International Conference on Case Histories in Geotechnical Engineering
(1993) - Third International Conference on Case Histories in Geotechnical Engineering

03 Jun 1993, 10:30 am - 12:30 pm

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Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 8.09

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SYNOPSIS Foundations for a power plant were constructed by drilling holes in cemented sand for 36" piers. The boreholes in the cemented sand did not cave. A major design change required the demolition of the original piers and pile caps with large hoe rams and the drilling of new 36" boreholes in the same location. The new drilling contractor experienced widespread caving, which he was unable to remedy. The authors first investigated the possibility that the second contractor used inferior equipment or techniques. Then the authors investigated the possibility that a loss in soil cohesion occurred due to the vibrations from pier/pile cap demolition and casing installation. Analyses performed included (1) peak particle velocity evaluation, (2) laterally loaded pile/fatigue analysis, and (3) finite element analysis. It was concluded that significant loss of cohesion due to these vibrations was plausible and that the loss of cohesion could account for the hole caving.

INTRODUCTION

Foundations for a power plant at a southwestern U.S. site were constructed by drilling holes in cemented sand for the 36" piers. These drilling operations by the contractor resulted in no hole caving (corresponding to concrete overruns of 5 to 10% or less).

Because of a major design change, the owner of the power plant found it necessary to demolish these piers and pile caps, and to construct new pile caps at a somewhat different elevation. Demolition was a substantial undertaking which spanned about four months. Hoe rams used in the pile cap demolition delivered about 2600 ft-lb of energy at a frequency of about 12 cps. The probable effects of this foundation demolition on soil cohesion and borehole stability formed the major part of the studies to be described in this paper.

After demolition of the old piers and pile caps, a new drilling contractor (Contractor 2) was hired to drill new 36-inch holes in the same location. Very significant caving of the holes occurred, with concrete overruns of 20 to 30% being very common. Hole caving was so pronounced that it was necessary to install casing in many of the holes. The casing was installed with a vibratory hammer, which added further vibrational energy to the cemented soils. Peak particle velocities were measured at the surface during the installation of the casing.

The authors were part of a team that was commissioned to investigate the causes of the hole caving. The possibilities were divided into two distinct categories. The first is the obvious possibility that Contractor 2, who drilled the holes which caved, used inferior drilling techniques or equipment and that precautions were not taken to prevent the caving. The second category of possibilities investigated was that of a change in the site conditions between the time the original piers were drilled and the time the new piers were drilled. Specifically, the possibility that vibrations generated by the demolition and the driving of the casings destroyed part of the soil cohesion was studied.

DRILLING TECHNIQUES AND EQUIPMENT

Drilling techniques and equipment were investigated by first reviewing a voluminous correspondence file containing memos, letters, and reports from various parties presenting their observations, conclusions, and claims. Next a series of interviews was conducted with drillers, inspectors, and other persons who were on site and had first-hand knowledge about the conditions.

It would be difficult, of course, for the drilling Contractor 2 and his employees to be unbiased regarding their equipment and techniques. However, the reports, letters, and interviews represented opinions from many parties not affiliated with drilling Contractor 2, and the consensus was strong that he did not use unusual or inferior equipment or techniques. In fact, faced with the financial losses resulting from hole caving, he employed every precaution and trick in his repertoire and called on others for advice in his efforts to stop the hole caving.

Some additional events are also relevant. Bids were invited for pier drilling in an area immediately adjacent to but outside the sphere of influence of the demolition zone. Another contractor, Contractor 3, got the job and drilled successfully with no caving. Prior to bidding, Contractor 2 also drilled two holes in the adjacent area and experienced no caving. Contractor 2 used the same crew, equipment, and techniques which resulted in hole caving in the demolition area. The cemented sands and silts in the two areas were described as indistinguishable.

