LECTURE 5

PILES SUBJECTED TO GROUND MOVEMENTS

OUTLINE

- Negative friction on piles
- Piles in swelling or expansive soils
- Piles in soil undergoing lateral movement
- “Generic” design charts
- Piles near embankments
- Effects of pile installation on existing piles

SOME SOURCES OF GROUND MOVEMENT

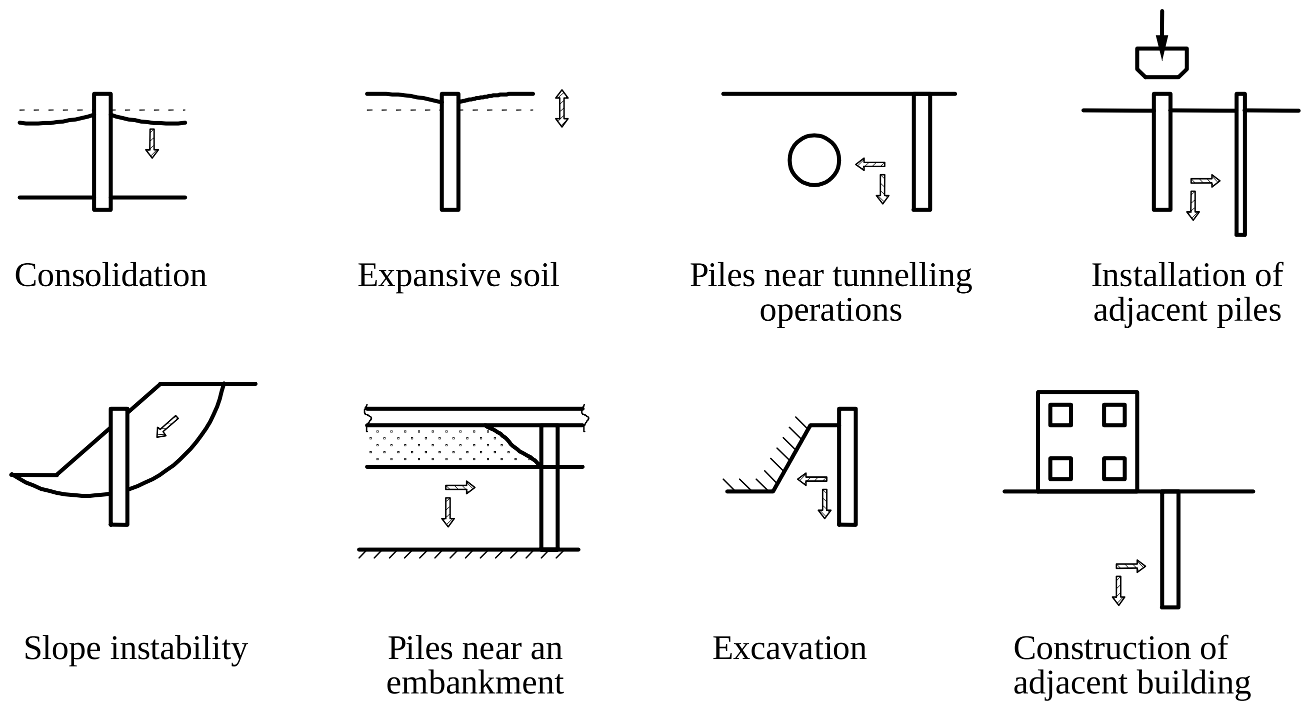


FIG. 1 SOME SOURCES OF GROUND MOVEMENT

NEGATIVE FRICTION ON PILES

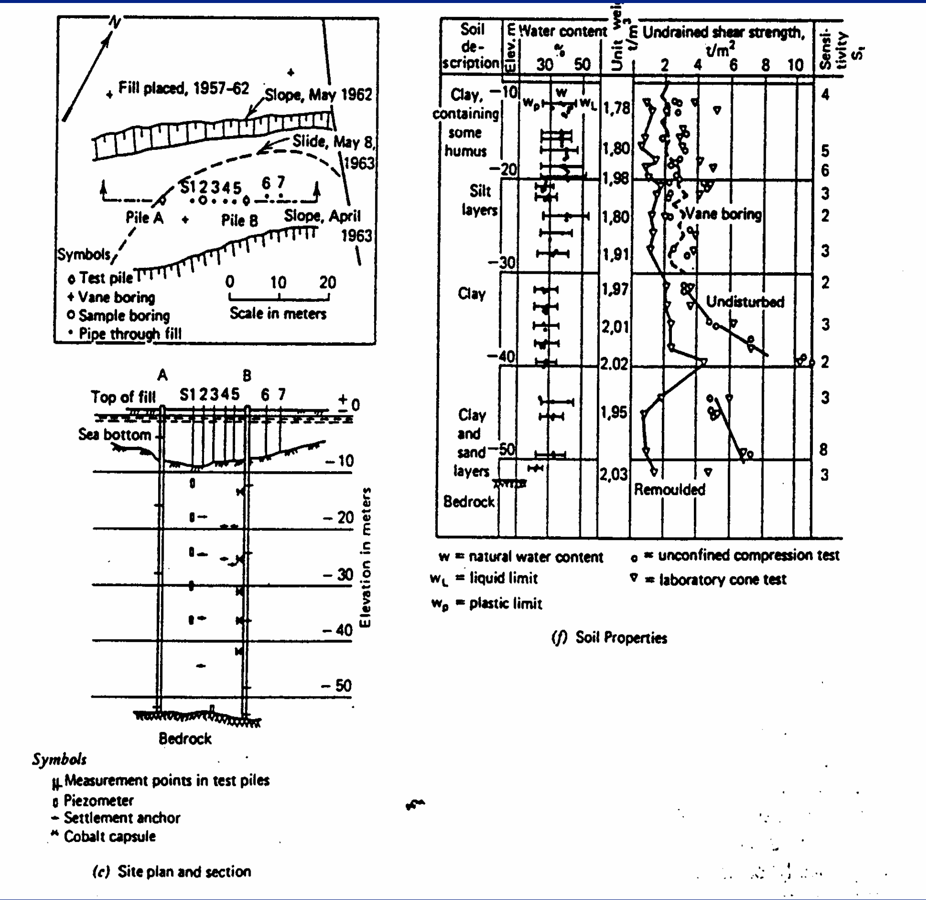
- "Negative friction" is the downward shear stress generated by the action of soil settling past the pile
- It gives rise to additional forces in a pile, termed "downdrag" forces
- In one case, forces approaching 9000 kN have been measured, and in several cases, forces of 2000 kN or more have been reported

MAIN EFFECTS OF NEGATIVE FRICTION

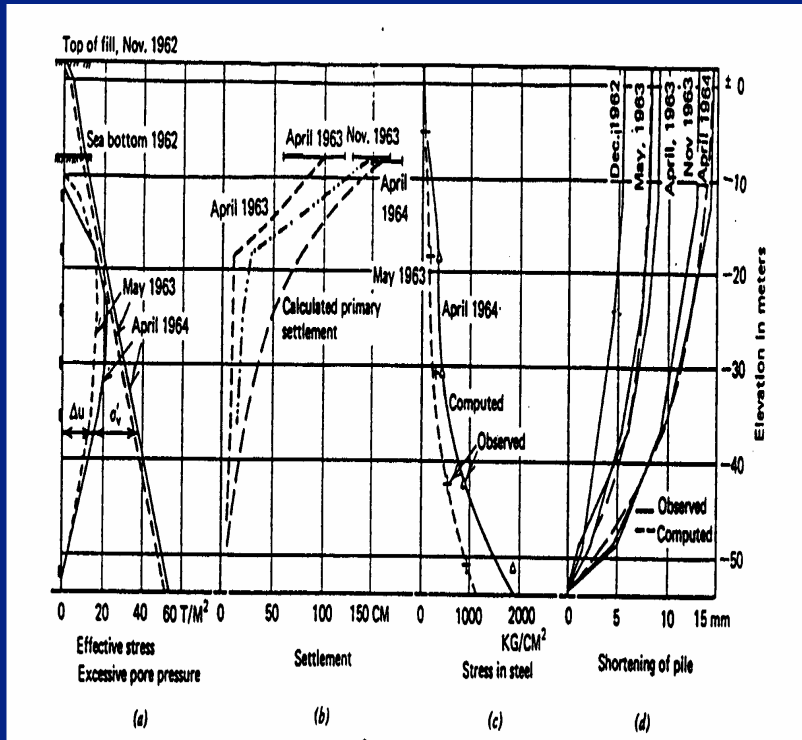
- Increased axial load in the pile – possible problems with structural integrity
- Increased settlement of the pile.

- **IT DOES NOT SIGNIFICANTLY REDUCE THE GEOTECHNICAL AXIAL CAPACITY OF THE PILE !**
- For geotechnical failure to occur, the pile must move past the soil.
- If this happens then the previous negative friction becomes positive, and so contributes to pile capacity as before.

EXAMPLE OF FIELD MEASUREMENTS (Bjerrum et al, 1969)



(c) Site plan and section (f) Soil Properties

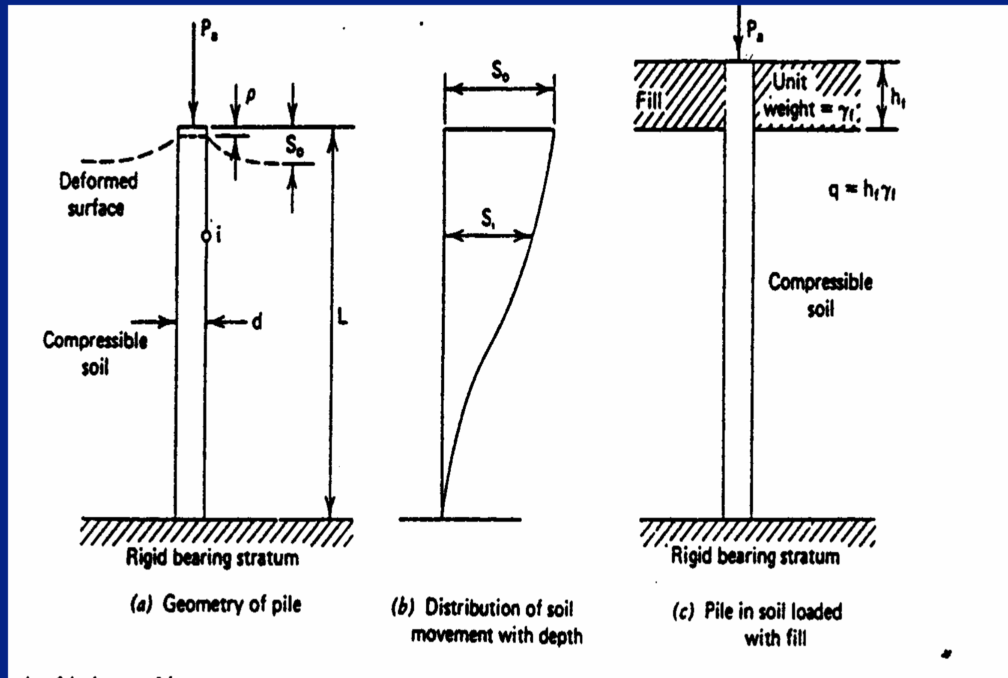


(a) Excess pore pressure and effective stresses in ton/m²; (b) settlement in cm; (c) computed and observed steel stresses in kg/cm²; (d) computed and observed shortening of pile in mm.

SIMPLE ANALYSIS OF DOWDRAG FORCES – END BEARING PILES

ASSUMPTIONS

- **Full slip occurs between pile & soil along pile length**
- **Maximum downdrag force occurs after completion of consolidation processes – i.e. under DRAINED conditions**



SIMPLE ANALYSIS OF DOWDRAG FORCES – END BEARING PILES

From Coulomb expression:

$f_s = c_a' + K_s \tan \delta' \sigma_v'$

Usually for soft clays, $c_a' = 0$

$\mathbf{f_s = K_s \tan \delta \sigma' = \beta \sigma_v'}$

Typically, $\beta = (1\text{-}\sin \phi') \tan \phi' = 0.2 – 0.3$ for soft clays.

Downdrag force at any depth is:

$P_N = \Sigma f_s. C. dz$

Maximum value for end bearing pile is at tip:

$P_{Nmax} = \Sigma \beta \sigma_v' C dz$ (summation over pile length)

ESTIMATION OF PILE HEAD MOVEMENT – END BEARING PILES

Settlement can be approximated as the sum of:

1. **Elastic compression of pile due to applied load**
2. **Elastic compression of pile due to downdrag forces**
3. **Pile tip movement.**

Components 1 and 2 can be calculated from simple column compression equation.

Component 3 can be treated via the tip as a rigid footing on the bearing stratum:

$$S_{tip} = (P_{Nmax} + P_a)\,(1-\nu_b^2) \,/\, (\,d_b\,E_b\,)$$

FLOATING PILES

- The **“NEUTRAL POINT”** is the depth at which the shaft friction changes from negative to to positive
- Positive friction is developed below the neutral point
- Thus, downdrag force is SMALLER than for end bearing piles
- But, the pile head movement is LARGER
- For homogenous soil, neutral point is located 0.71L below pile top.

- **Selection of Allowable Load is usually a matter of keeping the settlement to a tolerable value**

FLOATING PILES – SIMPLE DESIGN METHODS FOR ALLOWABLE LOAD

Some simple design methods have been developed

- **Tomlinson (1975):**

  $P_a - P_u/F - P_{s1}$

- **CPI (1989):**

  $P_a = (P_u - P_{s1})/F - P_{s1}$

- **Van der Veen (1986):**

  Lesser of:

  $P_a = (P_{bu} + P_{s2})/F_1 - (P_{s1} + P_{s2})$

  or $P_a = (P_{bu} + P_{s2})/F_2$

  (F1 = 1.7, F2 = 2.5)

