LECTURE 6

RESPONSE OF PILES TO GROUND MOVEMENTS FROM TUNNELLING & EXCAVATION

OUTLINE

- Characteristics of pile response near tunnels
- Design charts for single piles
- Comparisons with test results
- Response of pile groups
- Characteristics of pile response near excavations
- Design charts for single piles
- Measured & computed behaviour

TUNNELLING OPERATIONS

ANALYTICAL METHOD FOR MOVEMENTS
(Loganathan & Poulos, 1998)

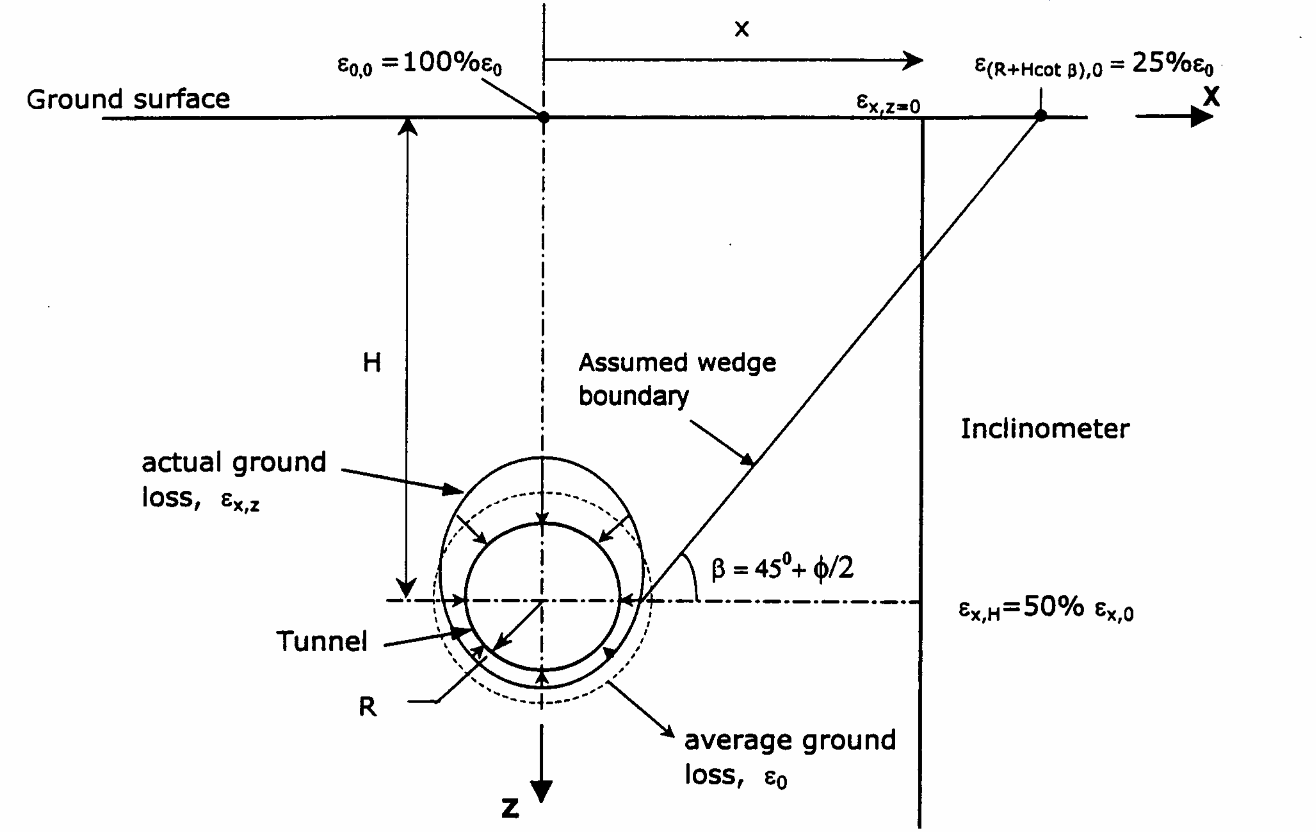


FIGURE 1:- Ground Deformation Patterns and the Ground Loss Boundary Conditions

ANALYTICAL METHOD (Loganathan & Poulos, 1998)

Settlement at depth z:

$$S_z = \varepsilon_0 R^2 \left[-\frac{z-H}{x^2+(z-H)^2} + (3-4\nu)\frac{z+H}{x^2+(z+H)^2} - \frac{2z[x^2-(z+H)^2]}{[x^2+(z+H)^2]^2} \right].$$

$$\exp\left\{ -\left[\frac{1.38x^2}{(H+R)^2} + \frac{0.69z^2}{H^2} \right] \right\}$$

ε_0 = average ground loss ratio

ANALYTICAL METHOD (Loganathan & Poulos, 1998)

COFFEY

Surface Settlement:

$$S_{z=0} = 4\varepsilon_0 (1-\nu) R^2 \frac{H}{H^2 + x^2} \exp\left[-\frac{1.38x^2}{(H+R)^2} \right]$$

ε_0 = average ground loss ratio

ANALYTICAL METHOD (Loganathan & Poulos, 1998)

Horizontal Movement at depth z:

$$S_x = -\varepsilon_0 R^2 x \left[\frac{1}{x^2 + (H-z)^2} + \frac{3-4\nu}{x^2 + (H+z)^2} - \frac{4z(z+H)}{(x^2 + (H+z)^2)^2} \right]$$

$$.\exp\left\{ -\left[\frac{1.38x^2}{(H+R)^2} + \frac{0.69z^2}{H^2} \right] \right\}$$

SOME CHARACTERISTICS OF PILE RESPONSE NEAR TUNNELS

Parametric Study

- Tunnel
  - D = 6 m
  - H = 20 m
  - Average volume loss = 1, 2.5, 5 %
- Pile:
  - d = 0.5 – 1.2 m
  - L = 15, 20 25 m
  - x/H = 0 to 2

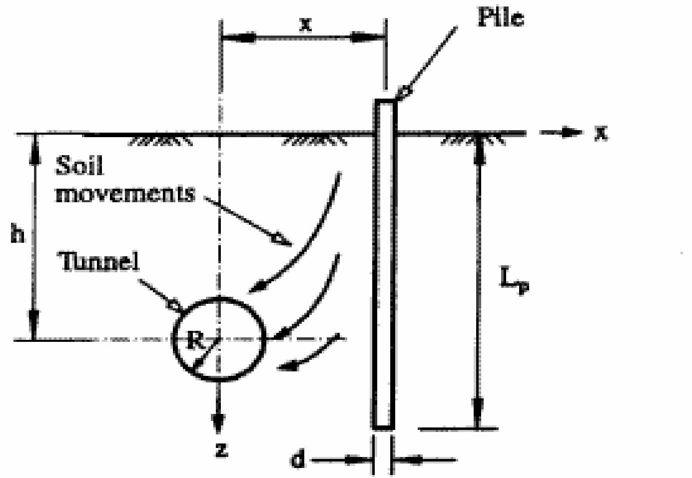
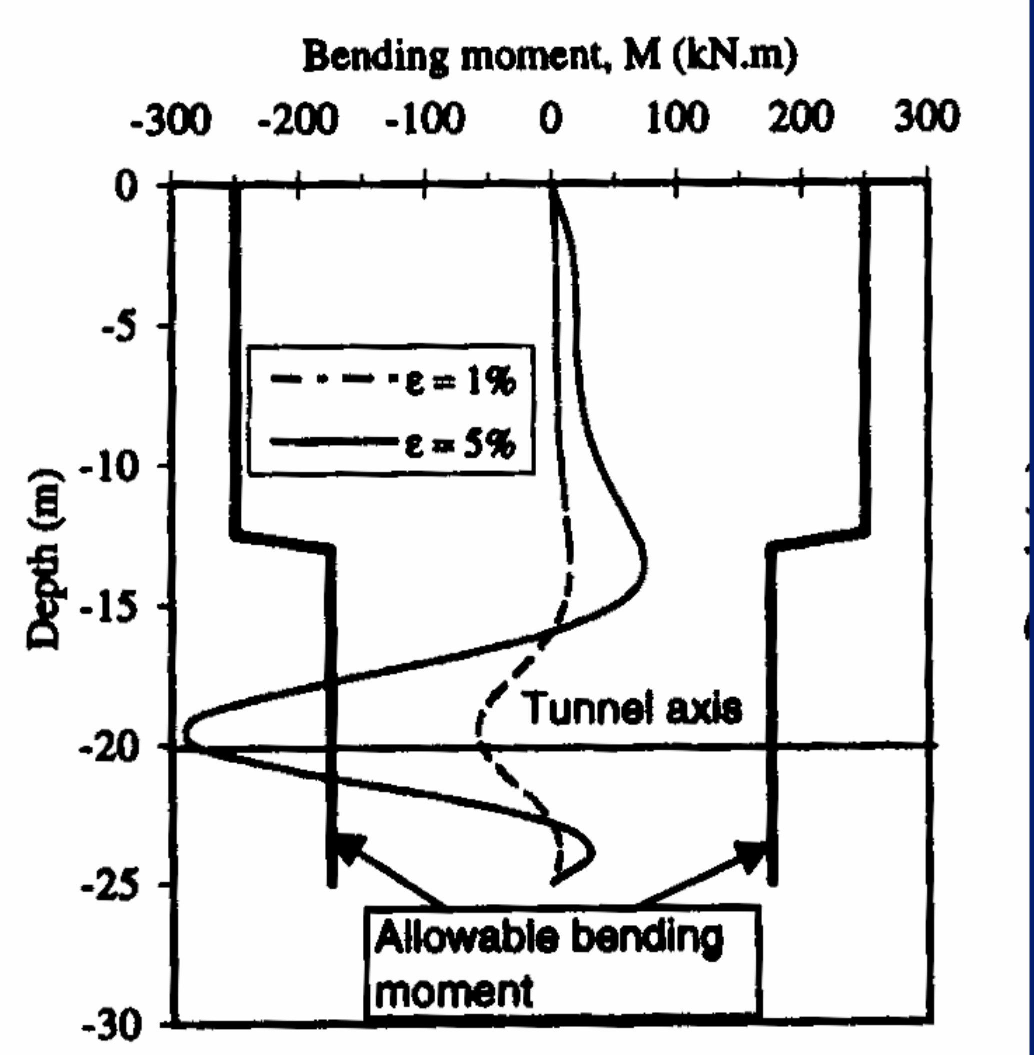


FIG. 1. Pile Adjacent to Tunneling—Basic Problem Analyzed

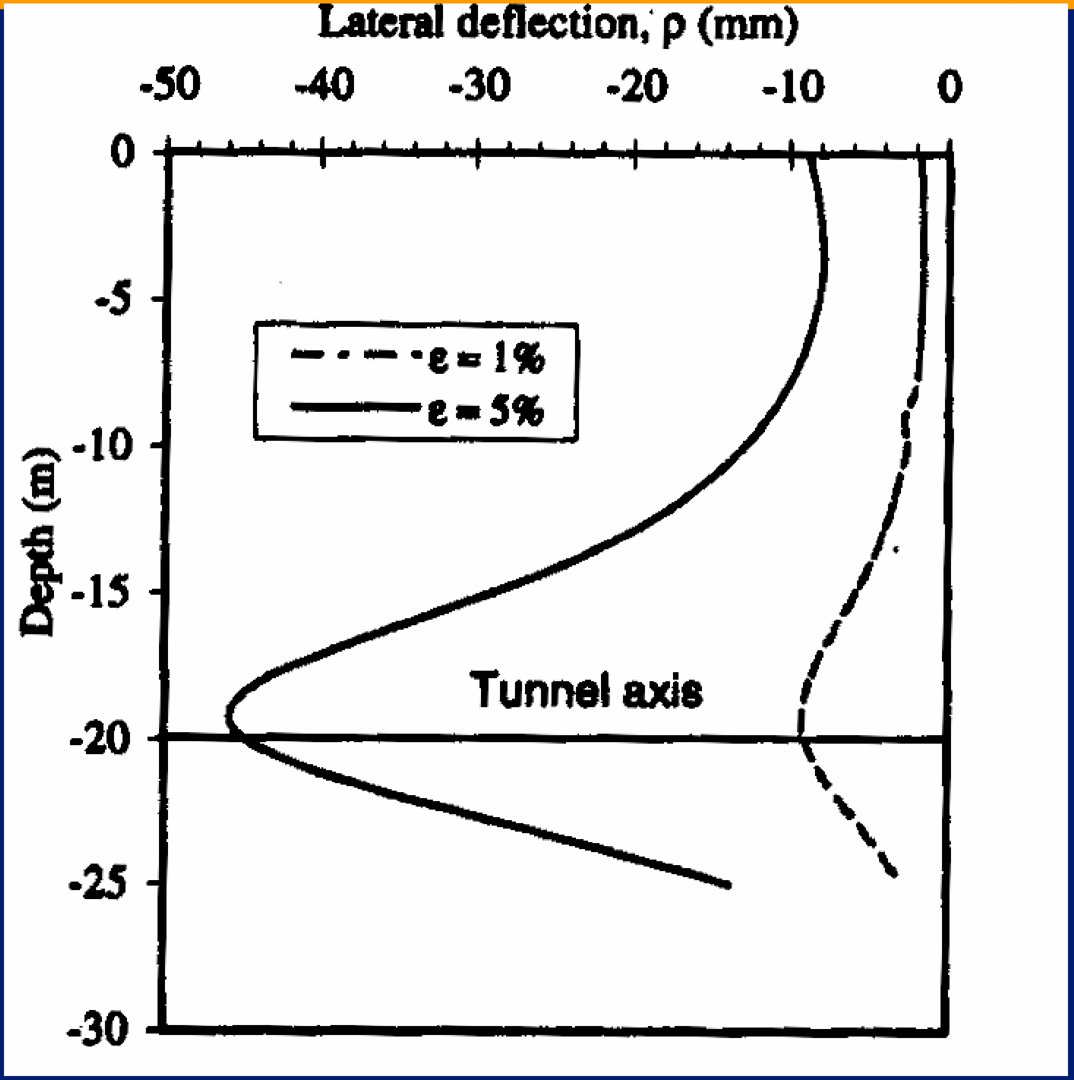
BENDING MOMENT DISTRIBUTIONS



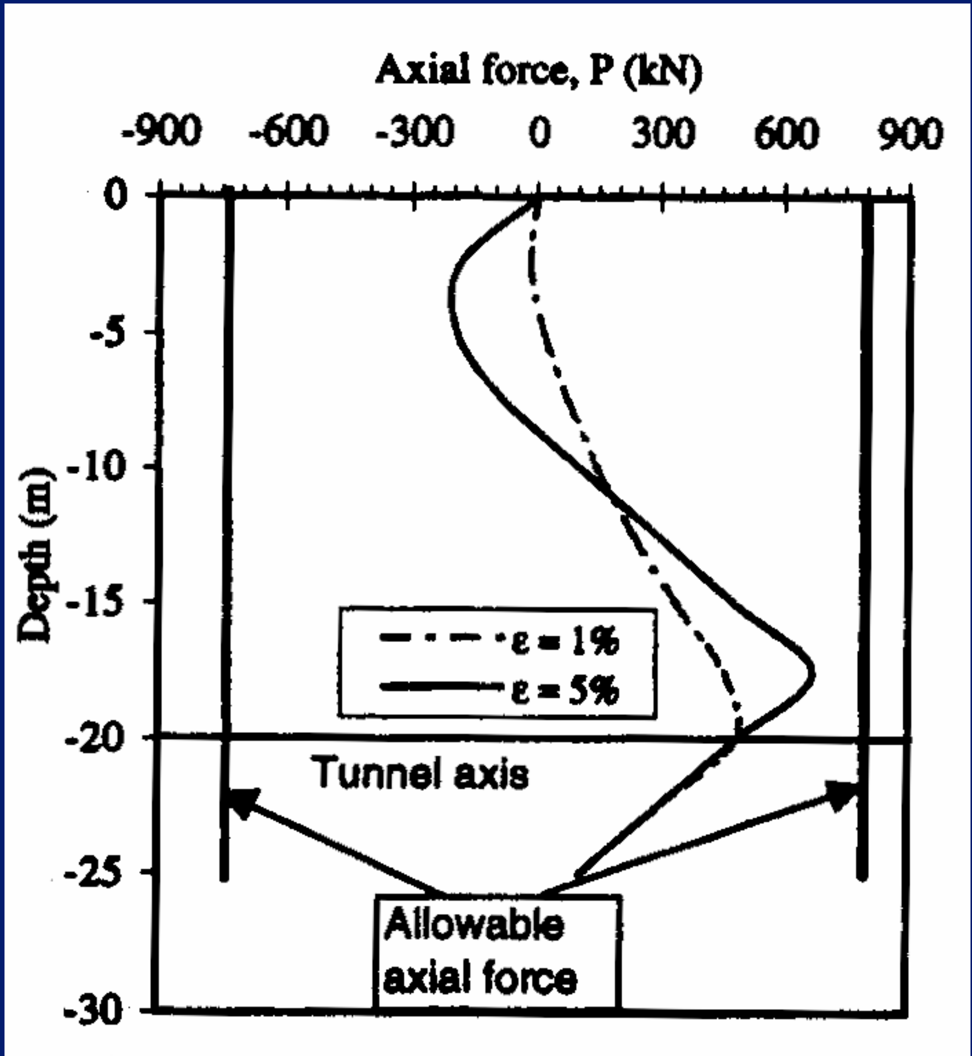
Largest moment occurs at or near level of tunnel axis

Note major effect of ground loss

LATERAL DEFLECTION OF PILE



AXIAL INDUCED FORCE IN PILE



Note tension in upper part of pile due to “stretching” by ground settlement increasing with depth

COMPARISONS WITH FLAC

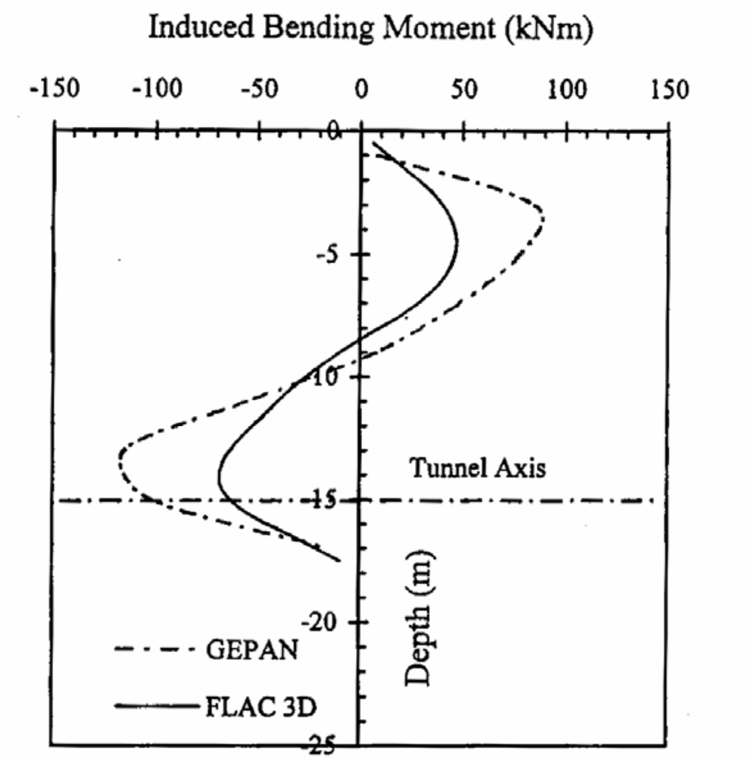


Fig. 6. Comparison of tunnelling-induced bending moment

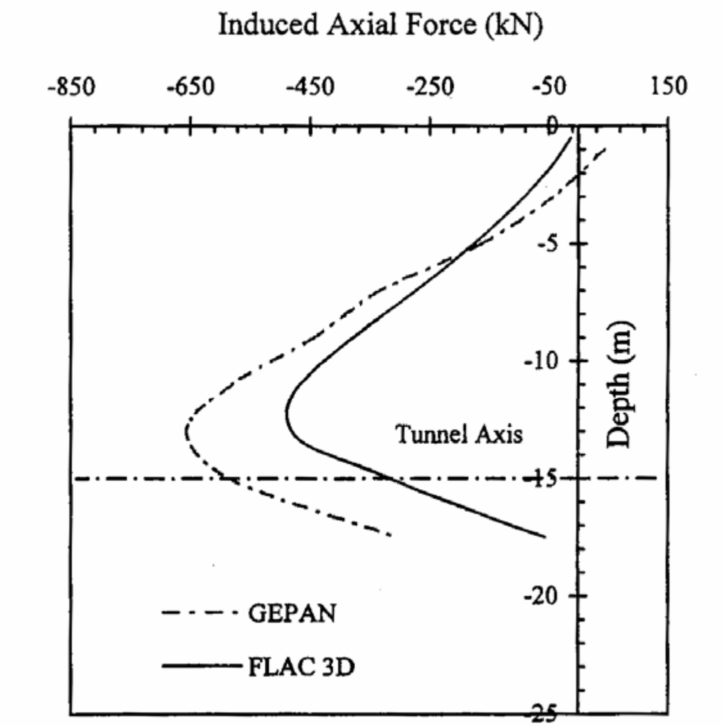


Fig. 7. Comparison of tunnelling-induced axial down drag force

COMPARISONS WITH FLAC

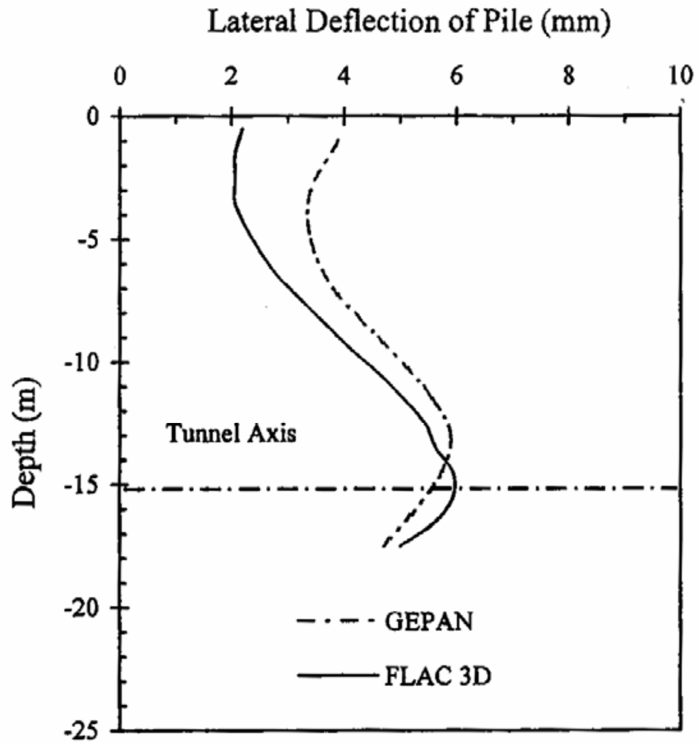


Fig. 8. Comparison of tunnelling-induced lateral deflection of pile

- GEPAN analysis) is generally conservative compared to FLAC
- Similarly for ERCAP & PIES
- General characteristics of behaviour are very similar
- Boundary element programs are much easier & quicker to run than FLAC.

