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# Prediction of behaviour of piled building foundations due to tunnelling operations

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ABSTRACT: This paper describes a method of analysing the settlement and rotation of a pile group located near a tunnel. This soil-structure interaction problem involves three stages:

1 Estimation of the distributions of free-field soil settlement with depth, and with distance from the tunnel;
2 Analysis of the response of a single pile to these soil settlements;
3 Analysis of the behaviour of a pile group via a simplified interaction analysis which takes account of the effects of axial loading due to the building loads, ground-induced settlement of the piles within the group, and interaction among the piles within the group.

A simplified analysis is developed for the analysis of the pile group, and allows for the consideration of a fully rigid cap. The analysis also allows for the simulation of pile removal (if the tunnel passes through the piles), the installation of additional underpinning piles, and a change in the capacity and stiffness of the piles because of the proximity of the tunnel.

An example of the application of the analysis to a case in South East Asia is described.

## 1 INTRODUCTION

One of the important issues of tunnelling in urban areas is the assessment of the likely impact of tunnel construction on nearby buildings. While much attention has been given to the ground surface movements arising from tunnelling (for example, Peck (1969), New and O'Reilly (1991), Mair et al (1996), Loganathan and Poulos (1998)), the consideration of the effects of tunnelling on piled foundations requires a more detailed examination of the soil-foundation interaction between the ground movements and the piles. Both axial and lateral responses are induced in piles because of the corresponding ground movements. Some analyses incorporating such interaction have been reported by Chen at al (1999) who have also presented some design charts to assist in the assessment of the forces, moments and displacements induced in a single pile by tunnelling-induced ground movements. Centrifuge tests described by Loganathan et al (2000) and Loganathan and Poulos (2002) have revealed pile behaviour which is consistent with that predicted theoretically.

This present paper extends the work in the abovementioned papers to examine the impact of tunnelling-induced ground settlements on the settlement and tilt of a structure supported by a pile group. The results of single pile analyses are incorporated into a simplified pile group analysis, which can also consider the effects of partial or complete loss of capacity and stiffness of some of the piles because of the tunnelling operations. An example of the application of this type of analysis is presented to illustrate the general response characteristics of pile group behaviour.

## 2 ANALYSIS OF SINGLE PILE RESPONSES

The basic approach adopted herein has been described by Chen et al (1999), and will be summarized very briefly here. The basic problem of a single pile is shown in Figure 1, where a single pile is located adjacent to a tunnel under construction. Both vertical and lateral ground movements will be generated by the tunnelling process, and will induce corresponding responses in the pile. The pile-soil interaction analysis is carried out in two stages:

1 The ground movements due to tunnelling are estimated by use of the closed-form expressions developed by Loganathan and Poulos (1998);
2 These ground movements are then used as input into analyses of pile-soil interaction for axial and lateral response, in order to obtain the behaviour of the pile.

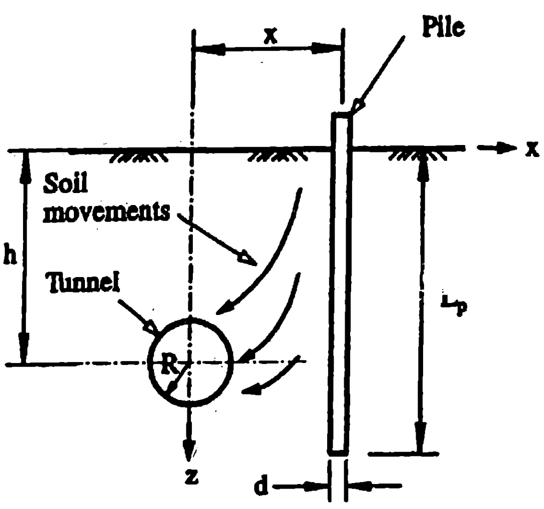


Figure 1. Pile adjacent to tunnelling – basic problem analyzed.

The lateral pile response analysis uses the simplified boundary element analysis described by Poulos and Davis (1980), and can be implemented via the program PALLAS (Hull, 1987) or ERCAP (CPI, 1992). In this analysis, the pile is represented as a simple elastic beam, while the soil is represented as an elastic continuum. The lateral displacement of each element into which the pile is divided can be related to the bending stiffness and the horizontal pile-soil stresses. The lateral soil displacement of each corresponding soil element can be related to the soil modulus or stiffness, the pile-soil interaction stresses, and the free-field soil movement at that point. A limiting lateral pile-soil stress can be specified so that local failure of the soil can be allowed for, thus permitting a non-linear response to be obtained.

