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ABSTRACT: Despite the common occurrence of defects in concrete piles, there is little information on the behaviour of a pile group containing defective piles. The objective of the paper is, via a program called GEPAN, to assess the load-displacement performance of groups containing defective piles under general loading conditions. An attempt is made to relate the nature of the defects, pile spacing, pile stiffness/flexibility factors, to the behaviour of group, as represented by the group displacement, load redistribution, and “off-line” effect. Some important results are developed in this paper, including the influence of defects in increasing pile movements and altering the load distribution within a group. The results may provide some guidance for assessing the performance of a pile group containing defective piles and may be useful in deciding whether or not remedial action needs to be taken.

RESUMÉ: Malgré l’événement commun des pieux défectaux, il y a peu d’information du comportement d’un groupe avec pieux défectueux. L’objectif de cette communication est, via un program GEPAN, évaluer le comportement charge-tassement des groupes avec des pieux défectueux, sous les charges généraux. On a essayé d’établir un rapport du comportement avec l’espèce de défaut, l’espace des pieux, et la rigidité des pieux. Quelques résultats importants sont développés dans le papier, compris les effets des défauts sur le tassement et la distribution des charges dans les pieux. Les résultats peuvent donner des conseils pour évaluer le comportement d’un group avec les pieux défectueux, et à décider si les actions remédiées sont nécessaires.

1 INTRODUCTION

It is a common experience to encounter defects in concrete piles. Such defects have been discussed extensively in the literature, but there is little information on the behaviour of a pile group containing defective piles. In many cases, it has been assumed that the defective pile will not carry any load and an additional pile or piles have been installed within the group to compensate for the defective piles. Such a procedure can be both costly and time-consuming, and it is therefore of some interest to examine whether such remedial works are indeed justified, or whether the group containing the defective pile (or piles) can still function satisfactorily.

An interaction-factor-based group analysis and corresponding computer program, DAMPIG, were developed by Poulos (1997). For defective piles, reduction factors were input for axial stiffness, these being obtained from an independent analysis for a defective pile, using the program DAMPIG (Poulos, 1997). Via these programs, a simple hypothetical x3 vertically loaded group containing defective piles was studied. A more general elastic analysis of pile groups containing pile defects has been developed by Xu and Poulos (2000). The analysis has been implemented via the program GEPAN, which is more rigorous, because it is able to study specific defects in one or more piles rather than merely “defective piles in a group”, like DAMPIG.

The objective of this paper is, via GEPAN, to study the general load-displacement performance of groups containing defective piles. An attempt is made to relate the type of defects, pile spacing, pile stiffness/flexibility factors, to the load-displacement behaviour of the group. The results may provide some guidance for assessing defect-induced factors, such as, group stiffness reduction, load redistribution and “off-line” effect.

2 PROGRAM GEPAN

To implement the interaction analysis for pile groups containing defective piles, a program called GEPAN (General Pile Analysis) has been developed by Xu and Poulos (2000) using 3-D boundary element analysis. It is a general rigorous elastic analysis of pile foundations, considering all load/deformation components for each of the piles with arbitrary dimensions, and also incorporates full coupling effects. A global equation can be set as shown in Equation 1:

\[
\begin{bmatrix}
A & B & \emptyset & D & X_e \\
\emptyset & \emptyset & G & H & X_h \\
O & P & Q & R & X_e \\
S & \emptyset & V & X_e & \emptyset \\
\end{bmatrix}
\begin{bmatrix}
Y_q \\
Y_c \\
Y_q \\
Y_p \\
\end{bmatrix}
= \begin{bmatrix}
\emptyset \\
\emptyset \\
\emptyset \\
\emptyset \\
\end{bmatrix}
\]