3-D FINITE ELEMENT ANALYSES
Mroueh and Shahrour (2002)

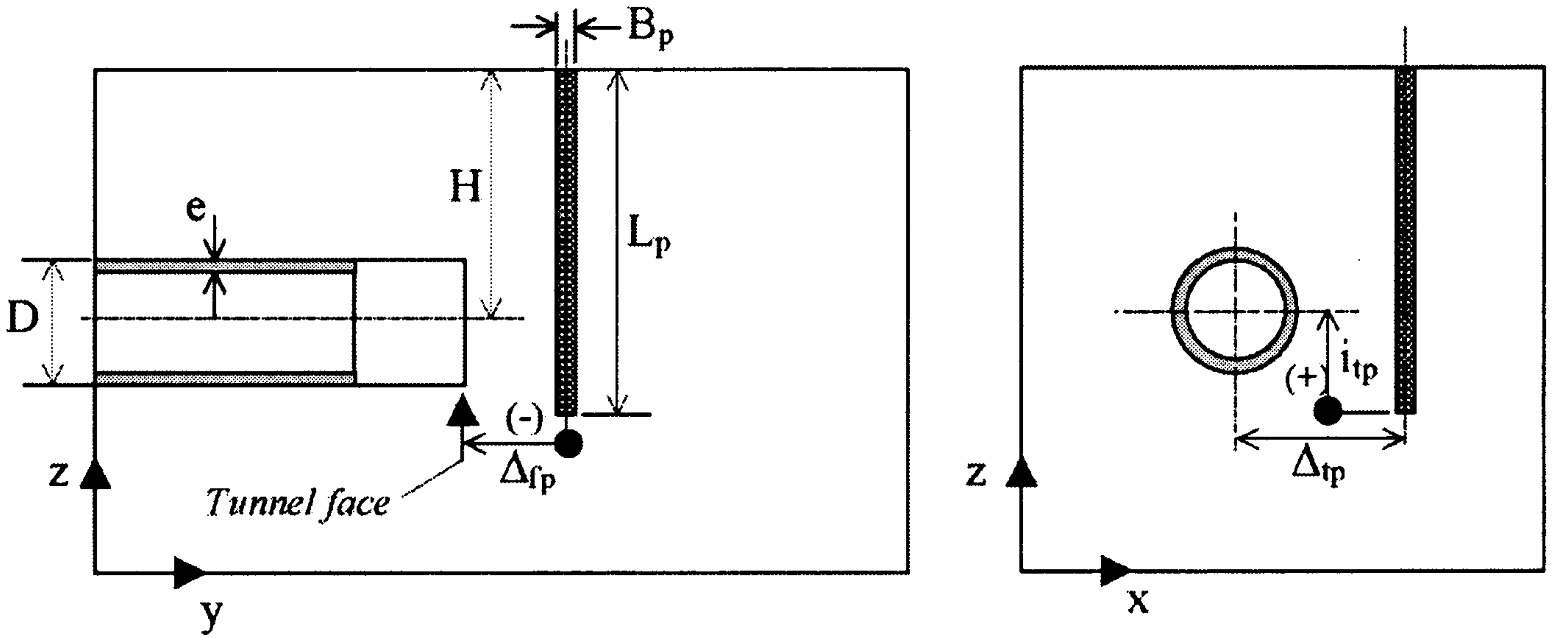


Figure 1. Problem under consideration: interaction between tunneling and adjacent piles.

3-D FINITE ELEMENT ANALYSES
Mroueh and Shahrour (2002)

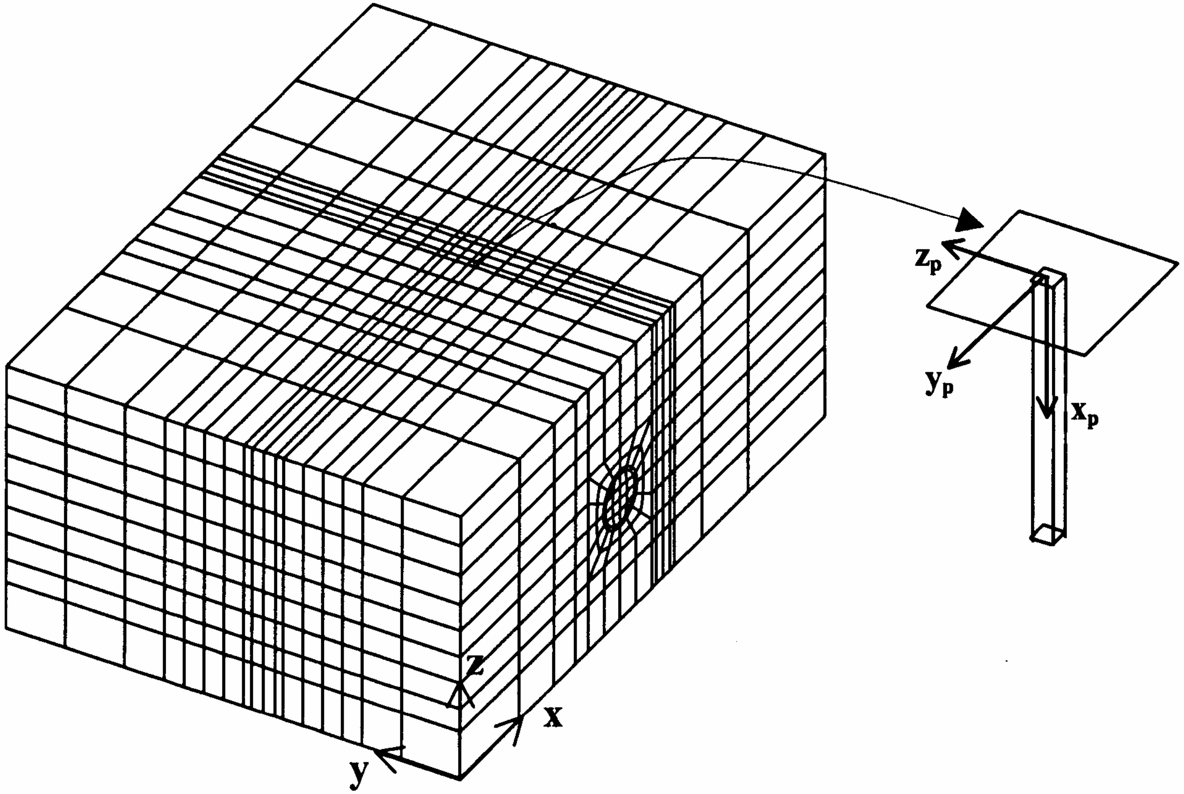


Figure 3. Three-dimensional finite element mesh used for the pile/tunneling interaction. (3111 20-node isoparametric hexahedral elements; 14 300 nodes; 38 222 dof.).

3-D FINITE ELEMENT ANALYSES
Mroueh and Shahrour (2002)

Details of Problem Analyzed:

- Tunnel lining – E = 35000 MPa
- Soil:
  - Es = 30 MPa
  - c = 5 kPa
  - ϕ = 27 degrees
  - ψ = 5 degrees
- Pile:
  - L = 22.5 m
  - d = 1.0 m
  - Ep = 23500 MPa

3-D FINITE ELEMENT ANALYSES
Lateral pile deflections

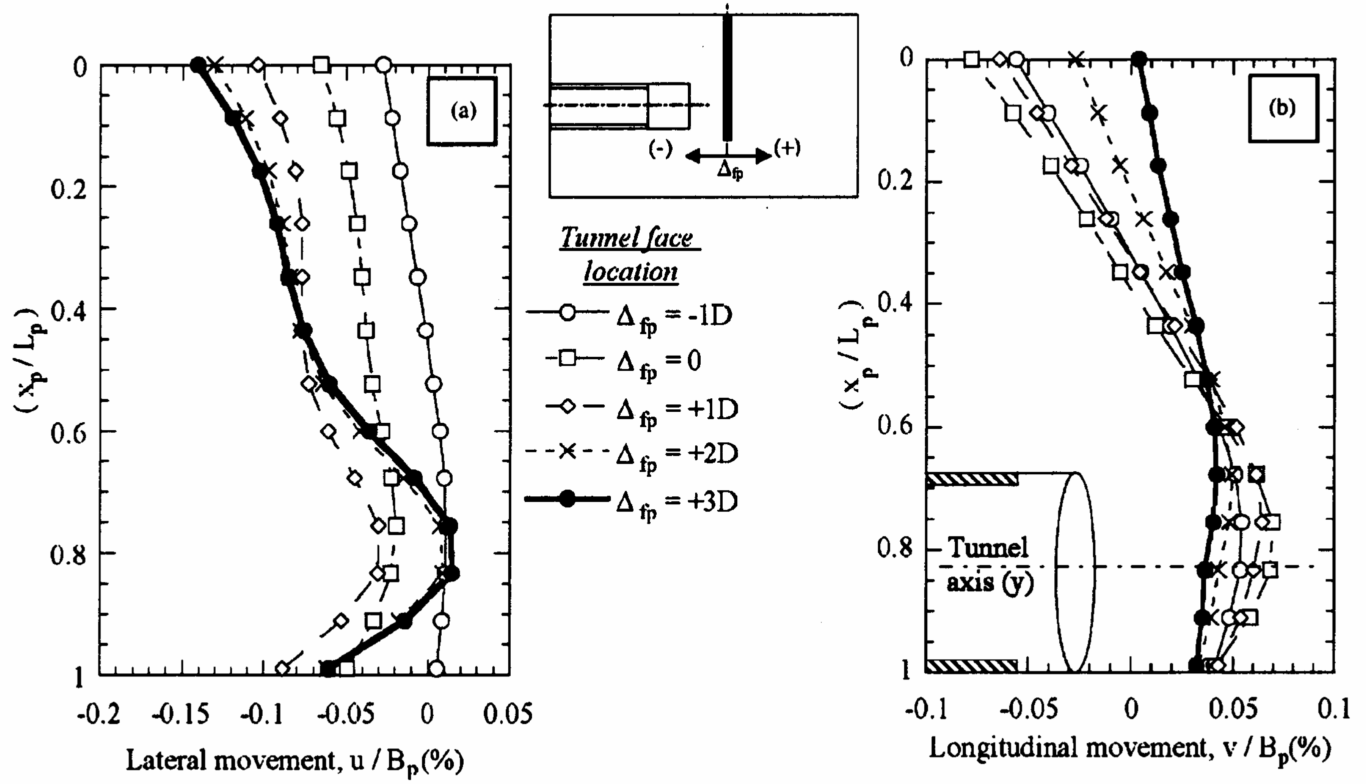


Figure 5. Pile deflection due to tunneling (reference example): (a) lateral section and (b) longitudinal section.

3-D FINITE ELEMENT ANALYSES
Axial force and bending moments

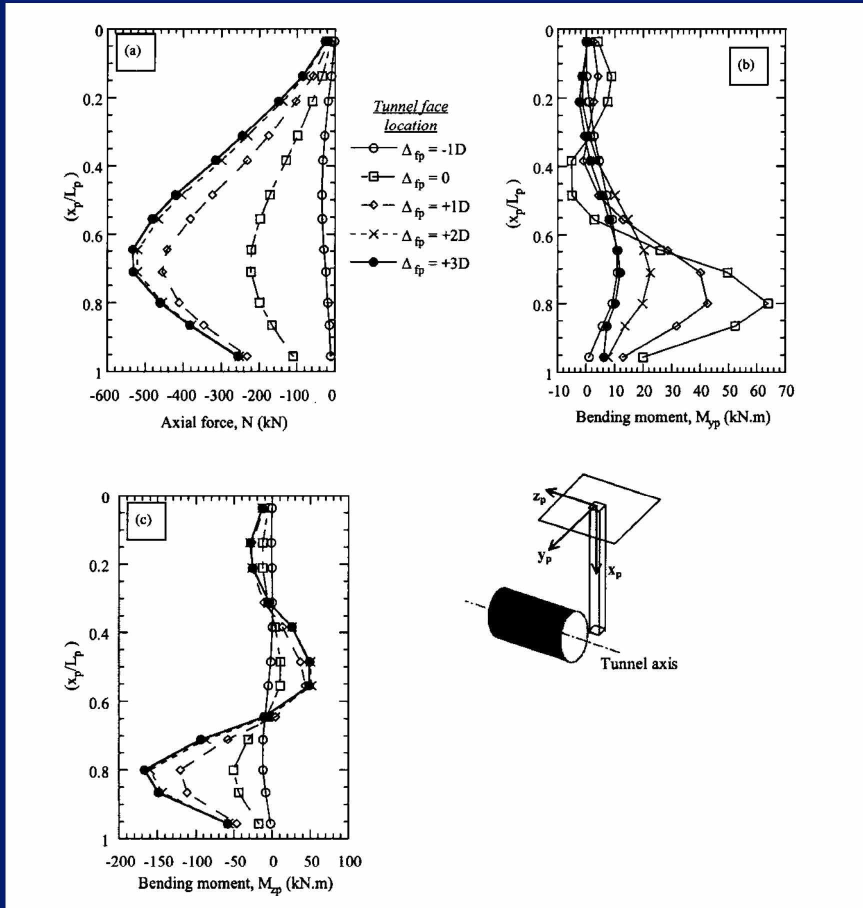


Figure 6. Internal forces induced by tunneling (reference example): (a) axial force (*N*), (b) bending moment (M_{yp}) and (c) bending moment (M_{zp}).

- Maximum axial force and lateral moment values occur when face is past pile

- Maximum longitudinal moment values occur when face is level with pile

3-D FINITE ELEMENT ANALYSES

Effect of tunnel depth on axial force & bending moments

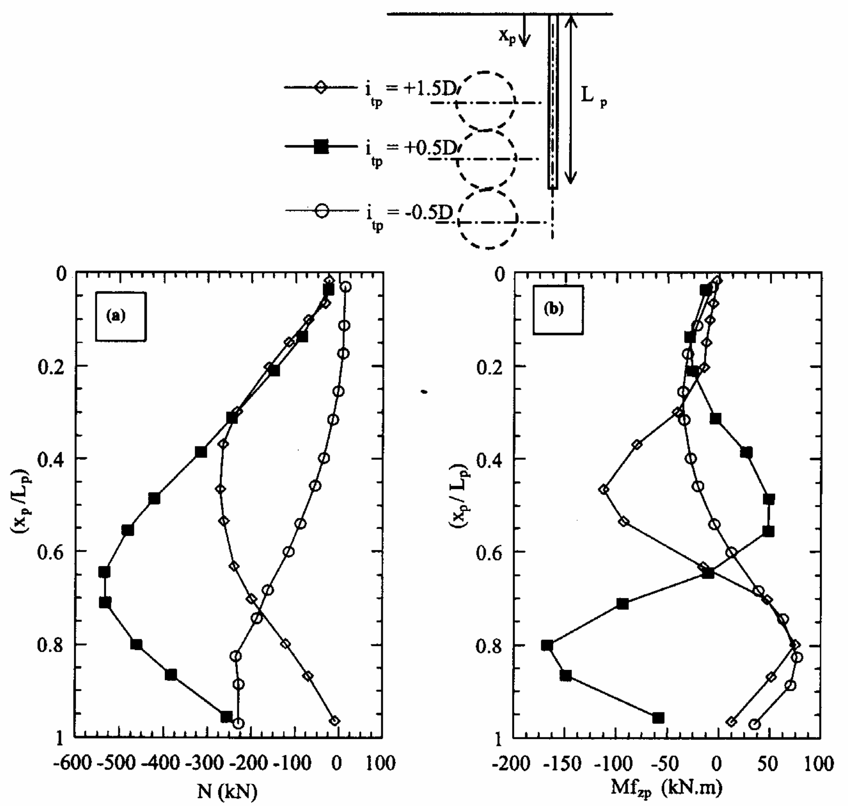


Figure 8. Influence of the vertical tunnel/pile distance i_{tp}: (a) axial force (N) and (b) bending moment (M_{zp}).

- Maximum force and moment occur when pile tip is at or just below tunnel invert

DESIGN CHARTS FOR SINGLE PILES NEAR TUNNELS

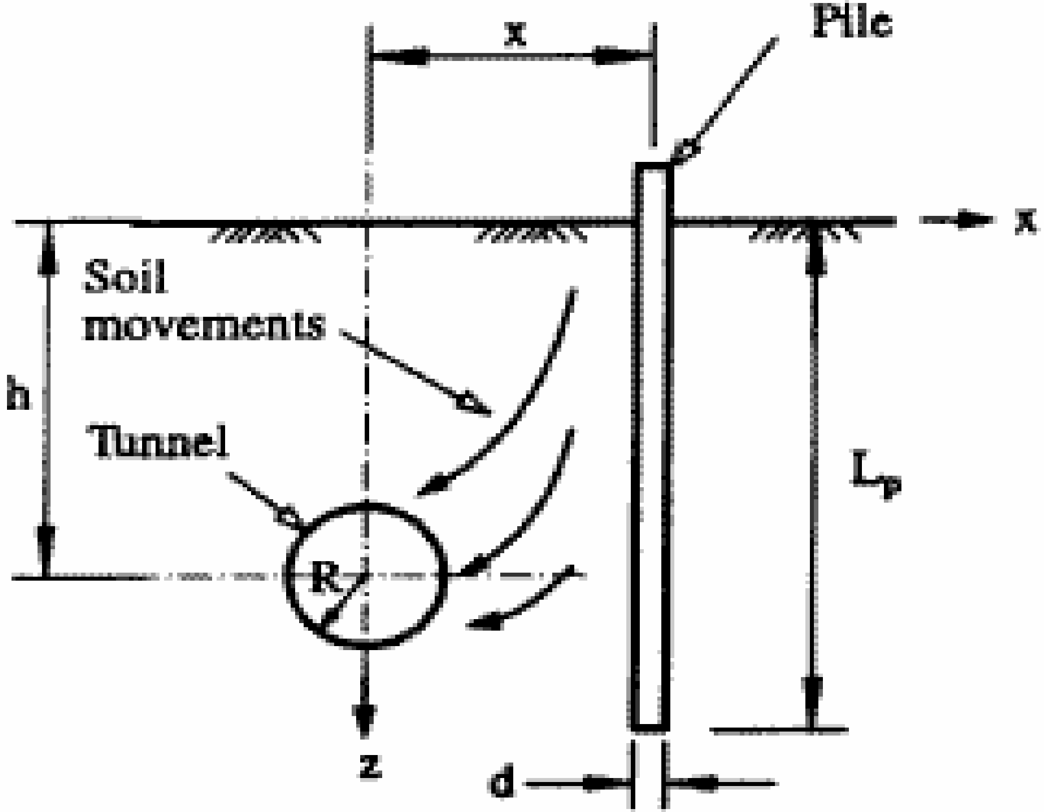


FIG. 1. Pile Adjacent to Tunneling—Basic Problem Analyzed

DESIGN EQUATIONS

- Lateral Response
  - $M_{max} = M_b.k_{cu}^m.k_d^m.k_{lp}^m$
  - $\rho_{max} = \rho_b.k_{cu}^r.k_d^r.k_{lp}^r$
- Axial response
  - $+P_{max} = P_b.k_{cu}^p.k_d^p.k_{lp}^p$
  - $v_{max} = v_b.k_{cu}^v.k_d^v.k_{lp}^v$