Consideration of all the data collected led to the conclusion that use of unusual or inferior drilling equipment or techniques by Contractor 2 was unlikely to be the cause of the hole caving. Attention was then turned to the second possibility, which relates to the destruction of all or part of the soil's cohesion by the demolition vibrations.

STUDY OF POSSIBLE CHANGED SITE CONDITIONS

In this context the term "changed site conditions" does not refer to a broad legal definition but rather to possible changes in the soil properties due to the vibrations caused by demolition.

These studies were performed by making two analyses as follows:

(1) Analysis of potential damage to cemented sand due to vibrations using the maximum allowable peak particle velocity approach.
(2) Analysis of potential damage to cemented sand due to vibrations using results of a laterally loaded pile analysis to estimate velocities and strains and use of fatigue data from the literature.

The first analysis amounts to using guidelines which have been established through field experience and observations relative to safe levels of vibrations.

Peak Particle Velocity Analysis

Peak particle velocities were measured at the site during casing vibration, for which an MDT V-36 vibratory pile driver/extractor was being used. The casing tip was about 30' deep at the time of the measurements and those measured velocities are plotted vs. distance from the energy source in Figure 1 as data points. The curves shown will be discussed subsequently.

For comparison to the observed data, the following equation for v, peak particle velocity, was used (Wiss, 1981):

$$v = K\,(r/E^{b})^{-a} = K(E^{b}/r)^{a} \qquad (1)$$

where:
- v is in inches per second (ips)
- r = distance from energy source (ft)
- E = energy generating vibrations (ft-lb)
- K = constant ≈ 0.16 for dry sand
- b = constant ≈ 0.5
- a = constant between 1 and 2 with values very commonly between 1 and 1.5

For plotting in Figure 1, the constants listed above were adopted with a = 1.25. Eqn (1) has been based on many field observations and has been well-accepted by practitioners. The parabola represented by Eqn (1) plots as a straight line on a log-log plot when v is plotted vs. (E^{b}/r). This equation becomes somewhat unsatisfactory when r approaches zero because v becomes infinite. A more satisfactory solution would be obtained if v approached the velocity of the driving mechanism (say v_o) as r approached zero. With a slight modification, Eqn (1) can be made to achieve this result.

$$v = K\,(E^{b}/(r+c))^{a} \qquad (2)$$

The introduction of another constant, c, as shown in Eqn (2), causes v to approach v_o as r approaches 0. For the particular case where measurements were made at the site, the v_o value was 17.3 ips and E was estimated to be 8100 ft-lb. For these conditions, c becomes 2.12 ft, for v_o=17.3 ips. Eqn (2) was used to calculate v vs. r for the vibratory pile driver, and is labeled in Figure 1.

The match of the curve to the measured data is fairly good, being neither biased significantly to the low side or the high side. However, the scatter in the observed data precludes fitting any curve of this form precisely to the field data.

In order to put the above modification to Eqn (1) in perspective, it should be noted that the effect of the added constant c becomes negligible after r exceeds about 10 '. Also, none of the conclusions which are subsequently drawn would be affected whether c were included or not.

Eqns (1) and (2) provide a basis for estimating the effect of driving energy on the particle velocity, v. The relationship obtained from these equations is that v varies approximately with $E^{0.62}$. The vibratory pile driver was estimated to deliver 8100 ft-lb; whereas, the pneumatic hammers (hoe rams) used in demolition delivered about 2600 ft-lb, on average. Thus the peak particle velocities for the hoe rams would be predicted to be about 1/2 of those for the vibratory pile driver, as shown in Figure 1.

The duration of the demolition was orders of magnitude greater than that of casing driving. Thus, from a cumulative damage or fatigue standpoint, the damage to soil cementation due to demolition could have been equally or more severe.

For blasting and transient vibrations occuring near 3600 psi concrete, v_{safe} has been recommended as 5 ips (Wiss, 1981) and 4 ips (Atkins and Dixon, 1979). A value of 5 ips was used as a conservative estimate of v_{safe} for cured concrete. For the cemented sandy silts and silty sands at the site it was assumed that $\phi' \approx 40°$ and $c' \approx 5$ to 25 psi (use $c' \approx 15$ psi), based on typical values for cemented sand (Clough et al, 1981).

