PILE BENDING DURING EARTHQUAKES

by
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SYNOPSIS

There are few if any actual measurements of pile bending during earthquakes; only post-seismic or simulated effects can be presently studied. To better understand pile bending, a survey of published field and laboratory case histories has been made and conclusions are drawn. Those conclusions are then used as assumptions for available dynamic response analyses of soil profiles to rationally estimate pile curvature. The resulting maximum curvature values are then used to design piles to withstand the induced curvature moment, and ranges of real curvature values for prototype piles are described.

INTRODUCTION

It has generally been assumed that embedded piles move in phase with soil layers during an earthquake, although there is little organized data to support such an assumption. To study this, a review was made of case histories of pile-supported bridges, docks and buildings during earthquakes in Alaska, Japan and Venezuela which indicates that the patterns of pile failure or absence of pile failure closely parallel the soil behavior. Information on pile bending stresses, pile response, pile-soil interaction and the locations of critical bending is available in a few published laboratory studies mostly from Japan. The findings tend to support the basic assumption that piles generally move with the surrounding soil during an earthquake, and that if no soil failure occurs, a rational pile curvature prediction can be made using lumped-mass or SHAKE/LUSH/FLEX analyses for a specific earthquake at a specific site. The pile bending problem is primarily one of ductility rather than of strength, and the resulting radii of pile curvature range from 1000 feet in small (magnitude 5 minus) nearby earthquake events to of the order of 200 feet in great (magnitude 8 plus) nearby events.

FIELD BEHAVIOR OF PILES

A detailed survey(1) has been made of a widely published series of bridge and dock failures in the 1964 Alaska and Niigata earthquakes(2,3,4), and an absence of pile failures was noted (even though the buildings collapsed) in the 1967 Caracas event. In most cases the piles were partially exposed for direct post-earthquake observations and measurements. Vertical and battered piles subjected to both heavy and light dead loads were studied. Based on these field observations several general conclusions can be drawn:

1. Embedded piles appear to follow the soil mass during an earthquake.
2. If the surrounding soil fails by liquefaction or shearing, the pile will fail and the supported building likely will be damaged.
3. If the soil does not fail the pile does not fail even though the building may be heavily damaged by high accelerations and adverse dynamic response.

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4. Heavily loaded piles may not move entirely in phase with the soil, and batter piles will exert large and possibly damaging reaction forces on pile caps.

LABORATORY AND MODEL TESTS

A series of interesting and innovative laboratory model tests was then surveyed(1) and further understanding of pile bending was developed; see especially the work by investigators such as Kubo(5). The model findings enlarge upon the field findings and the following conclusions can be reached:

1. Piles generally do not cut through or resist the soil mass in any major manner during profile vibration.
2. Piles do not reduce the sway (horizontal) component of building response although they may reduce or stiffen rocking response.
3. Embedded piles are bent into curvatures of various radii when the surrounding soils undergo cyclic movements.
4. Lateral loads, butt shears and moments in piles are reduced by 50 to 85 percent if the building is keyed into the soil surface with grade beams, pile caps or deep basements.
5. Two critical bending locations in keyed buildings are: a) at the pile butt just below the cap; b) deeper at the point of maximum pile curvature.
6. Free-standing unkeyed structures such as docks or offshore platforms have a third critical bending location near the first point of apparent fixity below the mudline.

PILE BENDING ANALYSIS AND DESIGN

Pile bending or shear in the butt, and bending near the mudline, can be analyzed by several published quasi-static methods(1) and will not be discussed further. The main purpose of this paper is to describe a rational analysis of curvature along the deeper embedded portions of a pile based primarily on dynamic response analyses.

Once a design acceleration-time history and a given soil profile is established by appropriate methods, the horizontal soil profile displacement at various depths along the pile can be calculated. In the early 1970's lumped-mass, shear-spring analyses(6) were used and an exposed outcrop acceleration-time history was applied directly at the bedrock level beneath the soil profile. Later response analyses such as SHAKE(7) became available, which allow modification of the unconfined outcrop acceleration input to account for boundary effects imposed by the overlying soil profile; this often reduces the level of baserock input motion.