(1)

where \( \emptyset = \) zero matrix, \( A = \) matrix of pile and soil behaviour at all elements, \( B = \) matrix of pile element displacements due to pile tip displacements, \( D = \) matrix of pile element displacements due to pile head loads, \( G = \) matrix of pile cap loads due to pile cap displacements by cap-tie-cap beam forces (to allow for pile caps joined by tie beams), \( H = \) matrix of pile cap loads due to pile head loads, \( O = \) matrix of pile head displacements due to pile element stresses, \( P = \) matrix of pile head displacements due to pile tip displacements, \( Q = \) matrix of pile head displacements due to pile cap displacements, \( R = \) sub-matrix of pile head displacements due to pile load head loads, \( S = \) matrix of pile head loads due to pile element stresses, \( V = \) matrix of pile head loads due to pile head loads, \( \emptyset = \) zero vector on RHS, \( Y_q = \) vector of element stress offsets, \( Y_{q_e} = \) vector of pile element displacements due to head loads of individual piles, \( Y_p = \) vector of pile element displacements due to extra soil displacement/stress/forces, \( Y_c = \) vector of loads on pile caps, \( Y_p = \) vector of pile head loads of individual piles, \( X_e = \) vector of pile soil stresses, \( X_t = \) vector of pile tip displacements, \( X_c = \) vector of pile cap displacements, \( X_f = \) vector of pile head forces at the pile cap. By solving Equation 1, the behaviour of pile group containing defective piles, under 3-D loading, can be analyzed. Details of the various matrices, and a variety of applications for pile foundations using equation 1, are given by Xu (2000).
I— — « I 1.2

Defective pile no 4
Case 1:
22 pile group
Defective pile no 1 or 2 or 4 or 5
Case 2:
y pile group
Defective pile

Figure 1. Geometry of two "standard" pile groups

3 "STANDARD" CASES

In order to provide "benchmark" results, two "standard" case (22 and 32 pile groups, both containing a defective pile) are considered, as shown in Fig. 1. In an elastic analysis, the key parameters of an intact pile are assumed to be: pile Young’s modulus $E_p$, soil Young’s modulus, $E_s$, diameter $d$, cross-sectional area $A$, length $L$, vertical load $P$, and horizontal load $P_x$ on a cap’s centre. The following main dimensionless parameters are assumed: $L/d=20$, pile-soil stiffness factor $K=10^3$ and $E_p/d=20$ for axial load; pile-soil flexibility factor $K_s=10^3$ and $E_s/d=20$ for lateral loading, where $K=E_p/E_s$ and $K_s=E_s/E_p$ (Poulos & Davis, 1980). For convenience, in the analysis, the pile defects are represented by simple idealizations. Necking, one of most common defects, is considered in this paper, and is idealized via a reduction in the value of local diameter of a pile. The parameters of necking are the diameter $d_d$, length $L_d$, area $A_d$, pile Young’s modulus $E_{pd}$ and depth $z_d$ of the necked zone. The “standard” necking in the present solution is characterized by the parameters $A_d/A=0.3$, $L_d/L=0.3$, $z_d/d=0.2$, with $E_{pd}/E_p=1$ for case 1 and 0.01 for case 2.

4 EFFECTS OF PILE DEFECTS IN A VERTICALLY-LOADED PILE GROUP

Analyses have been carried out to examine the effect of necking on the 22 pile group. Figure 2 shows that, as expected, larger values of the ratio of cap settlement to pile diameter, $S/d$, occur as the ratio of necked to intact area, $A_d/A$, decreases.

For ranges of values of $A_d/A$ and $s/d$, load distributions within a pile group with a rigid cap are shown in Figure 3, the pile head load, $P$, being expressed as a fraction of load on a corresponding intact pile in the group, $P_i$. The load at pile 1 (diagonally opposite the defective pile 4) decreases, as the ratio of necked area to the defective pile 4, $A_d/A$, decreases. Increases of load occur at piles 2 and 3 (next to the defective pile 4) and result from a decrease of $A_d/A$ in the defective pile 4. The load on the defective pile 4 decreases, as the ratio $A_d/A$ of the pile 4 decreases. Th load distribution tends to become less uniform as the neck area decreases, and also as the pile spacing decreases.