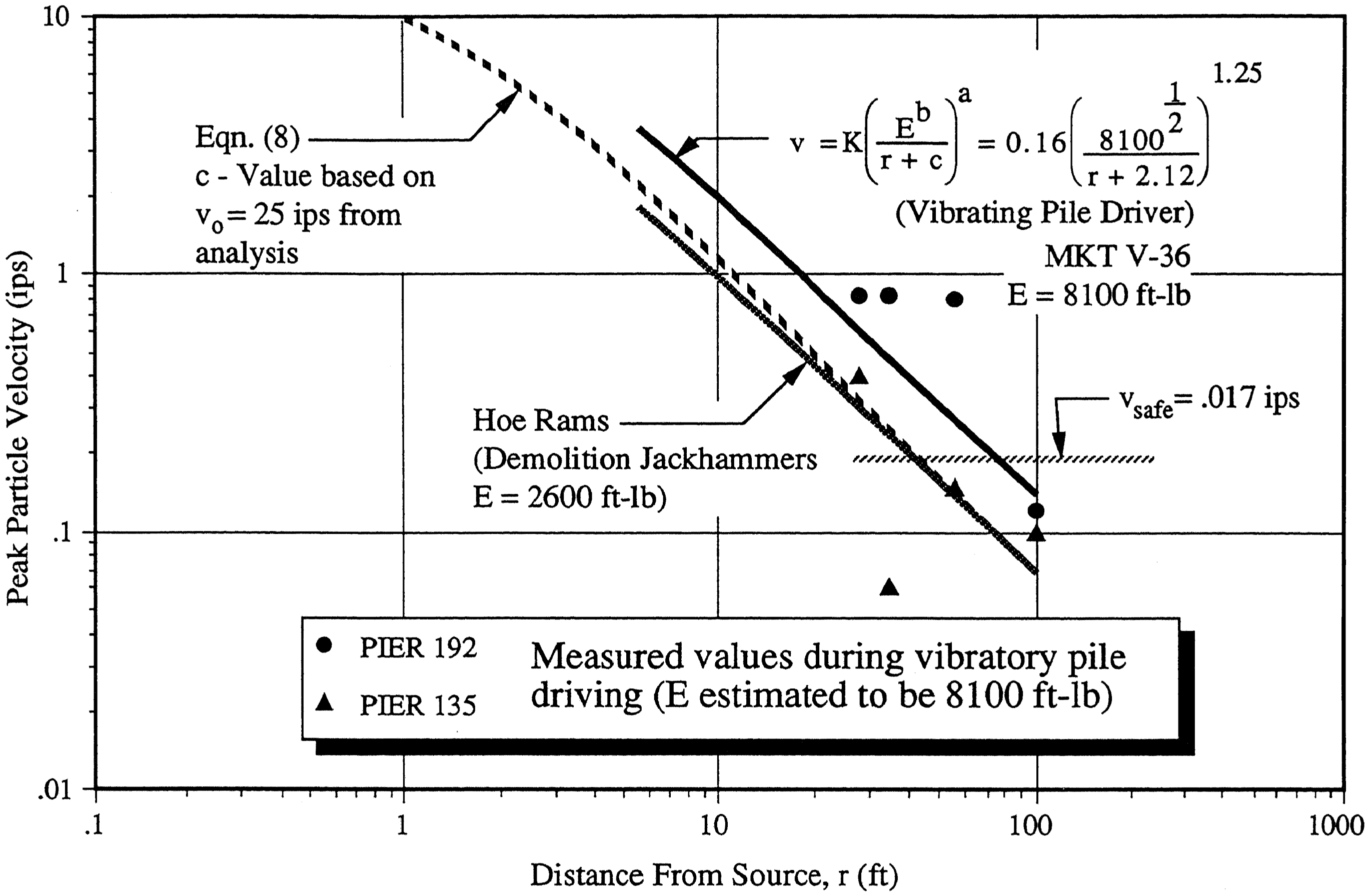

Figure 1 - V_p vs. Distance for Power Plant Site

A comparison of v_{safe} for cemented sand to v_{safe} for concrete should be made on the basis of tensile strength. Even though the macroscopic stress state may be compressive, fatigue cracking due to vibration is likely to arise from tension failures at particle contacts.

For cemented sand, the tensile strength, σ_t, is approximately 1/2 the value of cohesion, or about 7.5 psi for this case (Kelzieh, 1991). For concrete, a tensile strength of about 540 psi (i.e. $9\sqrt{f_c'}$) is reasonable. Therefore,

$$\frac{(v_{safe})_{cem.\ sand}}{(v_{safe})_{concrete}} \approx \frac{7.5\,psi}{540\,psi} \approx 0.0139 \qquad (3)$$

A value four times this ratio was used for the analysis to obtain a conservative estimate of v_{safe} for cemented sand. In this context being conservative means taking care not to conclude that the cemented sand would be damaged if it were in fact not damaged. Thus $v_{safe} \approx 4(0.0139)5$ ips = 0.28 ips for cemented sand subjected to blast or transient vibrations was used in this analysis.

Reduction factors for steady state vibrations, compared to transient, were suggested by Wiss (1967) to be 0.2 to 0.5. In a later publication Wiss (1981) suggested 0.5 and 0.85 for high and low stress amplitudes, respectively. The vibrations in question cause stresses which are quite low compared to the peak strength, but not so low compared to the cohesion. Therefore, a value of 0.60 was adopted, leading to v_{safe} for steady-state vibrations for cemented sands $\leq 0.60(0.28) \approx 0.17$ ips.

Using $v_{safe} \leq 0.17$ ips in Figure 1 indicates that all cemented soil within about 40 to 65 feet of demolition work is likely to be damaged (i.e., loss of cohesion) by the sustained vibrations, depending on whether the vibrating pile driver curve or the hoe ram curve is more representative of the velocities. A lower, less conservative estimate of v_{safe} above would have resulted in a prediction of even more widespread damage to the cemented sand.