BASIC CURVES

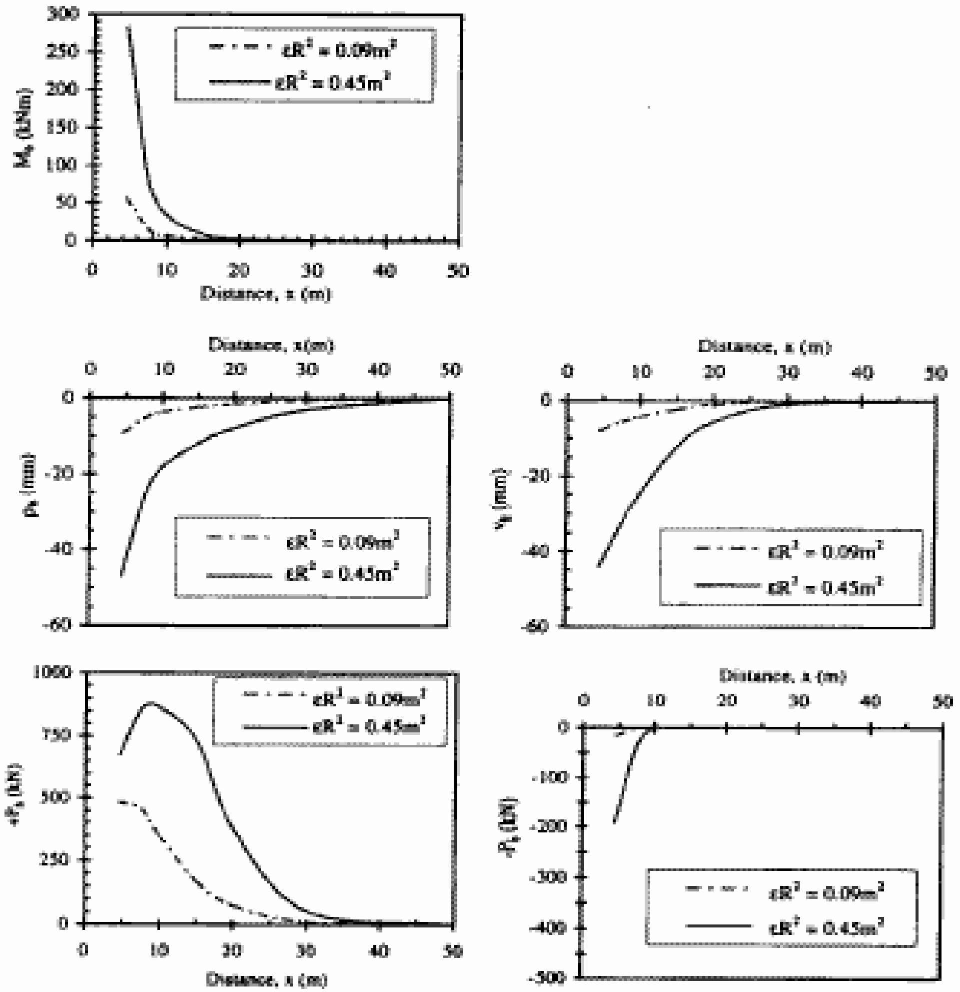


FIG. 4. Maximum Pile Responses versus Distance *x* for Long Pile Case

CORRECTIONS FOR SHEAR STRENGTH

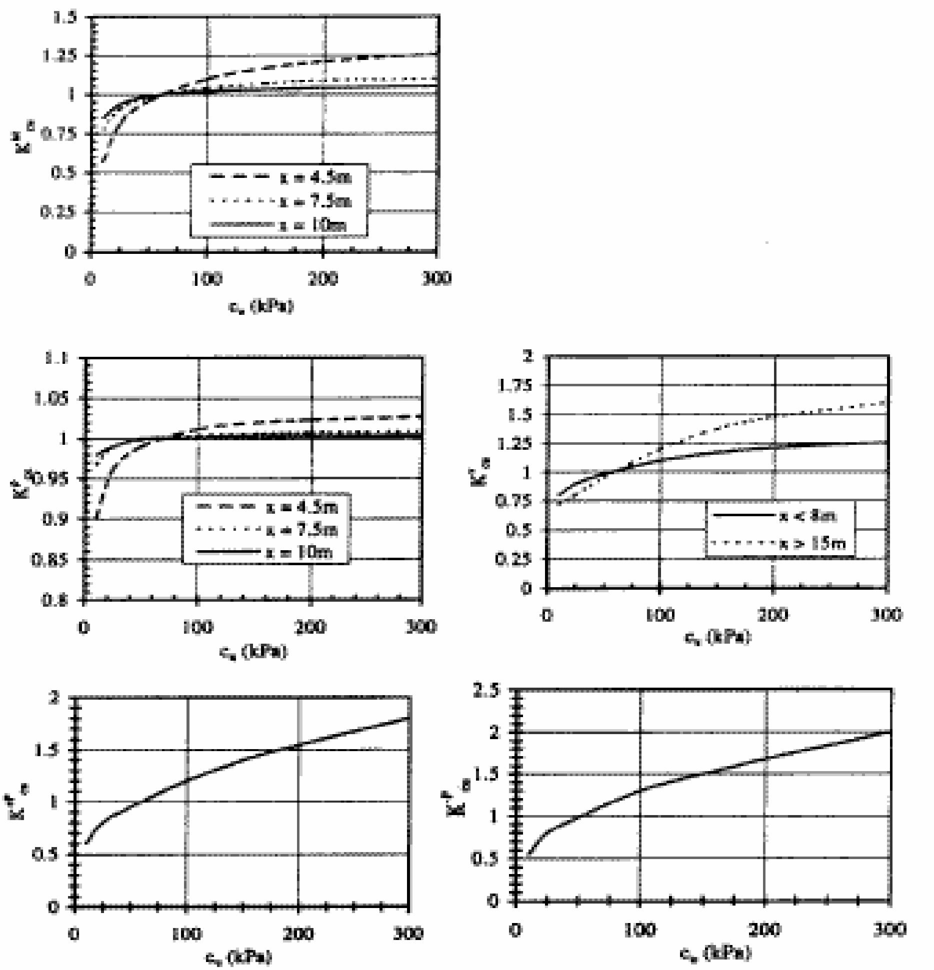


FIG. 6. Correction Factors for c_u

CORRECTIONS FOR PILE DIAMETER

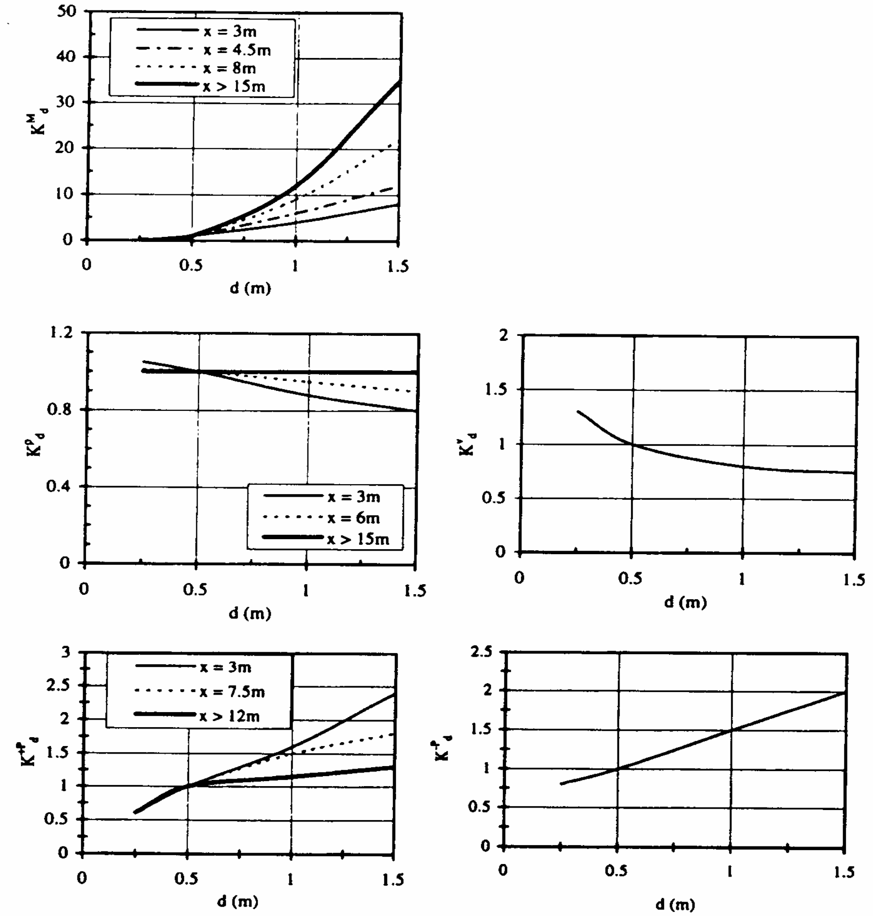


FIG. 7. Correction Factors for *d*

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CORRECTIONS FOR RELATIVE PILE LENGTH

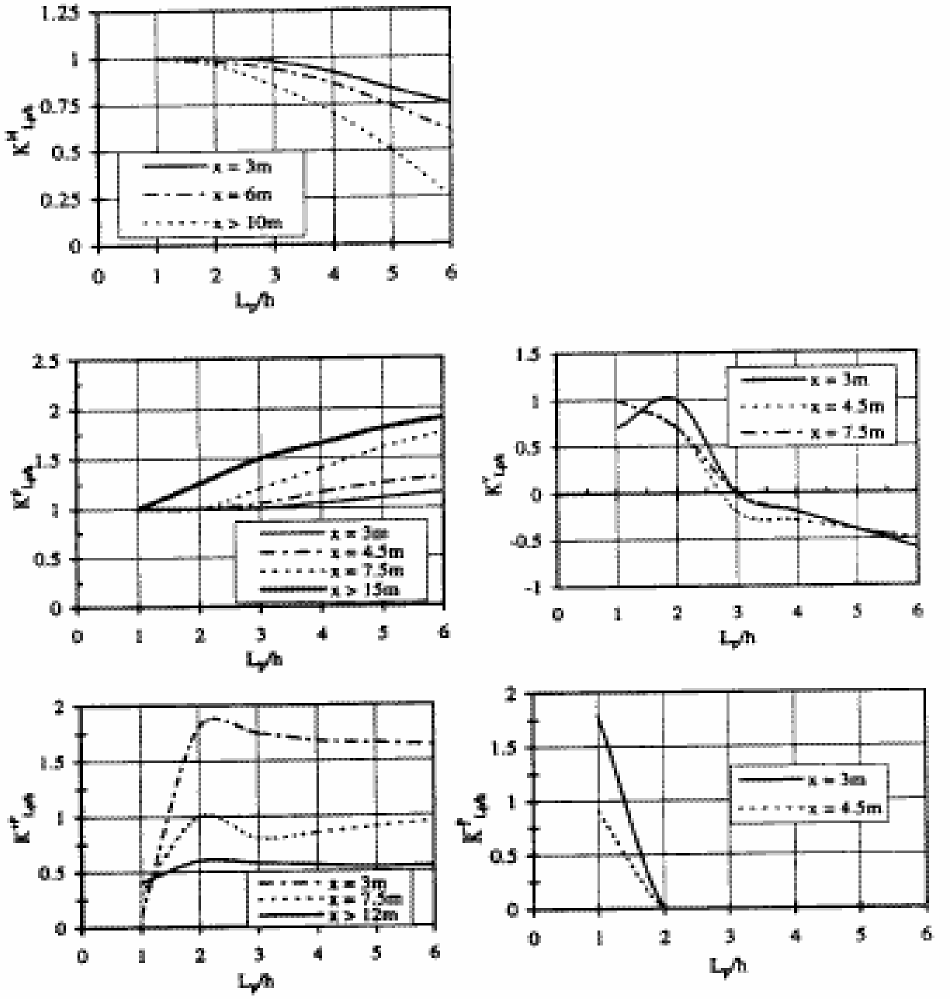
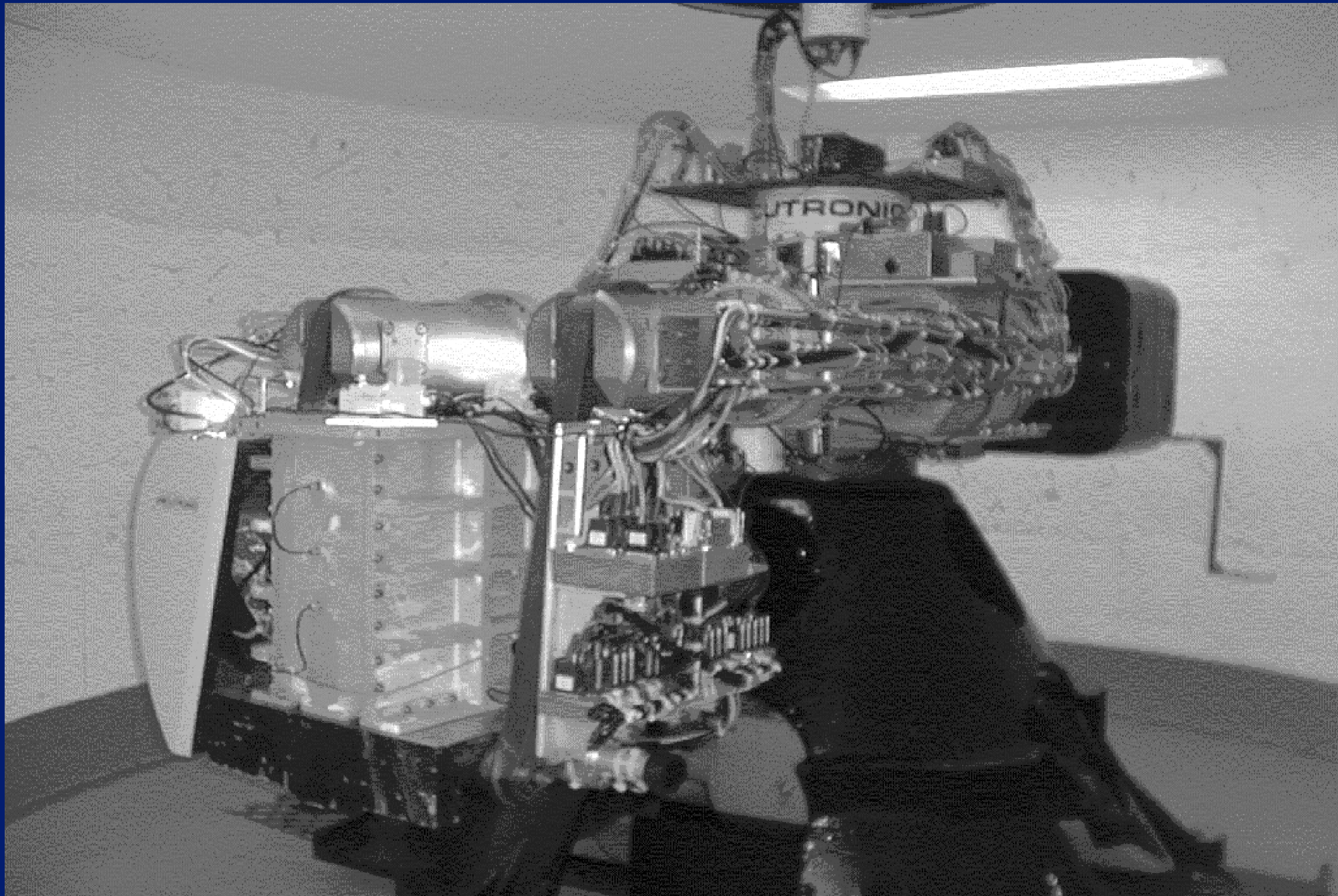


FIG. 8. Correction Factors for L_p/h

GEOTECHNICAL CENTRIFUGE (UWA)



CENTRIFUGE TEST SETUP

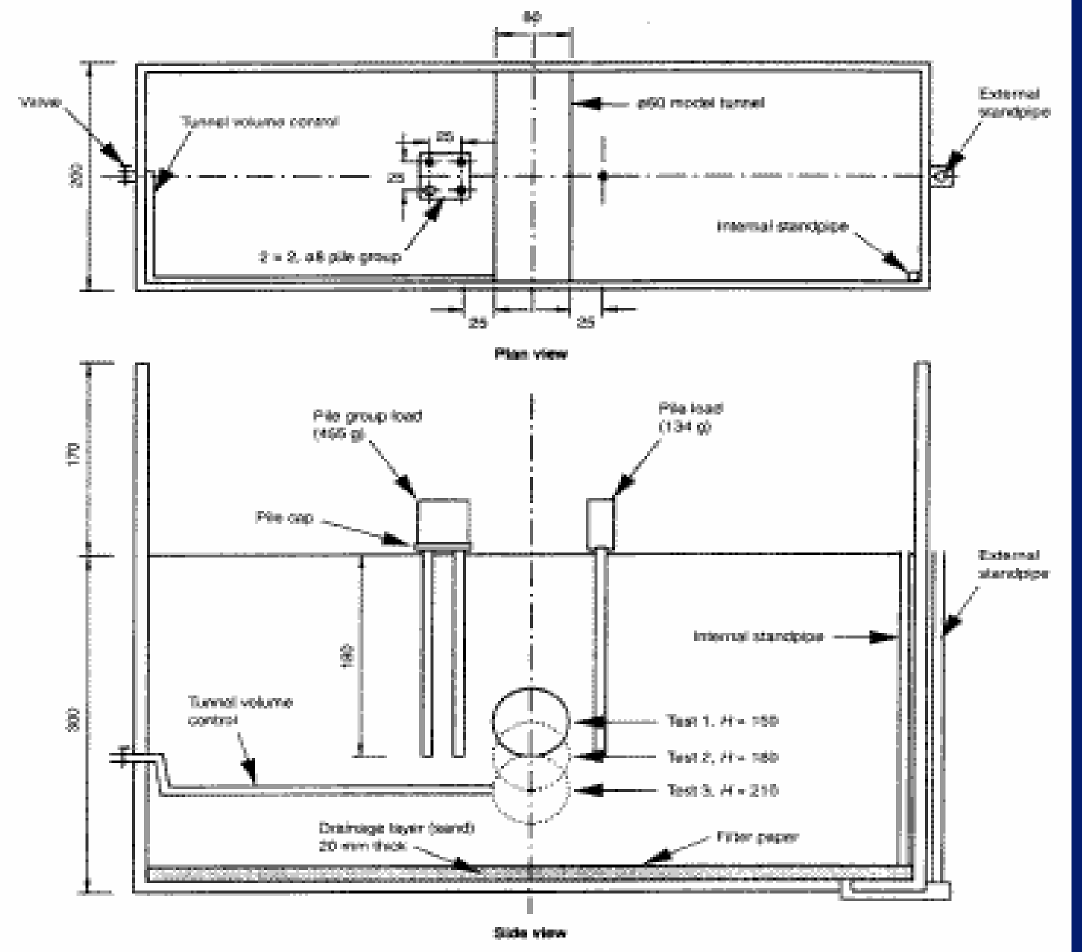
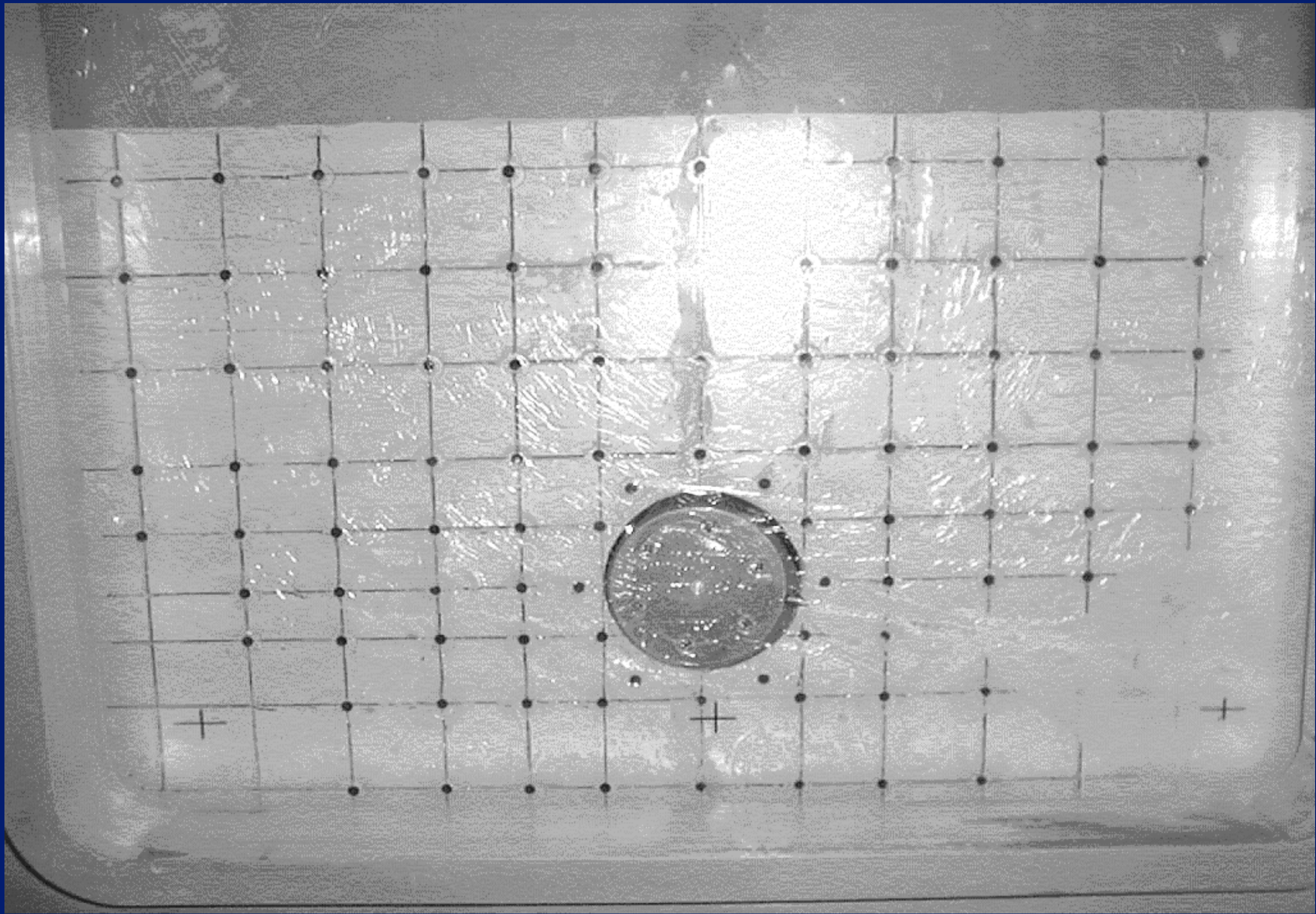
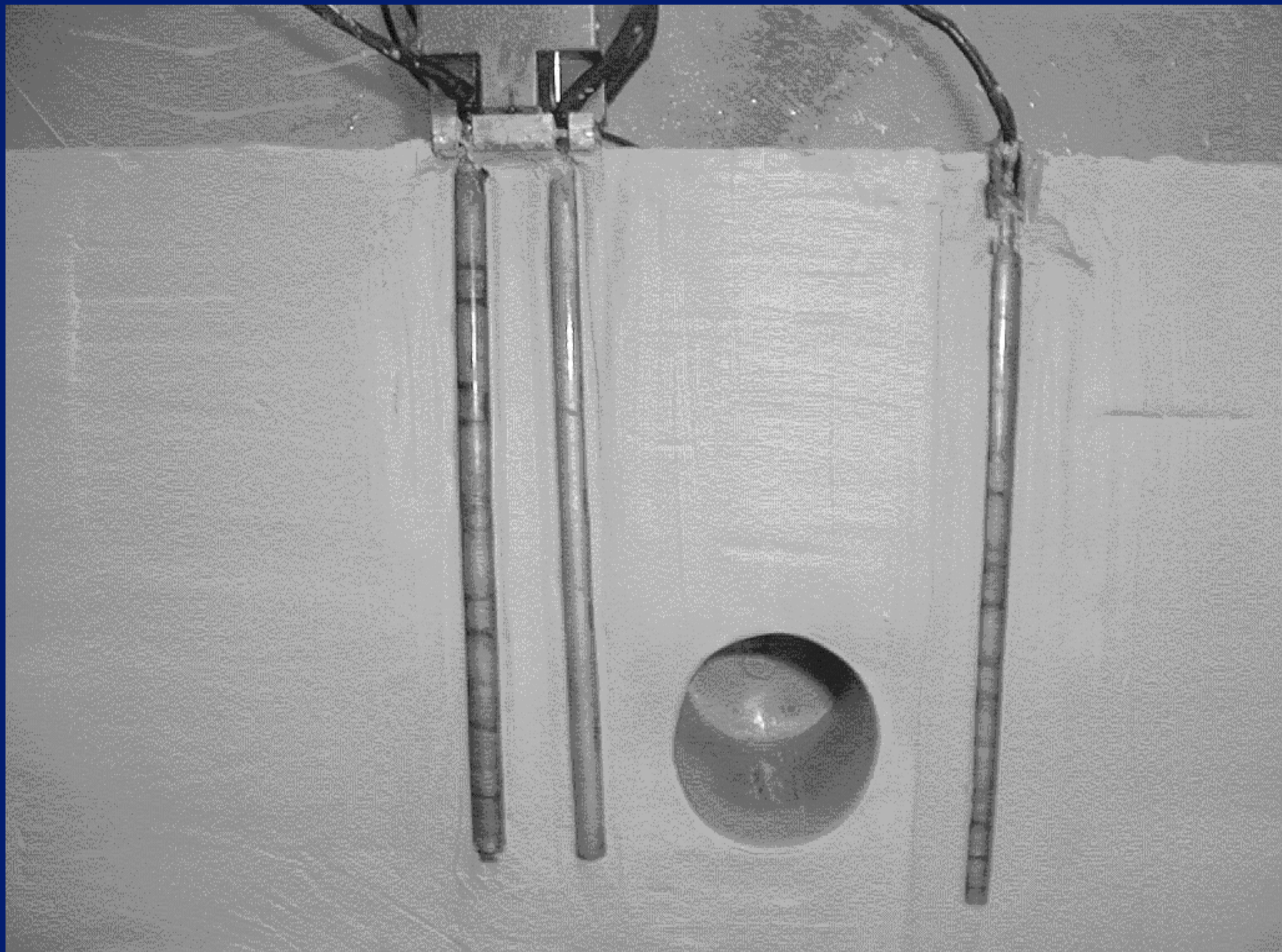


