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## Analysis of Piles Under Dynamic Loading

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# Analysis of Piles Under Dynamic Loading

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**SYNOPSIS** This paper presents a method of analyzing piles for transmission poles. The various design loads are summarized and the application of various types of load factors is described. Methods of determining required pier embedment and design shear stresses are recommended. Construction factors which might impact cost are also discussed.

## INTRODUCTION

The need for a method of designing concrete piles for transmission poles has increased in recent years because of a tendency for environmental groups to favor this type of structure versus lattice towers. The single tubular shaft is a more graceful structure, less noticeable at a distance, and requires less land area. The single pole foundation, however, is subject to much greater overturning moments than the typical tower footing, and older methods of analysis of piers subject to large moments have provided footings of excessive size and cost.

In this paper a method of analysis and design reported recently by this author (1979) to provide economical pole foundations for 230KV and 500KV transmission lines, is presented in detail.

## DESIGN LOADS

The loads applied by the pole to the top of the pile are the result of:

- A. Horizontal pull of the conductors
- B. Wind on the pole and conductors
- C. Unbalanced loading from broken conductors.
- D. Construction loads (while stringing conductors.
- E. Gravity loads from conductors, pole, insulators, ice, etc.

National Electrical Safety Code (NEC) provides wind, snow, and ice loads to be used for designs in each geographical area. Use of this criteria, however, needs to be tempered by the designers judgement, as the transmission line may often traverse "pockets" of unusual climatological conditions not accounted for in NEC.

The NEC also provides load factors to be applied to the design wind, conductor, gravity, and construction loads. The load factors are used to establish the "Ultimate" or "Yield" loading on the tubular arms and shaft of the transmission pole. The code does not, however, address load factors to be used in establishing the ultimate resistance of the pier to rotation in soil. These should stem from a mutual agreement of the designer and geotechnical engineer, and are usually a reflection of the consultant's confidence in his own laboratory and field work. The consultant should provide separate load factors, too, for each of the five load types A,B,C,D,&E, above, utilizing greater load factors where the maximum design load is subject to the vagaries of weather.

Since conductor tension will relax substantially after initial construction, the consultant and designer may chose to use initial line tensions for A & C in tandem with reduced load factors, or line tension after one year with increased load factors. Load factors to be applied to design loads in designing rebar and concrete should be in accordance with the code of the American Concrete Institute (ACI). Again, there are no provisions in that code for the relaxation of applied loads, but the economy to be gained from such a phenomenon should be considered in design, particularly for angle poles.

## FIELD INVESTIGATIONS AND TESTS

On typical transmission line projects, the geotechnical engineer provides the pile designer graphical representations of soil depth verses ultimate passive pressure as shown in figure 1.

As shown in the example, allowable pressure typically decreases with an increase in pier diameter.

Ultimate Passive Resistance (Kips/S.F.)

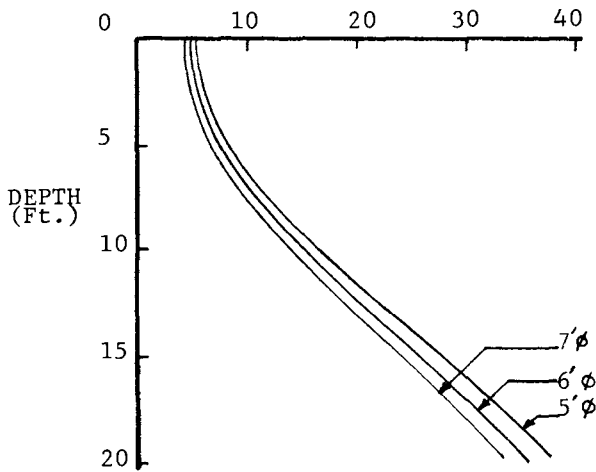


Figure I

This is often the result of his analysis of:

- A. Standard penetration tests by a test boring rig.
- B. Shear tests of "Undisturbed" soil samples
- C. Pressure meter tests
- D. Field compression tests
- E. Full scale load tests

After several iterations of tests C,D,&E in a specific geological mass, these would no longer be required for similar masses as the tests of A&B would enable the geotechnical engineer to properly identify or classify the soil and relate it to load capacity values assigned previously to that mass.