Laterally Loaded Pile/Fatigue Analysis

The hoe rams used in demolition delivered about 2600 ft-lb of energy at an average frequency of about 12 cps during demolition of the piers. These loads were near horizontal during most of the demolition. Therefore a laterally loaded pile analysis using p-y curves was performed. The p-y curves needed for the analyses were obtained from data on similar sands. For a y value of 2", p ranged from 900 lb/in at the surface to 4900 lb/in at a depth of 50'.

Iterations were performed until one-half the product of the lateral load times the deflection matched 2600 ft-lbs. This match was obtained with a deflection at the top of the pier of 0.44 in. The 3' diameter pier was taken as 60' long. A parametric study showed that the deflection was not extremely sensitive to the accuracy of the assumed soil properties. If the load increased linearly with deflection, then both the load and the deflection would not be extremely sensitive to the accuracy of the assumed soil properties.

Computation of v_{max}

If the deflection of the top of the pier (and the corresponding soil particle movement) are assumed harmonic, then:

$$d = A\sin 2\pi ft \qquad (4)$$

where:
- d = displacement
- A = maximum amplitude of displacement
- f = frequency
- t = time, and

$$\text{velocity} = v = d' = 2\pi fA\cos 2\pi ft \qquad (5)$$

$$\text{and,}\quad v_{max} = 2\pi fA \qquad (6)$$

If A is chosen to be 0.33" (which is conservative compared to the 0.44" value calculated from the laterally loaded pile analysis) and f=12 cps, then:

$$v_{max} = 2\pi(12)(0.33) = 25 \text{ ips} \qquad (7)$$

Computation of Attenuation of v With Distance, Treating the Top of the Pier as a Vibratory Energy Source