The SHAKE baserock input is then used with a one-dimensional finite element wave propagation analysis, LUSH(8), which has a 45 layer mesh to transmit frequencies accurately and better approximate soil profile response along the embedded pile length. LUSH is an equivalent linear procedure which iterates to obtain strain-compatible soil properties, and was modified to compute soil displacements relative to bedrock for every time step throughout the seismic event. In the earlier lumped-mass analyses a simple geometric expression for curvature, K, over a half chord length, H, for a mid-chord deflection, Δ, was used, where $K = \frac{2\Delta}{H^2}$. Curvatures were then calculated for adjacent layer displacements computed at the time only when ground surface displacement was a maximum (not necessarily conservative).

In more recent analyses the LUSH displacement-time histories are input to FLEX, which computes instantaneous curvature values based on a standard finite difference approximation. FLEX thus yields the maximum value of curvature and its time of occurrence along the pile. In general, the SHAKE/LUSH/FLEX finite difference analysis has been found to yield larger, more rational predictions of bending than the previous lumped-mass analyses because the maximum curvature values are computed for each discrete level in the profile.

Typical results of both types of analysis are given in Figure 1 for a building site on the shore of San Francisco Bay. The profile consists of 25 feet of rubble fill over 25 feet of soft bay mud; stiff clays then dense sands and very stiff clays underlie the mud and extend to bedrock some 600 feet below grade. The input earthquake motion was a synthetic 8+ magnitude event 16 miles away yielding a nearby peak outcrop acceleration of 0.45 gravity at a predominant period of 0.38 second. SHAKE was used to refine the outcrop input to a peak bedrock acceleration of 0.28 gravity at 600 feet below the site. The subject building is a 14 story concrete structure which was built in 1971. It is supported on 95-foot-long 12-inch-square prestressed concrete piles which were provided with extra steel reinforcement(1) to withstand with a safety factor of two the lumped-mass solution pile bending predicted in Figure 1.

The pile bending problem is primarily one of geometry and ductility rather than one of resistance to bending, and as Figure 1 indicates, the maximum curvature likely occurs in the profile where rapid changes in soil modulus occur such as near the boundaries of soft soil layers. Several other bending analyses by Seed(1) as well as by the authors for soft mud profiles indicate that for large earthquakes the maximum pile curvature values are likely not much more than about 6×10^{-4} inches^{-1}.

For use in preliminary concrete pile bending assessments, most of the above findings have been combined into one design curve as shown in Figure 2. Curvature, K, is related to radius, R, and to the induced curvature moment, M_c, ($M_c = \frac{EI}{R}$, in its simplest form). Figure 2 suggests what values of curvature moments prestressed concrete piles would have to be designed for, if they are to remain structurally intact during induced earthquake bending.

Actual full scale bending tests(1) have demonstrated that a standard 12 inch square prestressed concrete pile can sustain a curvature as sharp as 3×10^{-4} inches^{-1} and that with slim piles and extra spiral or longitudinal steel(1), curvatures of 5 to 6×10^{-4} inches^{-1} can be accommodated without ultimate failure, and at a cost premium of about 10 to 15 percent over the standard pile.

CONCLUSION

Piles rarely fail by excessive bending in earthquakes if the soil does not fail. Rational analyses are available to estimate seismic pile bending. Induced pile curvatures are sharpest at transition boundaries between relatively soft and stiff soil layers, and may range from less than 1×10^{-4} inches^{-1} in small earthquakes to as high as about 6 x 10^{-4} inches^{-1}. Bending induced in soft soil sites by moderate nearby earthquakes up to about magnitude 7 (2 to 3 x 10^{-4} inches^{-1} curvature) likely can be withstood with no difficulty by standard modern steel or prestressed concrete piles. Induced moment capacity of prestressed concrete piles can likely be increased for some of the larger seismic events by adding extra steel. There is a need to confirm these conclusions by actual field instrumentation on piles in seismic areas. The conclusions in this paper are based principally on a few sites and seismic events; as such they may be somewhat site and earthquake specific. However, it is believed that the general concepts are valid, and that more practising engineers will be encouraged to utilize pile bending analyses at other seismically active soft soil sites.