The axial pile response also uses a simplified boundary element analysis (Poulos and Davis, 1980) and is implemented via the computer program PIES (Poulos, 1989). The pile is modelled as an elastic column, while the soil is represented as an elastic continuum. The pile is divided into a series of elements, the vertical movements of which are related to the applied load, the vertical pile-soil interaction stresses, the pile compressibility and the pile tip movement. The vertical movement of the corresponding soil elements depend on the pile-soil interaction stresses, the modulus or stiffness of the soil, and the free-field soil movements imposed on each element. Again, allowance is made for slip at the pile-soil interface so that the vertical pile-soil stresses do not exceed the limiting values (ultimate skin friction along the shaft, ultimate end bearing pressure at the base).

In the analyses carried out for the response to tunnelling, it is assumed that the lateral and axial responses are de-coupled, and can be considered independent of each other.

## 3 SOME BASIC ASPECTS OF SINGLE PILE BEHAVIOUR

It is useful to review the basic aspects of behaviour of single piles prior to considering the behaviour of pile groups. Although this paper focuses on the settlement of pile groups, consideration of the lateral behaviour of piles is still important from the point of view of structural integrity. Chen et al (1999, 2000) present solutions for a typical pile adjacent to a tunnel, for ground loss values of 1% and 5% (the latter being an extreme value for most circumstances). The tunnel is assumed to have a diameter of 6m with the centreline being 20 m below the surface. The computed ground movements at 4.5 m from the tunnel axis (i.e. 1.5 m from the tunnel extrados) are shown in Figure 2. The pile is 0.5 m in diameter and 25 m long, and is assumed to have 2.5% steel reinforcement in the upper 12.5m and 1% reinforcement in the lower 12.5m. The soil is assumed to be a uniform clay with a Young's modulus of 24 MPa and an undrained shear strength of 60 kPa.

The solutions for pile response are reproduced in Figure 3, from which the following characteristics can be seen or inferred:

1 The pile deflections, forces and moments increase as the volume loss increases;
2 The settlement of the pile is relatively uniform along the pile length;
3 Both tensile and compressive axial forces are induced in the pile by the vertical soil movements. The limiting shaft friction is developed along the pile if 5% volume loss occurs;
4 The lateral deflection of the pile is similar to the soil deflection;
5 The maximum bending moment occurs just above the level of the tunnel axis;
6 The maximum bending moment for 5% ground loss exceeds the allowable moment capacity of the pile near the tunnel axis level.

It is also interesting to note that the settlement of the pile exceeds the settlement of the soil at the ground surface, and is approximately equal to the ground settlement at between 1/2 and 2/3 of the pile length. Further, additional analyses reported by Loganathan and Poulos (2002) indicate that the effects of pile group interaction through the soil (pile-soil-pile interaction) do not have a great effect on the induced settlement, deflection, axial forces and moments. Thus, for design purposes, and for the purposes of the further analysis in this paper, the solutions for a single pile can be used to examine the response and structural integrity of piles within the group.

Analysis results such as those shown in Figure 3 clearly indicate the significant effect which tunnelling-induced ground movements can have on nearby pile foundations.