Fig. 1. Basic configuration of centrifuge model (dimensions in mm; H, depth to tunnel centre-line; ●, instrumented piles; ○, dummy pile)

CENTRIFUGE MODEL TEST SETUP



CENTRIFUGE MODEL TEST SETUP



COMPARISON OF SOIL SETTLEMENTS

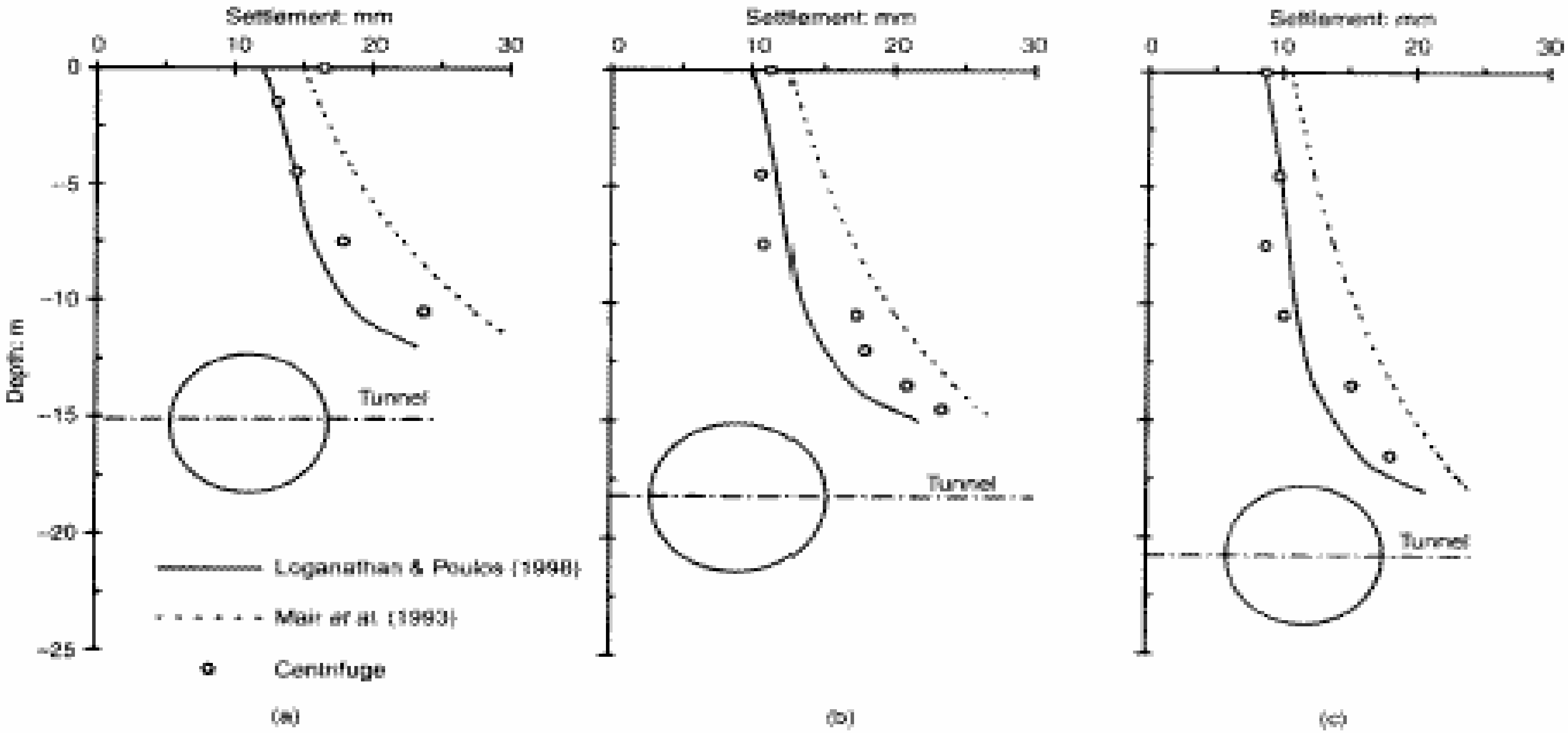


Fig. 13. Comparison of subsurface profiles: (a) test 1; (b) test 2; (c) test 3

COMPARISON OF LATERAL SOIL MOVEMENTS

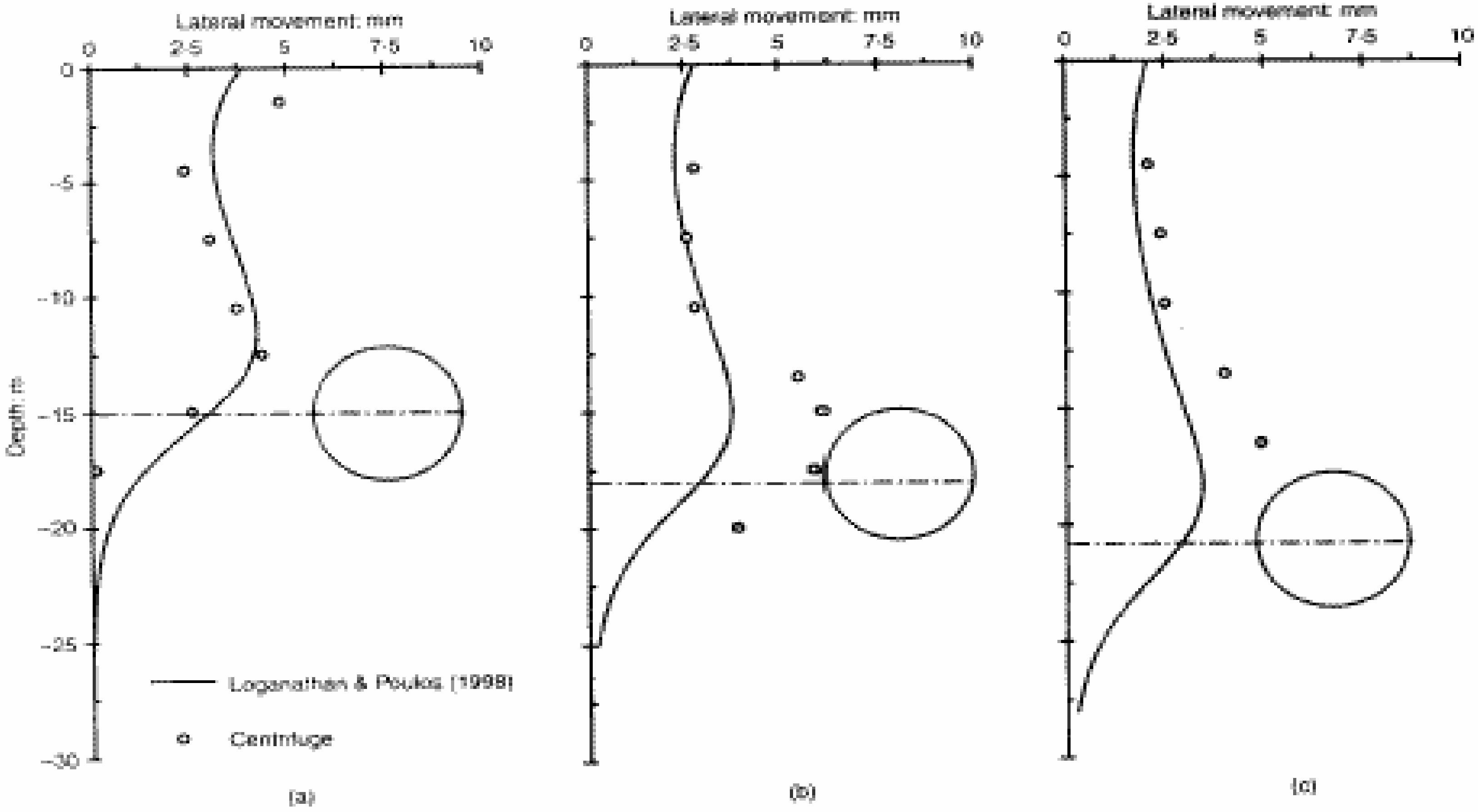


Fig. 14. Comparison of lateral soil movements 5·5 m from the tunnel: (a) test 1; (b) test 2; (b) test 3

MAXIMUM PILE MOMENTS

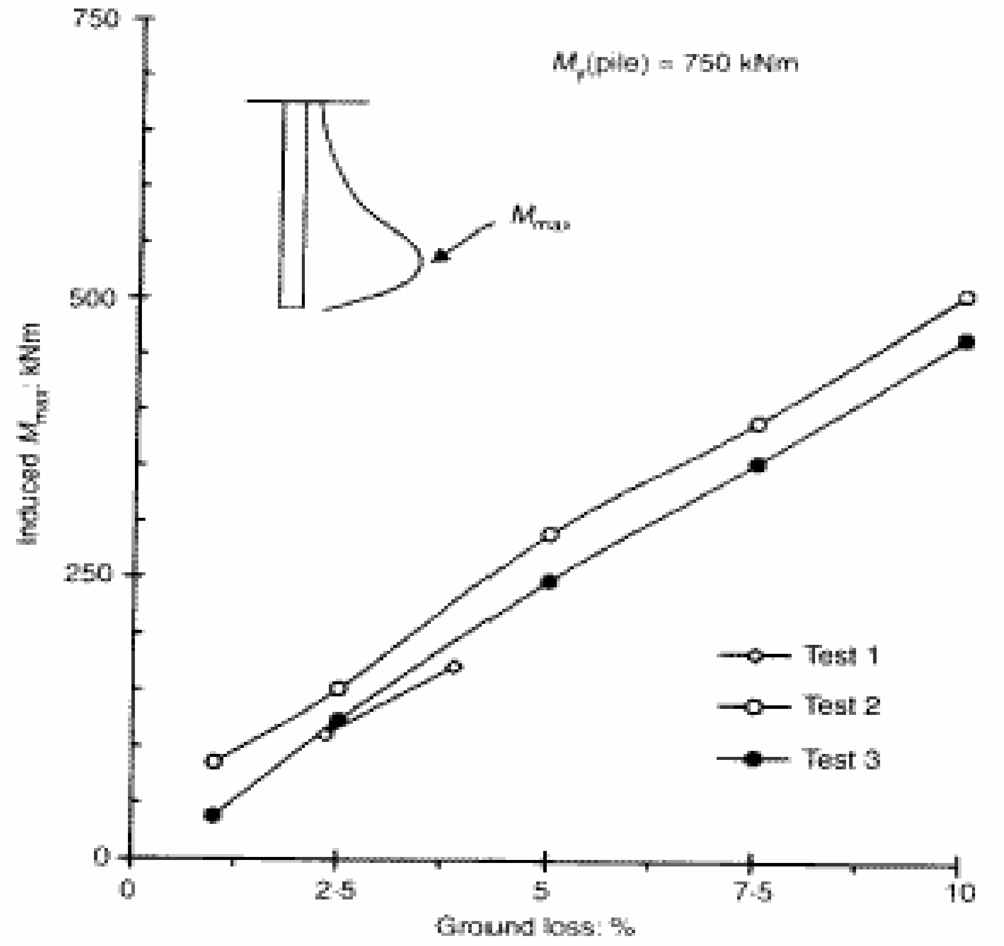
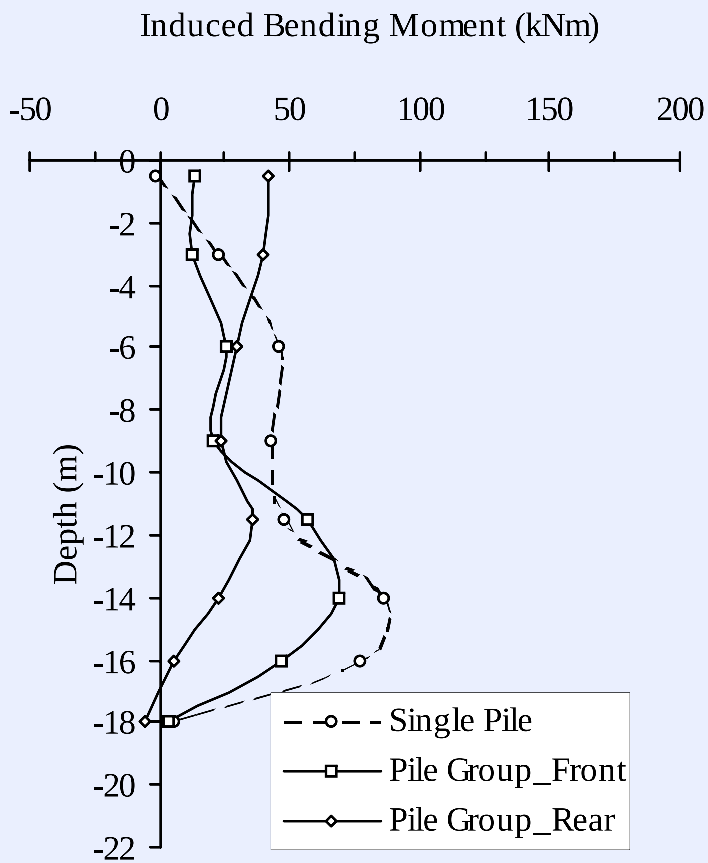
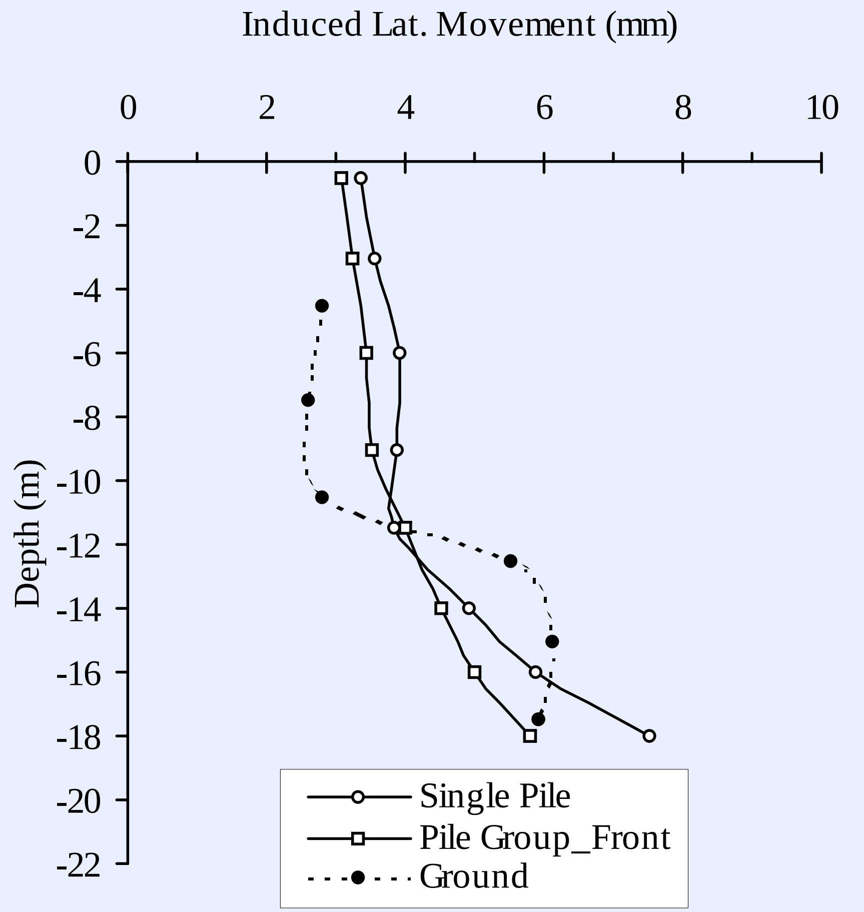


Fig. 19. Tunnelling-induced maximum bending moments for varying ground loss values