Eqn (2) was given as:

$$v = K(E^b/(r+c))^a \qquad (2)$$

Again taking K=0.16, b=0.5, a=1.25, and v_o as 25 ips, c becomes 0.9. Then:

$$v = 0.16(2600^{0.5}/(r+0.9))^{1.25} \qquad (8)$$

can be used to get v vs. r. The results are shown in Figure 1 as a dashed curve, which merges with the hoe ram curve for larger r.

Fatigue Curve

To establish a plausible fatigue curve for the bond cementation in the cemented sand, either two points or one point and a slope are needed. Fatigue curves for asphaltic concrete materials have been published by various investigators (Rauhut and Kennedy, 1982). These curves show slopes of 20 to 30% per log cycle. Mitchell, et al (1974) cites fatigue curves for soil cement which show a slope of 12% per log cycle. This slope was considered more appropriate for the case in hand.

Data presented by Dobry (1982) was used to estimate a single point on the curve. Dobry showed that a shear strain of about 0.01% in 10 cycles is typically required to break sand particles free and initiate pore pressure development during cyclic loading of saturated sands. This value represents a reasonable estimate of the strain required to break cementation bonds, even though many of the sands tested by Dobry may have had little or no cementation. In fact, due to the brittleness of calcite, gypsum, and even dried very fine silt, the shear strain required for breaking cementation bonds may well be less than 0.01%. This single point, together with the 12% slope from the soil cement tests, was used to estimate the fatigue curve for the cemented sand at the site, as shown in Figure 2.

Estimation of Number of Load Repetitions and Shear Strain Levels at the Site

The average frequency at which the hoe rams operated during demolition was reported to be about 12 cps. Demolition using up to 3 hoe rams continued for about 4 months. Thus any given point may have been subjected to vibrations for a few days up to a few weeks. Accordingly, the number of repetitions was estimated to range from about one to four million, as indicated on Figure 2.

Using the one-dimensional wave propagation approximation, the normal strain, ε, can be estimated by

$$\varepsilon = v_p/c \qquad (9)$$

where:
- v_p = peak particle velocity
- c = p-wave velocity taken as 1000 fps

The shear strain varies from 1.5ε for triaxial conditions o 2ε for plane strain conditions. A value of 1.5ε is used here ıs a slightly conservative estimate. Shear Strain, γ, as a unction of distance from the source, is presented in Table 1.

Table 1 -- Computed Values of Shear Strain vs. Distance from Energy Source

v_p, ips	Distance from Hoe ram	Distance from Vibratory Pile Driver	ε, %	γ, %
0.96	10'	18'	0.008	0.012
0.45	20'	35'	0.0037	0.0056
0.30	30'	50'	0.0025	0.00375

The data points from Table 1 are plotted on Figure 2. Data points on or above the fatigue curve correspond to fatigue failure. These data indicate that, for distances less than about 30' for the hoe ram and about 50' for the vibratory pile driver, fatigue failure of the cementation appears plausible.

Finite Element Analysis

As further check on the reasonableness of the velocities calculated by Eqn (2), a finite element analysis was performed. Space limitations do not permit a detailed presentation of the analysis and results. Instead, only a brief description of the analysis and a few key results will be given.