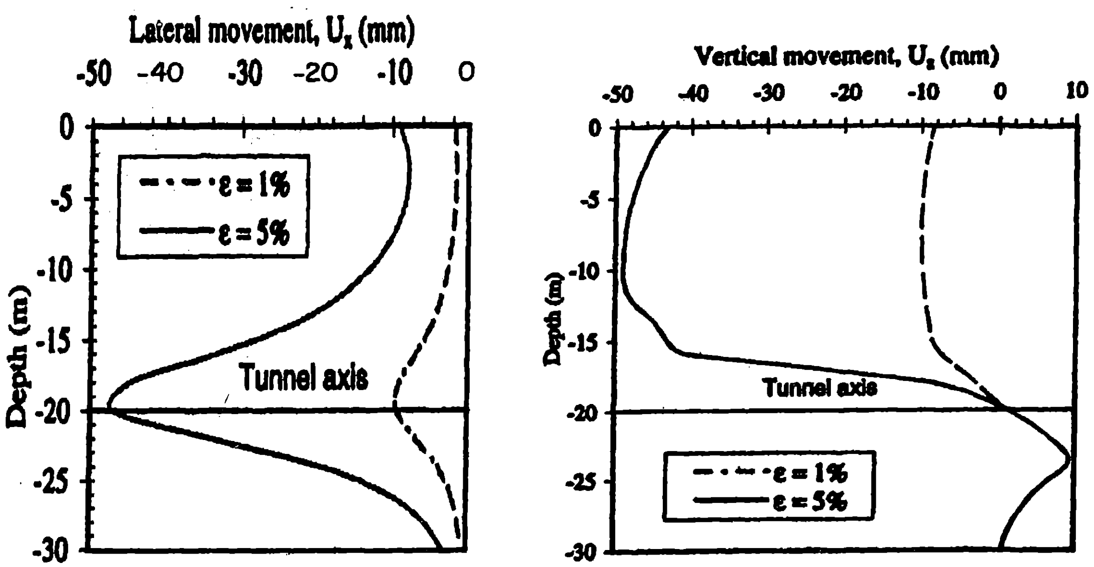


Figure 2. Computed soil movements at x = 4.5m.

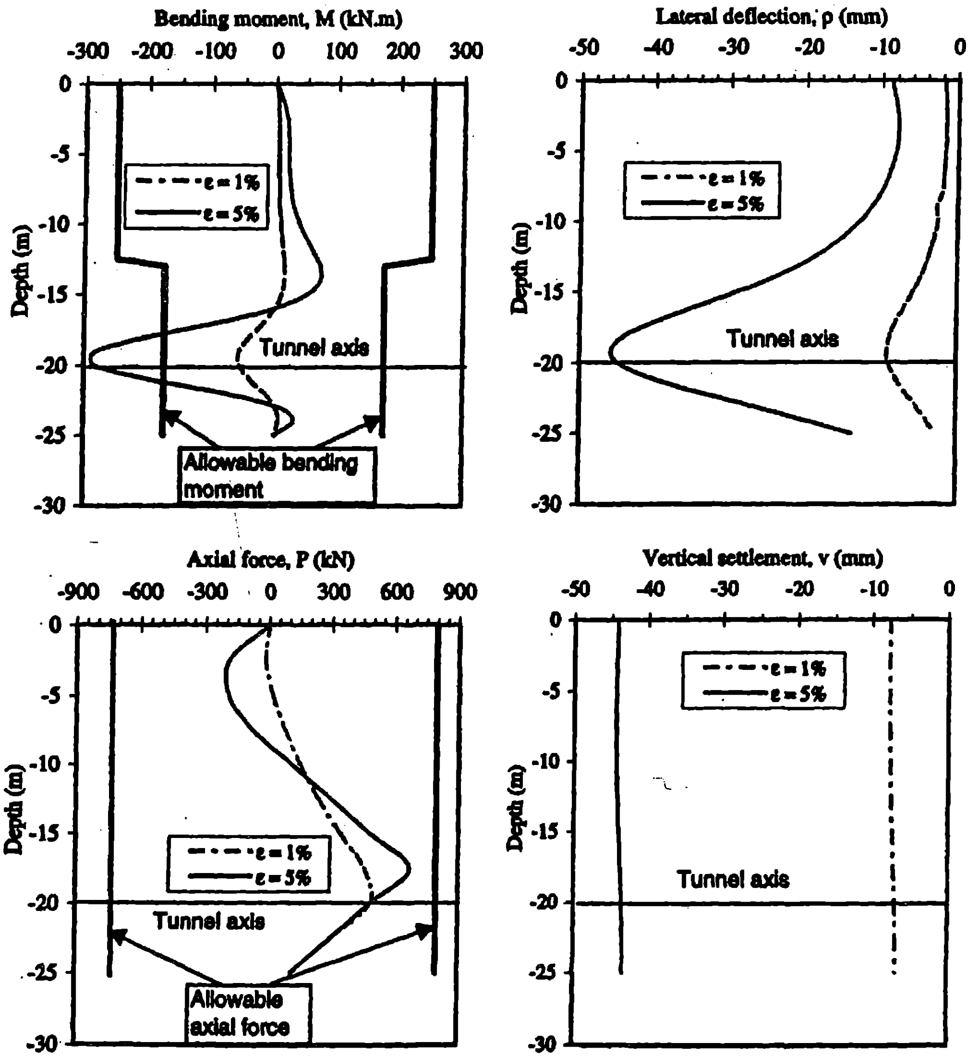


Figure 3. Typical pile response at x = 4.5m for long pile case ($L_p$ = 25m).