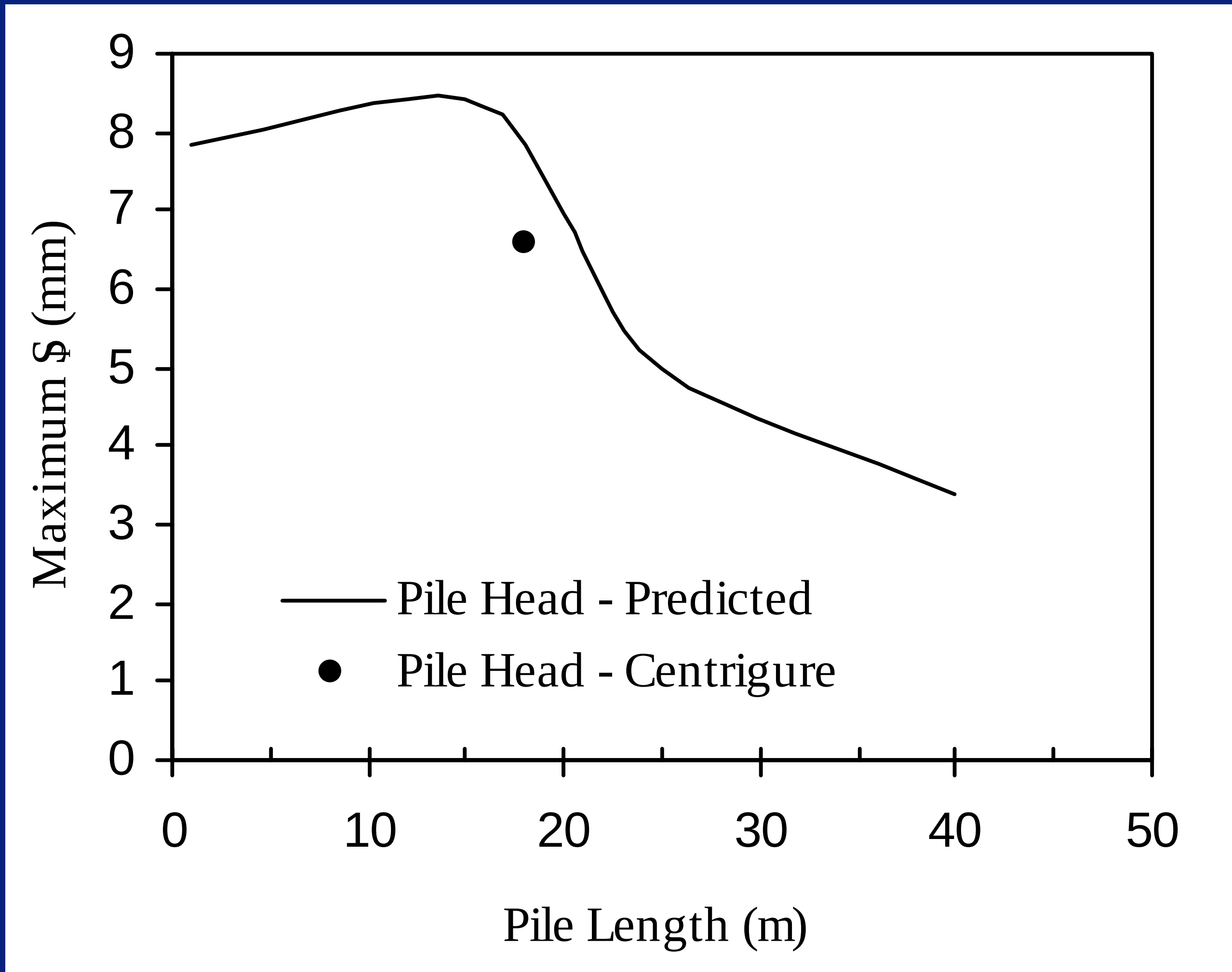
BENDING MOMENT DISTRIBUTIONS



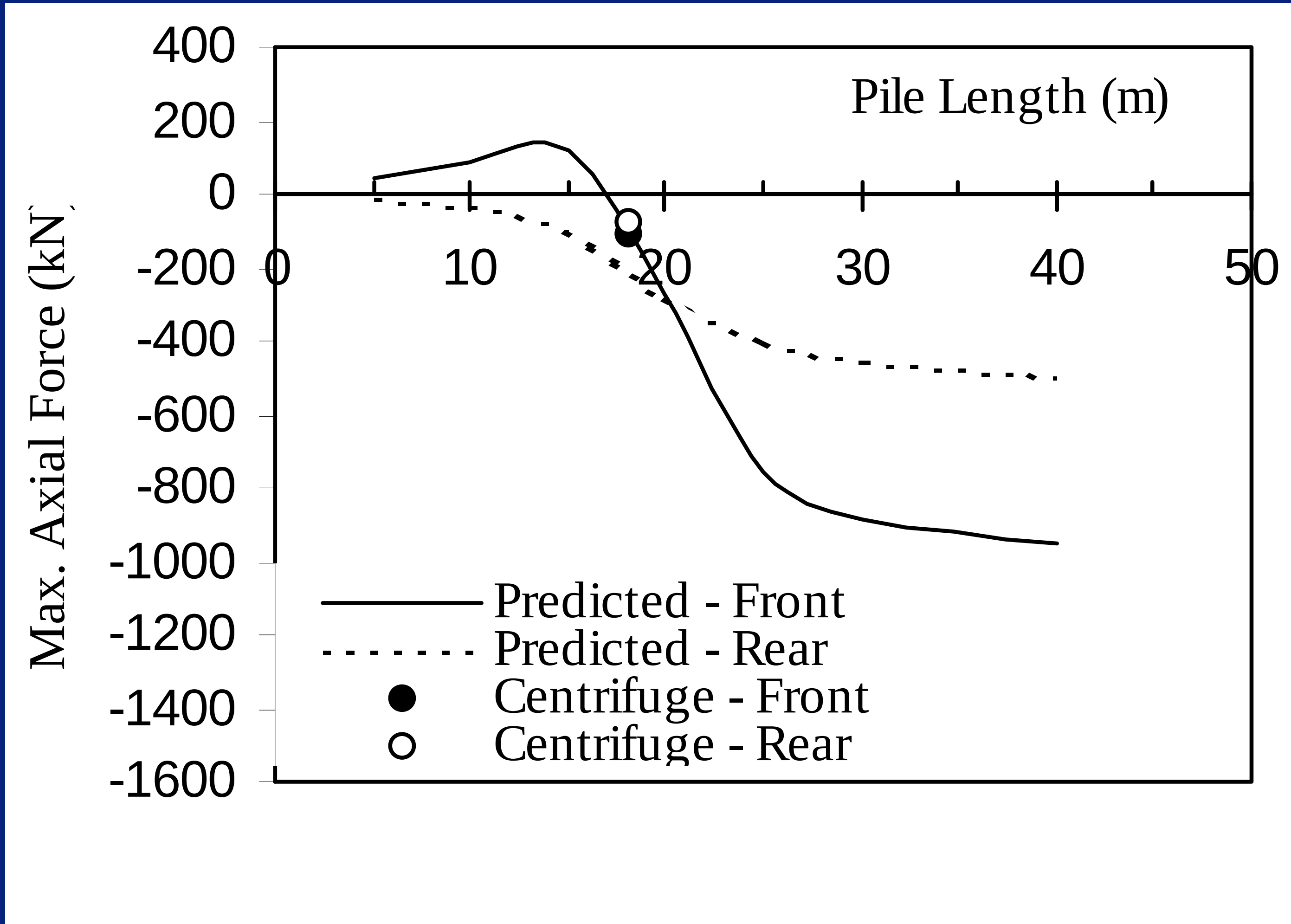
INDUCED LATERAL PILE MOVEMENT DISTRIBUTIONS



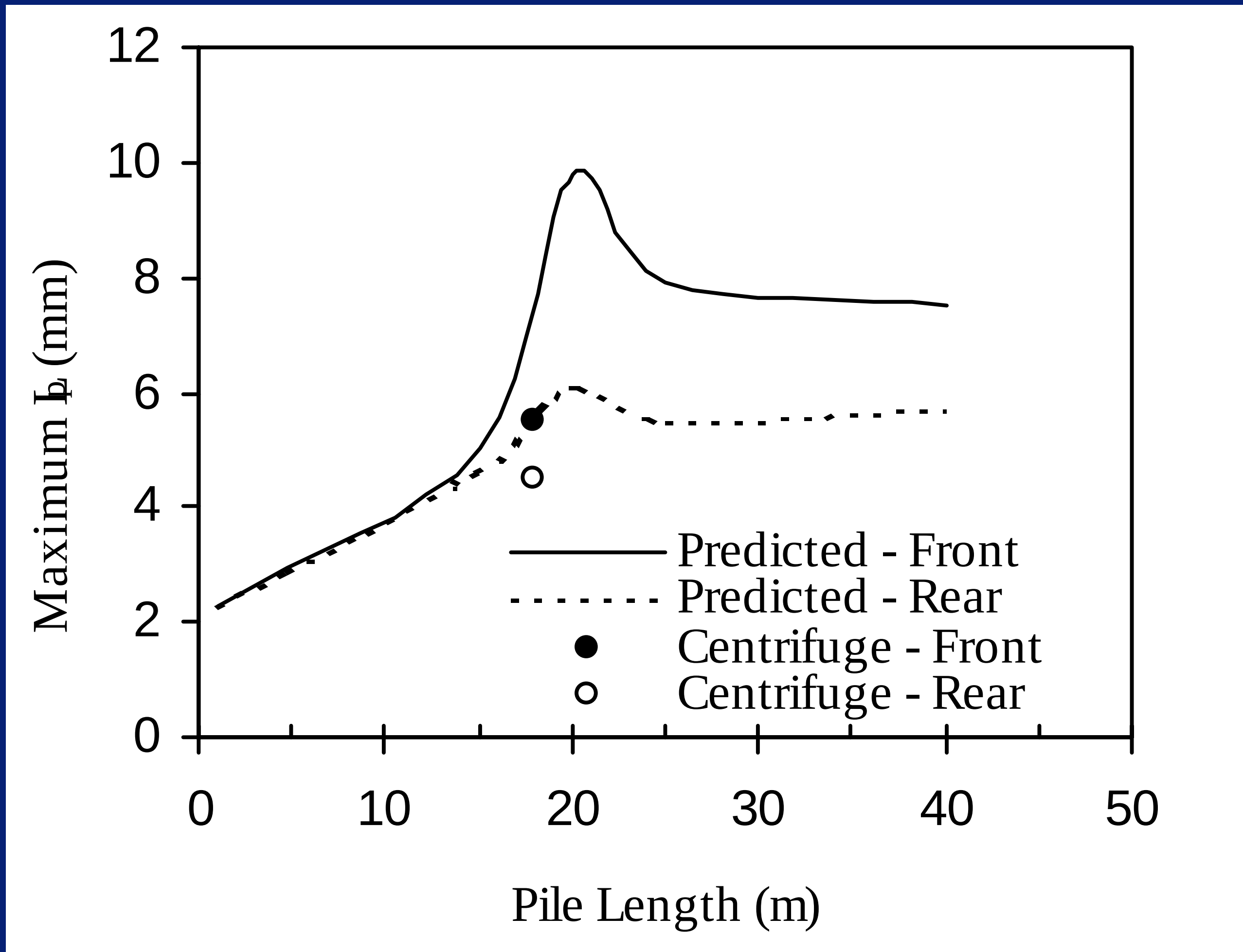
MEASURED AND COMPUTED PILE SETTLEMENTS



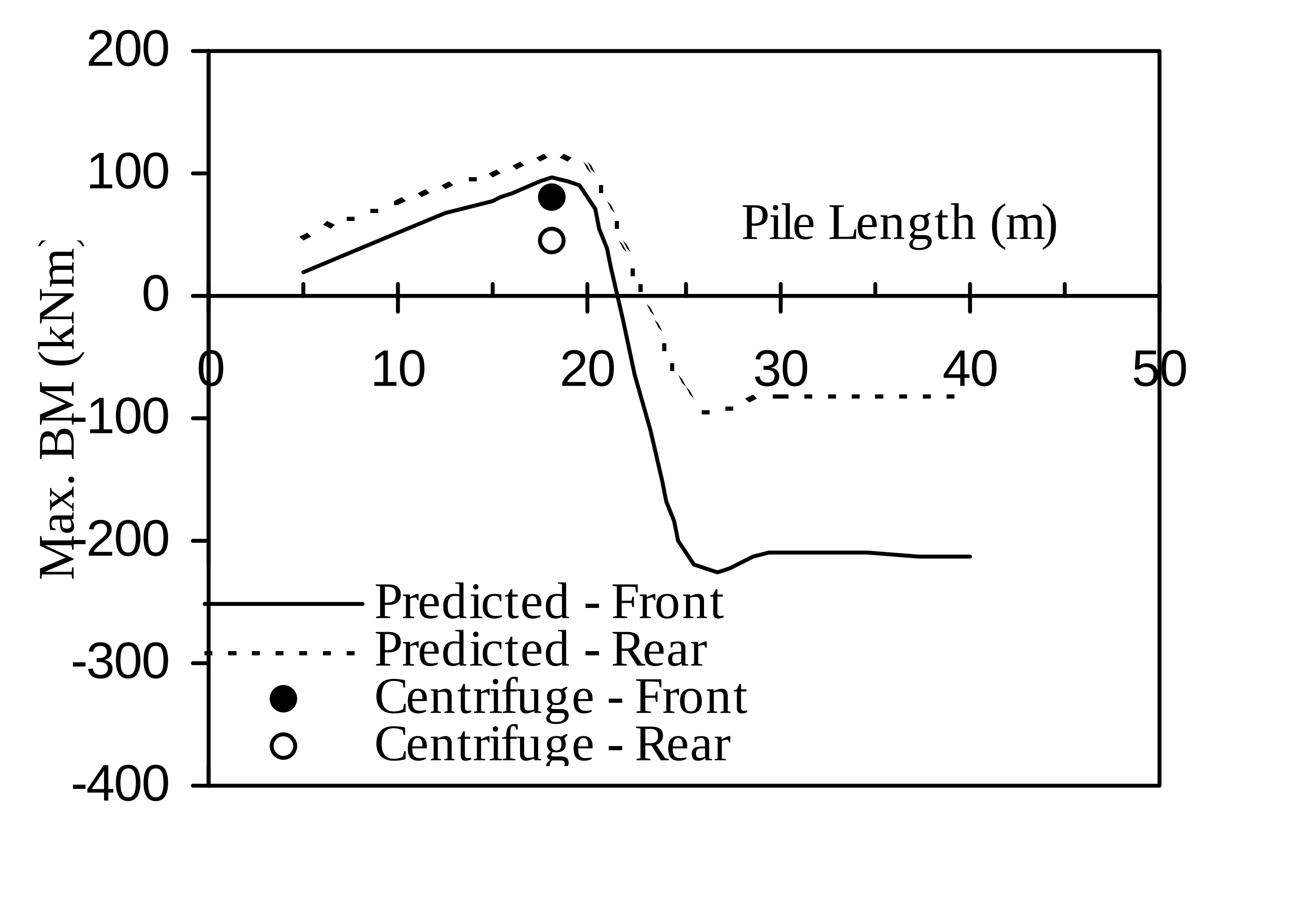
MEASURED AND COMPUTED PILE DOWNDRAG FORCES



MEASURED AND COMPUTED LATERAL PILE MOVEMENTS



MEASURED AND COMPUTED PILE MAXIMUM MOMENTS



RESPONSE OF PILE GROUPS

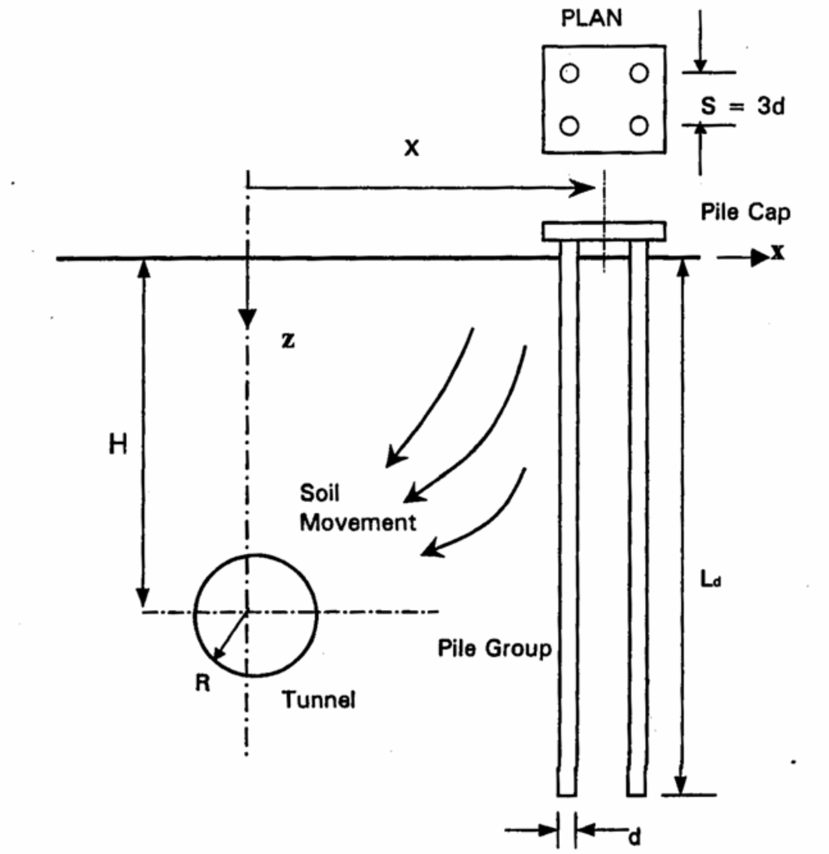


Fig. 9. Pile group adjacent to tunnelling—the basic problem analysed

Typical example of 4-pile group compared with a single pile at the same distance from the tunnel.

RESPONSE OF PILE GROUPS

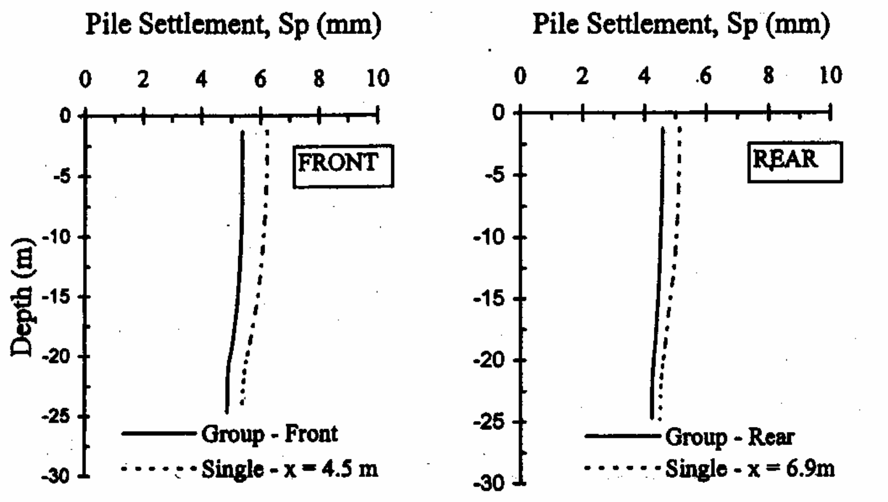


Fig. 10. Comparison of the settlement of a pile in a group and a single pile at equal distance from the tunnel axis

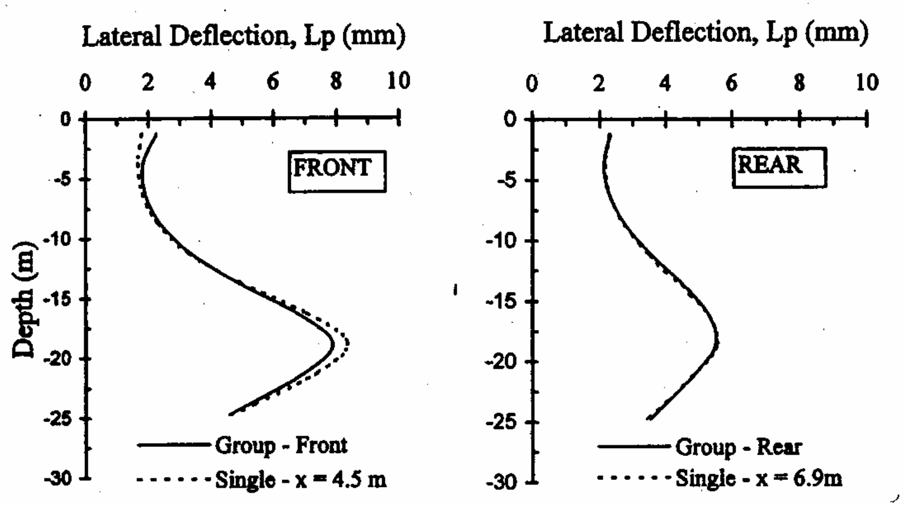


Fig. 11. Comparison of the lateral deformation of a pile in a group and a single pile

Settlements

Lateral deflections

RESPONSE OF PILE GROUPS

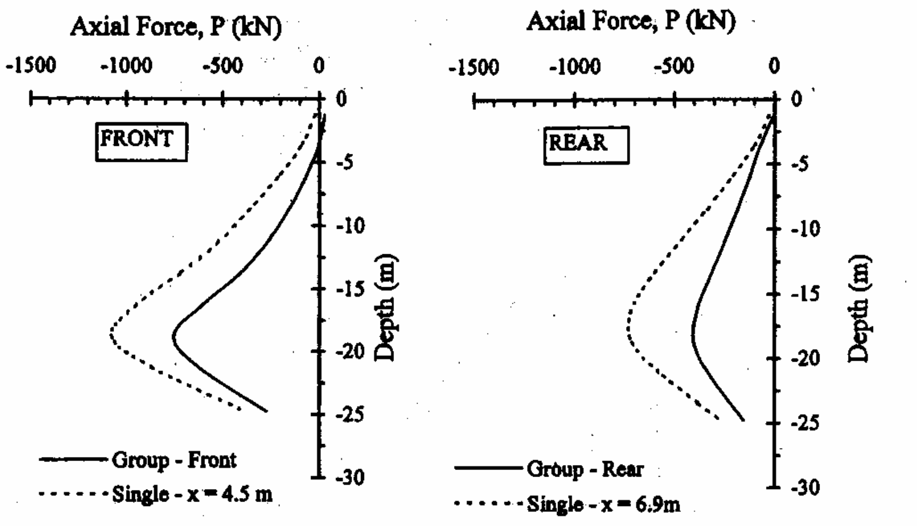


Fig. 13. Comparison of the induced axial forces on a pile in a group and a single pile

Induced Axial Force

- Settlements and lateral deflections of group & single pile are similar
- Axial forces in group less than an a single pile
- Thus, is conservative to use single pile solutions for a small group

MAIN CONCLUSIONS ON EFFECTS OF TUNNELLING

- Tunnelling can induce significant deflection and forces in piles
- Effects are most severe when pile is near tunnel
- Largest effects are when pile tip at or near tunnel invert
- Group effects reduce axial force and bending moments
- Pile cap condition has little effect – can usually assume free-head condition, unless pile is restrained.