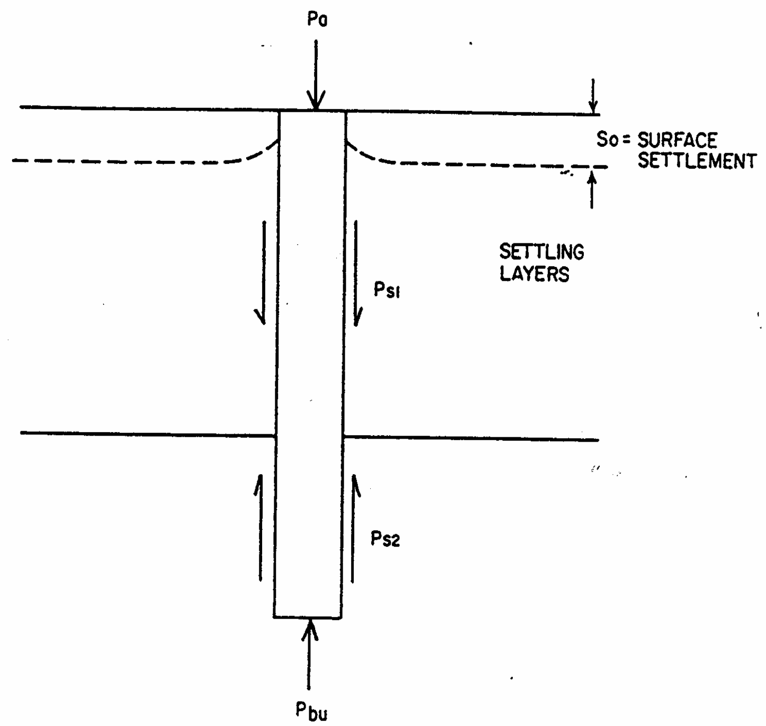


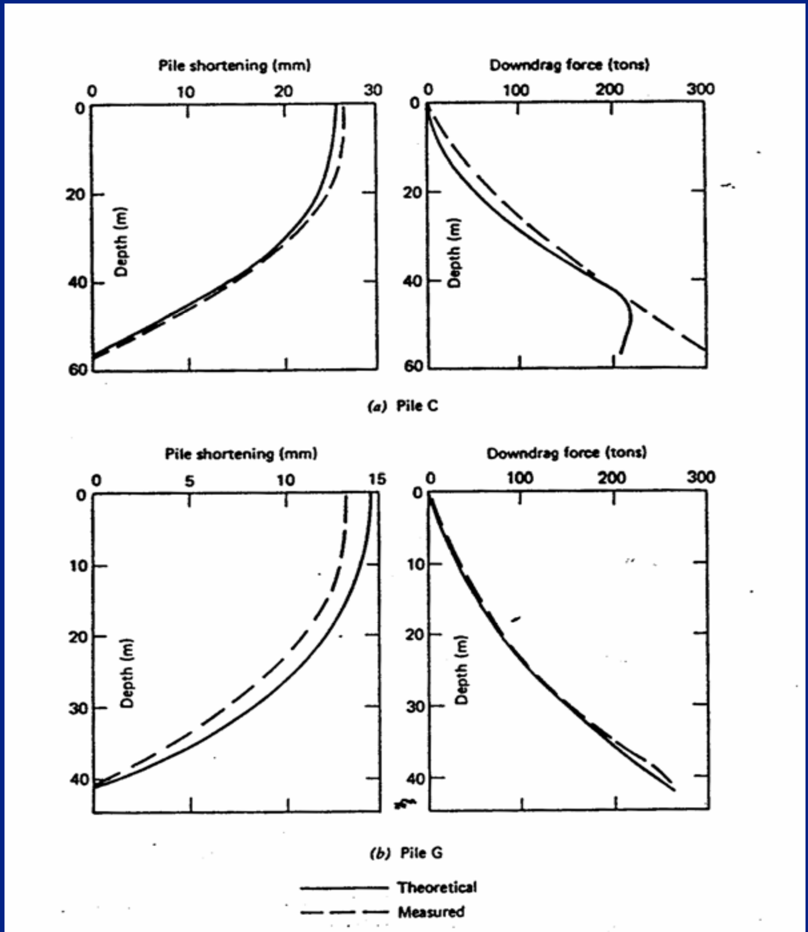
FIGURE 1 DEFINITION SKETCH

PILE-SOIL INTERACTION ANALYSIS

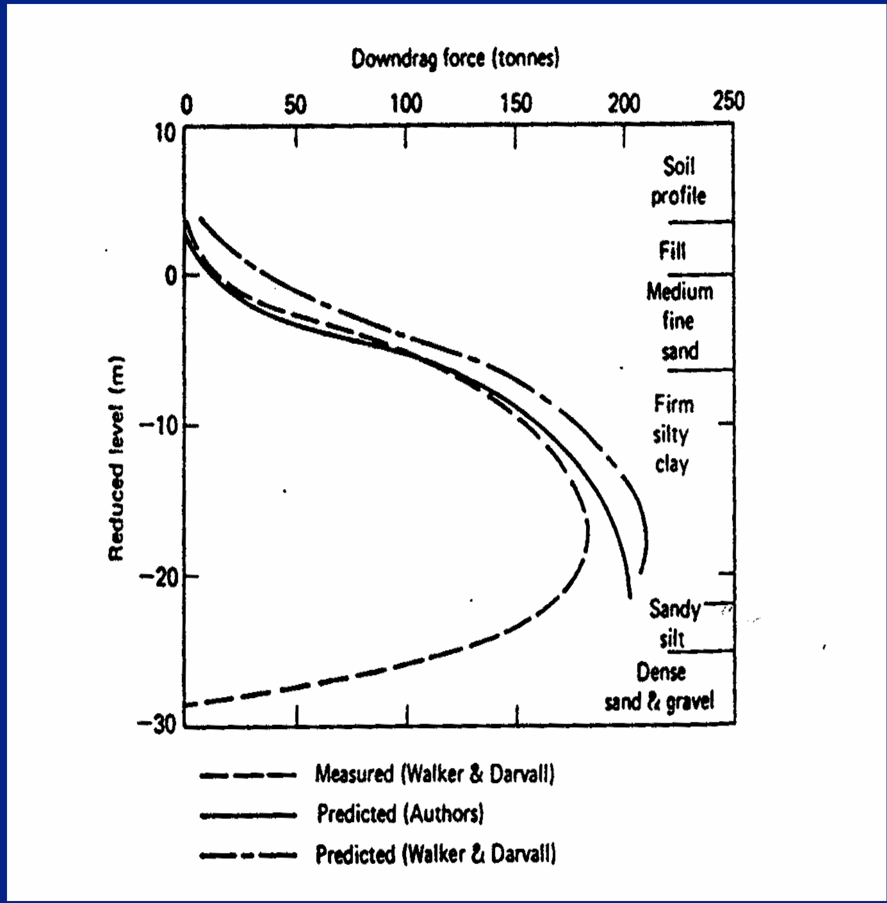
- Negative friction is a pile-soil interaction problem
- Can be analyzed by same methods as pile settlement
- Free-field soil movements must be incorporated into the analysis
- Require use of computer programs e.g. PIES (Poulos, 1989)
- Can then allow for effects such as:
  - Partial pile-soil slip
  - Rate of development of downdrag
  - Effects of bearing stratum
  - Group effects
  - Delay of pile installation

MEASURED AND CALCULATED BEHAVIOUR

Bjerrum et al (1969)



Walker & Darvall (1973)



MEASURED AND CALCULATED BEHAVIOUR (Okabe, 1973)

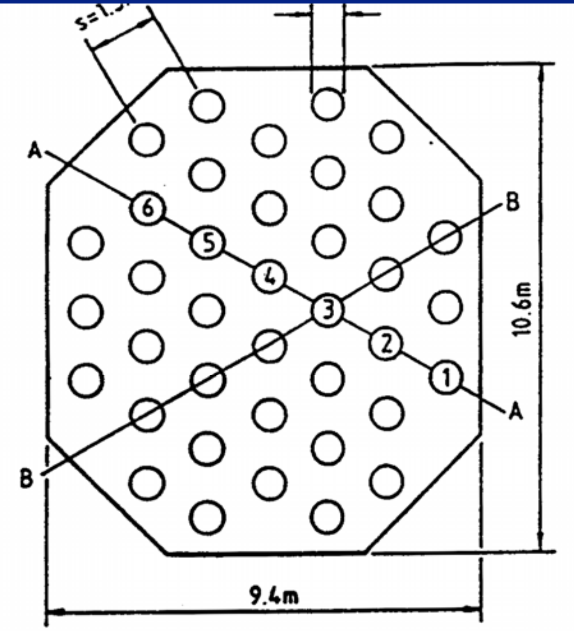


FIG. 12. Configuration of Pile Group (Okabe 1973)

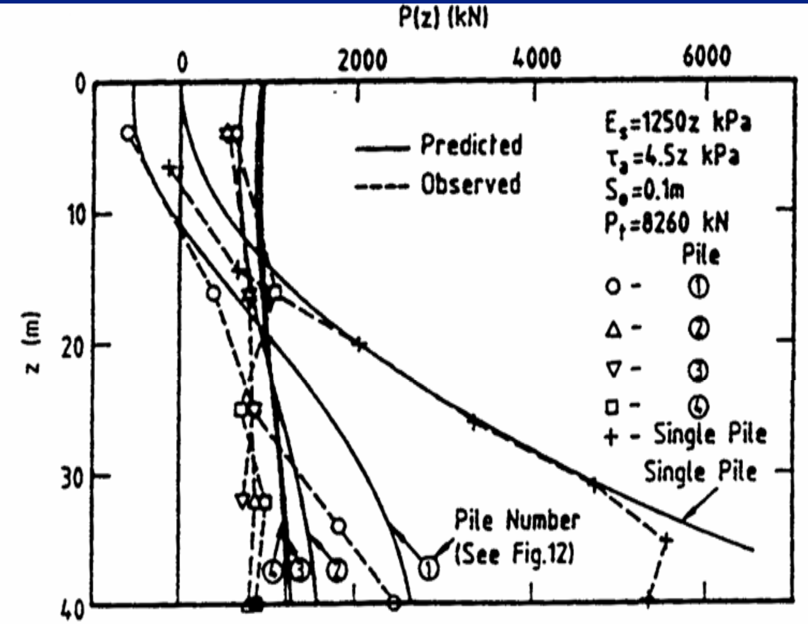


FIG. 13. Distribution of Axial Load along Shaft in Group

SOME FINDINGS FROM PILE-SOIL INTERACTION ANALYSES

COFFEY

- For short or stiff piles, require relatively small soil movements to develop full slip (1-5% diameter)
- For very long compressible piles, may require much larger movements (>50% diameter)
- Rate of development of downdrag forces is generally comparable to rate of settlement of soil layer
- Group effects suppress free-field soil movements – thus, group interaction effects are HELPFUL.
- Downdrag forces in a group are generally less than for single piles, especially for inner piles.
- So, use of single pile analysis is conservative.

SIMPLIFIED APPROACH TO ESTIMATING NEGATIVE FRICTION

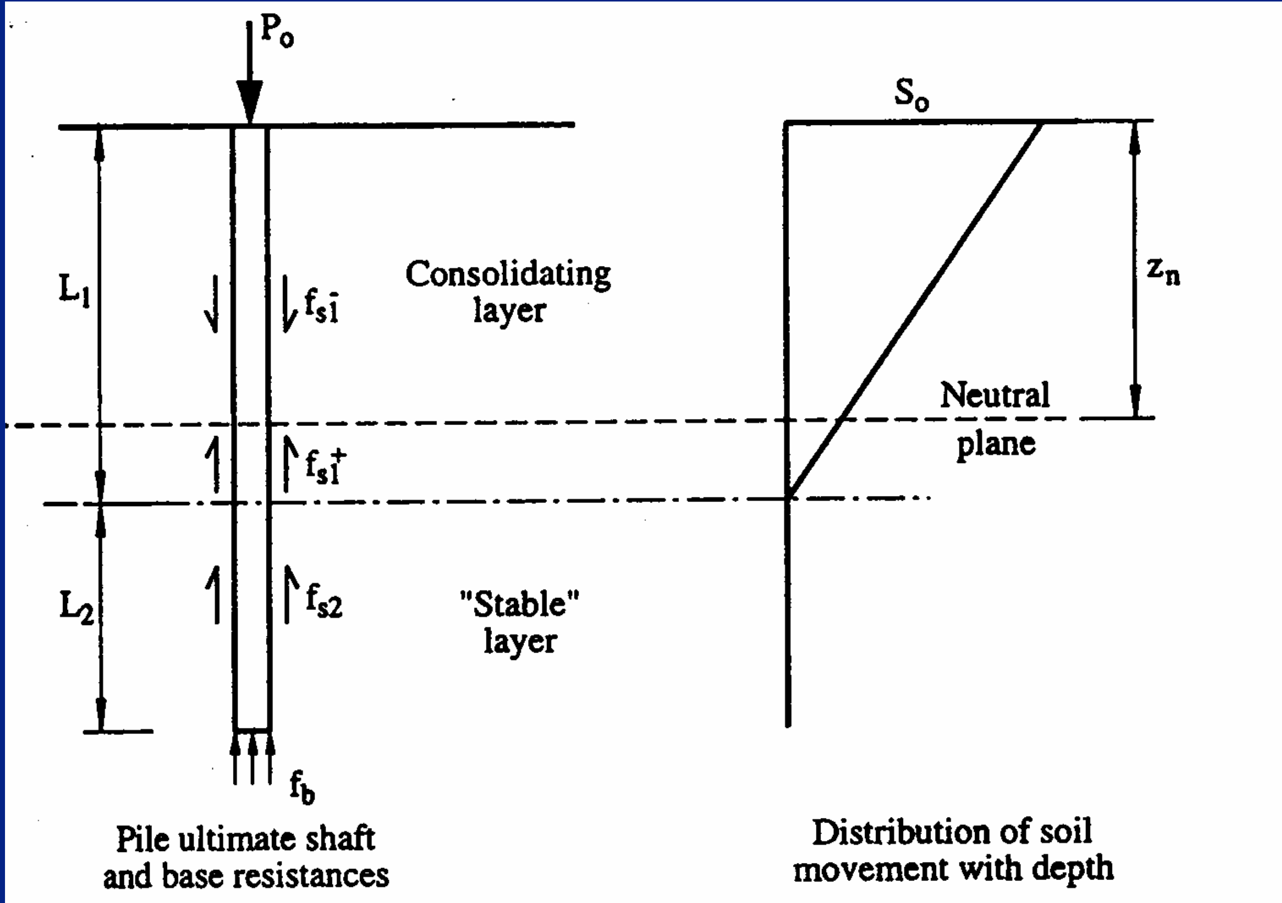


Fig. 2 Simplified Negative Friction Problem

SIMPLIFIED APPROACH TO ESTIMATING NEGATIVE FRICTION

- Compute location of neutral axis (for equal positive and negative frictions in a layer);
  - $z_n = 0.5(L_1+(f_{s2}/f_{s1}).L_2 +(f_b.A_b - P_0)/f_{s1}.C$
- Compute maximum axial force in pile as:
  - $P_{max} = P_0 + f_{s1}.C.z'$
    where $z' = L_1$ if $z_n > L_1$, or z_n if $z_n < L_1$
- Compute pile head settlement for Options (a) & (b) and take larger value.

SIMPLIFIED APPROACH TO ESTIMATING NEGATIVE FRICTION

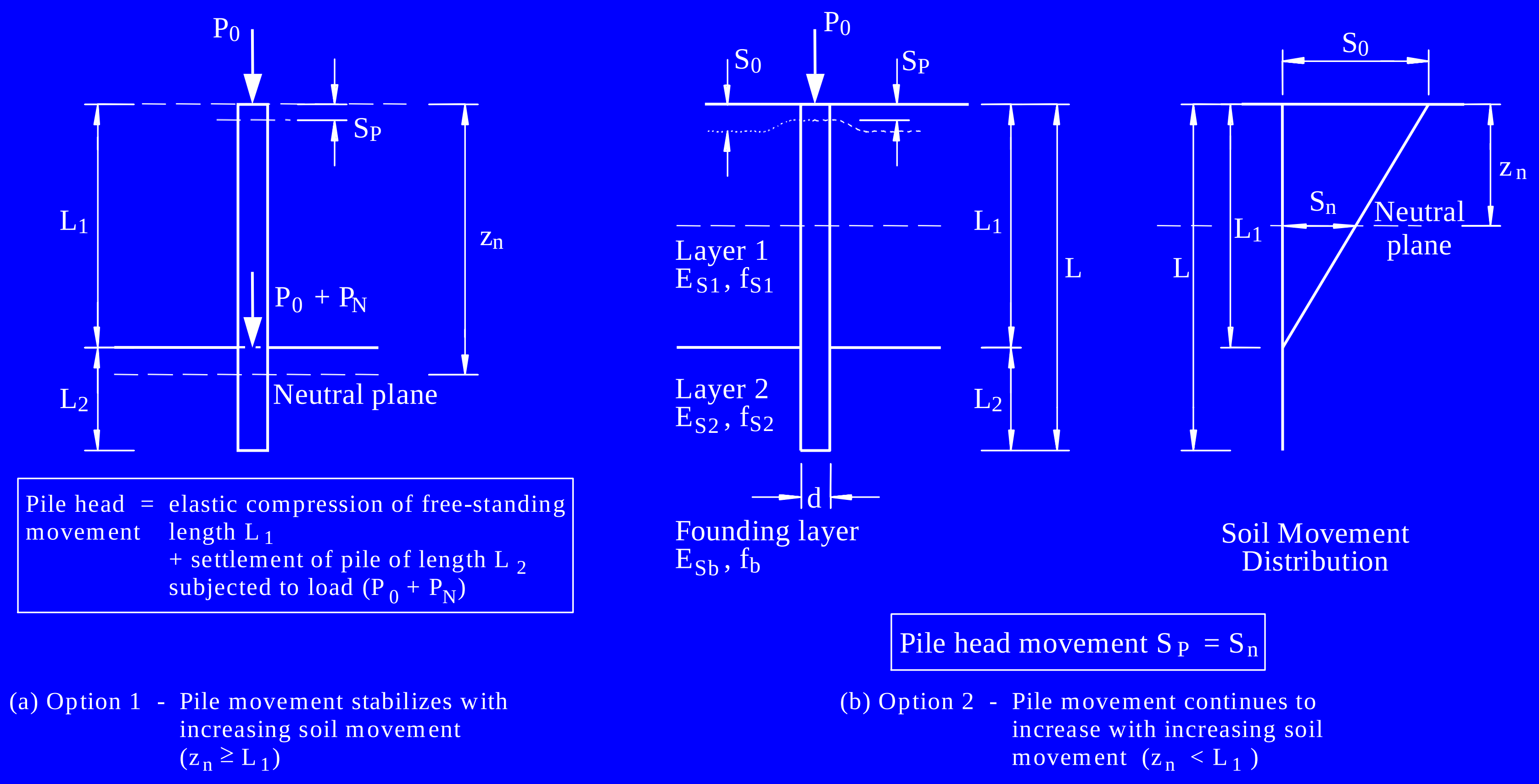


Fig. 2 Simplified approaches to estimating pile head movement

SIMPLIFIED APPROACH TO ESTIMATING NEGATIVE FRICTION

- If the neutral plane lies at or below the top of the stable layer, then the pile settlement will not increase indefinitely with increasing soil movements
- For this to occur, the **ALLOWABLE APPLIED LOAD** is:

$$P_a = F_{s2} + P_b - P_N$$

where P_N = maximum downdrag force at top of stable layer.