Of particular interest is the fact that the induced bending moments may exceed the structural capacity of the piles. This implies that the lower part of the pile could be broken and may not be able to effectively resist axial loads, thus reducing the axial load capacity of the pile. Other "side effects" may also include loss of skin friction and soil stiffness along the upper part of the pile due to a reduction in lateral stress arising from the proximity of the pile shaft to the tunnel.

In the following section, an analysis will be developed for the settlement of a pile group with a rigid pile cap, and subjected to tunnelling-induced ground movements,

## 4 ANALYSIS OF THE SETTLEMENT OF PILE GROUPS

Figure 4 shows a typical group of piles adjacent to a tunnelling operation. Use can be made of the simple superposition method of pile group analysis suggested by Poulos (1968) and Poulos and Davis (1980). Assuming that the connection of the piles to the pile cap is effectively pinned, the increment in settlement of a typical pile i in the group can be expressed as follows:

$$\Delta S_i = \sum_{j=1}^{n} \Delta P_j \alpha_{ij} / K_j + \varsigma_i \Delta Sff_i + \Delta\theta_x (x_i - x_r) + \Delta\theta_y (y_i - y_r) \qquad (1)$$

where $\Delta P_j$ = increment of load on a pile j in the group; n = number of piles in group; $\alpha_{ij}$ = interaction factor for effect of pile j on pile i; $K_j$ = axial pile head stiffness for pile j; $\Delta Sff_i$ = incremental movement of the head of pile i due to tunnelling-induced ground movements; $\zeta_i$ = reduction factor for group effects ($\leq 1.0$); $\Delta\theta_x$ = incremental rotation of pile cap in x-direction; $x_j$ = x-coordinate of pile j; $x_r$ = reference x-coordinate; $\Delta\theta_y$ = incremental rotation of pile cap in y-direction; $y_j$ = y-coordinate of pile j; $y_r$ = reference y-coordinate.

Equation (1) can be written for all piles in the group, giving a total of n equations. In addition, the conditions of vertical and moment equilibrium must be satisfied. Thus, the following three additional equations apply:

$$\Delta V_G = \sum_{j=1}^{n} \Delta P_j \qquad (2)$$

$$\Delta M_x = \sum_{j=1}^{n} \Delta P_j (x_j - x_r) - \Delta V_G (x_g - x_r) \qquad (3)$$

$$\Delta M_y = \sum_{j=1}^{n} \Delta P_j (y_j - y_r) - \Delta V_G (y_g - y_r) \qquad (4)$$

where $\Delta V_G$ = applied vertical load increment on group; $\Delta M_x$ = applied moment increment on group, in x-direction; $\Delta M_y$ = applied moment increment on group, in y-direction; $x_g$, $y_g$ = coordinates of point of vertical load application.

A total of n+3 equations can thus be derived, the solution of which gives the n values of axial pile load, the common incremental group settlement at the reference point ($x_r$, $y_r$), and the incremental rotations $\Delta\theta_x$ and $\Delta\theta_y$ in the x- and y-directions respectively.

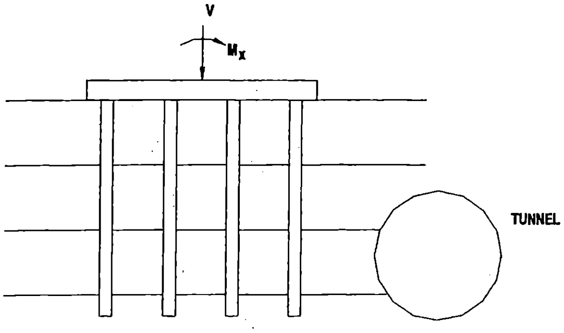
In applying the above analysis to the problem of tunnelling-induced settlements, the following assumptions have been made:

- The increment of pile head movement of a pile j due to tunnelling – induced soil movements, $\Delta Sff_j$, has been computed as the incremental soil movement at a depth of 2/3 of the length of pile j.
- The soil vertical movements have been computed from the equations given by Loganathan and Poulos (1998).
- Group effects on the ground movement - induced pile movements have been ignored, i.e. the factor $\zeta_i = 1.0$.
- The analysis is carried out incrementally, so that a complete sequence of events can be simulated.
- Typically, an event sequence consists of initial loading of the group, followed by the imposition of pile head movements caused by the tunnelling-induced ground movements. These pile head movements can be applied in stages, and can also arise from various sources, for example, the construction of more than one tunnel, including cross tunnels.
- The pile head stiffness of pile j, $K_j$, is a hyperbolic function of the pile load level, $P_j / P_u$, where $P_u$ = ultimate pile load capacity. Thus, the *incremental* pile head stiffness is given by:

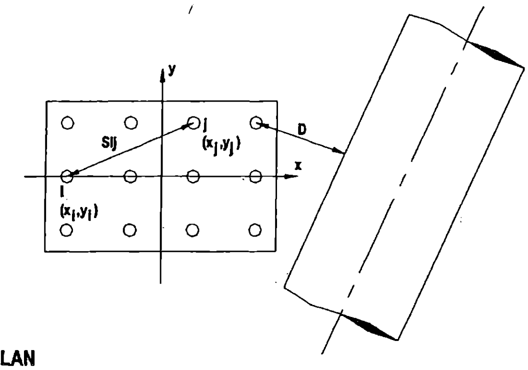
$$K_j = K_{jo} (1 - R_f P_j / P_{uj})^2 \qquad (5)$$

where $K_{jo}$ = initial tangent stiffness of pile j; $R_f$ = hyperbolic factor ($0 \leq R_f \leq 1$); a value of 0.75 has generally been adopted for the present calculations; $P_j$ = current load in pile j; $P_{uj}$ = ultimate load capacity of pile j.

- If the pile load reaches the ultimate load capacity, the incremental pile head stiffness for the following increment is set to a small fraction (typically 0.1%) of the initial pile head stiffness.
- The initial tangent pile head stiffness is computed from the simplified expressions developed by Randolph and Wroth (1978).
- Non-homogeneous soil profiles are treated as equivalent uniform profiles, via the approximation suggested by Poulos (1989).
- The interaction factors are computed via approximate curve-fitting expressions of the type suggested by Mandolini and Viggiani (1997).

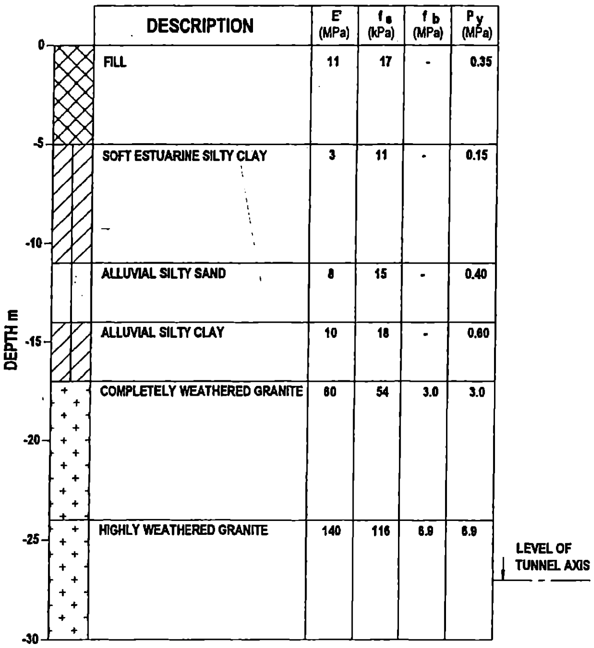


(a) ELEVATION



(b) PLAN

Figure 4. Basic problem of a pile group near a tunnel.



| DESCRIPTION | E' (MPa) | $f_s$ (kPa) | $f_b$ (MPa) | $P_y$ (MPa) |
|---|---|---|---|---|
| FILL | 11 | 17 | - | 0.35 |
| SOFT ESTUARINE SILTY CLAY | 3 | 11 | - | 0.15 |
| ALLUVIAL SILTY SAND | 8 | 15 | - | 0.40 |
| ALLUVIAL SILTY CLAY | 10 | 18 | - | 0.60 |
| COMPLETELY WEATHERED GRANITE | 60 | 54 | 3.0 | 3.0 |
| HIGHLY WEATHERED GRANITE | 140 | 116 | 6.9 | 6.9 |

Figure 5. Geotechnical profile and model.

