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$$\theta = \frac{dU_p}{dZ},$$
...(3.13a)

$$\theta = \frac{dU_p}{dZ},$$
...(3.13b)

$$M = E_p I_p \frac{d^2 U_p}{dZ^2}.$$
...(3.13c)

For the tapered pile, it is assumed that the tip is pinned, thus the moment is zero. The relative displacement at the tip is also zero. At the pile head, the slope of the pile is zero. The shear force at the pile head is equal to the inertia force of the above-ground mass. Here for the kinematic solution, the shear force is zero. With these assumptions and using the SSM (Ghazavi 2002; Ghazavi 2003), the analysis is carried out sequentially from the bottom segment to the top segment. Initially, an arbitrary value for rotation and displacement for the pile toe are assumed and corresponding shear force and moment at the toe are calculated using Eqs. (3.10)–(3.13). Here, zero moment for the pile toe is obtained. Having H, M, h at node 2 of the lowest segment, these values at node 1 of the lowest segment of the pile are then determined using Eqs. (3.10)–(3.13). Due to the continuity of the pile and rigid connection of neighbouring segments at a node, H, M, θ at node 2 are identical to those of node 1 of the next upper pile segment. The corresponding H, M, and θ for node 1 of that element are then calculated using Eqs. (3.10)–(3.13). From the equilibrium of the finite length at the projected area (Fig. 2c), the additional lateral force, DH, can be calculated using the approach of Novak and Aboul-Ella (1978). The taper angle in the present paper is assumed to be small, therefore ΔH and additional moment due to the vertical reaction of the soil on the projected area may be neglected. These sim- plifications help to assume that H, M, θ at node 1 of a pile segment are identical, respectively, to those values at node 2 of the next upper segment.

The above procedure continues in this manner from segment to segment until the values of H, M, and θ at the pile head are determined. With the assumptions made at the pile head, H and θ must be roughly zero, if not, the procedure resumes for other values at the lowest node of the pile. This procedure is continued until the suitable values at the pile head are reached.

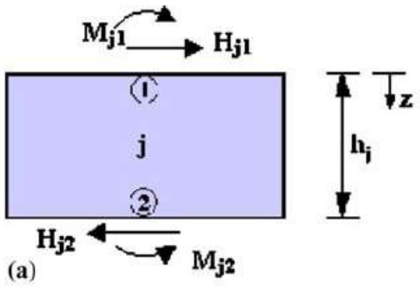
For straight-sided piles, Makris and Gazetas (1992) stated that for most practical cases of interest, the participation of the homogeneous solution of Eq. (3.10) is not as important to the total solution and can be indeed neglected (see Figure 8 in Makris and Gazetas). For tapered piles and with the assumption of small taper angles, it may be reasonable to assume the insignificant contribution of the homogeneous solution relative to the total solution. Thus the particular solution governs. Based on the solution of Eq. (3.9) (Makris and Gazetas 1992), the pile deflection at depth Z is approximated by

$$U_p(z) \approx U_g\left[\Gamma \frac{\cos(\beta Z) U_g}{\cos(\beta L)}\right] = \Gamma U_f(Z),$$
...(3.14)

where Γ is the ratio of the displacement amplitude of the pile to that of the soil. Γ may be normally termed kinematic interaction factor (Fan et al. 1991). This factor is given by

$$\Gamma = \frac{k_x + ic_x\omega}{E_p I_p \beta^4 + k_x + ic_x\omega - m_p\omega^2}.$$
...(3.15)

The influence of various parameters affecting the pile movement relative to the soil lateral displacement is shown in Eq. (3.15). There is particularly a tendency to monitor these relative displacements at the ground surface where sup- ported structures are present. It should be noted that in Eq. (3.15), parameters C_x, I_p, m_p, and A_0 and thus G vary from segment to segment along the tapered pile length. These parameters are deter- mined for each pile segment as idealised. A tapered segment is substituted by a cylindrical segment with a radius such that the volume of both remains the same. Thus, in general, the volume of the tapered pile is kept equal to that of the idelaised pile shown in Fig. 3.2a.



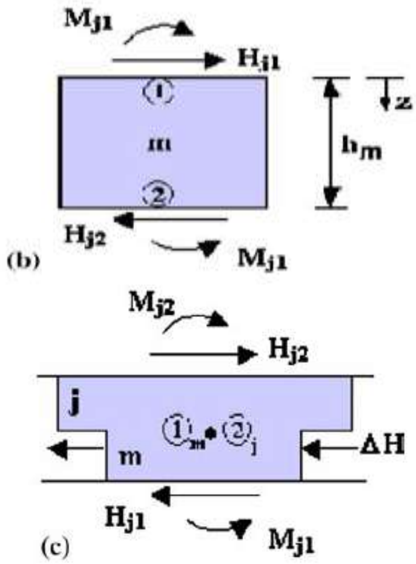


Figure 3.3 Idealization of two typical adjacent segments of tapered pile; (a) upper segment; (b) next lower segment; (c) force equilibrium at typical connecting node

V. CONCLUSION

An analysis for the kinematic seismic response of tapered piles was presented. The free-field displacement of the soil in lateral direction was estimated using the theory of one-dimensional wave propagation. The governing differential equation was derived and solved explicitly with appropriate boundary conditions. The role of various influencing parameters including the soil and the pile stiffness, pile slenderness ratio, and taper angles on the behaviour of the tapered pile was investigated. The results showed that tapered piles tend to be more flexible than uniform piles of the same length and volume. This flexibility increases for greater taper angles, less stiffness ratios (stiffer soils or more ductile piles), lower frequencies, and greater slenderness ratios (longer piles or smaller diameter). The tendency of piles to show more flexibility may be a desirable feature for foundation safety and needs more research. If the use of flexible piles is recommended in seismic areas, the use of tapered piles may be recommended in practical applications and in the design of piles. Further research work is required to generalise the findings in this paper.

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