(Note that this is based on settlement and not capacity considerations).

EXAMPLE OF NEGATIVE FRICTION ESTIMATION

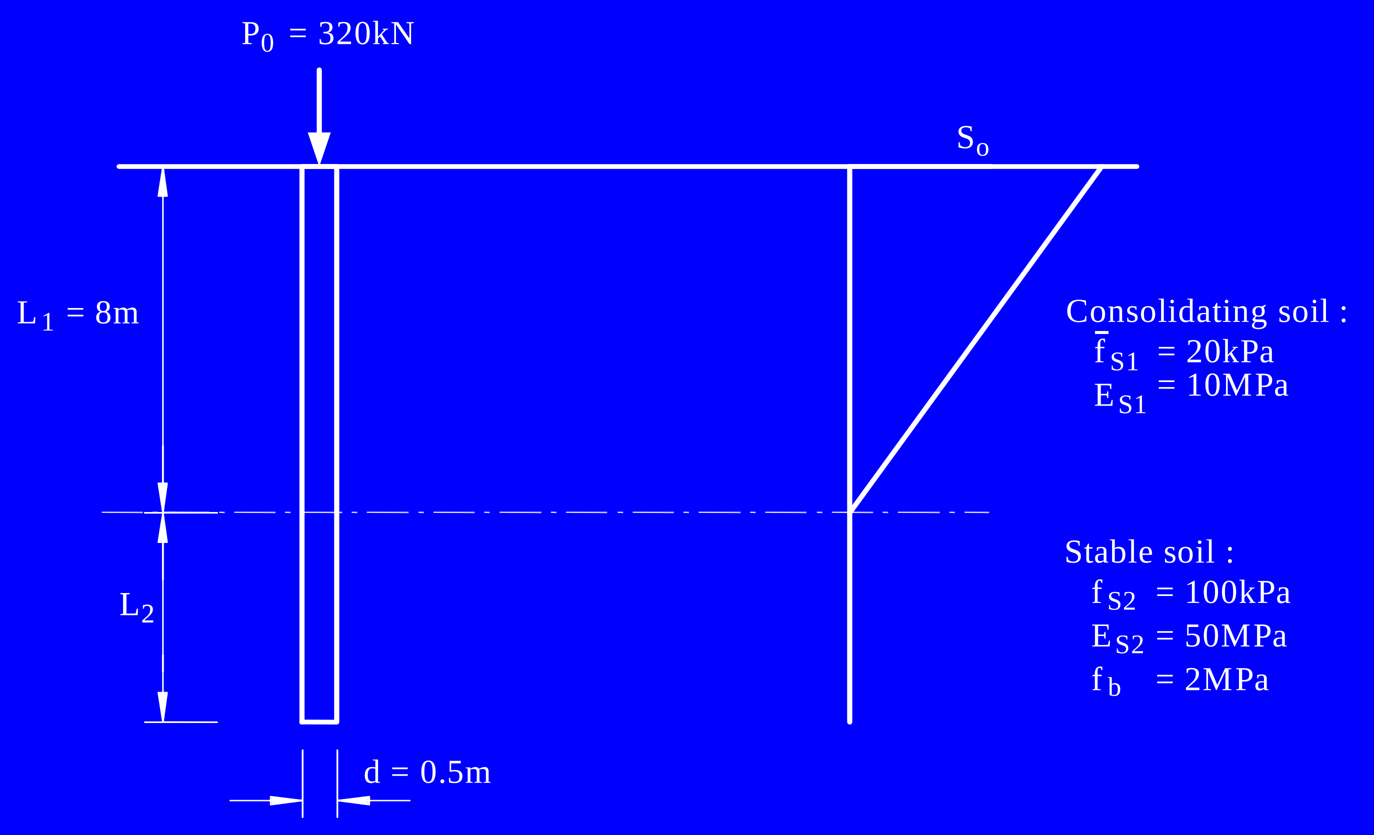


Fig. 3 Hypothetical example analysed

SOLUTIONS FROM SIMPLIFIED AND COMPUTER ANALYSES

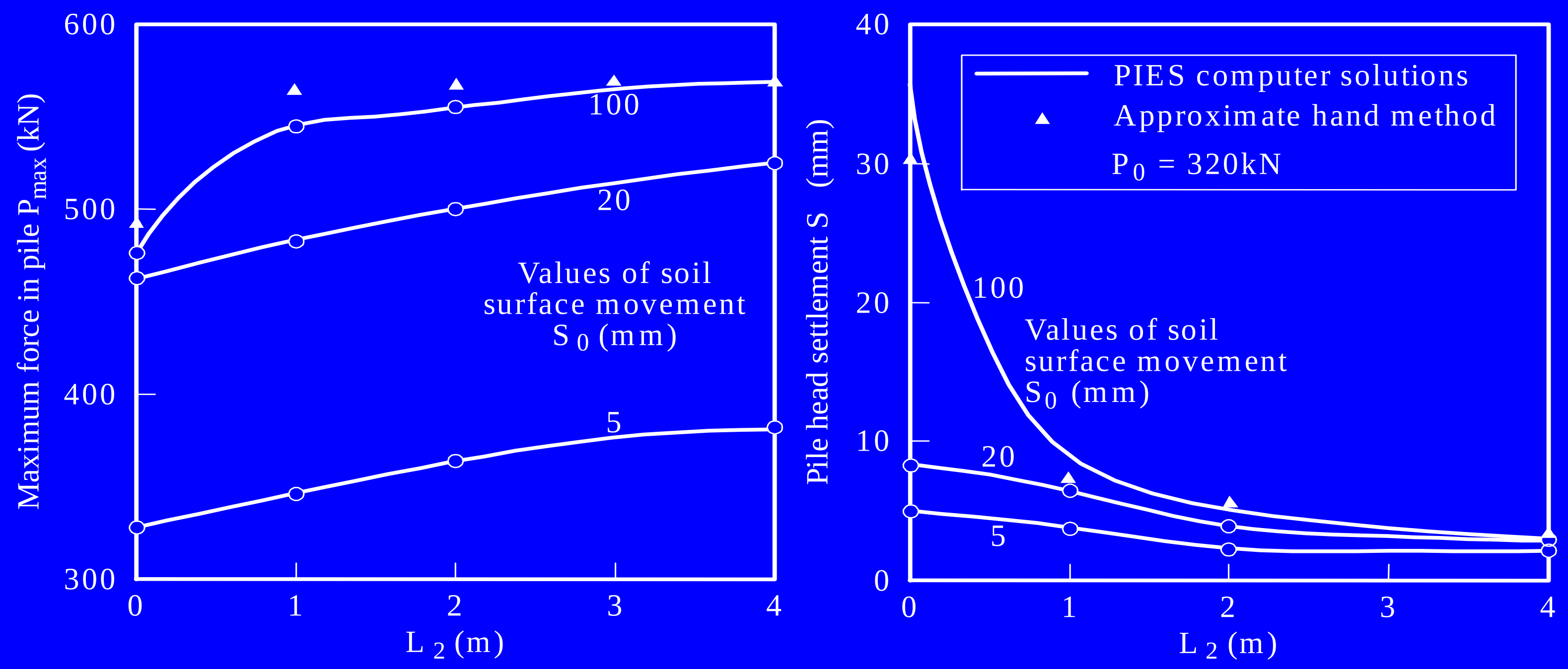


Fig. 4 Comparisons between solutions from hand and computer methods

REDUCTION OF NEGATIVE FRICTION

- **Surface Coatings**
  - Bitumen – can reduce negative friction by up to 90%
  - Bentonite slurry.
- **Electro-Osmosis**
  - Application of current between pile (Cathode) and an anode causes migration of pore water towards cathode
  - Reduces effective stress, and skin friction
  - Can give dramatic reductions in silty soil
- **Use of Dummy Casing Outside Pile**
  - Load bearing pile is protected

DIRECT PILE LOADING vs LOADING VIA GROUND MOVEMENTS

- **CANNOT** simulate the effect of negative friction by adding an additional head load.
- The mechanisms of pile loading are different for ground movements and direct loading.
- This is particularly important when trying to assess negative friction effects from pile load tests.
- Need to measure detailed distribution of ultimate skin friction, and then use in an negative friction analysis.

PILES IN SWELLING OR EXPANSIVE SOIL

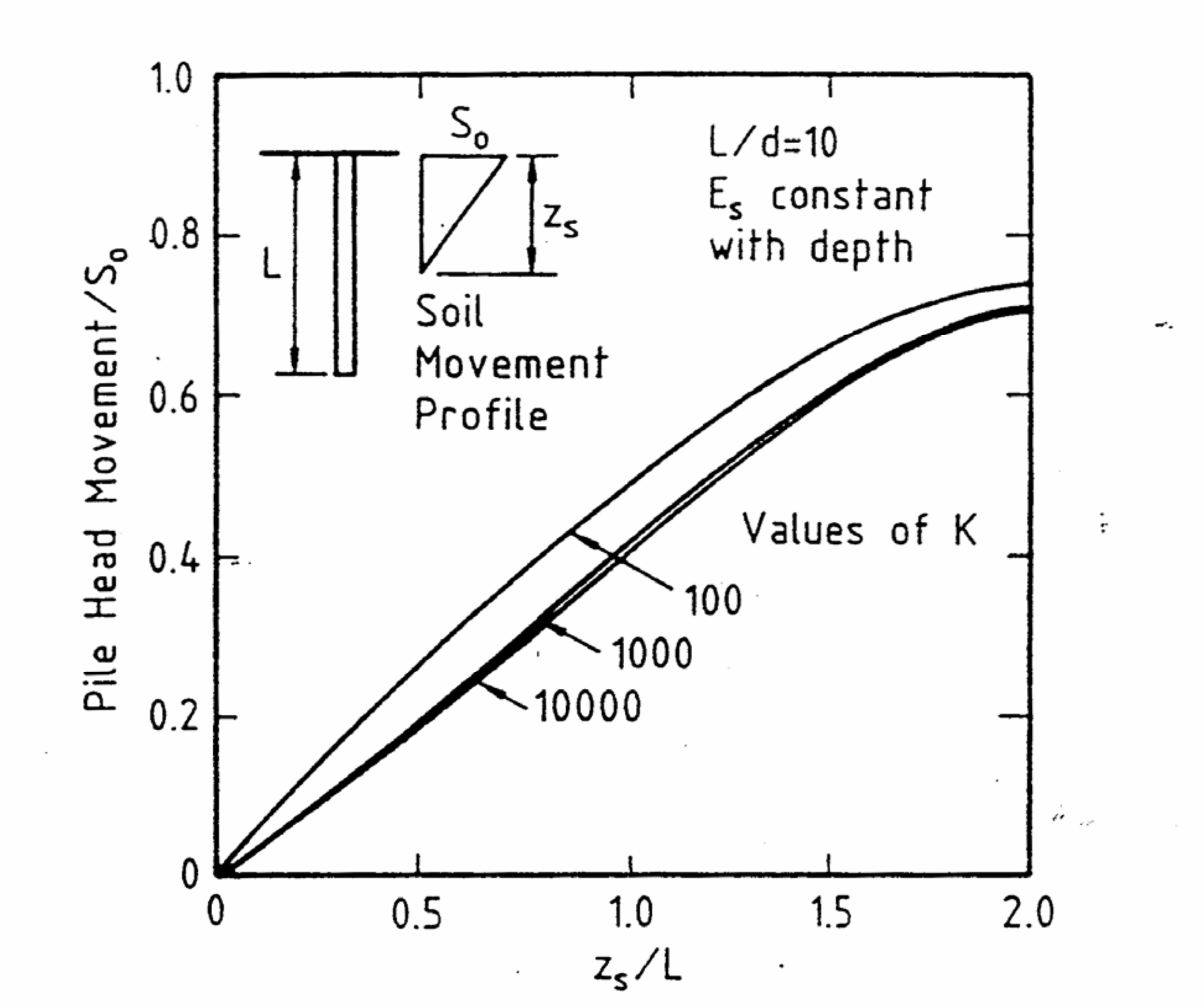
KEY CONCERNS IN DESIGN:

- How much will pile move due to soil movement?
- What forces (tensile) are induced in the pile?

- Analysis is similar to negative friction

- Problems arise because:
  - Expansive soils are usually unsaturated
  - Soil properties vary with moisture content/soil suction

PILES IN SWELLING OR EXPANSIVE SOIL - MOVEMENTS



PILES IN SWELLING OR EXPANSIVE SOIL – MAXIMUM FORCE

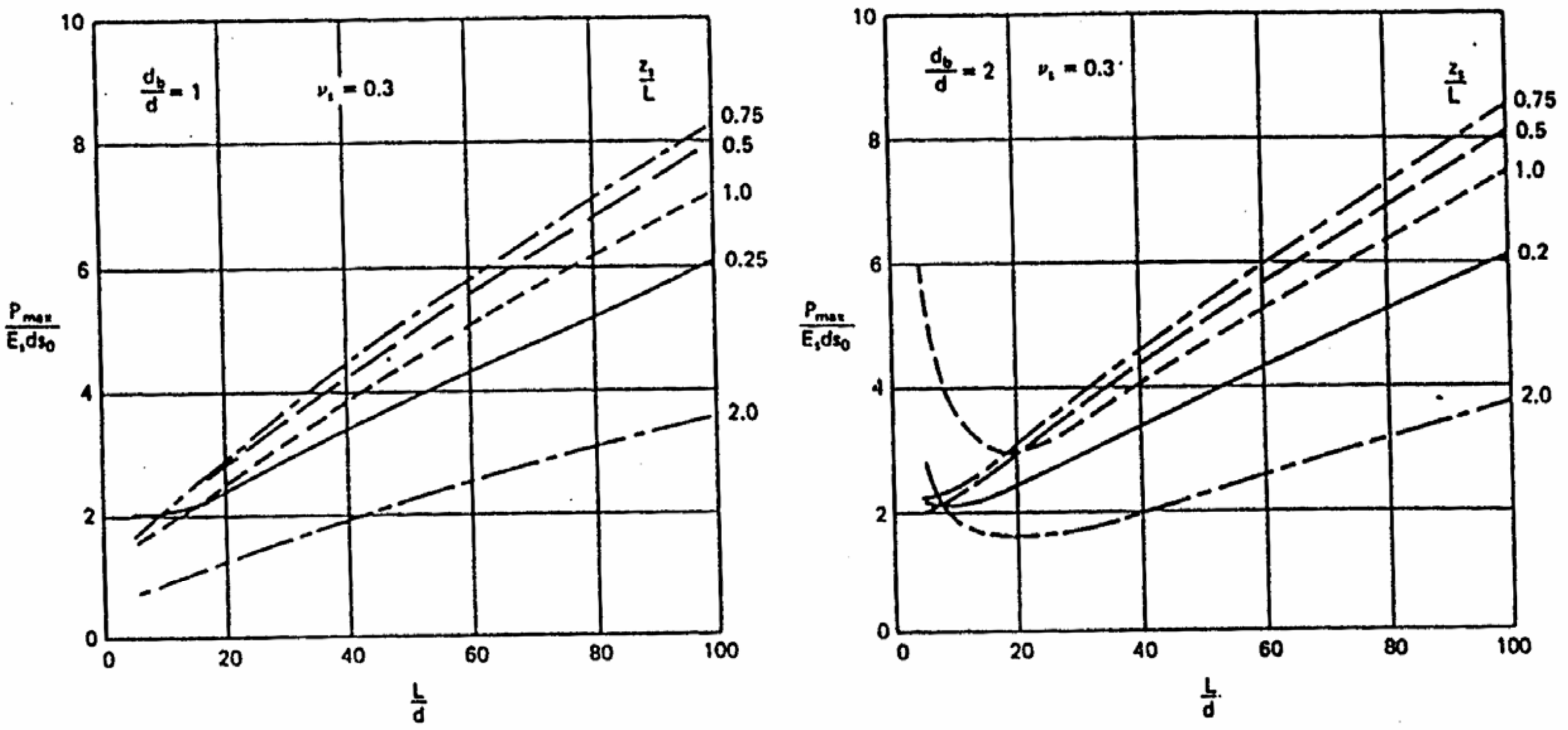


FIGURE 12.5 Elastic solutions for maximum pile load–uniform-diameter pile.