- For piles of different length, the interaction factor is taken to be the average value applicable for piles having the properties of pile i and pile j.
- Piles within the group can be "deactivated" to simulate complete loss of capacity or cutting of the piles during the tunnelling process. They can also be "activated", to simulate the construction of additional underpinning piles at some stage in the construction process.

To allow for the possible effects of the presence of the tunnel itself on nearby piles, the following assumptions are made:

1. There is no effect of the presence of the tunnel on the ultimate axial capacity of the pile if it is further than 4 pile diameters away from the tunnel at its nearest point.
2. If a pile is closer than 4 pile diameters, the ultimate shaft friction at any point along the shaft is reduced linearly in proportion to the distance from the tunnel, until it becomes zero when that distance is zero. A similar assumption is made with respect to the ultimate end bearing capacity and to axial pile head stiffness.

The above analysis has been implemented via a FORTRAN computer program PIGS (Pile Group Settlement), version 9-3. The additional bending moments and deflections induced in the piles are computed using the ERCAP analysis for a single pile, assuming the free-field horizontal ground movements to be given by the equation presented by Loganathan and Poulos (1998).

## 5 APPLICATION TO CASE STUDY

Figure 5 shows a typical soil profile for a city in South East Asia, and the geotechnical model adopted for the analysis. The foundation plan for a high-rise building is shown in Figure 6, including the alignment of a single 6m diameter tunnel to be constructed adjacent to the building. Various values of ground loss for the tunnel are assumed, up to 2.5%. For the purposes of the present analysis, the foundation plan has been simplified, and it is assumed that the foundation-structure system can be considered to settle and tilt as a rigid system. The initial vertical building load is taken to be 106 MN, and no initial moments are assumed to act.

Figure 7 shows the computed settlement, pile loads and tilt of the building foundation as a function of ground loss.

The following observations may be made from Figure 7:

- Initially, there is a uniform settlement of about 31 mm.
- Construction of the tunnel causes additional settlements, which are a maximum at the nearest corner (Pile 1), and a tilt in that direction.

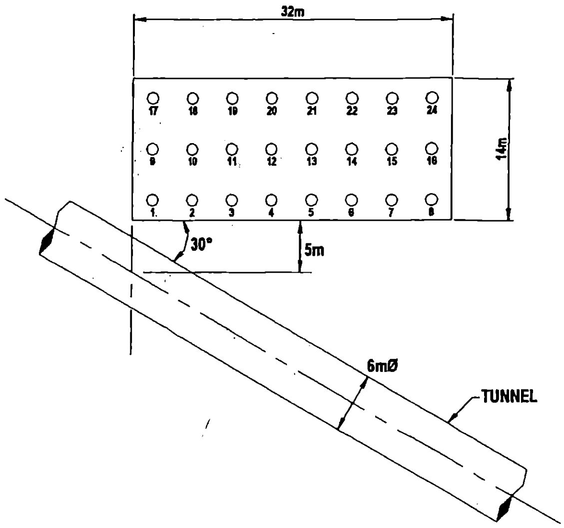
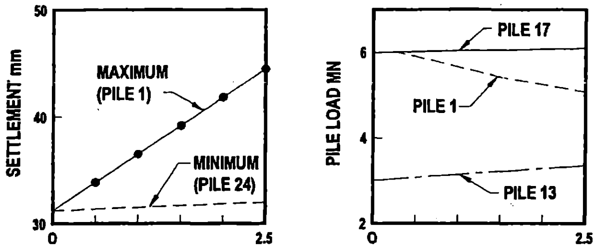
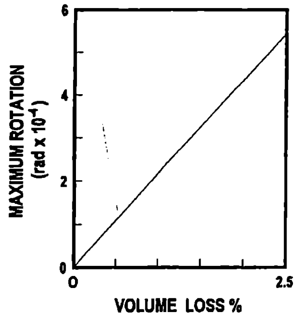


Figure 6. Plan of foundation piles and tunnel alignment.