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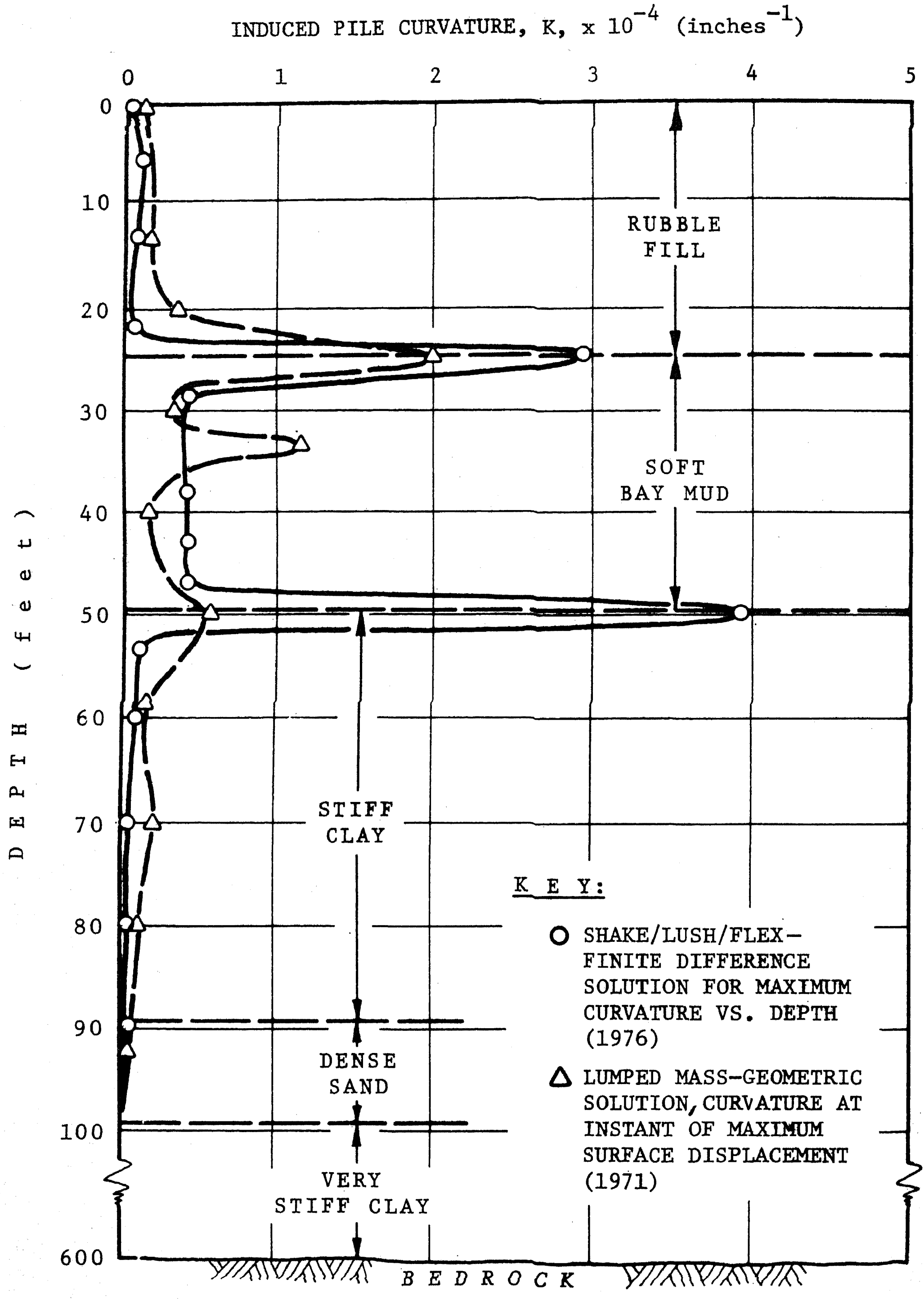

FIGURE 1 - Calculated Pile Curvatures at depth for a San Francisco Bayshore Site, and an 8+ Magnitude Earthquake 16 Miles Away.