For sites where compression, meter, or load tests aren't available, the ultimate lateral resistance of piles against transverse loads may be determined by a method presented by J. Brinch Hansen (1961). The method enables a direct determination of the horizontal pressures on the pile as a function of soil friction angle. For the resultant pressure per unit area of the pile face, Hansen writes the general expression:

$$e = \frac{1}{q} k_q + C K_c$$

Where  $\frac{1}{q}$  = The effective overburden pressure

$K_q$  = Earth pressure coefficient for overburden pressure

$K_c$  = Earth pressure coefficient for cohesion

C = Soil cohesion

Hansen also presents charts which enable a direct determination of the coefficients  $k_q$  and  $K_c$  from the soil friction angle.

The total transmission line should be divided into several geotechnical zones, and ultimate lateral resistance curves (see figure I) prepared by the consultant to represent the minimum soil characteristics to be expected in each. While standard penetration tests by a heavy boring rig aren't justified at all pole locations, they usually are at large angle points in the transmission line. A test hole by a small truck-mounted auger should be considered at all pole locations between the sites of major drill holes to at least verify strata depths and thicknesses.

Utilizing the load factors provided by the geotechnical consultant, the designer factors the design vertical load, shear, and moments to determine the "Ultimate" load applied by the pole to the top of the pile. The method of statics presented by Hansen (1961) can be used to verify that an embedded pile of assumed dimensions has an ultimate restraining moment at least equivalent to the applied, "Factored" one. The calculation proceeds in the following way, as shown in figure II:

- A. Estimate the required pier depth
- B. Calculate the resisting pressure on the pier from the passive pressure diagram provided by the geotechnical consultant (see fig. I)
- C. Determine the point of zero shear at  $L_1$  ( $V_{\text{passive}} = H$ )
- D. Calculate the maximum applied moment at  $L_1$
- E. Select  $L_2$  so that shear between points  $L_1$  and  $L_2$  equals shear between points  $L_2$  and  $L_3$ .
- F. Determine the resisting moment at  $L_1$
- G. If the resisting moment at  $L_1$  is less than the applied moment, increase  $L_3$  and repeat steps C thru F.

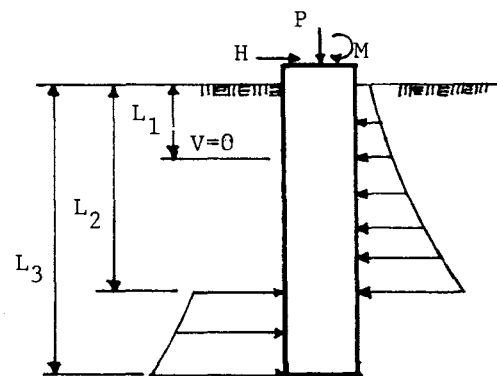


Figure II

While a large part of the applied forces can be negated thus when the pier is loaded by the ultimate stress diagram, the design shear stress is likely to be critical prior to "Ultimate" loading, that is, in the "working" stress range.

For this reason concrete piles should be checked for shear stress assuming the lateral force diagram that would prevail prior to "Ultimate" loading. For this calculation a method presented by Davisson and Prakash (1963) can be used.

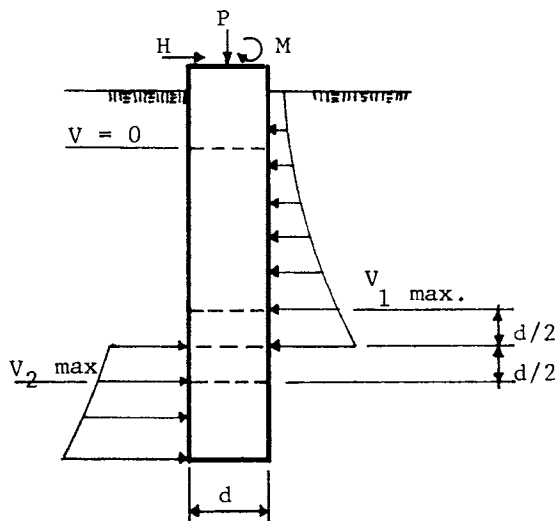
In that technical paper, piles are considered as essentially rigid members and a criterion is given for determining when the flexural member that serves as the pile is stiff enough to be considered rigid. Given the ground line moment and shear, the authors present simple equations which permit the designers to draw a passive pressure diagram as shown in figure IV.

The method requires first that the geotechnical engineer provide a value of the subgrade modulus ( $k_x$ ) to define the soil stiffness.