(a) SETTLEMENTS

(b) PILE LOADS



(c) MAXIMUM FOUNDATION ROTATION

Figure 7. Summary of effects of tunnelling on building performance.

- The maximum settlement and the tilt increase almost linearly with increasing ground loss. For 2.5% ground loss, the tilt reaches a value of about 0.00055 rad (1/1820), while the settlement at pile 1 is increased to about 44 mm (i.e. 42% larger than the original uniform settlement). The minimum settlement (at Pile 24) increases only marginally.
- The pile loads generally do not change greatly. However, the load in Pile 1 reduces because it loses both capacity and axial stiffness as a result of its proximity to the tunnel.

The effects of the tunnelling operations on lateral pile response can be computed via the analysis of a single pile subjected to the free-field lateral ground movements. The program ERCAP has been used to carry out this analysis, and the results are shown in Figure 8. The following points can be noted:

- The maximum moments (both positive and negative) may increase with increasing distance from the tunnel axis, up to a certain distance, before decreasing.
- A pile with its head restrained from lateral movement suffers much greater moments than a pile with an unrestrained head.
- The smallest moments are experienced by piles whose heads are pinned and unrestrained.

For the case considered, the maximum bending moment would be about 860 kNm for a pile with a restrained and fixed head, located about 15 m from the tunnel axis. For a bored concrete pile with 1% steel reinforcement and very small axial load, the yield moment is approximately 1450 kNm. Thus, piles having a restrained head could be subjected to moments that are a significant fraction of their yield moment capacity.

For design purposes, the simplified charts provided by Chen et al (1999) and Chen et al (2000) can be useful. For the case of 2.5% ground loss and a distance of 7.5m, and for a pile with an unrestrained free-head, these charts give a maximum moment of about 295 kNm and a maximum lateral movement of 12 mm (which occurs near the pile tip), which compare to the values from the ERCAP analysis of 192 kNm and 14 mm respectively. While the design charts give conservative values of moment, they nevertheless give some indication of the likely order of magnitude of both the moments and deflections to be expected due to tunnelling operations.

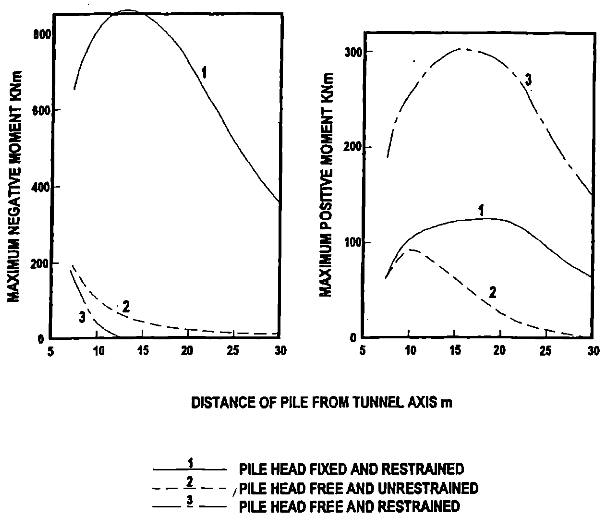


Figure 8. Computed maximum bending moments in pile adjacent to tunnel.

## 6 CONCLUSIONS

Ground movements induced by tunnelling operations can have a significant effect on the behaviour of nearby piles. For an individual pile, additional axial and lateral forces and moments can be induced together with additional settlement and lateral deflection. Such forces and moments can compromise the structural integrity of the pile. This paper has set out a means of analysing the response of a group of piles in the proximity of tunnelling operations. It uses the results of analyses of single pile response to consider the overall behaviour of the group, and also has the ability to simulate various stages in the loading and construction process. It can thus be used to predict the progressive development of settlements at various stages in the construction process. The example described in the paper demonstrates that the construction of the tunnel causes additional settlement and tilt of a nearby structure, while the additional bending moments induced by the tunnelling ground movements may approach or exceed the design moment capacity of the pile section, especially if the pile head is restrained from translation. The effects of the tunnelling-induced ground movements increase almost linearly with increasing ground volume loss, thus highlighting the importance of controlling such volume losses in the construction process.

## ACKNOWLEDGEMENTS

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