FIGURE 12.6 Elastic solutions for maximum pile load–pile with enlarged base.

PILES IN SOIL UNDERGOING LATERAL MOVEMENT

Examples include:

- Piles near retaining structures
- Piles in unstable slopes
- Piles near embankments
- Piles near excavations
- Piles near tunnels
- Piles near newly-installed piles

PILES IN SOIL UNDERGOING LATERAL MOVEMENT

In all cases, the piles are subjected to:

- Additional horizontal movements
- Additional bending moments and shears.

For structural serviceability and integrity, these values need to be estimated and designed for.

ANALYSIS REQUIREMENTS

Most effective way is a 2-stage process:

- Estimation of free-field soil movements
- Pile-soil interaction analysis of the influence of these movements on lateral pile response.

Pile-soil interaction analysis is an extension of laterally loaded pile analyses, with inclusion of free-field soil movements into equations. Can use a boundary element analysis – see Poulos & Davis (1980), Chapter 13.

THEORETICAL SOLUTIONS FOR IDEALIZED CASES

Solutions have been obtained for the following idealized cases:

- Linearly varying soil movement with depth
  - Uniform soil
  - “Gibson” soil
- Uniform soil movement with depth
  - Uniform soil
  - “Gibson” soil
- In all cases, the soil is assumed to be elastic.
- This gives CONSERVATIVE estimates.

DESIGN CHARTS FOR UNIFORM SOIL –Triangular Lateral Soil Movement

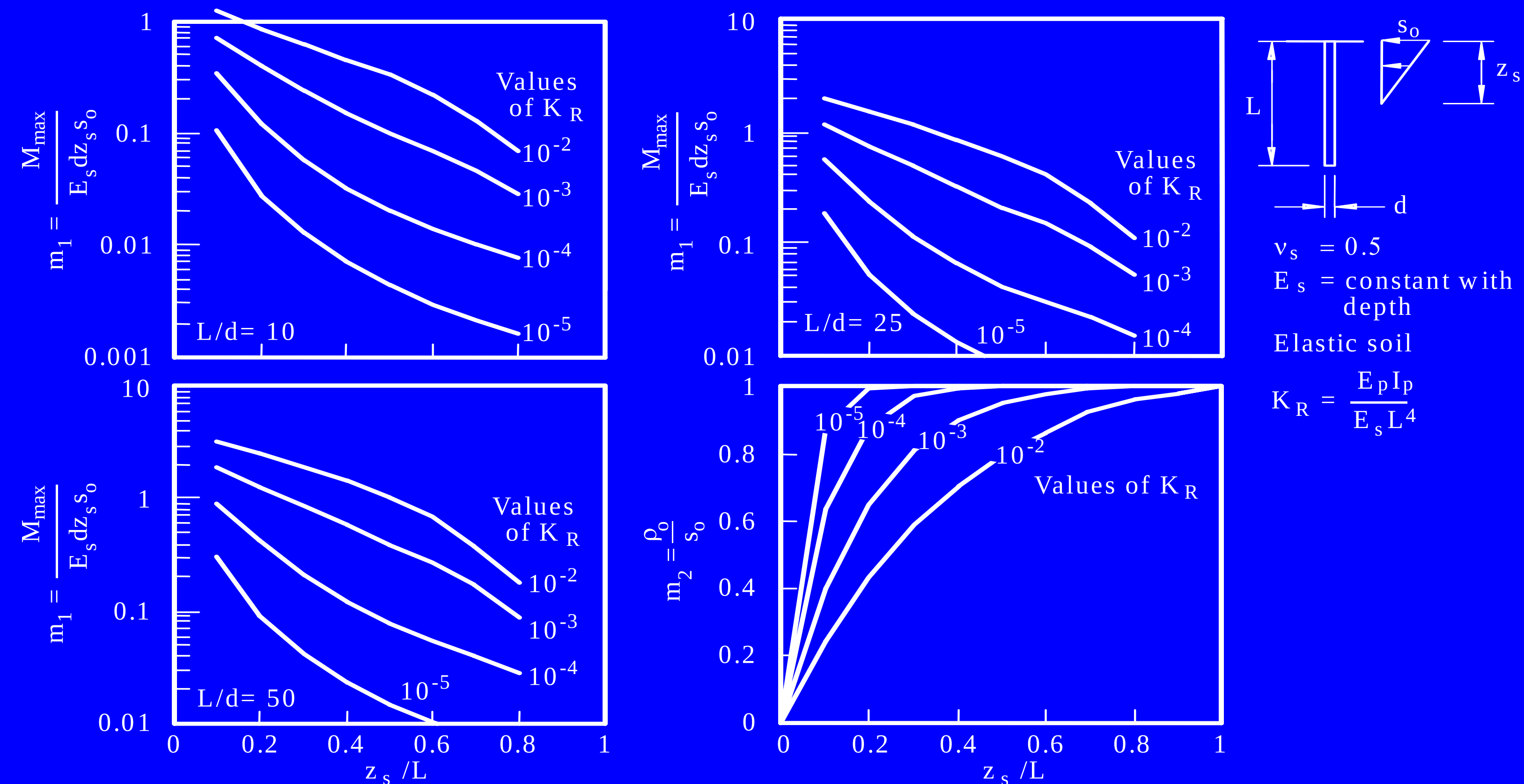


Fig. 5 Elastic solutions for unrestrained free-head pile in uniform soil (linear soil movement profile) (Chen and Poulos, 1997)

DESIGN CHARTS FOR UNIFORM SOIL –Uniform Lateral Soil Movement

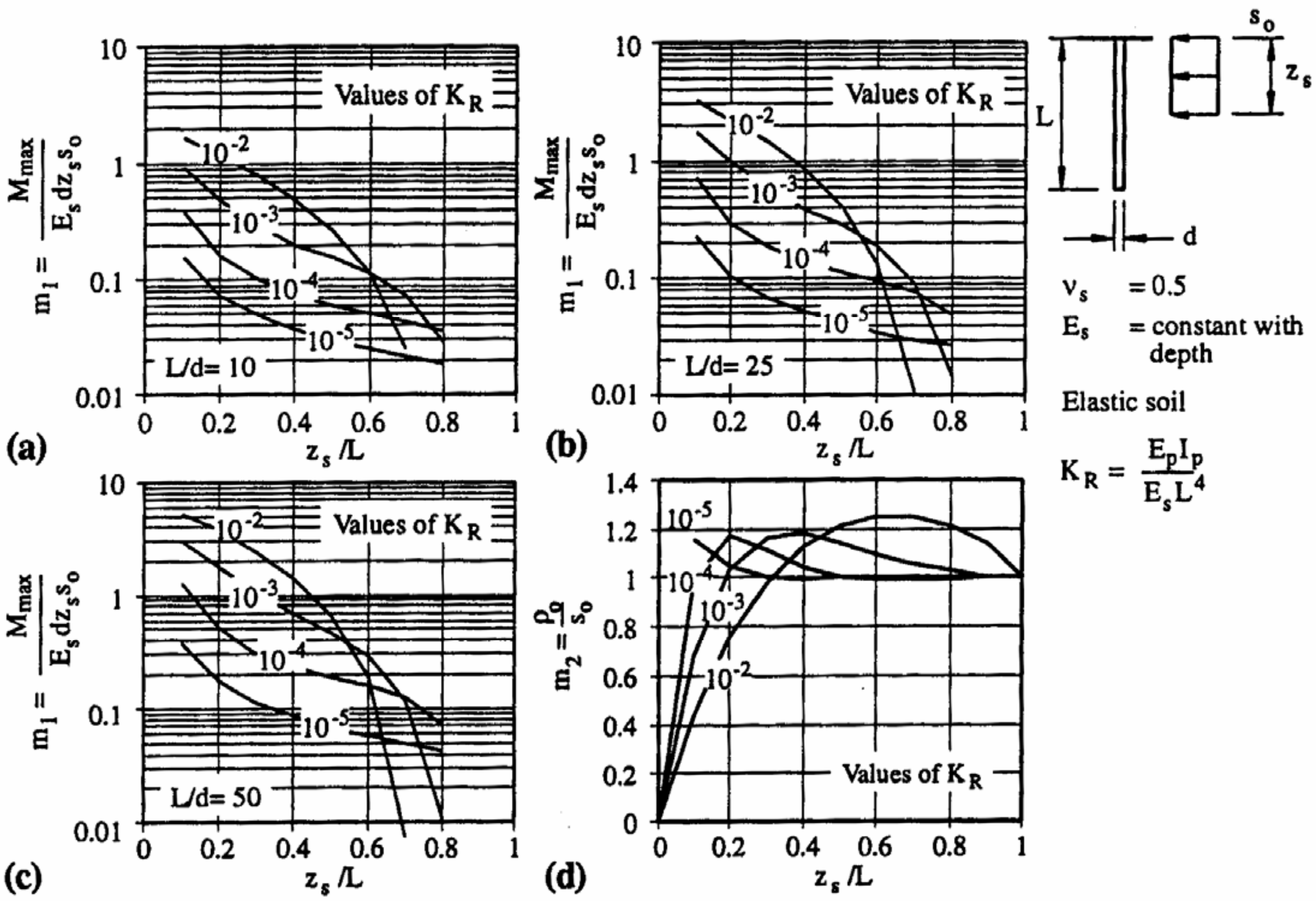


FIG. 4. Elastic Solutions for Unrestrained Free-Head Pile in Uniform Soil (Uniform Soil Movement Profile)

DESIGN CHARTS FOR GIBSON SOIL – Triangular Lateral Soil Movement

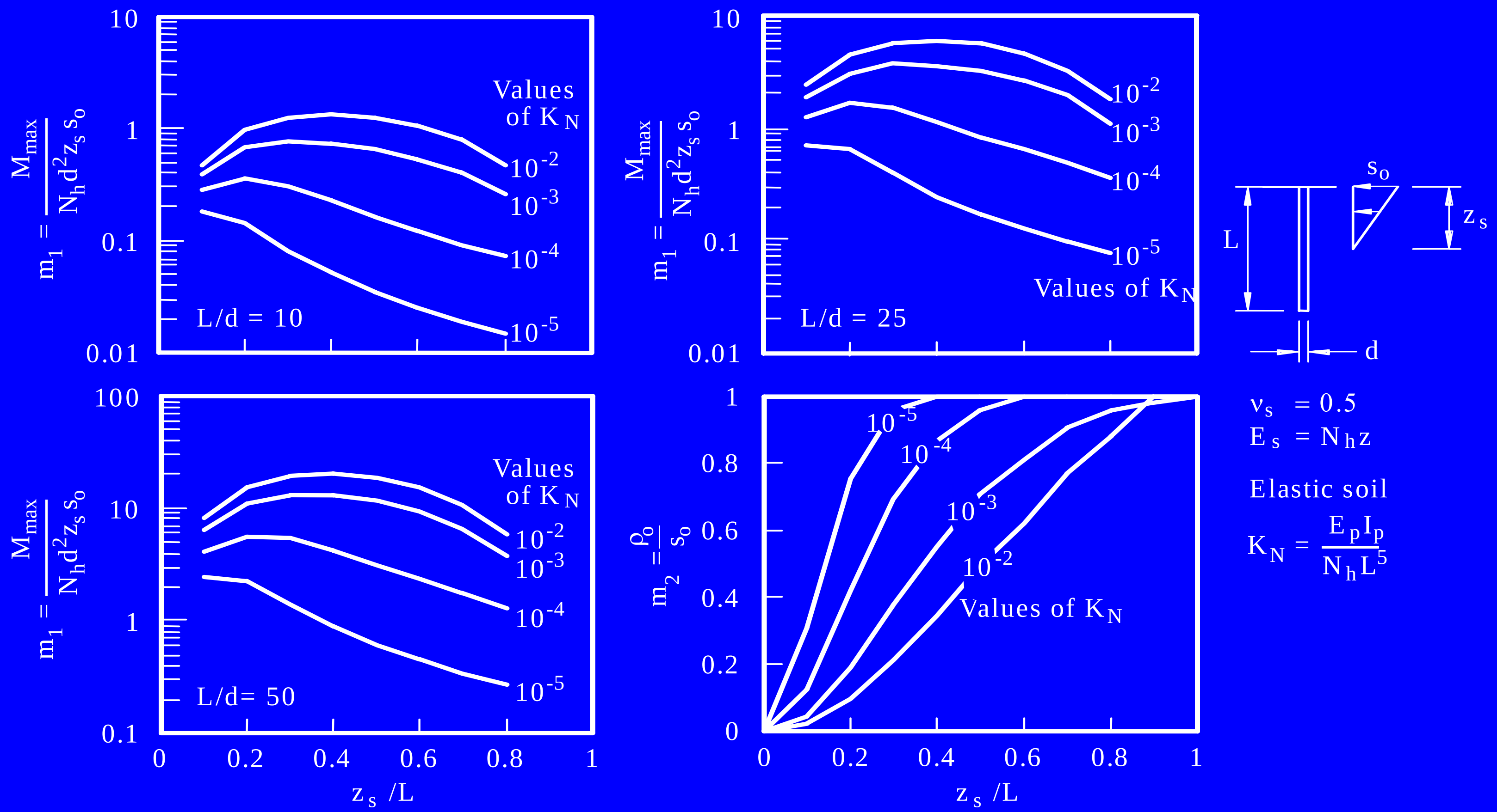


Fig. 6 Elastic solutions for unrestrained free-head pile in Gibson soil (Linear soil movement profile) (Chen and Poulos, 1997)