An interesting feature of group response with defective piles is that the group will deflect laterally and suffer a rotation under purely axial applied loading, e.g., “off-line” effects occur. The “off-line” movements, of course, will produce extra internal forces in the piles. Figure 4 shows the ratio of resultant pile head moment of a group containing a defective pile, $M$, and one of an intact pile group, $M_i$. It is shown that the ratio may be over 50 in the case of necking with $A_d/A=0.3$. However, the moments for an intact group are in fact very small and not usually considered in design. Allowance should be therefore made in the pile.
design for the larger pile head moments which may be induced by pile defects existing in the pile group.

Pile compressibility can be expressed in term of a pile stiffness factor \( K \), the effect of which is shown in Figure 5, where \( P_d \) and \( P_t \) are horizontal pile head loads on a “defective” group and intact group respectively. It demonstrated that the greatest changes in load re-distribution, induced by pile defects, occur in moderately compressible piles (\( K \) is between about \( 10^2 \) and \( 10^3 \)), while for both very soft piles and very stiff piles it approaches 1, i.e. the effect of load re-distributions due to the defect is small for both larger and less compressible piles.

5 EFFECT OF PILE DEFECTS IN HORIZONTALLY-LOADED PILE GROUP

Figure 6 show horizontal cap displacement \( S_n \) for a 22 pile group containing a neck, subjected to a centrally applied horizontal load \( P_h \). As \( s/d \) increases, \( S_n/S \) decrease. The more severe the necking, the larger is the value of \( S_n/S \) produced.

The effect of load distribution induced by a pile defect (necking), is shown in Figure 7. For the defect existing in pile 4, the loads in the four piles within the group are redistributed as follows: the load of the defective pile 4 decreases; the load of pile (the neighbor of the pile 4 and parallel to load \( P_h \)) increases; the values of the load fractions \( P_i/P \), of piles 1 and 3 are similar (the load in pile 3 is slightly larger than that in pile 1), but significantly smaller than those of piles 2 and 4. For \( s/d > 6 \) approximately, the effect of dimensionless spacing, \( s/d \), can be neglected.

6 EFFECTS OF POSITION OF DEFECTIVE PILES IN PILE GROUP

In order to analyse the effect of the position of defective piles in a pile group, a “standard” 32 ca-rigid floating group containing a defective pile has been considered as described in this section.

Three positions for a defective pile within the group are considered, as shown in Figure 1 in case 2, i.e. 1. at the corner (defective pile 1), 2. at the edge (defective pile 2), 3. at the center (defective pile 5).

Firstly, a centrally vertical load is considered to be acting on the group containing a defective pile which is located at the different positions. A plot of the ratio of pile head force \( P_h \) in defective group over corresponding head force in intact group \( P_t \), as show in Figure 8. It is shown that, among these three cases, the worst case is the defective pile is at the corner (pile 1) and the least severe case is when the defective pile is at the centre (pile 5). If the defective pile is at the corner, the piles beside the defective pile (pile 2 and 4) will suffer greater axial pile head force.

Secondly, a centrally applied horizontal load is considered. The ratio of lateral pile head force \( P_{hl} \) in defective group to the corresponding lateral head force in intact group \( P_{lt} \), with the different locations of the defective pile, are shown in Figure 9. Unlike the central vertical loading, these distributions of lateral head forces of intact piles due to the stiffness reduction of a defective pile are quite uniform.

7 CONCLUSIONS

From a 3-D general pile analysis, GEPAN, the main findings of the investigation on groups containing defective piles can be summarized as follows:

Additional pile head moments may be induced by pile defects existing in the pile group; group stiffness reduction is more sensitive for piles of moderate relative stiffness; when a defective pile exists within a group, the load on the defective pile decreases, while the loads on piles neighboring the defective pile may increase significantly in vertical loading; however the loads of intact piles may increase quite uniformly for horizontal loading; the “worst” position of a defective pile in a pile group is a corner.

Due to space limitations, only one kind of defect, i.e. necking.
has been considered in this paper. A complete defective analysis of groups containing different defects (necking, hone-combing, a softened base and their combinations), under general loadings, is presented in detail by Xu (2000).

REFERENCES