The piers were axisymmetric, as was the soil surrounding the piers. However, the load was applied in one direction during demolition; at least this was so during any brief period. Therefore, it was necessary to make the analysis 3-D. In order to obtain an output in terms of velocity, it was necessary to make the analysis dynamic. Fortunately the forcing function was harmonic, so only a very few cycles had to be computed. Program GIFTS (CASA/GIFTS, Inc, 1987)

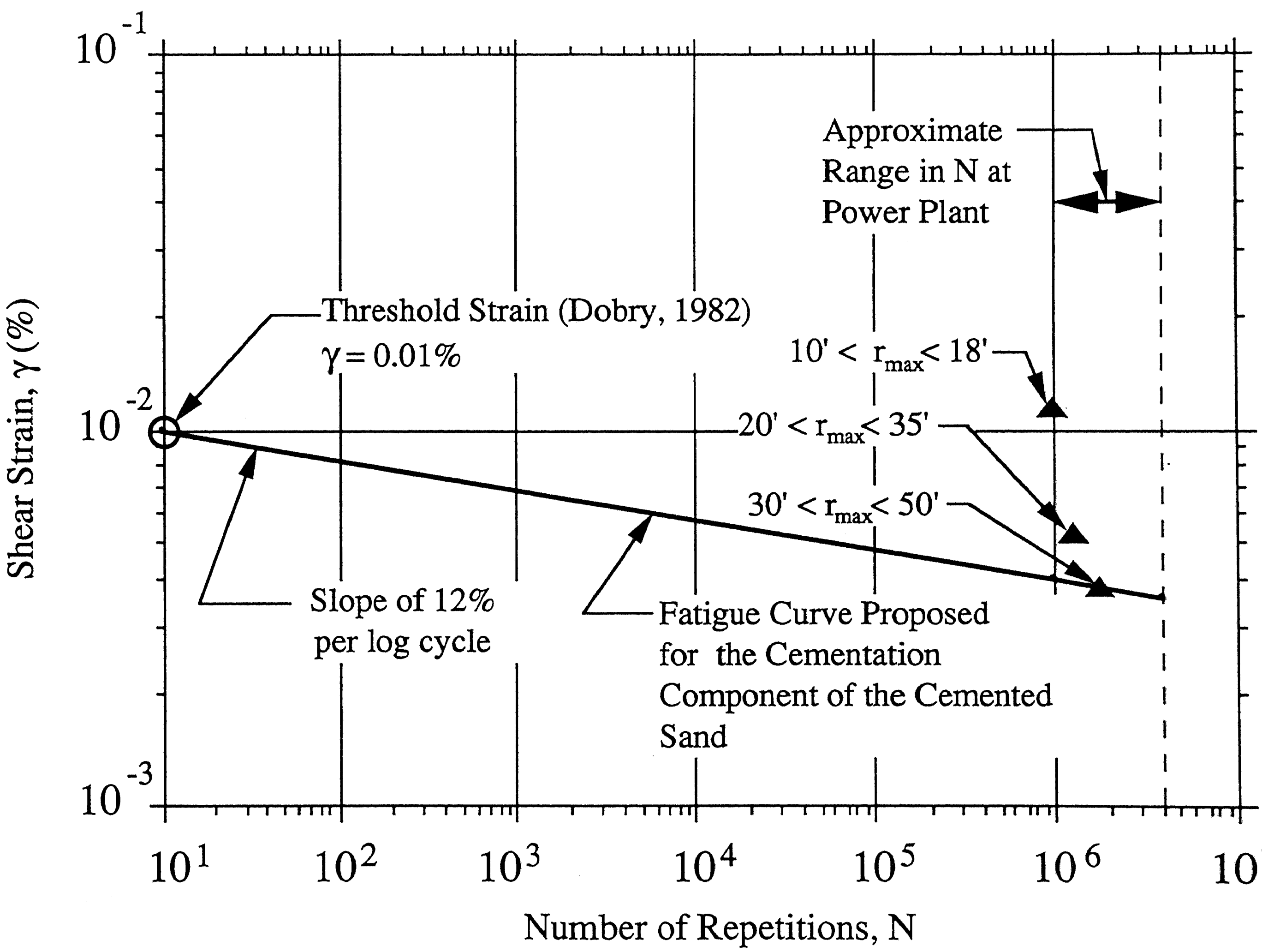

Figure 2 - Fatigue Curve for Cementation

was used for the analysis. The mesh had more than 1500 elements. Trial and error was again used to find a nodal point load on the pier at the surface that would produce a deflection corresponding to the required energy input of 2600 ft-lbs. This load was applied at a frequency of 12 cps and the peak particle velocity was computed at various nodal points within the surrounding soil mass, four of which are shown in Table 2.