DESIGN CHARTS FOR GIBSON SOIL – Uniform Lateral Soil Movement

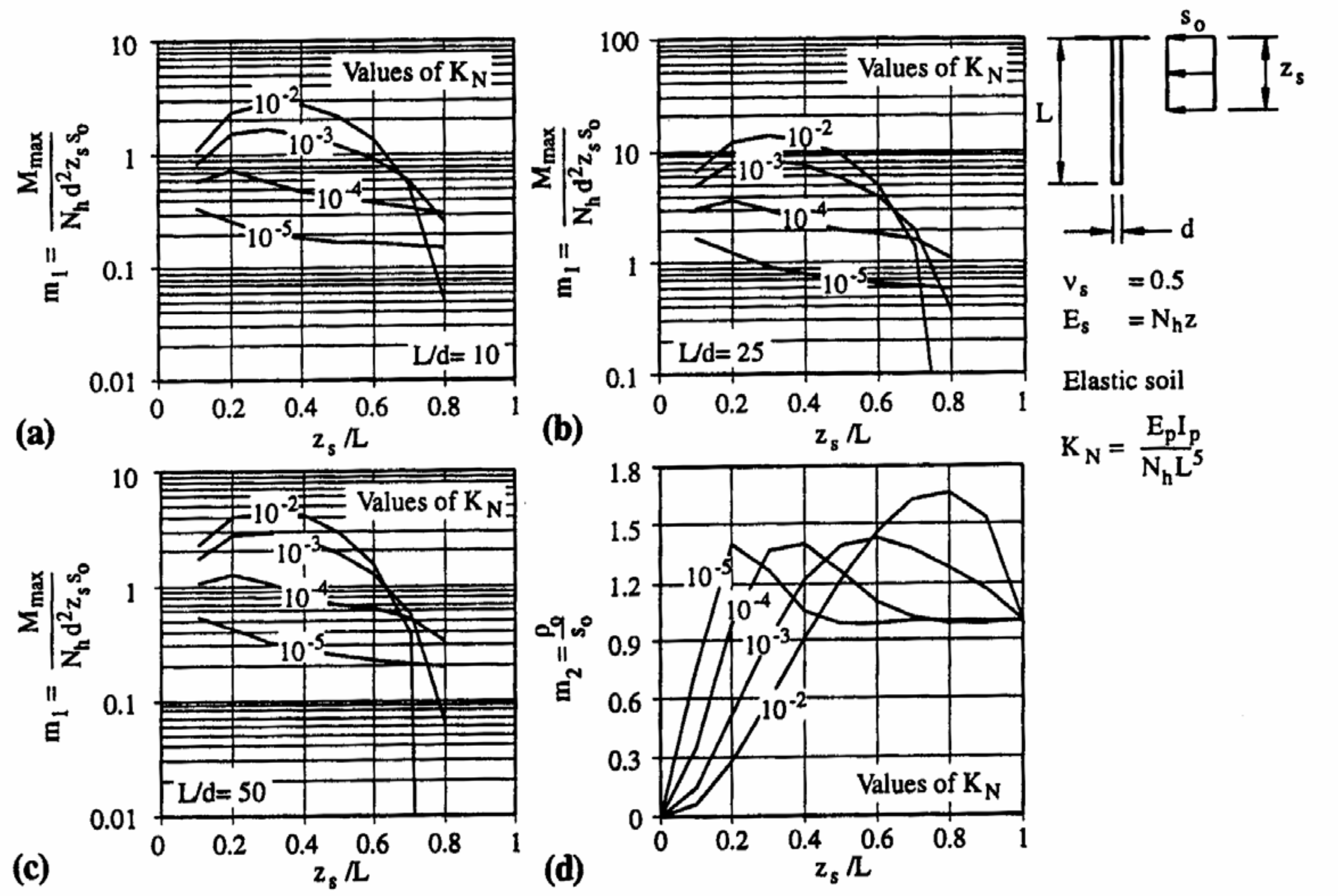


FIG. 5. Elastic Solutions for Unrestrained Free-Head Pile in Gibson Soil (Uniform Soil Movement Profile)

EFFECT OF PILE HEAD CONDITIONS

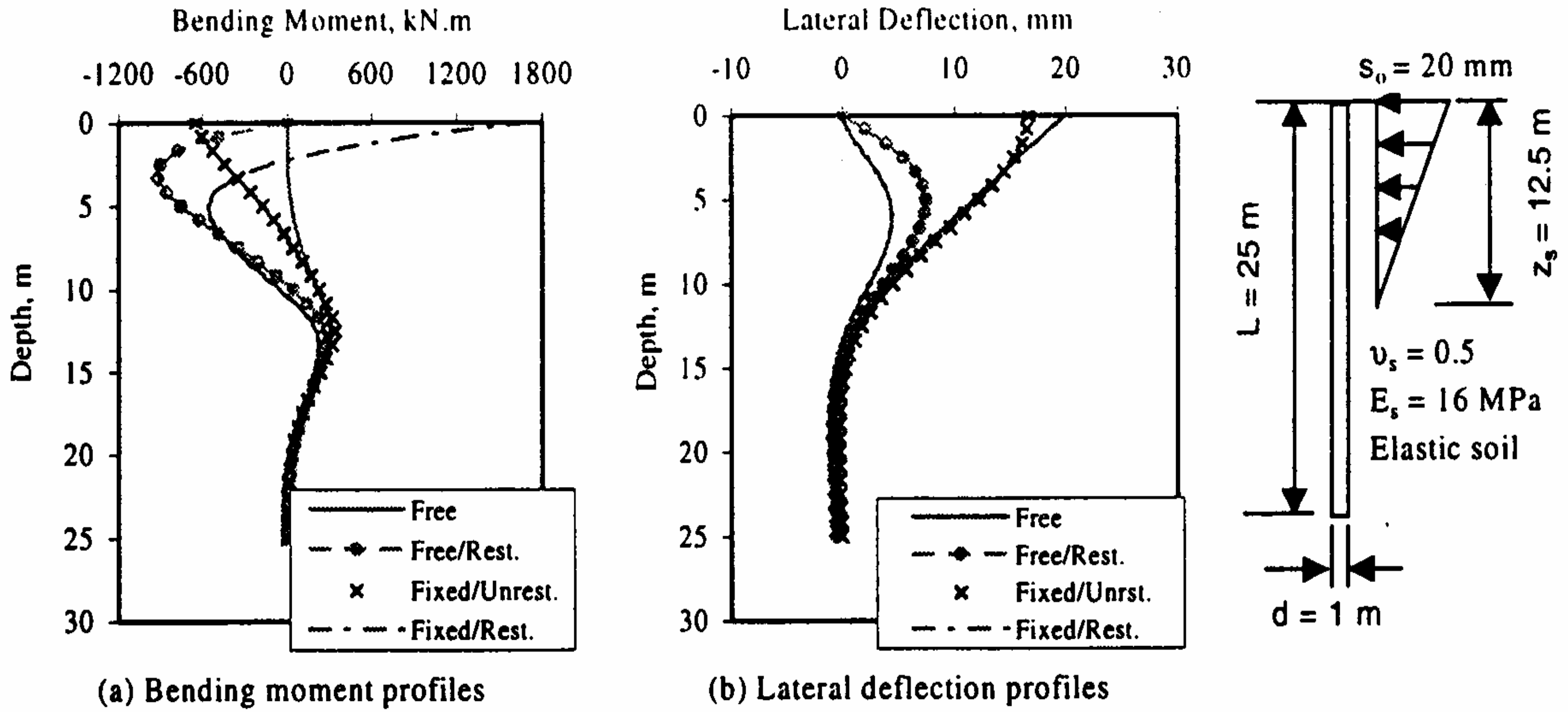
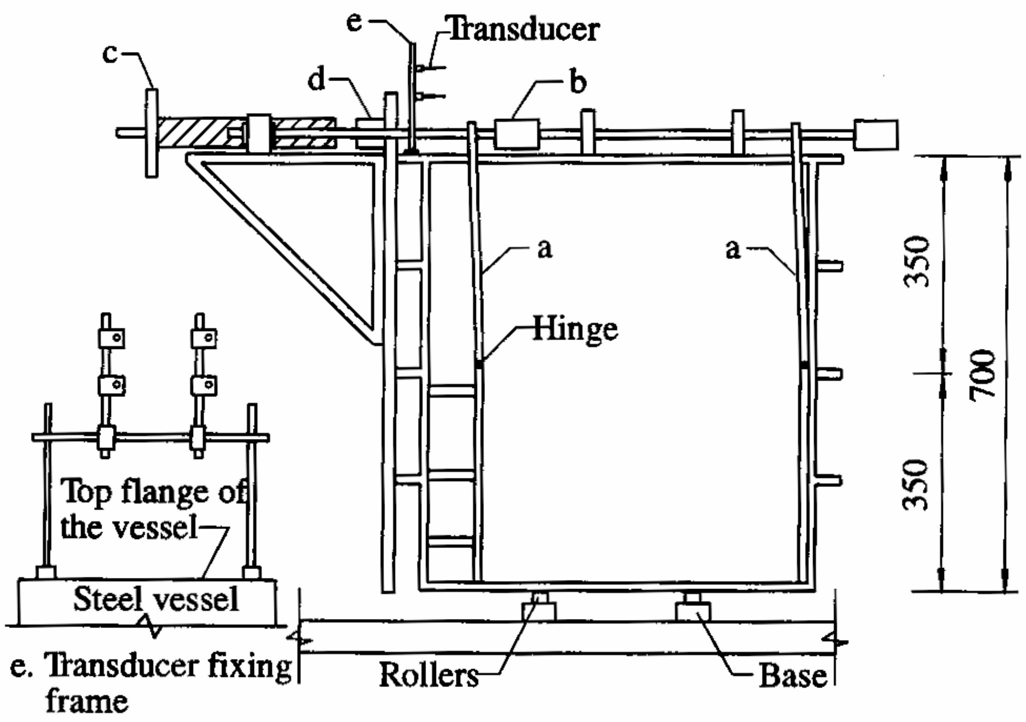


Figure 2 Effect of pile head condition on pile response (uniform soil, linear soil movement)

MAIN CONCLUSIONS FROM THEORETICAL SOLUTIONS

- Pile behaviour is largely governed by relative flexibility of pile K_R:
  - $K_R = E_p I_p / (E_s . L^4)$ (for uniform soil)
- For flexible piles ($K_R < 10^{-5}$), the pile deforms with the soil. Can thus estimate moments from estimated curvature of soil movement profile.
- For stiffer piles, deflection decreases but BM increases.
- Pile head restraint is important. Restraint decreases pile movements but increases BM and can also develop large restraining force.

COMPARISONS BETWEEN THEORETICAL SOLUTIONS AND MODEL TESTS

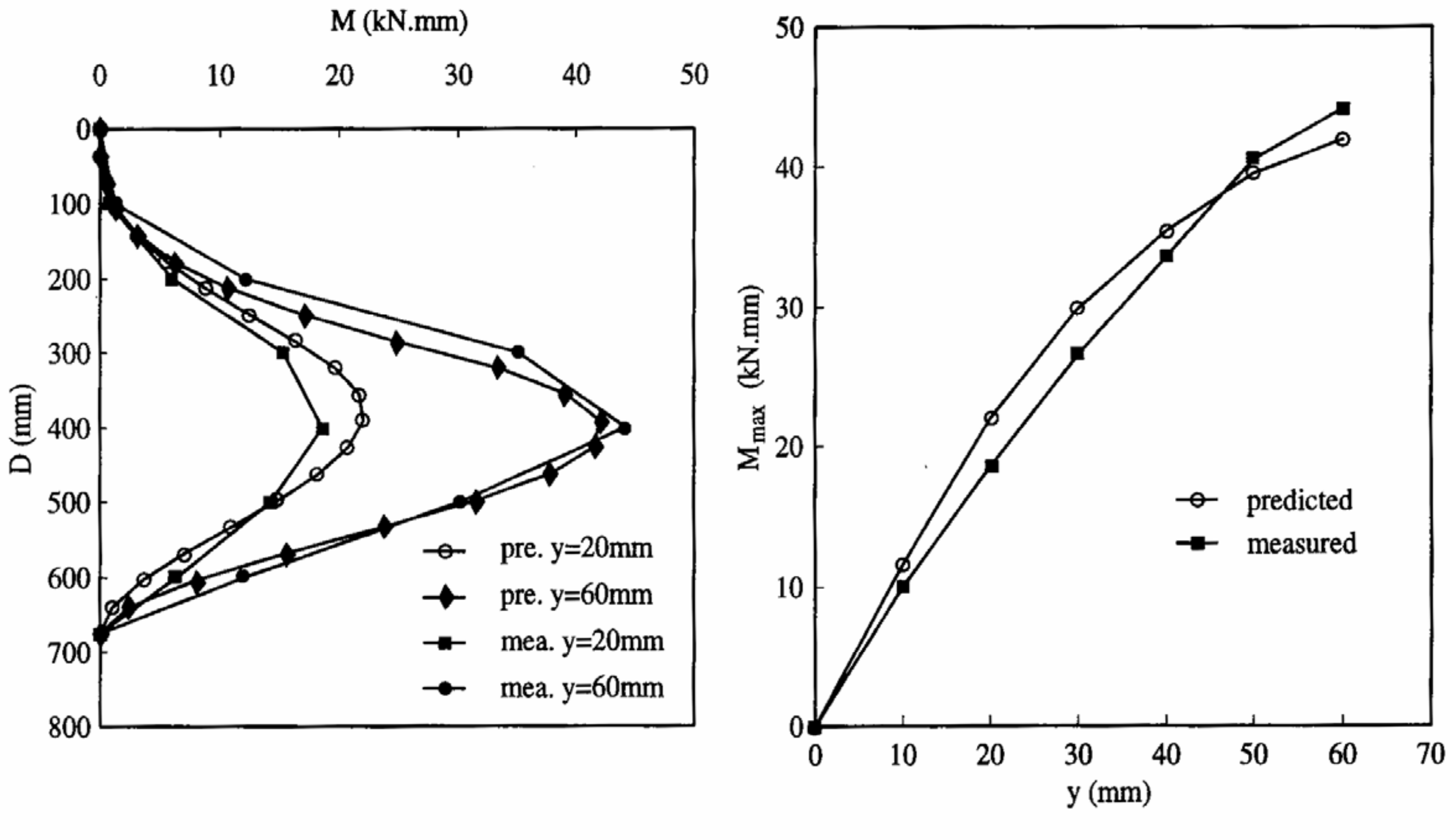


(b) Elevation view

Fig. 1. Experimental apparatus

Chen & Poulos, 1995)

COMPARISONS BETWEEN THEORETICAL SOLUTIONS AND MODEL TESTS



(a) M vs D

(b) M_{max} vs y

Fig. 6. The relationship between maximum bending moment and dimensionless embedded length

Chen & Poulos, 1995)

COMPARISONS BETWEEN THEORETICAL SOLUTIONS AND MODEL TESTS

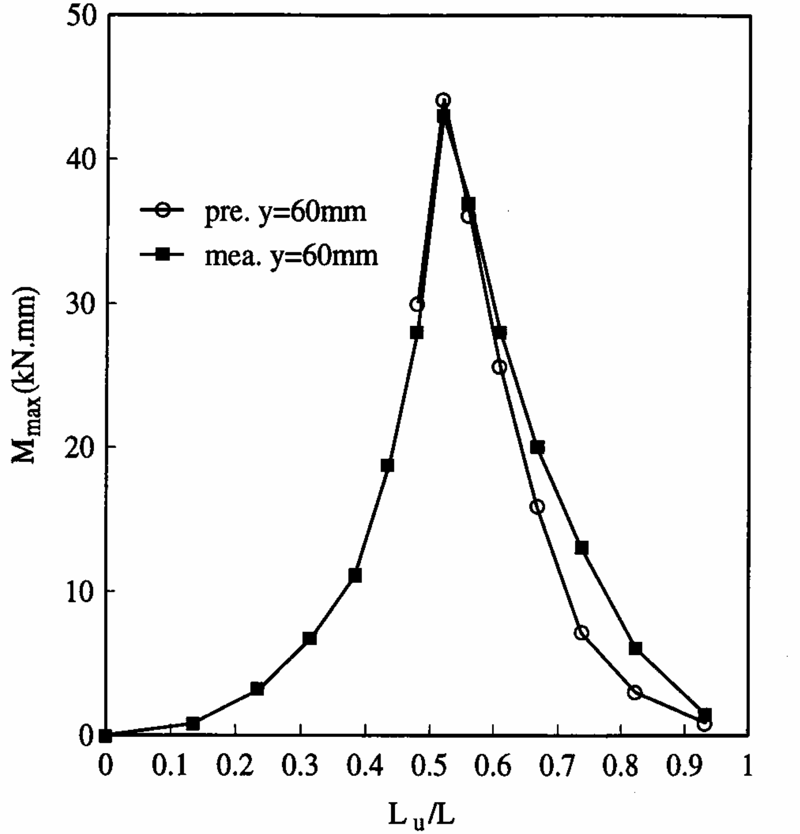


Fig. 7. Predicted and measured maximum bending moment vs dimensionless pile embedded length

(Chen & Poulos, 1995)

- Note that there is a depth of soil movement which gives maximum shear force

- Useful for stabilizing pile design

APPROXIMATIONS FOR SOIL MOVEMENTS IN PREDICTING PILE RESPONSE

When detailed movement assessments are not feasible, it may be possible to estimate soil movements as follows:

- **Excavation-Induced Movements**
  Assume linearly decreasing with depth to base of excavation
- **Embankment-Induced Movements**
  Assume linearly decreasing with depth to base of compressible layer
- **Movements from Slope Instability**
  Assume constant with depth down to sliding plane

PROBLEM OF PILE IN UNSTABLE SOIL

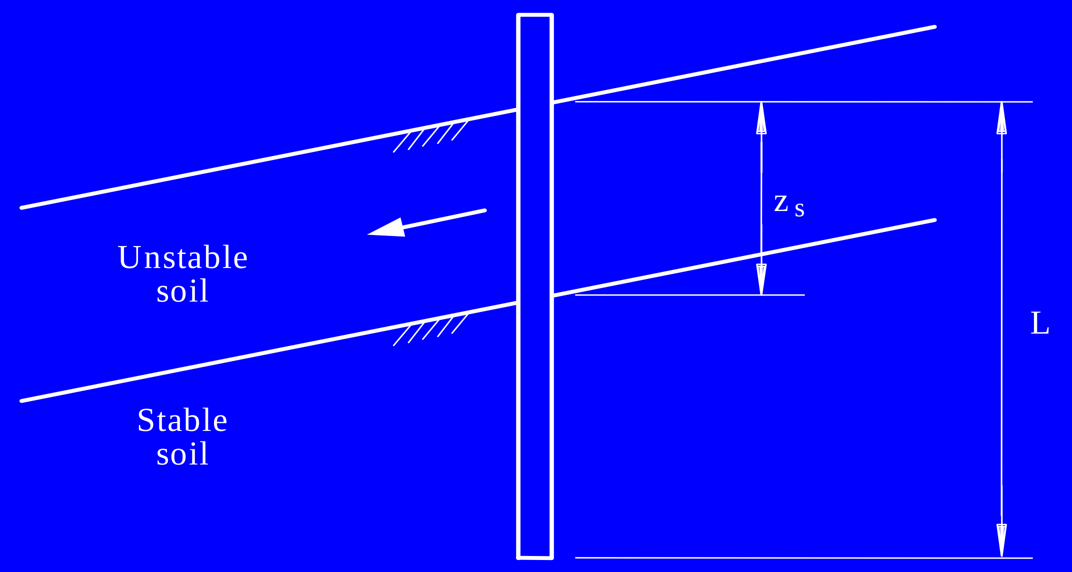
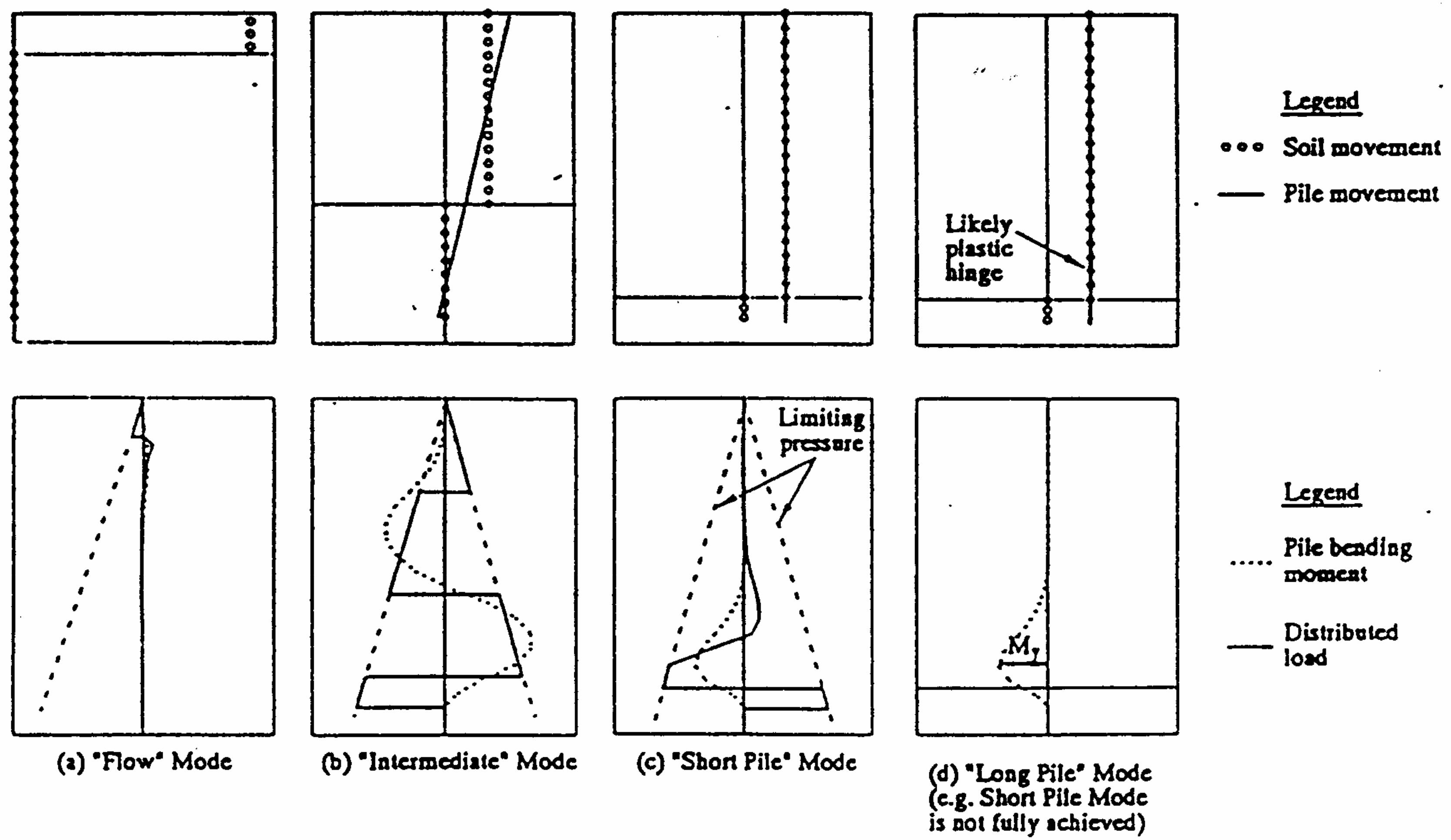


Fig. 7 Problem of pile in unstable soil

MECHANISMS OF BEHAVIOUR



MECHANISMS OF BEHAVIOUR

- **FLOW MODE** (shallow slides)
- **SHORT-PILE MODE** (deep slides)
- **INTERMEDIATE MODE** (Intermediate slide depths)
- **PILE YIELD MODE –**
  - pile itself fails
  - Can occur with any of the soil failure modes

MAXIMUM SHEAR FORCE DEVELOPED IN PILE BY SOIL

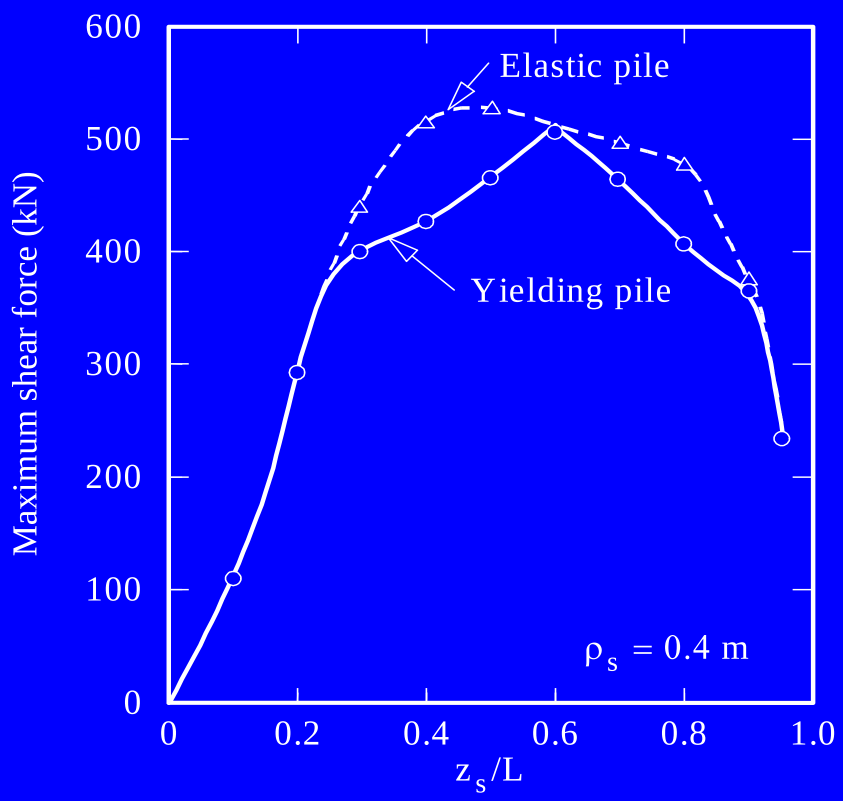
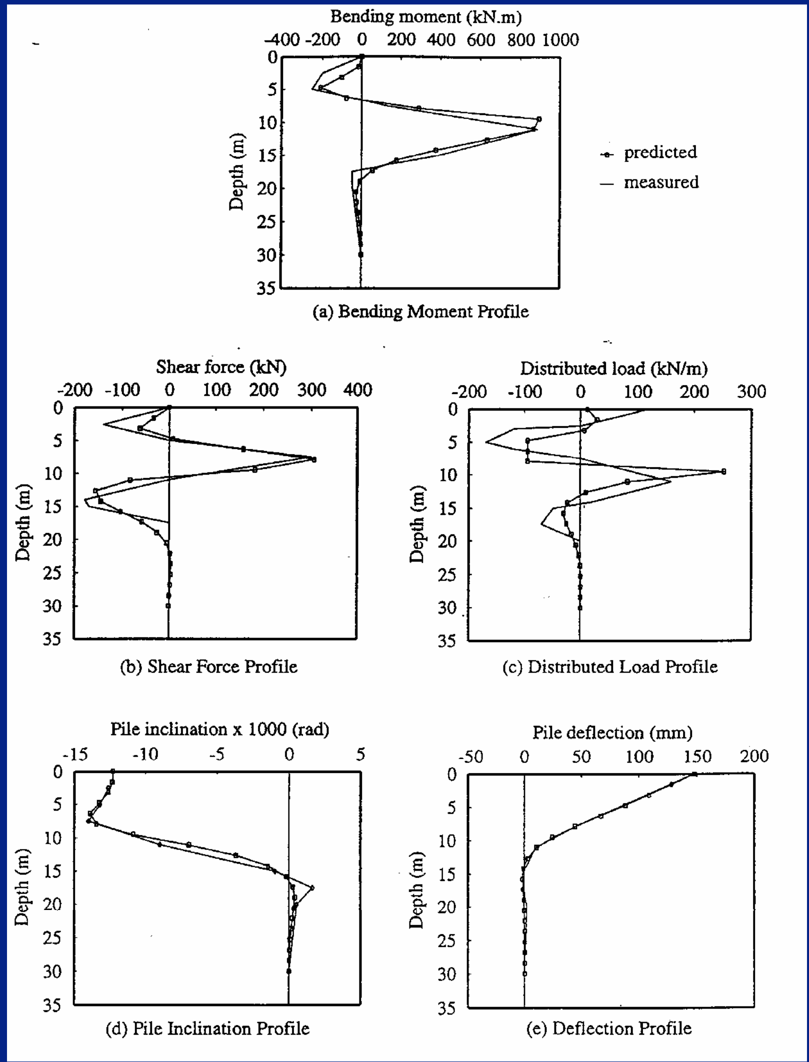


Fig. 8 Variation of maximum shear force with relative slide depth

COMPARISON WITH FIELD DATA

Field tests by Esu & D'Elia (1974).

Very good agreement between computed and measured responses for all aspects.



PILES NEAR EMBANKMENTS

PILES NEAR EMBANKMENTS – SIMPLIFIED APPROACHES

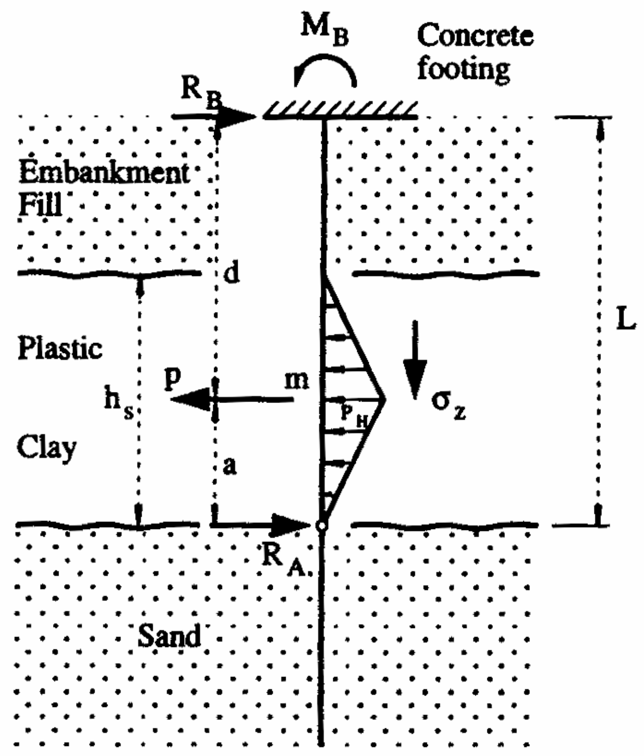


Fig.1 Method of Tschebotarioff (1973)

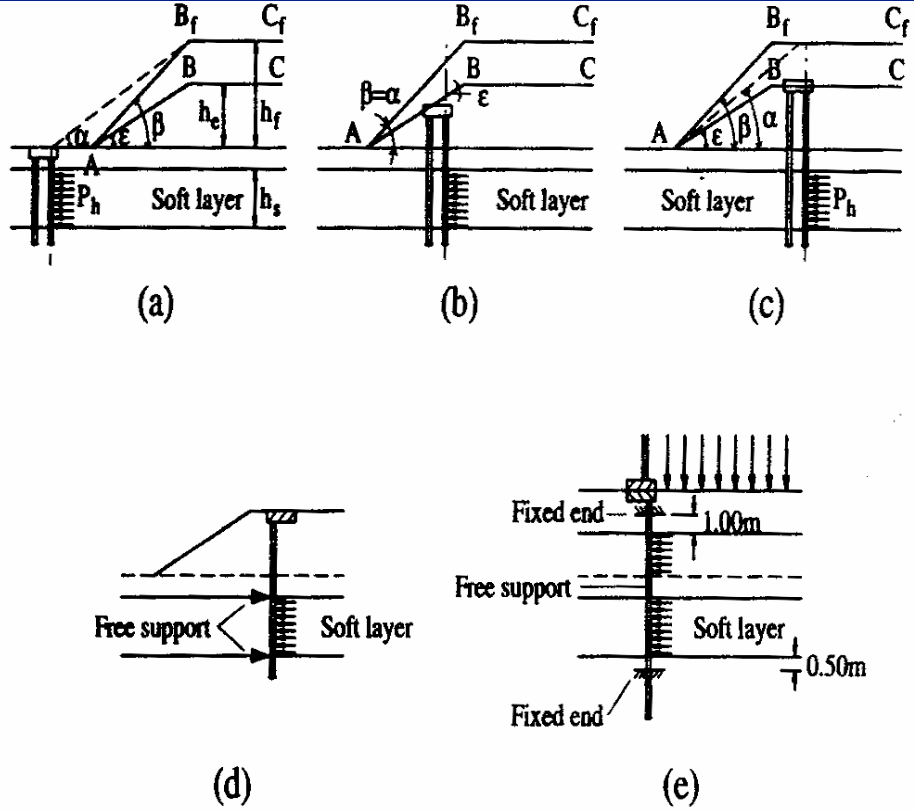


Fig.2 Method of De Beer and Wallays (1972)

PILES NEAR EMBANKMENTS – SIMPLIFIED APPROACHES

TABLE 1. Variants of the RTA Method

Method	Width Over Which Active Pressure Acts	Distance z_d (see Figure 5)
A1	d	0
A2	d	1m
B1	2d	0
B2	2d	1m