RESPONSE OF TUNNEL TO PILE GROUP LOADING - Settlement

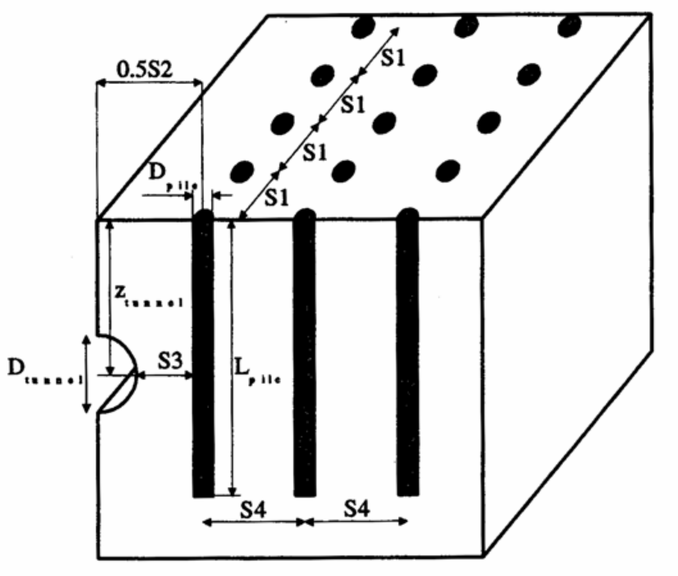


Figure 1. Geometric parameters in the modelling of pile-tunnel interaction

(D = 4.146 m)

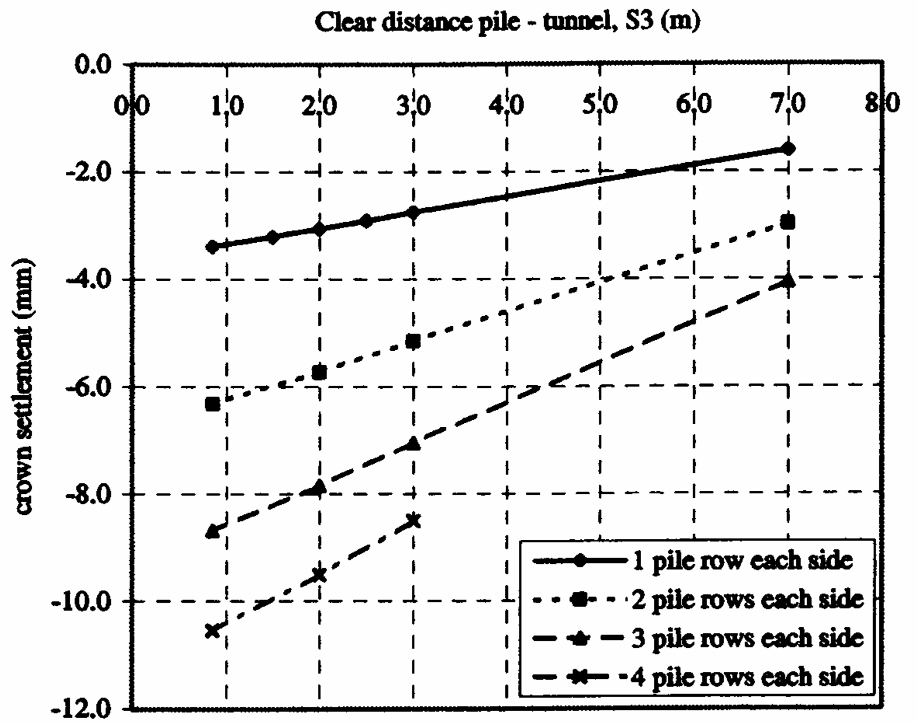
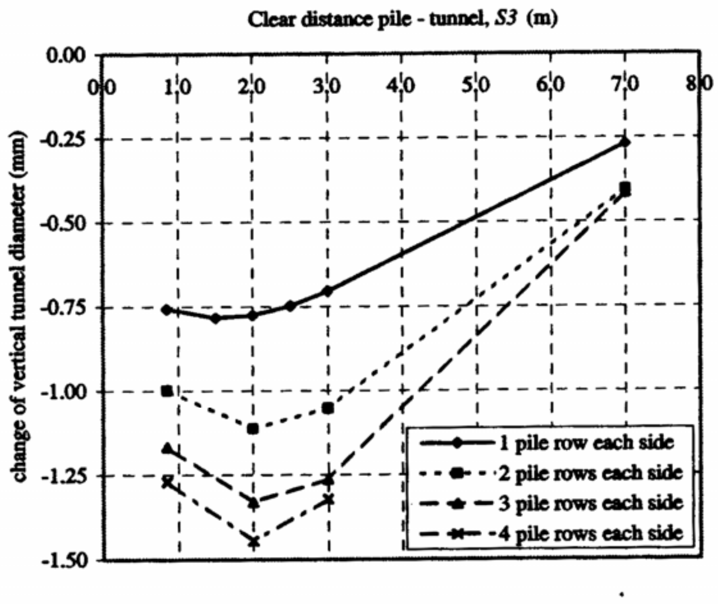


Figure 10. The influence of clear distance between pile and tunnel on tunnel crown settlement

RESPONSE OF TUNNEL TO PILE GROUP LOADING - Distortions

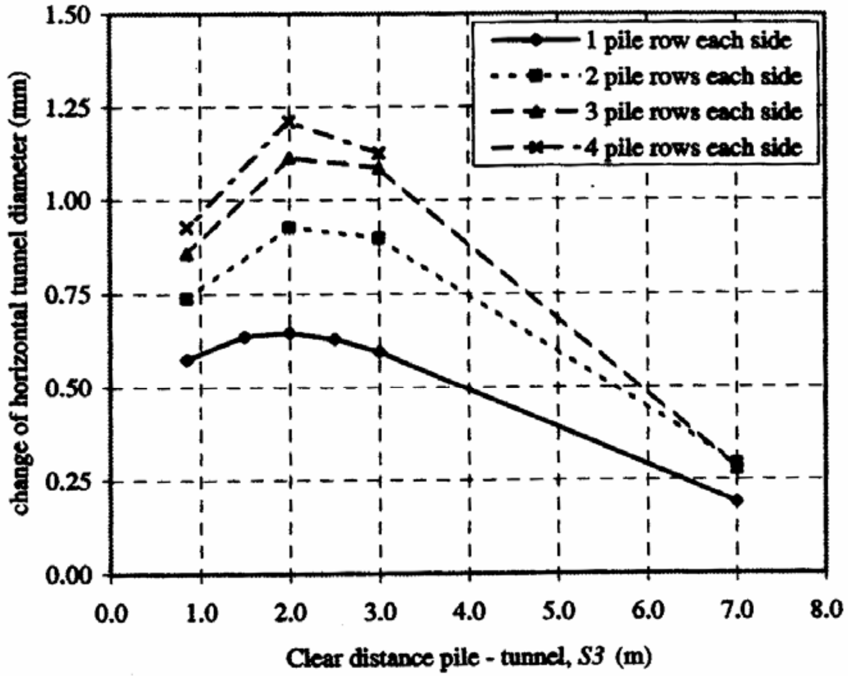


b)

Figure 8. The influence of the clear distance between piles and tunnel, *S3* on tunnel distortions.

a) increase of horizontal diameter

b) reduction of vertical diameter



a)

(D = 4.146 m)

CASE HISTORY APPLICATION - UK

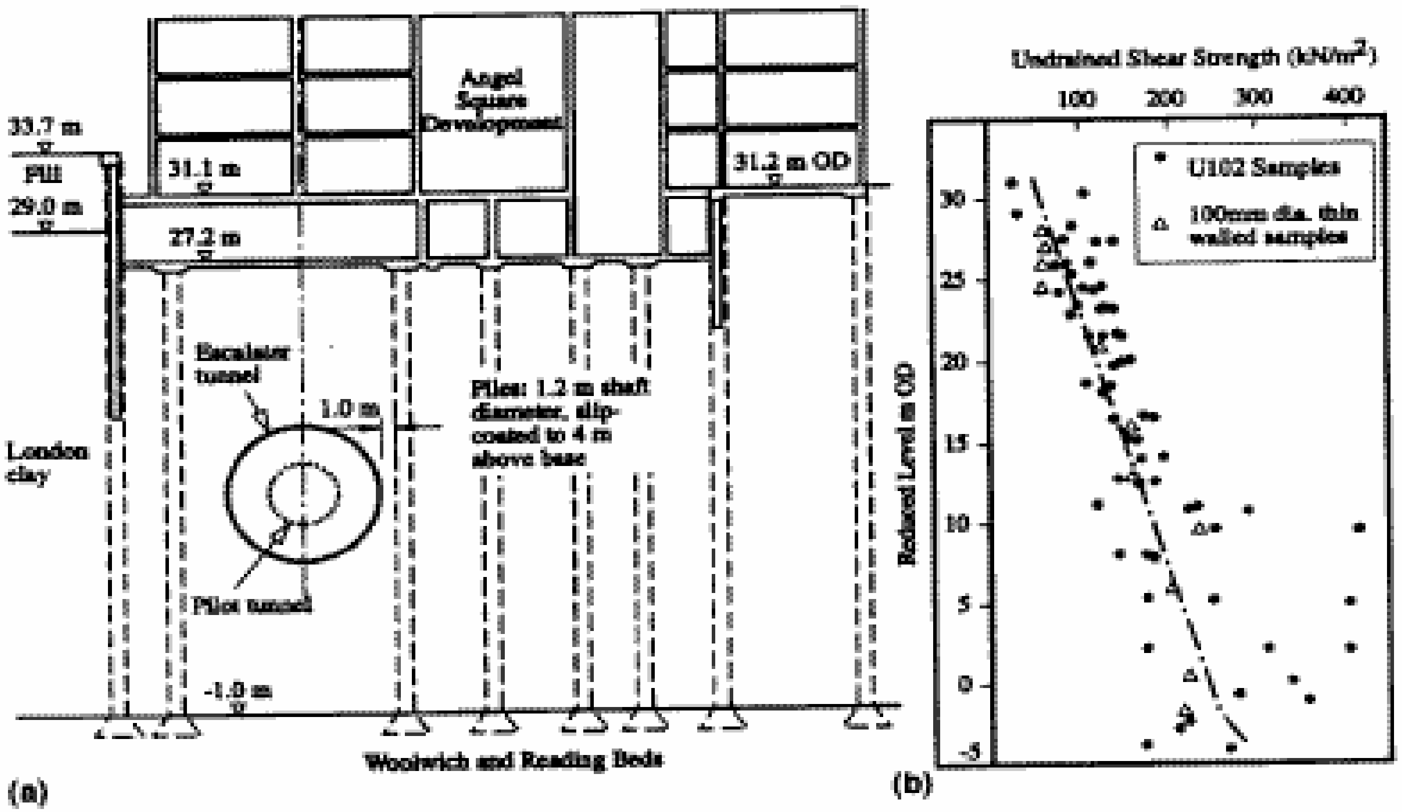


FIG. 9. Case History Studied Tunneling for Angel Underground Station [after Mair (1993) and Lee et al. (1994)] (a) Section through Angel Escalator Tunnel and Building Foundations; (b) Undrained Shear Strength

ANALYSIS vs MEASUREMENT

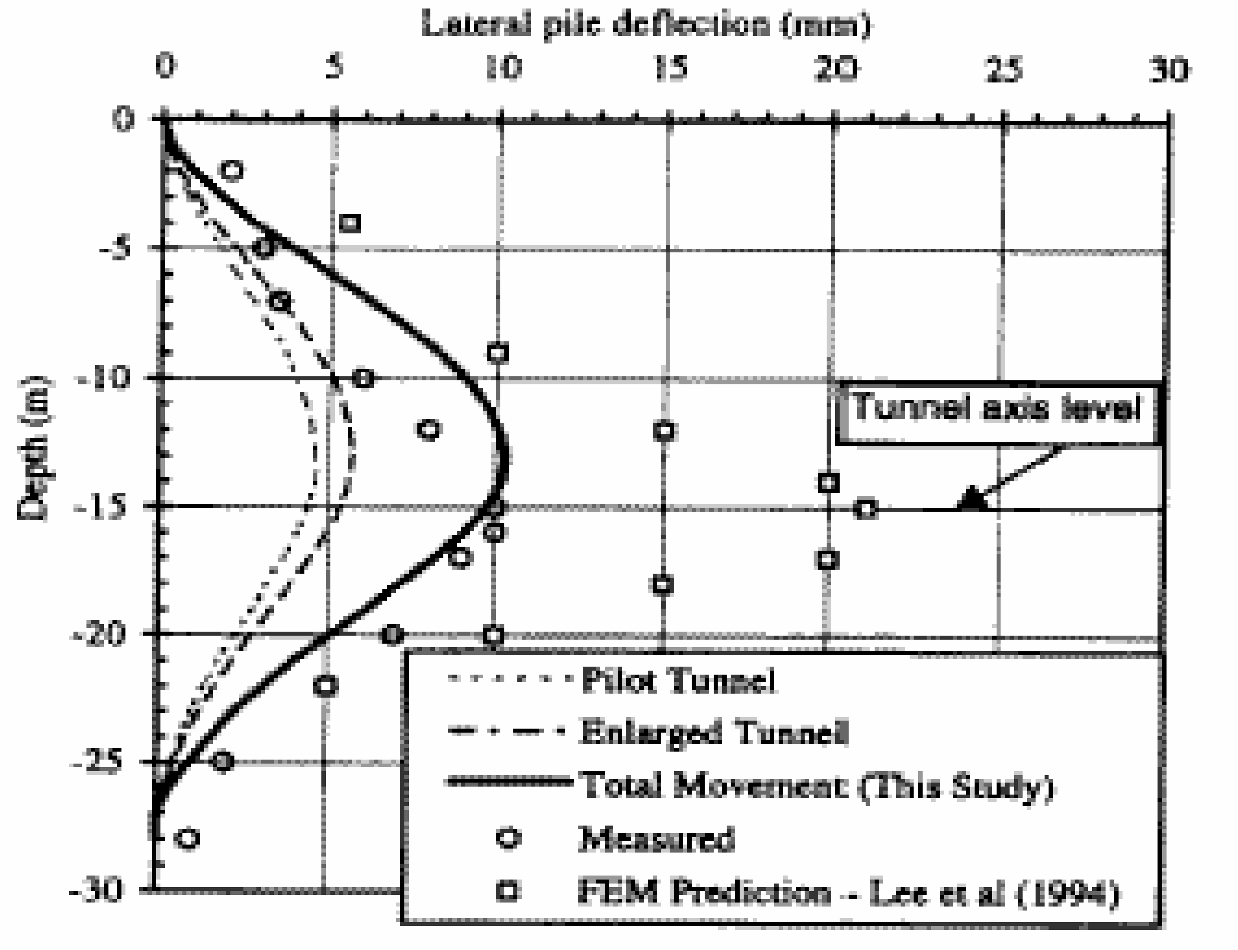
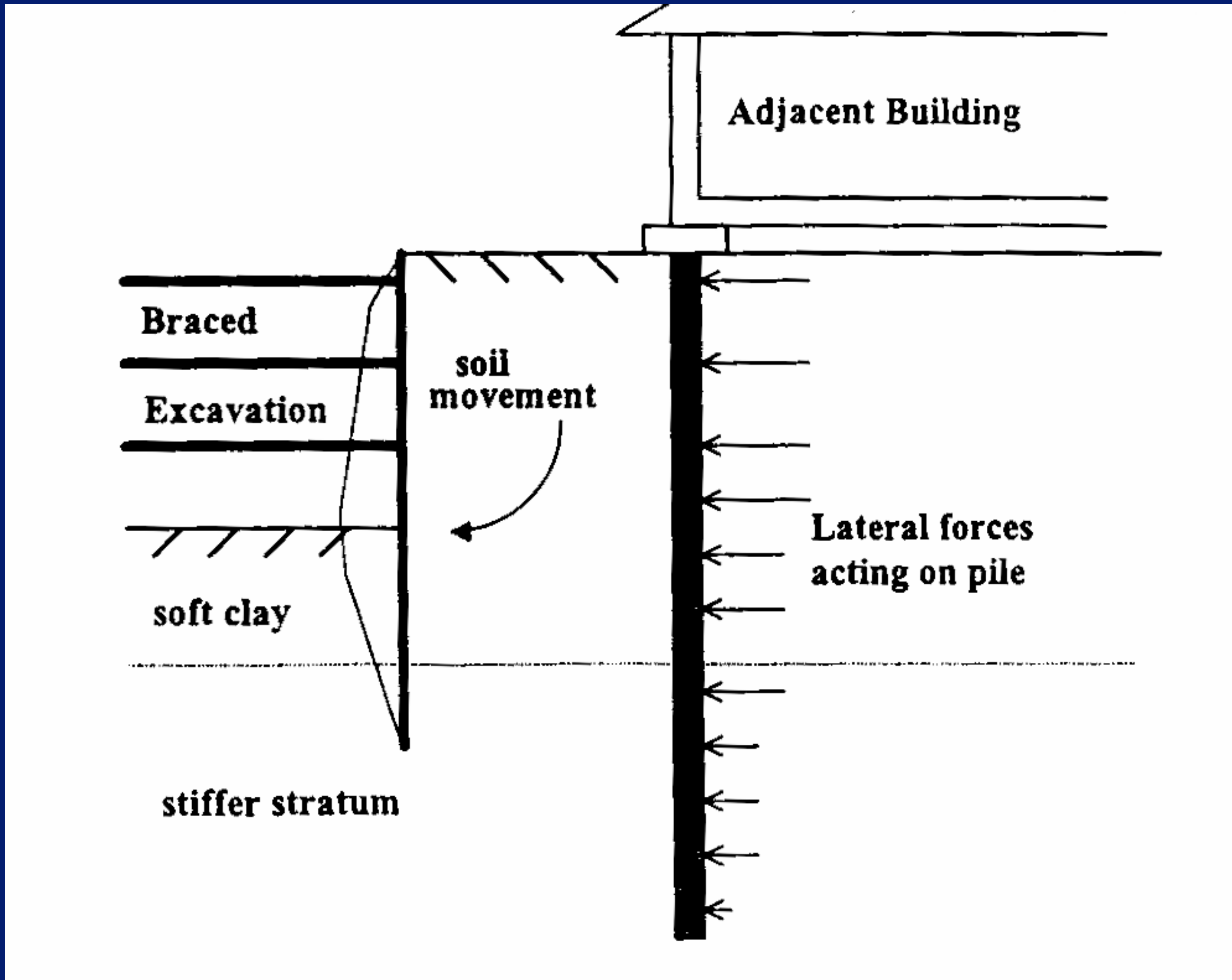