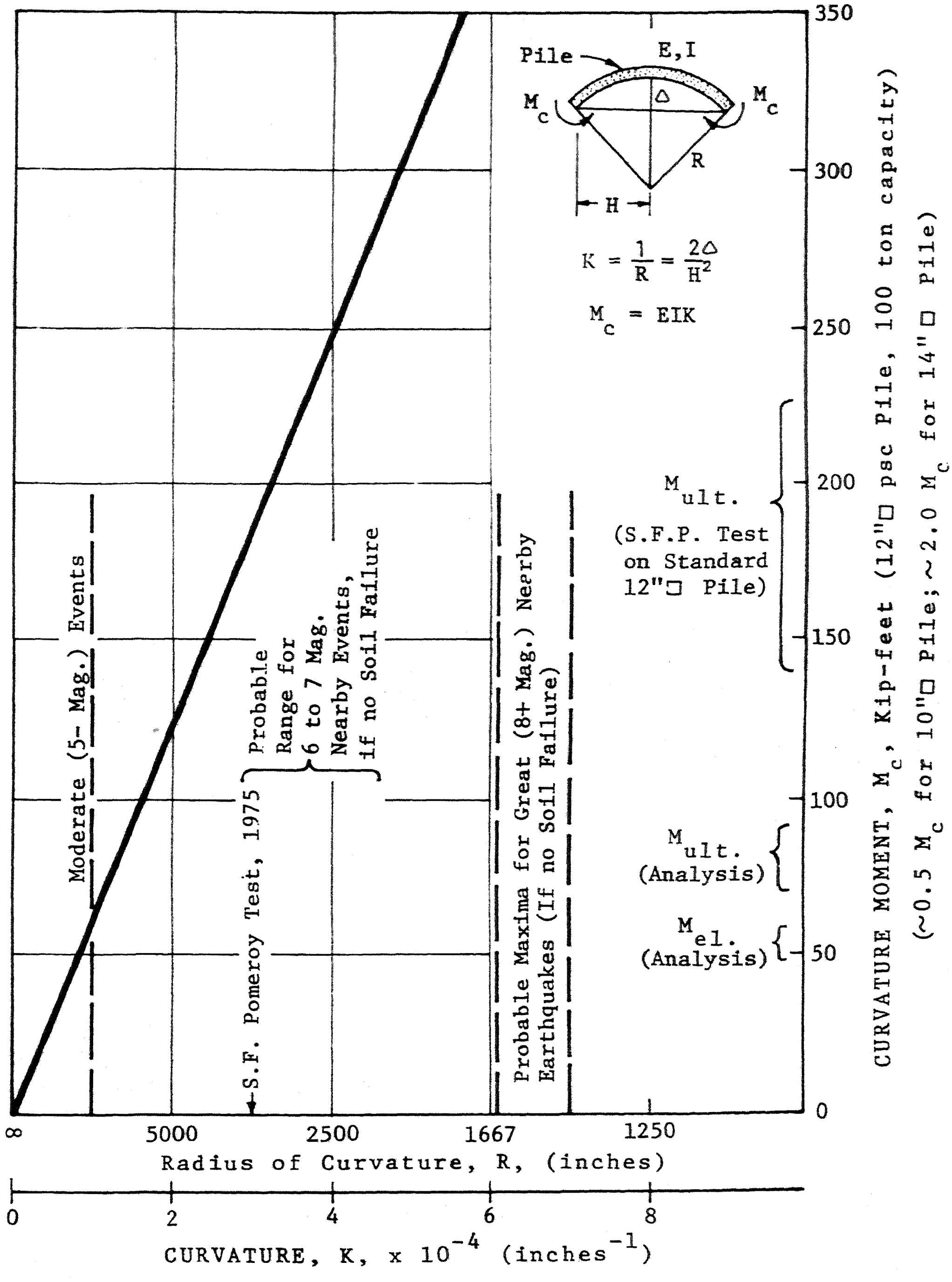

FIGURE 2 - Preliminary Pile Bending Design Curve For Common Prestressed Concrete Piles

DISCUSSION

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1. What will be effect of anchoring the piles (to their founding layers) on the lateral deflections and bending?

   Will it reduce and will it enable piles to take greater lateral loads ?

2. In such cases, what is preferred, a large number of a small diameter piles under the footing or a small number of large diameter piles ?

Author's Closure

Not received.