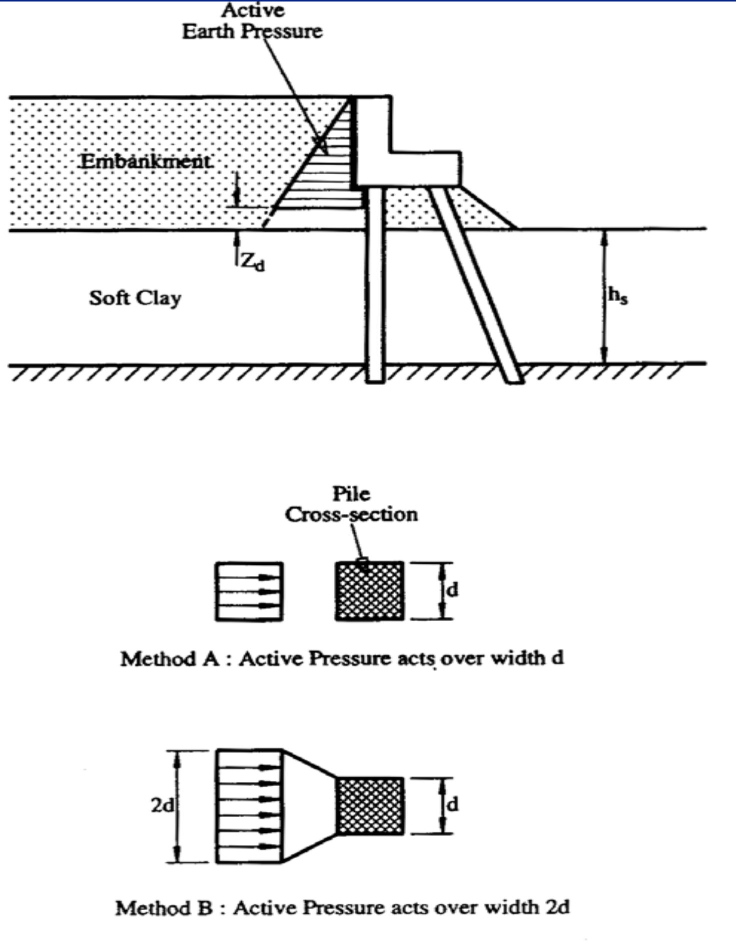


Fig.5 Assumptions in RTA Method

PILES NEAR EMBANKMENTS – WORK OF STEWART ET AL

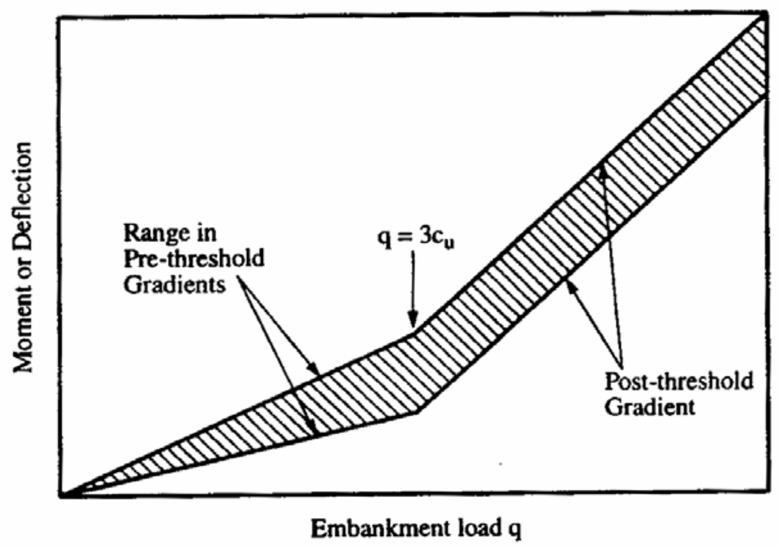


Fig.3 Construction of Design Envelopes on the basis of Empirical Relationships (Stewart et al, 1992)

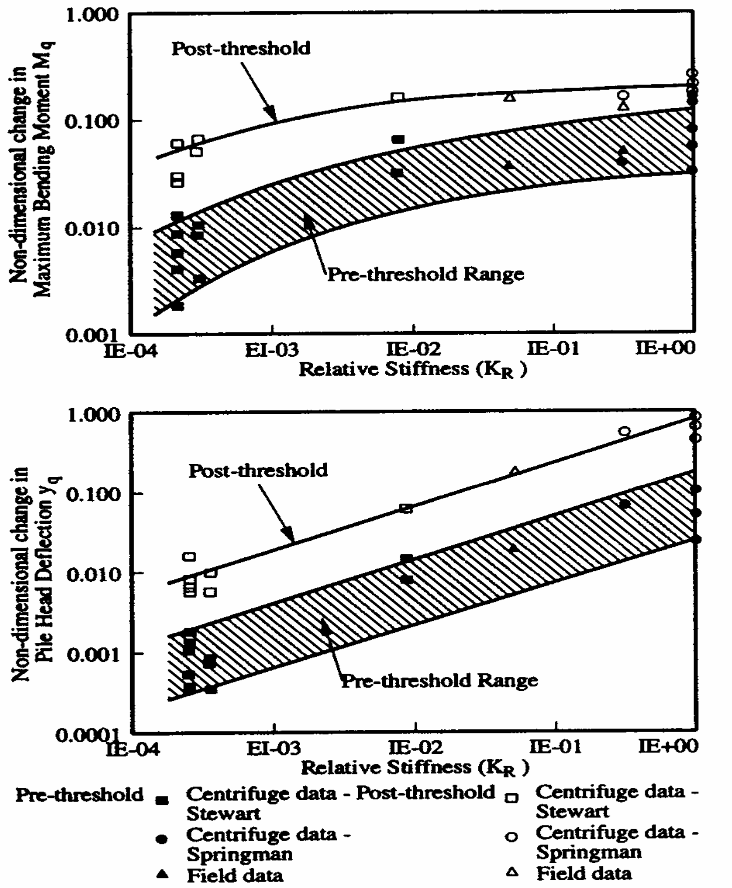


Fig.4 Non-dimensional Change in Maximum Bending Moment & Pile Head Deflection (Stewart et al, 1992)

COMPARISONS BETWEEN NUMERICAL ANALYSIS & CENTRIFUGE DATA

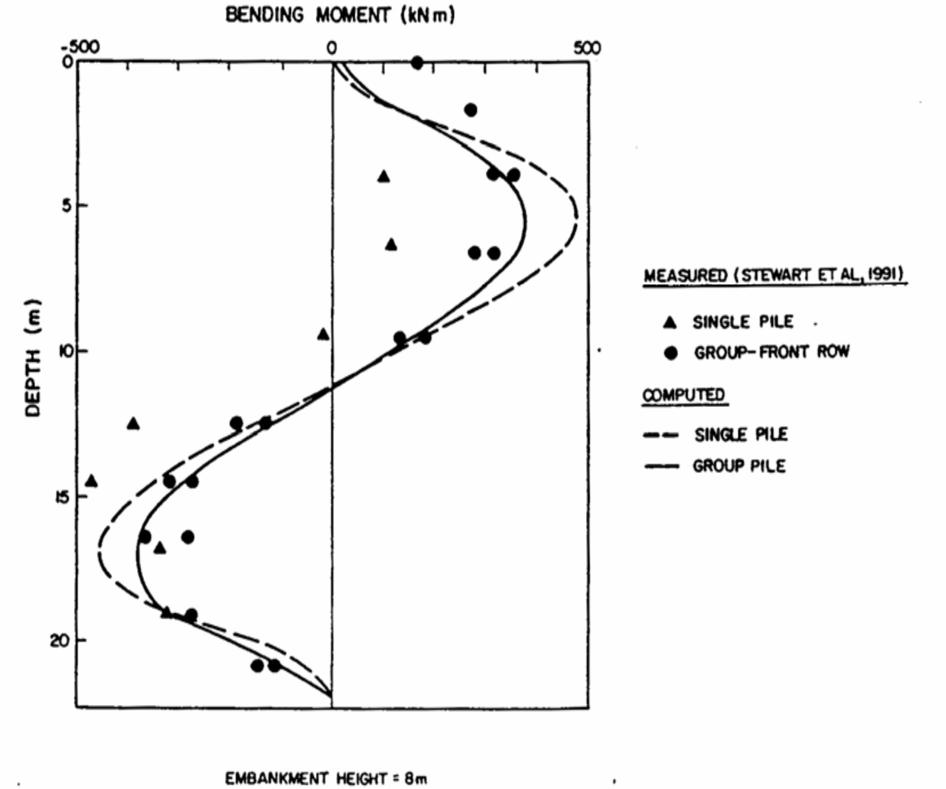


FIGURE 2 - COMPARISON BETWEEN MEASURED & COMPUTED BENDING MOMENT DISTRIBUTIONS - DEEP CLAY LAYER

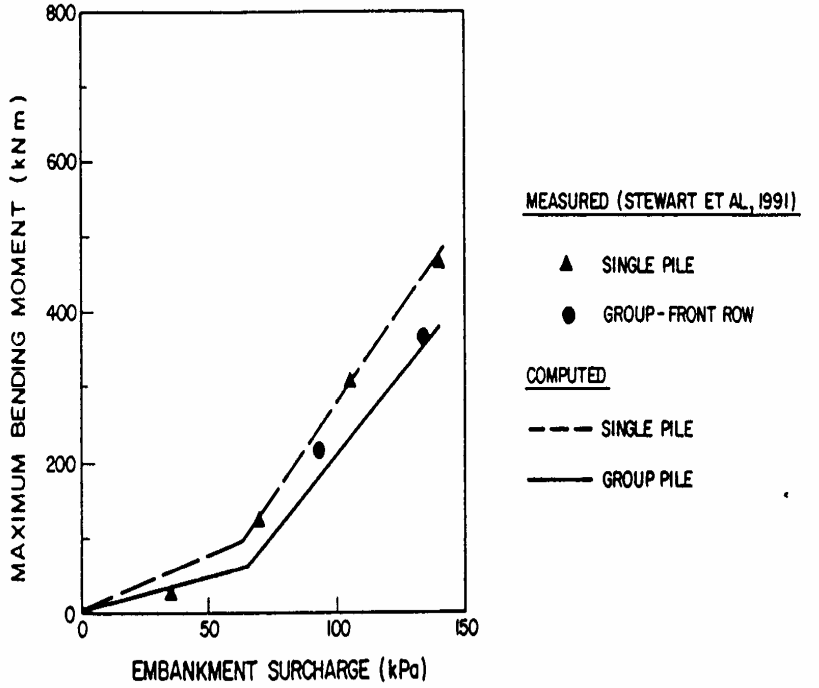


FIGURE 3 - COMPARISON BETWEEN MEASURED & THEORETICAL MAXIMUM BENDING MOMENTS - DEEP CLAY LAYER

ADVANTAGES OF DELAYED PILE INSTALLATION

Reduction of Axial Pile Load – limited effect

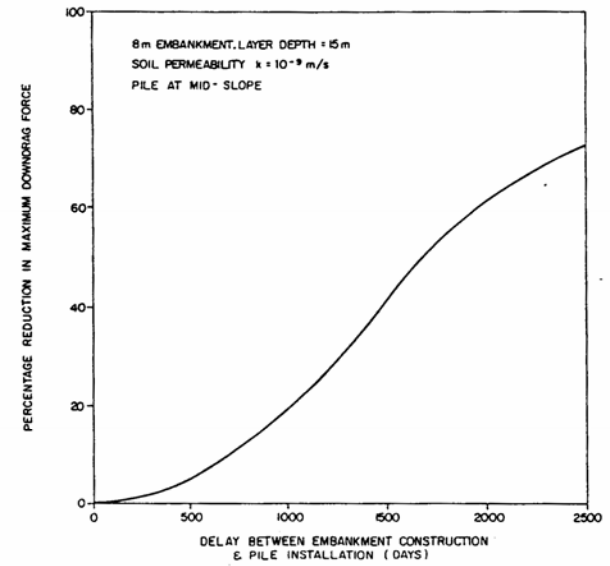
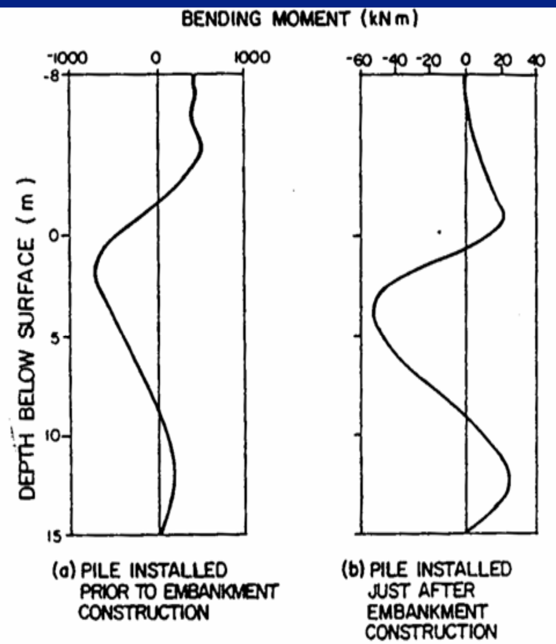