FIG. 10. Lateral Pile Deflection for Case History Studied

PILES NEAR AN EXCAVATION



PILES NEAR EXCAVATIONS

BASIC CASE FOR EXCAVATION ANALYSIS

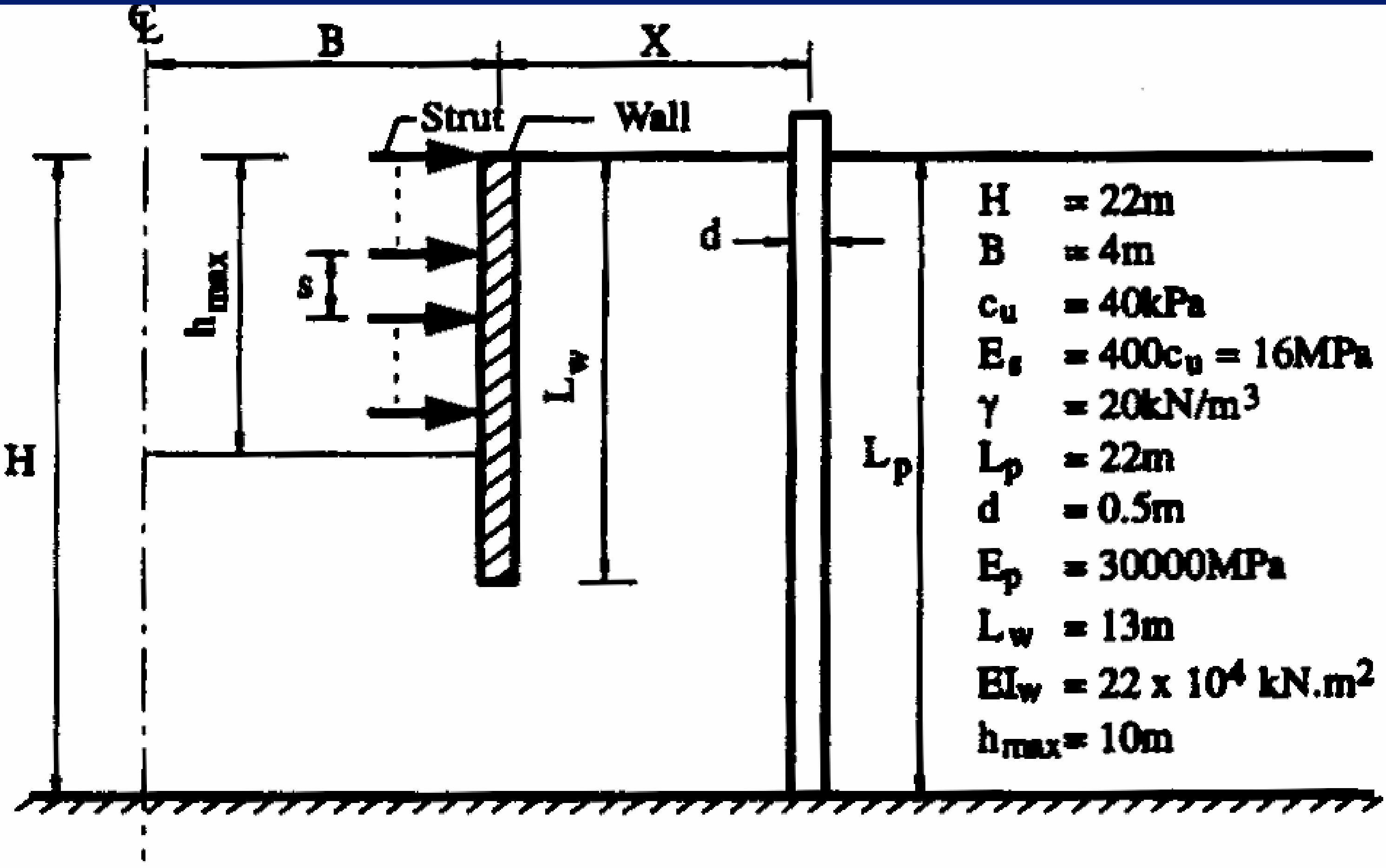


FIG. 1. Basic Problem Analyzed

TYPICAL PILE RESPONSES

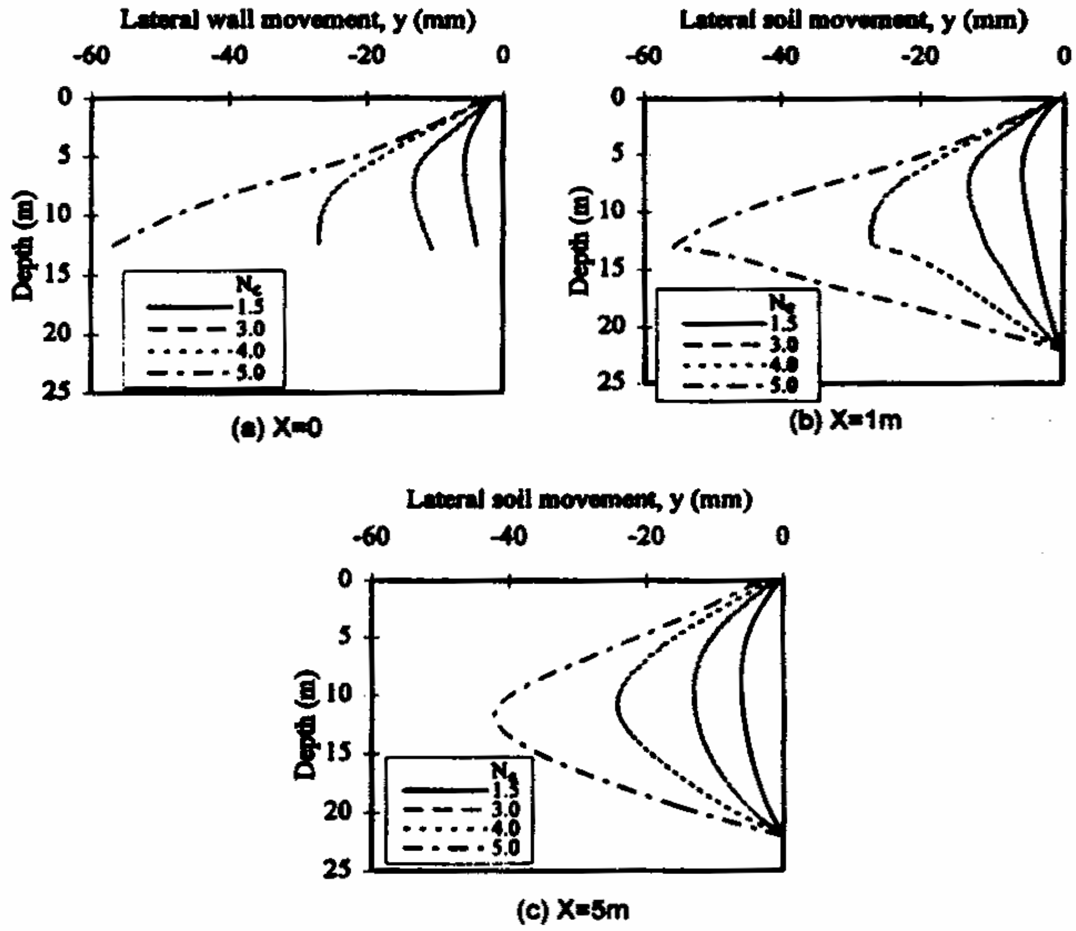


FIG. 3. Computed Lateral Wall and Soil Movement

MAXIMUM LATERAL SOIL MOVEMENT vs DISTANCE

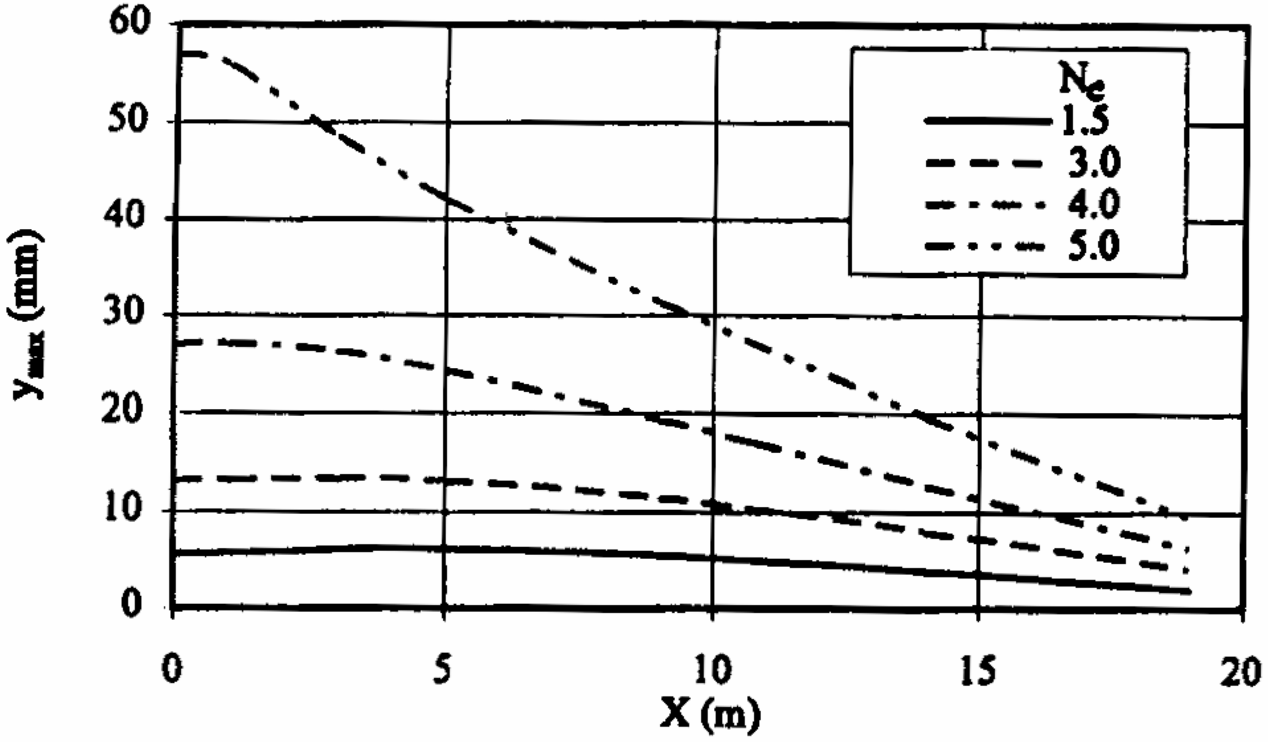


FIG. 4. Maximum Lateral Soil Movement versus Distance from Excavation Face

BENDING MOMENT vs DISTANCE

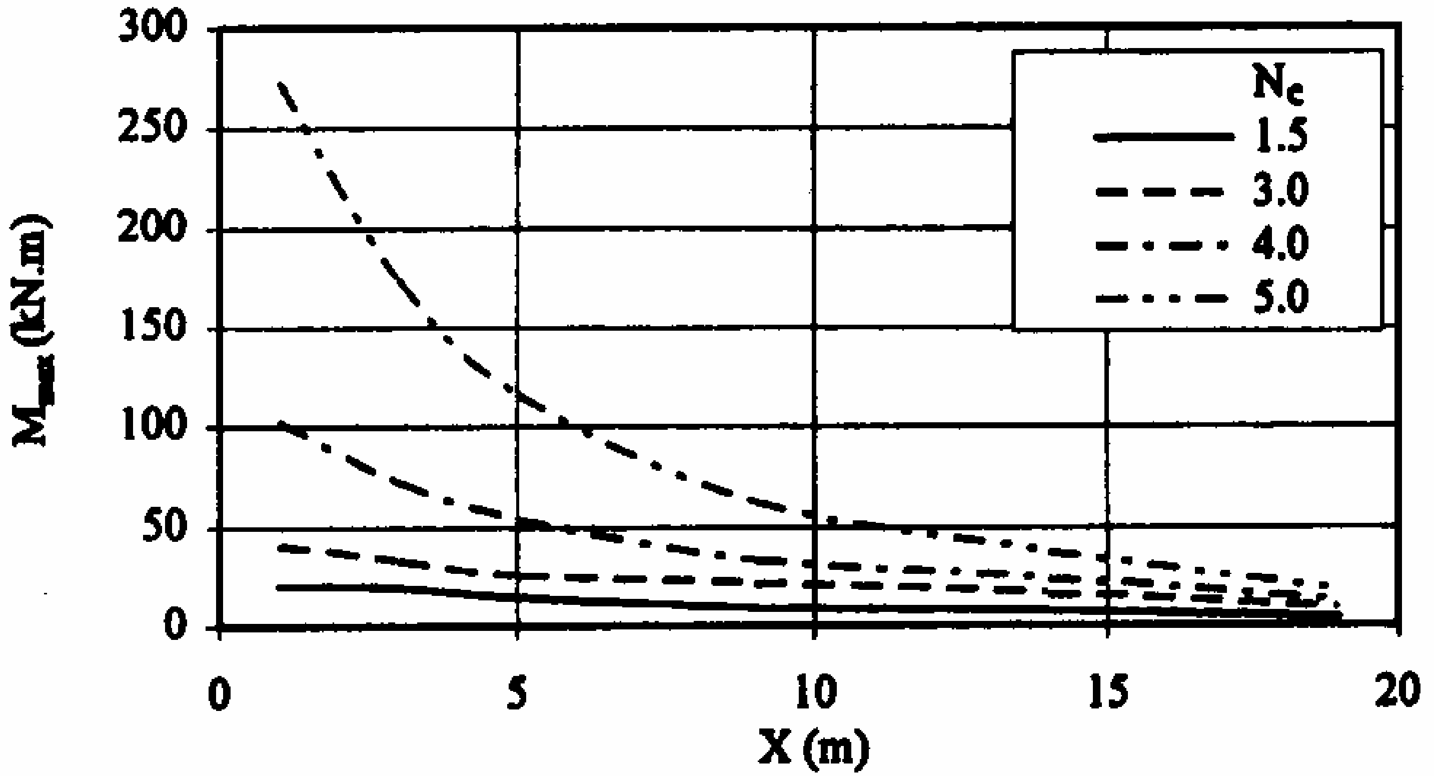


FIG. 6. Maximum Bending Moment versus Distance for Basic Problem

DETAILED PILE RESPONSES FOR BASIC PROBLEM

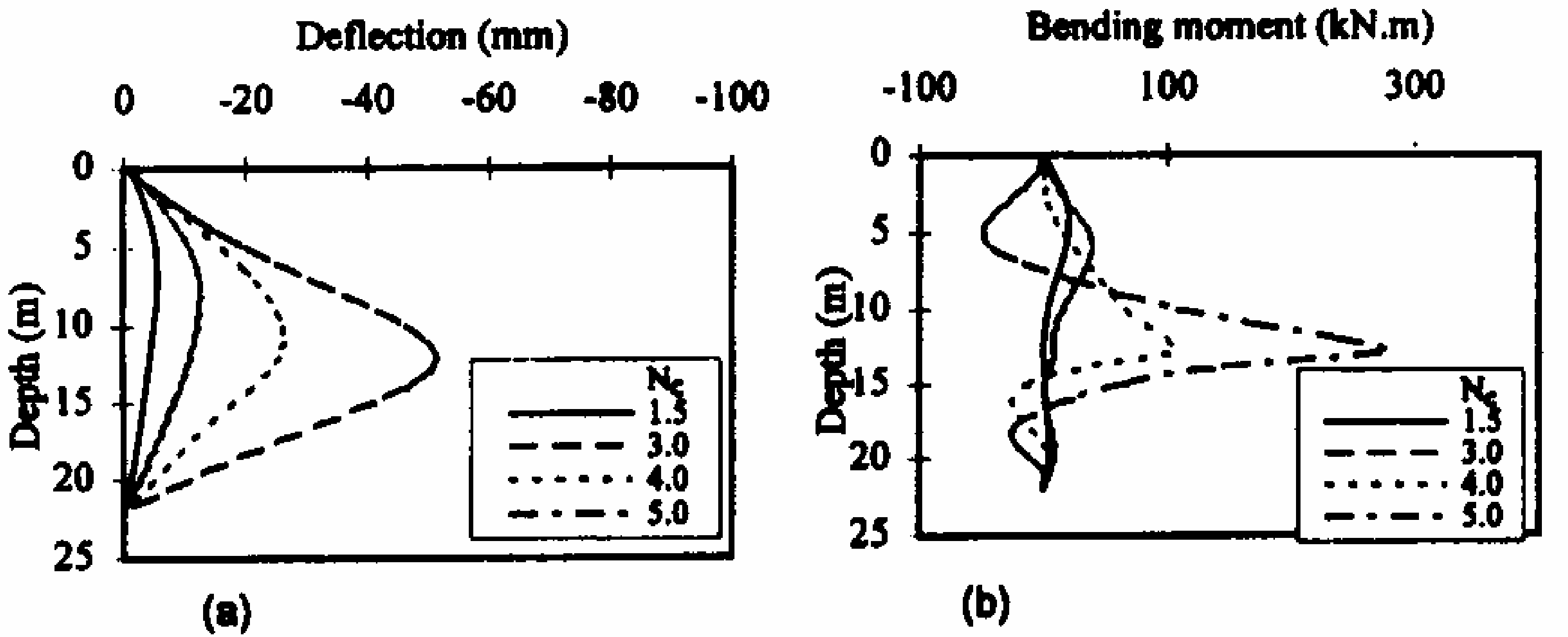


FIG. 5. Pile Response for Basic Problem: (a) Deflection Profile; (b) Bending Moment Profile

SENSITIVITY STUDY (Goh et al, 1996)

Table 1. Effects of variation of soil properties

Parameter	Variation of Max. BM
Reduce G/c_u of soft clay by 2 times	-5%
Increase G/c_u of soft clay by 2 times	+4%
Increase G/c_u for stiff clay by 2 times	0%
$p_y = 10.5c_u$ for soft and stiff clay	+6%

DESIGN EQUATIONS FOR LATERAL RESPONSE

MAXIMUM MOMENT:

- $M_{max} = M_b.k_{cu}.k_d.k_{Nc}.k_{EIw}.k_k.k_s$

MAXIMUM DEFLECTION

- $\rho_{max} = \rho_b.k_{cu}'.k_d'.k_{Nc}'.k_{EIw}'.k_k'.k_s'$

Basic values M_b, ρ_b depend on distance from excavation.

Correction factors are for undrained shear strength, pile diameter, excavation depth (stability number), wall stiffness, strut stiffness, strut spacing respectively