Table 2 -- Peak Particle Velocity by FEM

NP#	Total Distance From Energy Source	Peak Particle Velocity - ips
7	3'	4.1
214	36'	0.44
13	43.5'	0.30
238	63.5'	0.15

When these data points are superimposed on Figure 1, they plot between the curve for the hoe ram and the curve for the vibratory pile driver. This result helps to confirm that the velocities computed by Eqn (2) were reasonable and perhaps slightly conservative.

DISCUSSION OF RESULTS

All of the preceding analyses indicate that loss of soil cohesion due to vibrations may have extended to 40 ' distances from the demolished piers, and probably much further. Two important questions arise in connection with these results, however. "Why did some holes cave while others did not?" and "Why was caving more pronounced in the 20'-40' depth range instead of near the surface where vibrations were somewhat more severe?"

The answer to these questions is believed to be the variability of the soil cohesion at the site. It is quite reasonable to assume that the cohesion varied both laterally

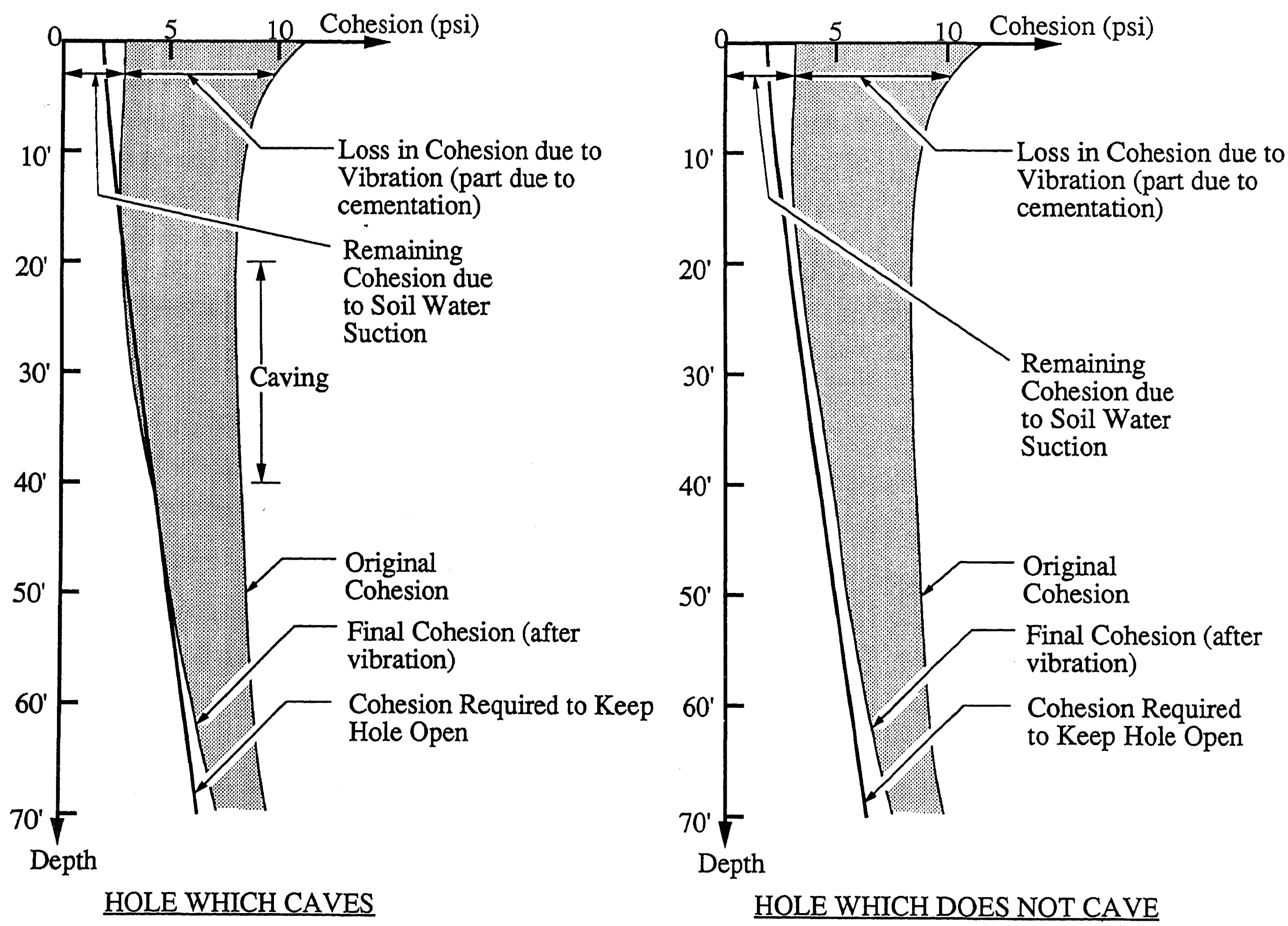

Figure 3 - Hypothetical Cohesion Variation

and vertically due to environmental and depositional processes. Such variation is consistent with the authors' experience at other cemented soil sites in the southwest. In addition, the soil cohesion has two components. One component is due to soil moisture suction (negative pore water pressure). These soils were all above the groundwater table and no perched water was observed. The second component is crystalline cement, such as carbonates, sulfates, silicates, etc. It is only the second component which is susceptible to damage from vibration. It is likely that the relative contributions of these two components could vary laterally and with depth. Furthermore, the damage to soil cohesion due to vibration would probably vary from one pier to another.

Figure 3 represents a possible variation of cohesion with depth for a hole that caved and a hole which did not cave. This diagram is meant to be qualitative only, as no actual cohesion measurements were made at the site. The curve furthest to the right in each case corresponds to the original total cohesion. The shaded zone represents the loss in cohesion, which diminishes