The bending moments to be utilized for rebar design should also be determined from the ultimate soil resistance diagram, adjusted as required to utilize the correct ACI load factors. Wang and Salmon (1973) presents a detailed analysis of flexural design for circular piers by the "strength" method. All rebar aren't usually required continuous to the bottom of the pier, but those extending beyond a cut-off point need to be sufficient in number to satisfy embedment bond.

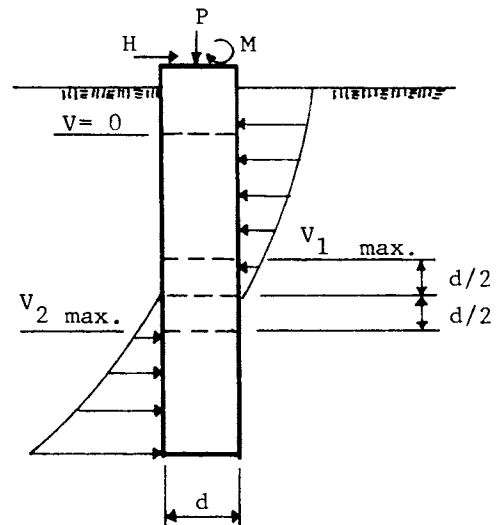
#### DETERMINATION OF PIER SHEAR STRESSES

An analysis of shear stresses in a concrete pile requires practical consideration of equal and opposite (or nearly opposite) reactions on a pile. The ACI code permits the designer to disregard applied forces within a distance  $d/2$  of the face of the support. Equating this condition to a rotating pile, applied forces within a distance  $d/2$  of the rotation point (see figure III) can be similarly ignored.



MAXIMUM SHEAR FOR PIER DESIGN  
(Ultimate Loads Applied To Pier)

Figure III



MAXIMUM SHEAR FOR PIER DESIGN  
(Working Loads Applied To Pier)

Figure IV

#### PRACTICAL CONSIDERATIONS DURING CONSTRUCTION

1. The pier shaft should not be larger in diameter than required to accommodate the anchor bolt cage, with 4 inches of concrete cover. Although only 3 inches are required in accordance with the ACI code, an additional inch of clearance should be provided all around in the design to allow for augered excavations which may be skewed slightly to the required vertical alignment of the anchor bolts. An enlarged, monolithic pier cap may be built when greater area is required to accommodate

the base plate.

2. The inclination of the augered pier isn't usually a problem unless the skew is severe, say 1 in 20. This is because the virtual eccentricity of the applied loads at the top of the pier is usually much greater by comparison, for high voltage transmission poles. When the eccentricity is relatively large, it may be combined with the eccentricity of the applied load to determine the maximum total design moment.

3. Although it is good construction practice to make the bottom of the pile excavation as dense as possible, extra compaction effort for deep transmission pole foundations may not be justified. Davisson and Prakash (1963) have indicated that shear resistance to rotation at the base of the pile may or may not be present. In providing the passive pressure versus depth graphs, the geotechnical consultant and design engineer should weight the additional resistance possible, versus the cost of compacting the bases of deep footings. Even assuming twelve inches of loose soil at the base and 50% eventual consolidation, it isn't likely that six inches of settlement would have an impact on the design or operation of the transmission line.

4. After free-falling concrete from great heights for many years in the construction of dams, it has been proven that such free-fall is not detrimental to the quality of the concrete provided:

- A. The fall is uninterrupted by rebar, anchor bolts, or other embedments.
- B. The concussion from the impact does not cause the sides of the excavation to cave.

For this reason, elephant trunks or drop pipes to the bottom of the pile aren't usually required. The concussion, and vibration resulting from it, should be sufficient to preclude the need for mechanical vibrators. This equipment may be required for the top eight to ten feet of the pile.

#### CONCLUSIONS

Although effort has escalated in recent years to find alternative concepts to the concrete pile for the support of high voltage transmission poles, the method is still quite efficient provided the designer applies reasonable load factors, initiates a comprehensive geotechnical investigation, utilizes sound pile analysis, and doesn't specify costly, unnecessary construction requirements. The method permits the job superintendent to auger a hole, set the anchor bolt cage, place concrete, and complete all work to grade that same day. In addition to the hole digger, only a small boom or crane is required to

handle the anchor bolt cage. The operation requires a minimum amount of labor and isn't required to coordinate with another trade, as is often the case when backfill is required around a direct embedded pole.

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