BASIC CURVES FOR BENDING MOMENT

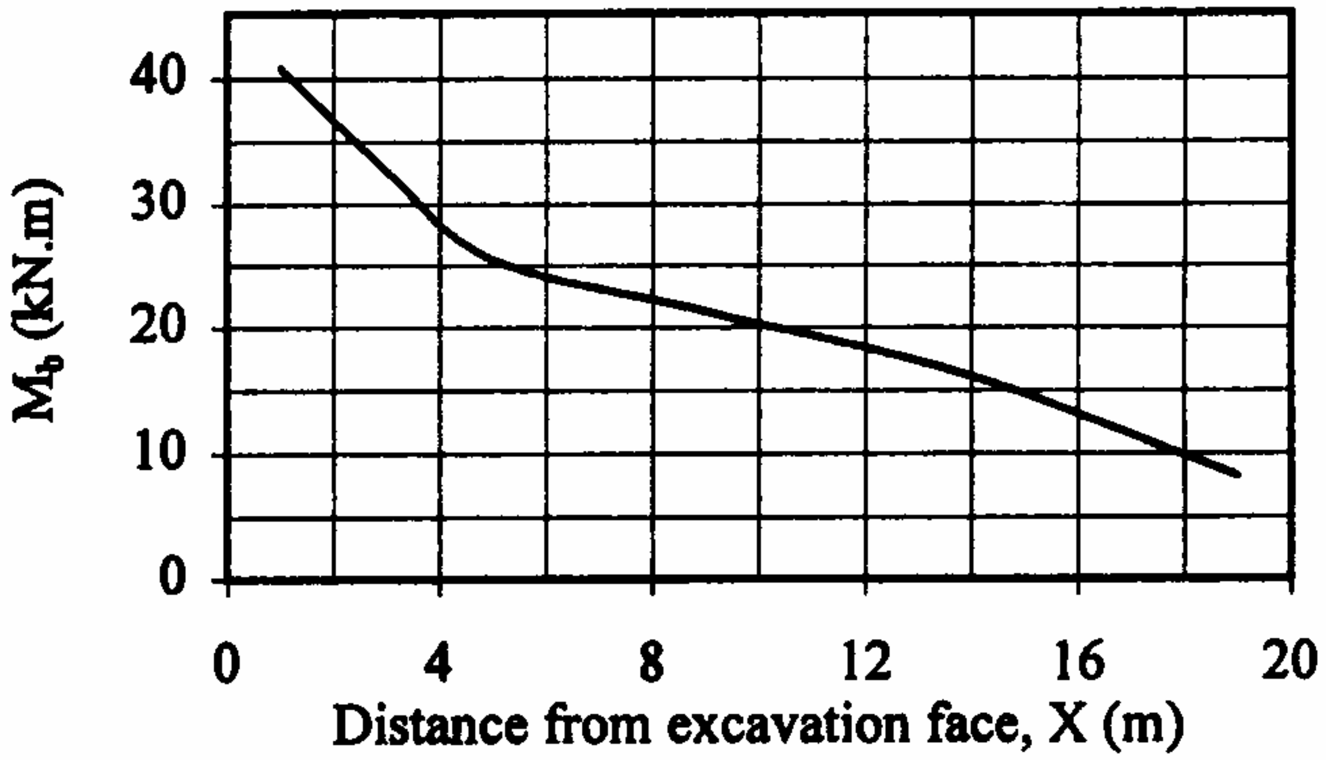


FIG. 7. Basic Bending Moment versus Distance from Excavation Face

CORRECTION CURVES FOR BENDING MOMENT

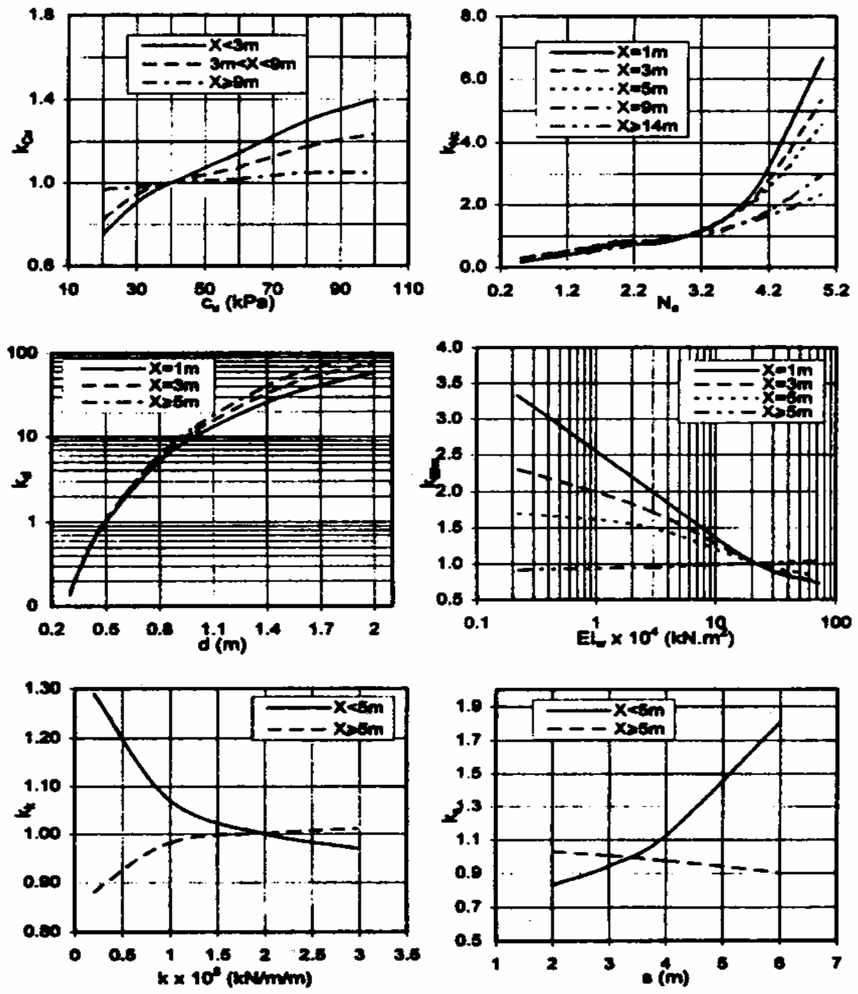


FIG. 8. Correction Factors for Bending Moment

BASIC CURVES FOR DEFLECTION

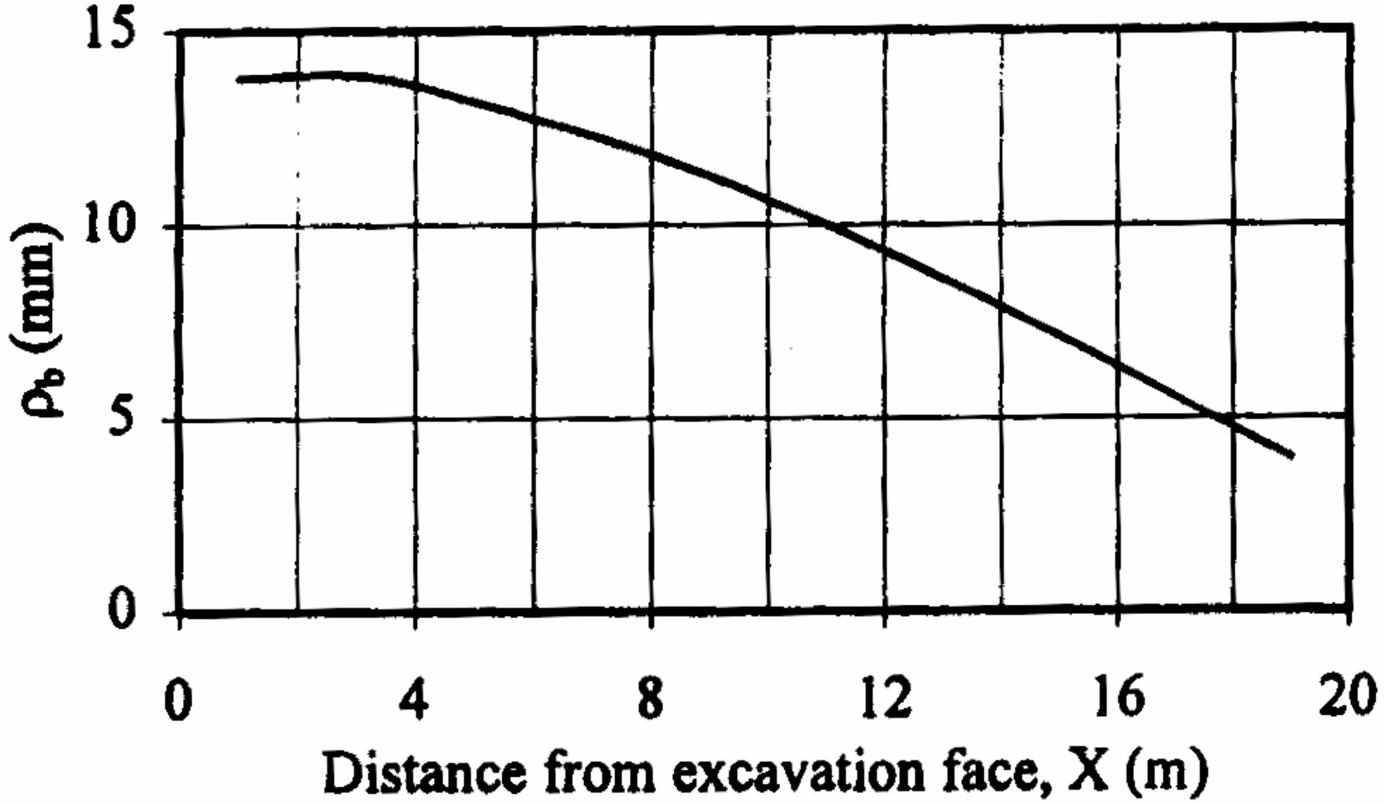


FIG. 9. Basic Deflection versus Distance from Excavation Face

CORRECTION CURVES FOR DEFLECTION

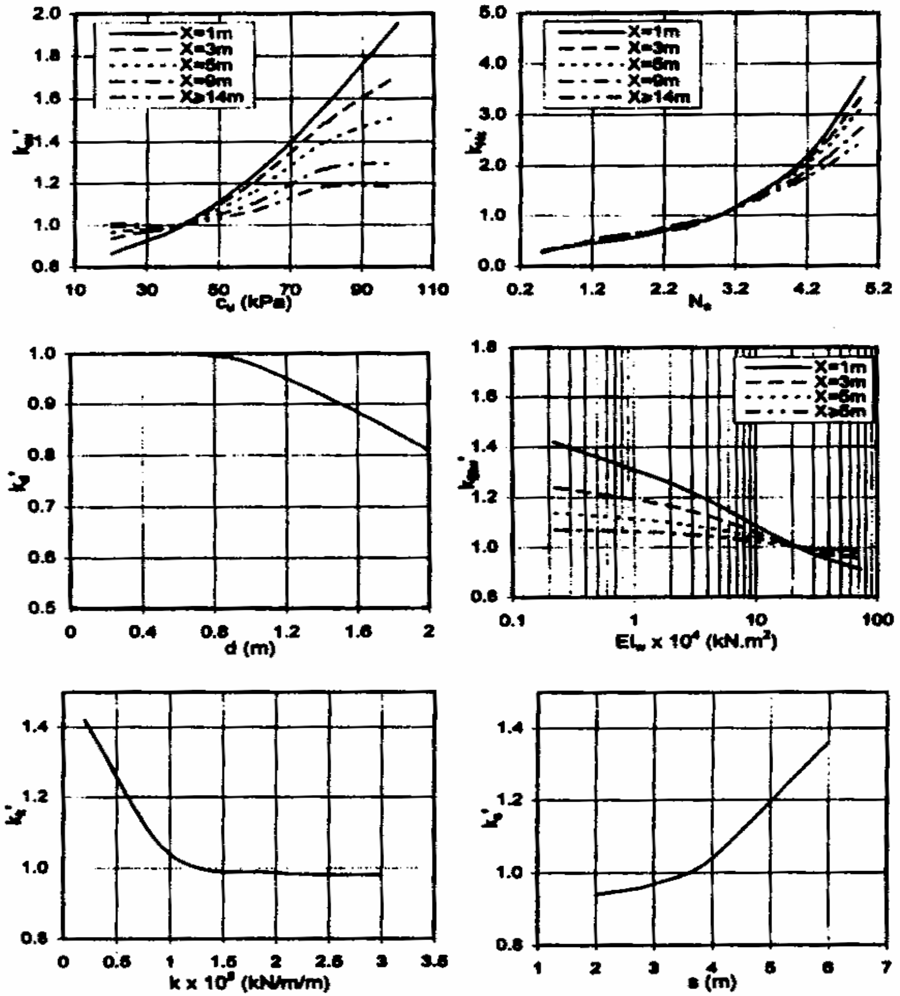


FIG. 10. Correction Factors for Deflection

MEASURED & COMPUTED BEHAVIOUR – CASE 1

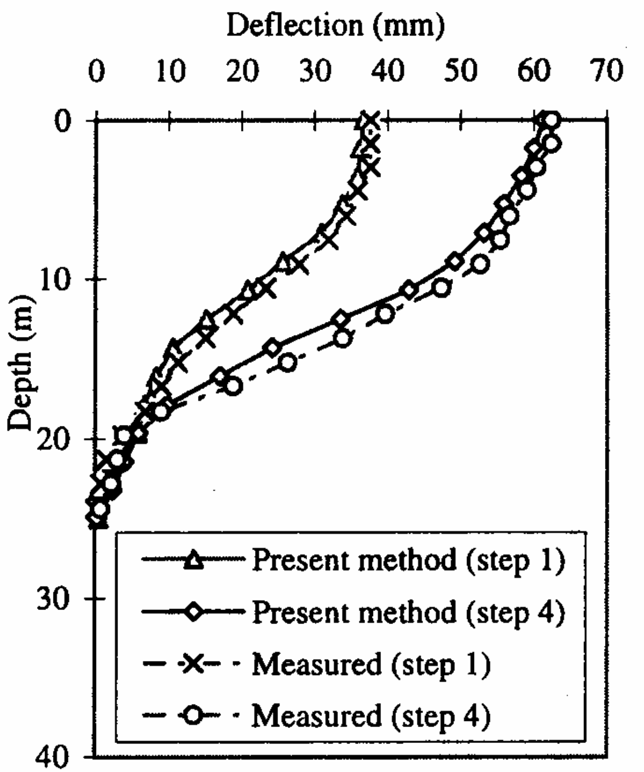


FIG. 12. Pile Deflection Profile for Case 1

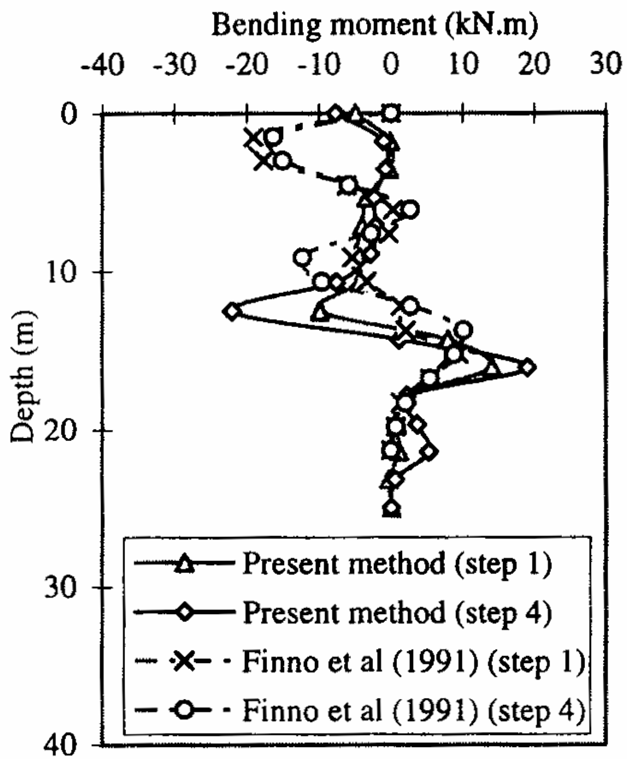


FIG. 13. Pile Bending Moment Profile for Case 1

MEASURED & COMPUTED BEHAVIOUR – CASE 2

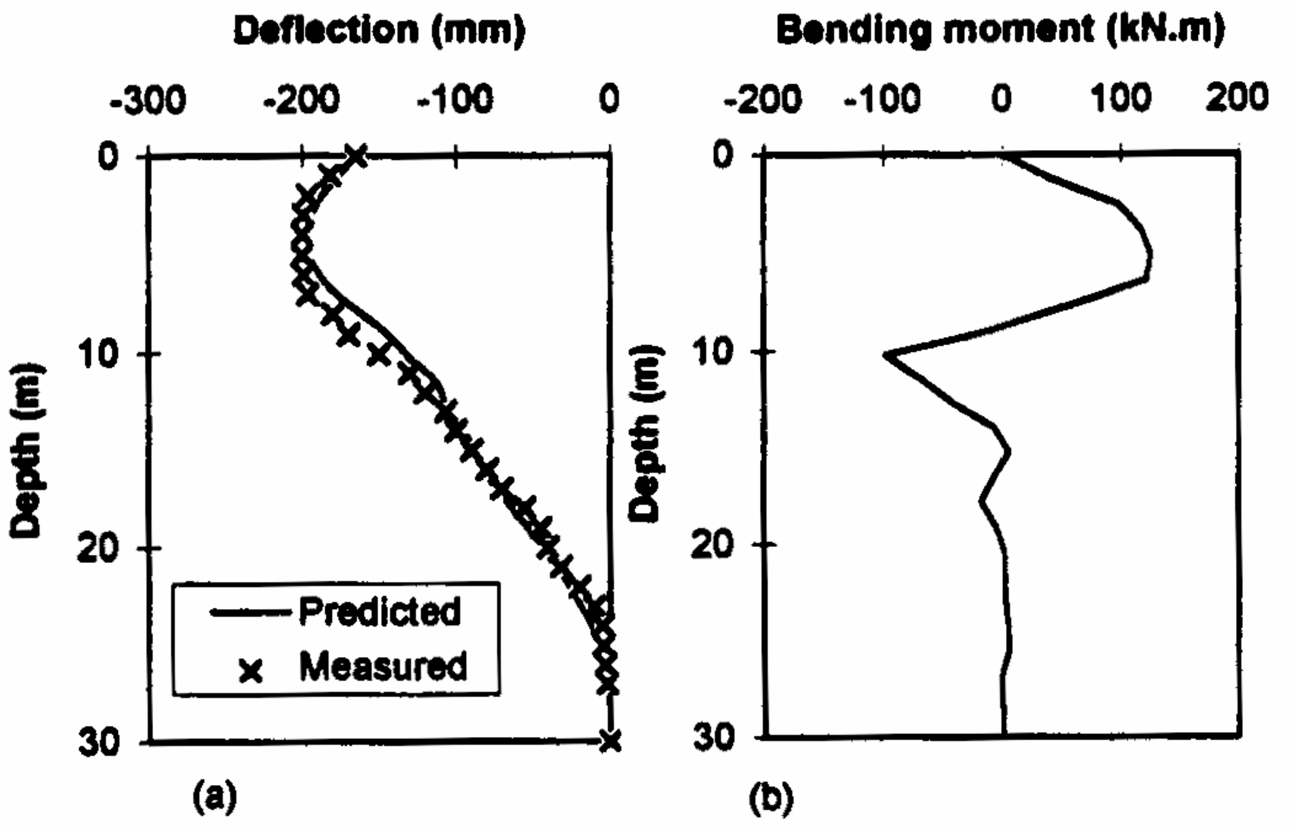


FIG. 14. Pile Response for Case 2: (a) Deflection Profile; (b) Bending Moment Profile

EFFECTS OF EXCAVATION-INDUCED MOVEMENTS ON PILES

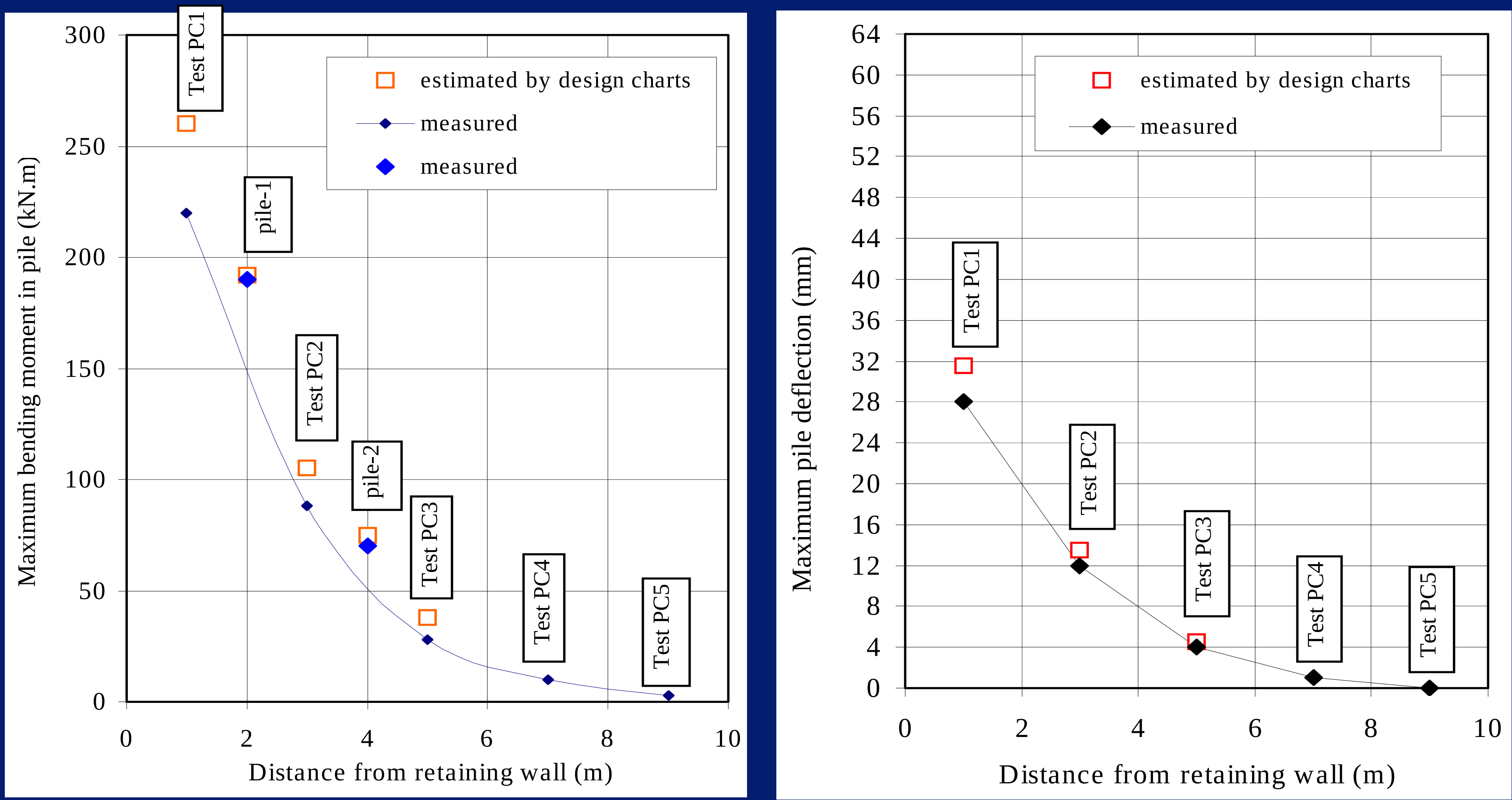


Fig. A Estimated and Measured Maximum Pile Bending Moments and Deflections

CASE STUDY:
TILTED BUILDING IN INDONESIA

BUILDING AFFECTED BY EXCAVATION

EFFECT OF CONSTRUCTION OPERATIONS ON A BUILDING

- 9-storey building in Indonesia
- Uncontrolled excavation near one corner
- Building tilted and continued to tilt
- Eventually demolished
- Study made of possible causes of the tilting
  - Various hypotheses examined
  - Soil-structure analysis carried out

GEOTECHNICAL PROFILE

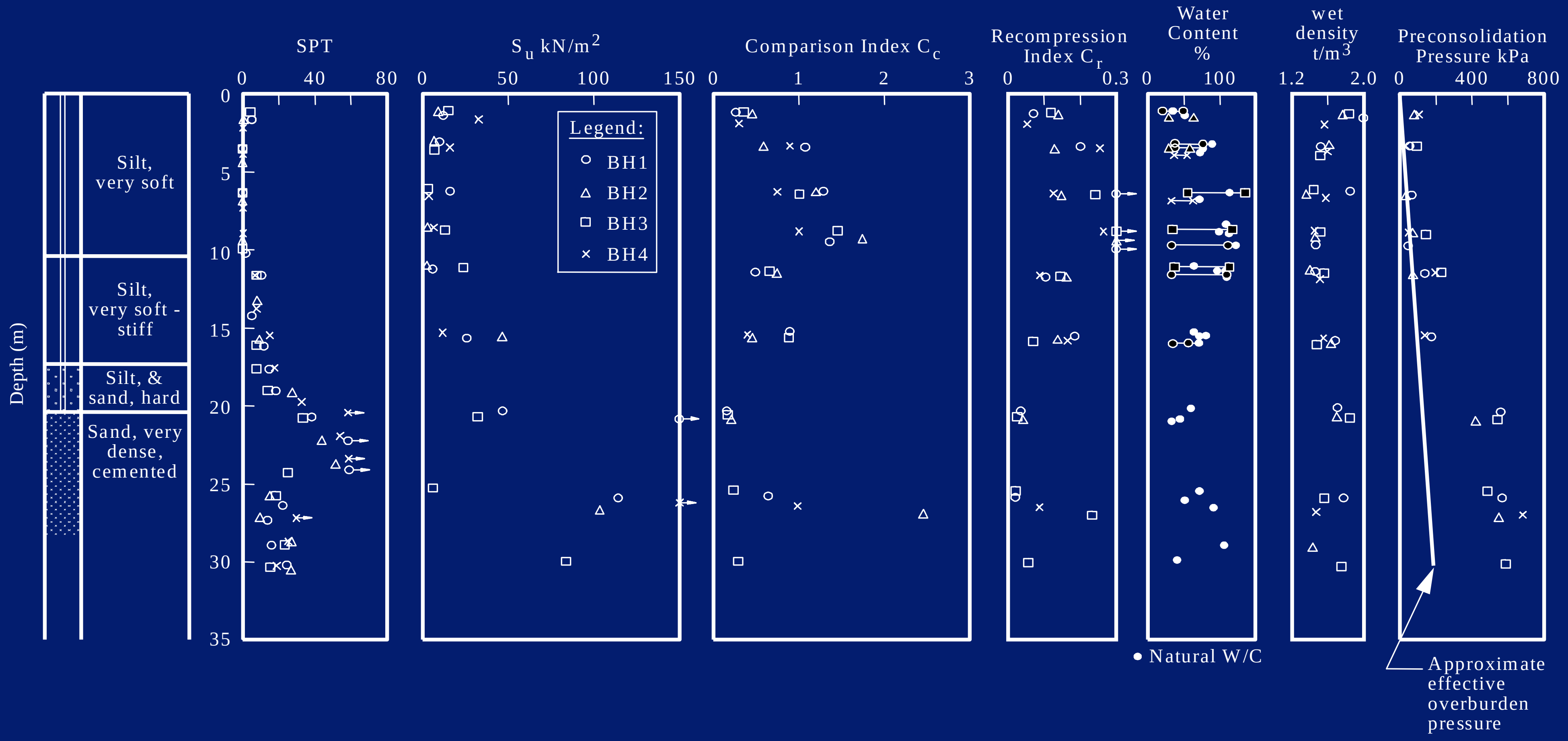


Figure 15 Summary of Engineering Properties

EVIDENCE OF GROUND MOVEMENTS

STRUCTURAL CAPACITY OF PILES

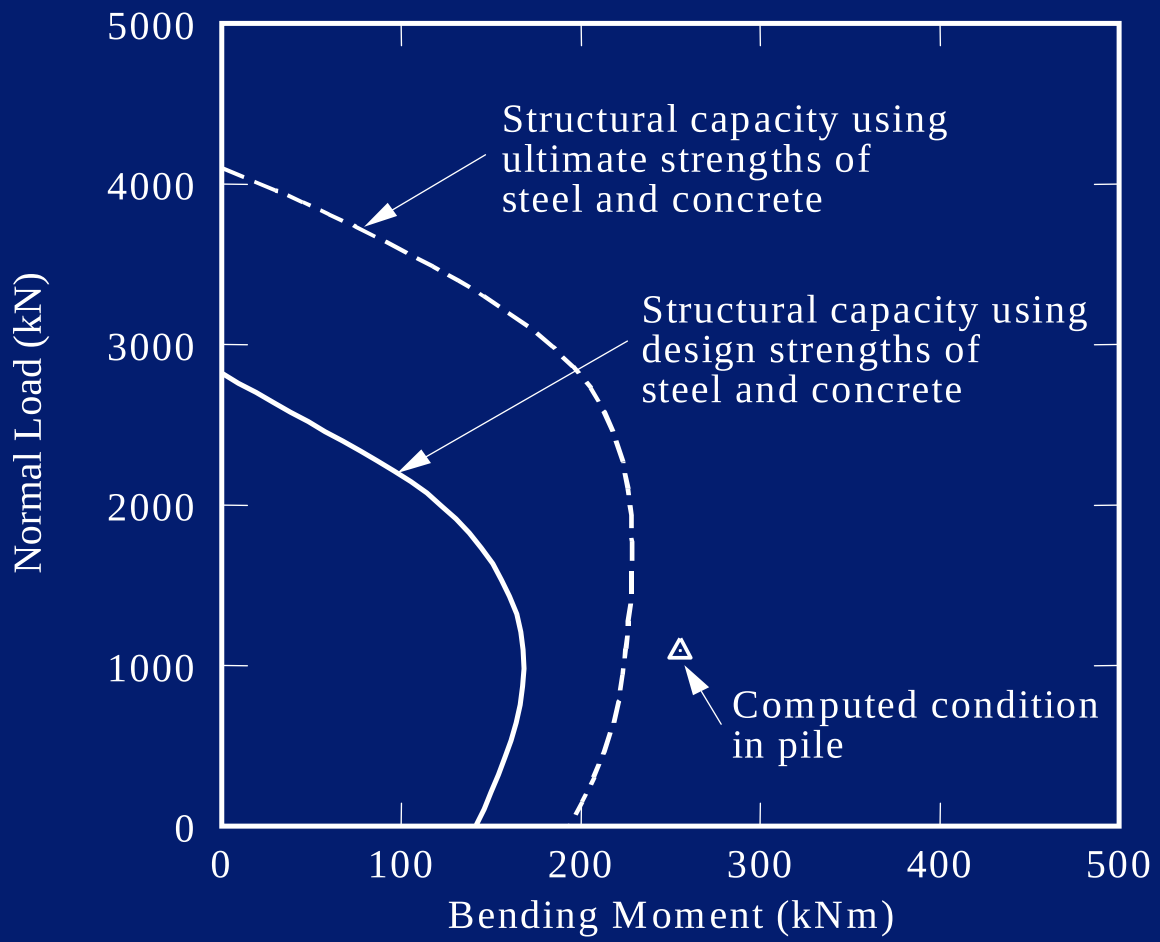


Figure 18 Structural Capacity of Office Building Piles

Conclusion:

Induced moment due to excavation was sufficient to cause structural failure of the piles near the uncontrolled excavation.

EXCAVATION FAILURE - MALAYSIA

THE CONSEQUENCES FOR A NEARBY BRIDGE

Relative movement