with depth. Shown on the left side of each diagram is the cohesion required to keep the hole from caving, which increases with depth, of course. Caving occurs at come critical combination of the original cohesion, loss in cohesion, and cohesion needed to keep the hole from caving. This critical combination apparently developed more frequently in the 20'-40' depth range than at other depths. It can be seen that there is very little difference, qualitatively or quantitatively, in the diagram on the left where caving occurs and the diagram on the right where caving does not occur.

CONCLUSIONS

All of the analyses performed for this study indicate that loss of soil cohesion due to vibrations from pier demolition and casing installation is quite plausible. Although most of the analyses were approximate and involved assumptions, these assumptions were typically conservative, leading to the conclusion that damage to soil cohesion was quite likely. In view of the fact that the equipment and techniques used by the drilling contractor were not found to be inferior, a reduction in the soil cohesion is probably the most likely explanation of the anomalous hole caving.

It is probably not the usual practice to be concerned about the effects of vibration on sandy soils. Perhaps this is because we expect that vibration will cause densification, which in turn causes an increase in friction angle and a decrease in compressibility. If settlements during vibration are not a problem, then we might ordinarily assume that the soil would be unchanged or improved. However, the results of this study show that loss of soil cohesion due to vibration can have detrimental effects on borehole stability and perhaps the stability of vertical and near vertical slopes as well, particularly in cemented deposits of granular soils.

The Wiss Equation (1), or Equation (2), proved to be quite useful in computing probable decay of peak particle velocity with distance. When either soils or structures at a construction site are subjected to significant vibrations, measurement of peak particle velocities is a good investment. The analyses performed for this study would have been very difficult without these measurements.

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