FIGURE 8 – INFLUENCE OF DELAYED INSTALLATION ON MAXIMUM AXIAL FORCE DEVELOPED IN PILE AT MID-SLOPE

Pile Moment Distribution – MAJOR effect



PILES NEAR EMBANKMENTS

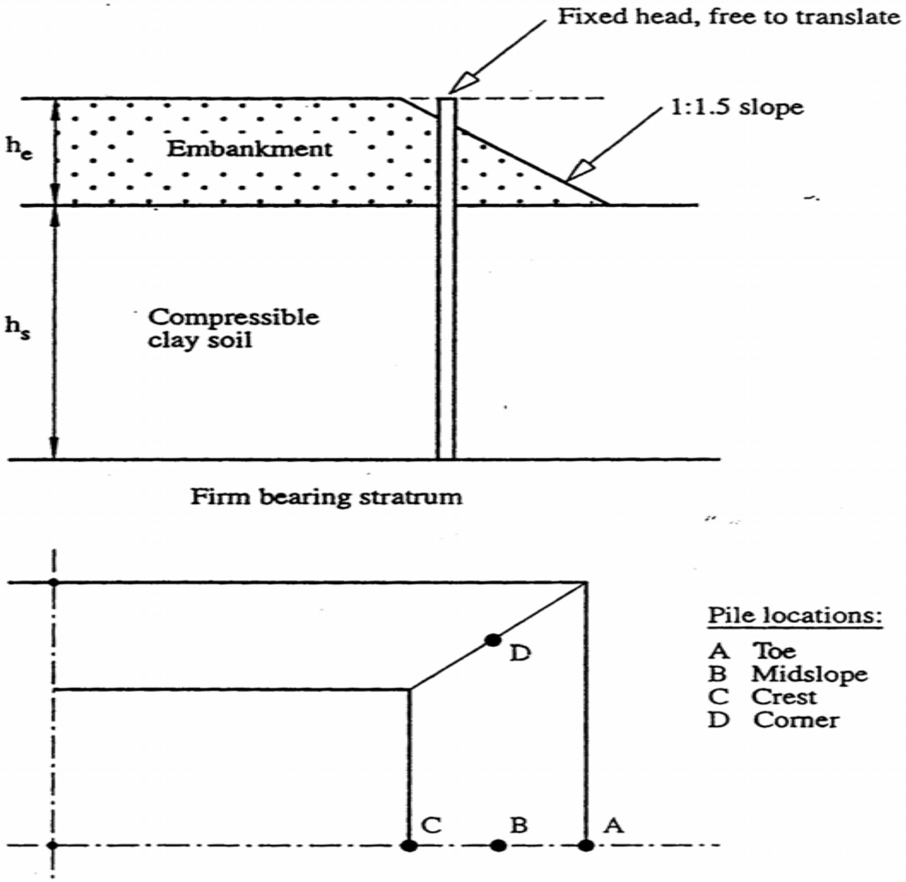


FIG.9 PROBLEM OF PILE WITHIN OR NEAR EMBANKMENT

DESIGN CHARTS FOR PILES NEAR EMBANKMENTS

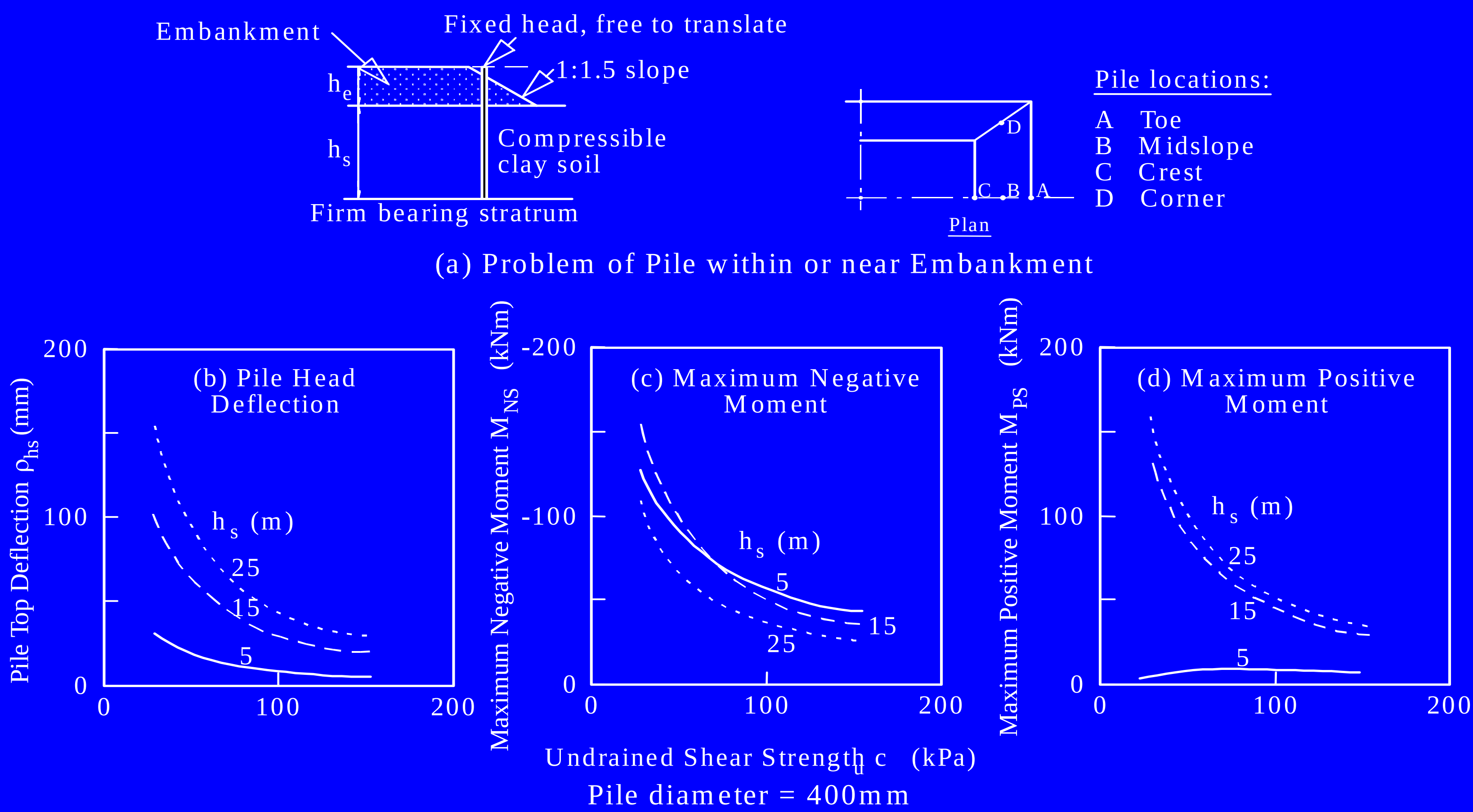


Fig. 9 Design charts for pile at crest of embankment - Embankment height = 8m

COMPARISON OF VARIOUS METHODS

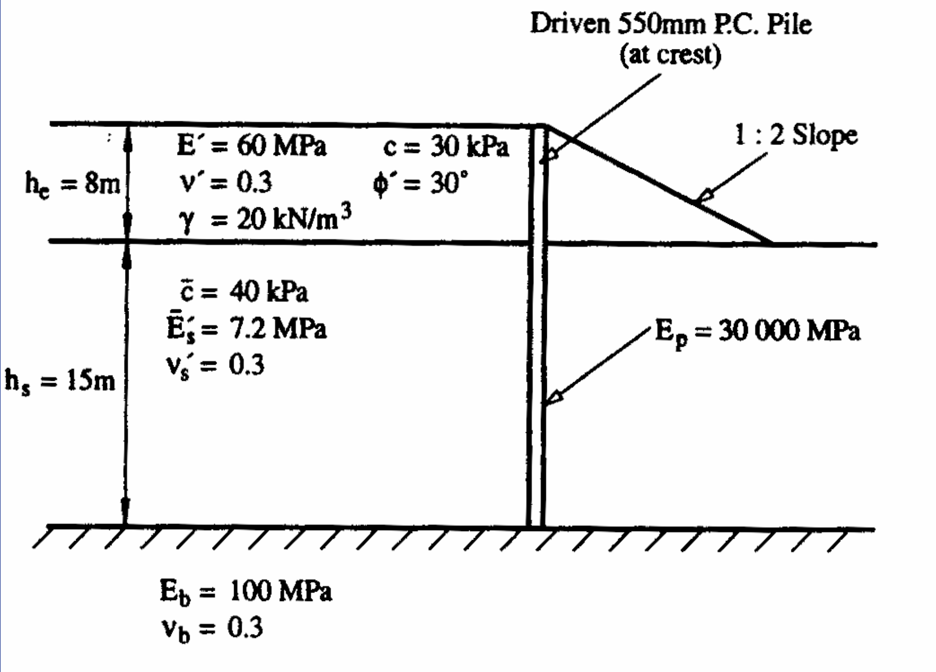
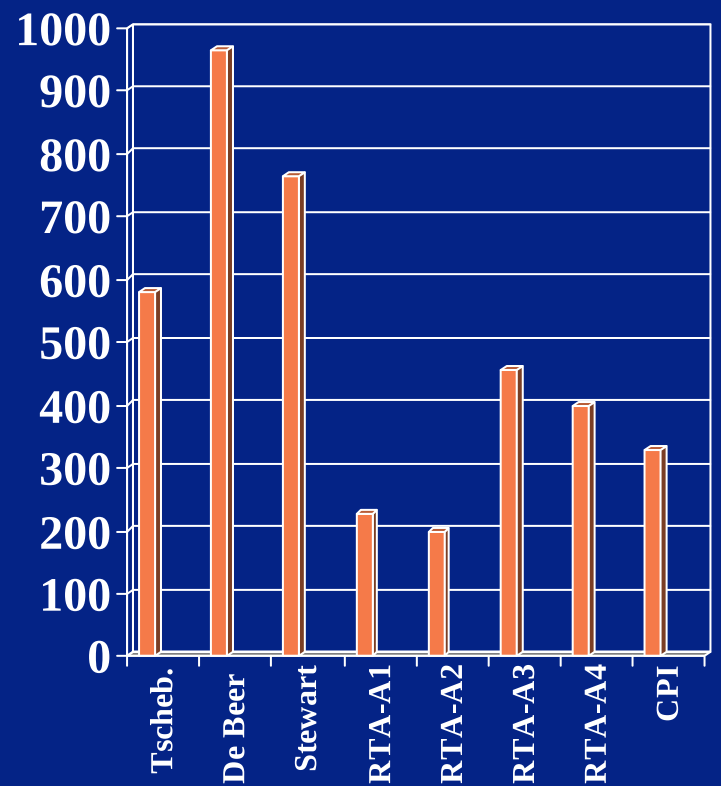


Fig.10 Idealized Hypothetical Case

Maximum BM for Hypothetical Case



SOME FINDINGS

- Delayed installation of piles, until after embankment construction, can be very beneficial
- Simplified design methods may be unreliable
  - May either over-estimate or under-estimate lateral pile responses
  - Depends on layer thickness
  - Stewart et al curves do not allow for delayed installation, hence tend to over-estimate
- For axial response, simple approach based on conventional negative friction calculations appears adequate

CONSEQUENCES OF GROUND MOVEMENTS

EFFECTS OF PILE INSTALLATION ON EXISTING PILES (in clay)

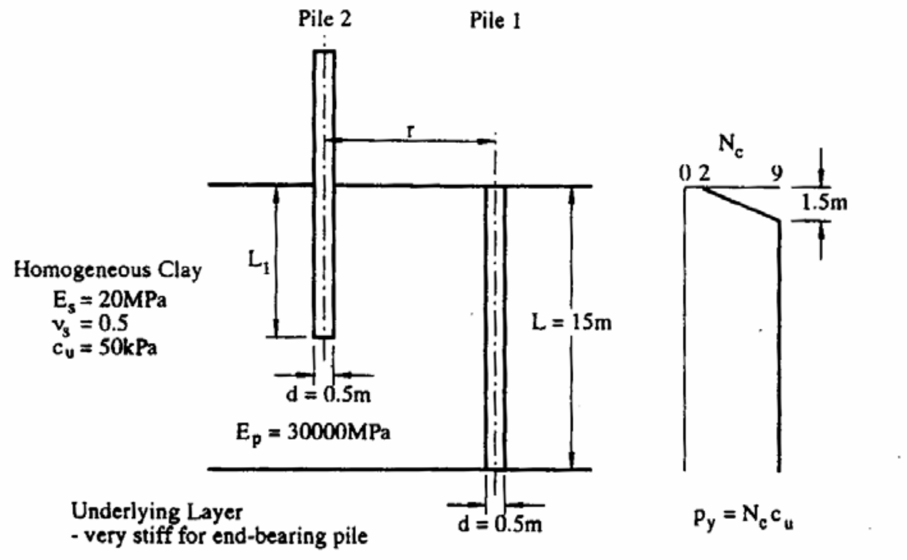


FIG. 5. Basic problem analysed. c_u, undrained shear strength; E_p, Young's modulus of pile; N_c, lateral bearing capacity factor; p_y, ultimate lateral pressure.

The Basic Problem

- Pile driving causes vertical and lateral ground movements
- These movements in turn interact with existing piles
- They are subjected to additional forces, moments and movements

GROUND MOVEMENTS DUE TO PILE INSTALLATION

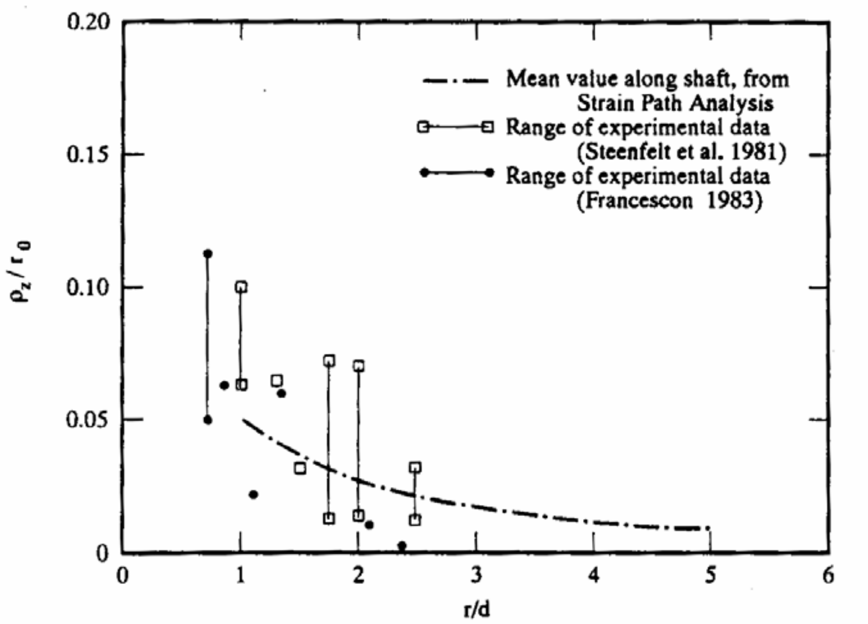


FIG. 4. Vertical displacements in soil due to pile driving.

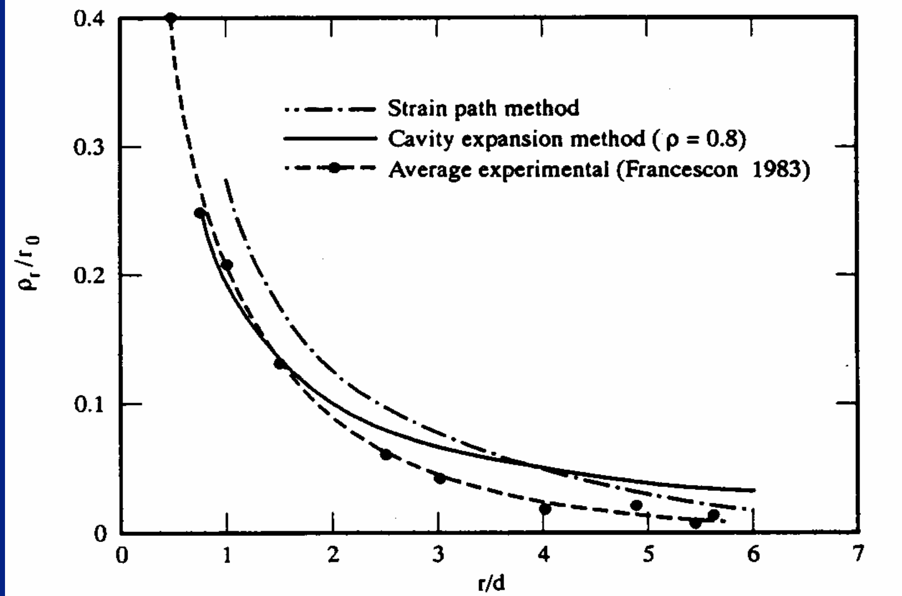


FIG. 3. Radial displacements in soil due to pile driving.

Vertical

Radial

EFFECTS OF GROUND MOVEMENTS – VERTICAL RESPONSE

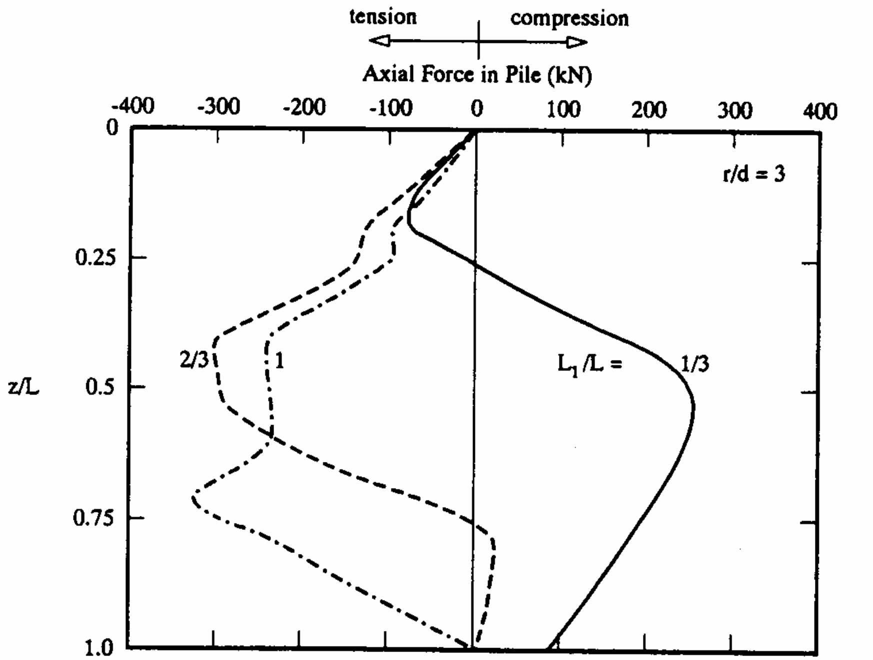


FIG. 8. Distribution of axial force in end-bearing piles induced by installation of adjacent pile.

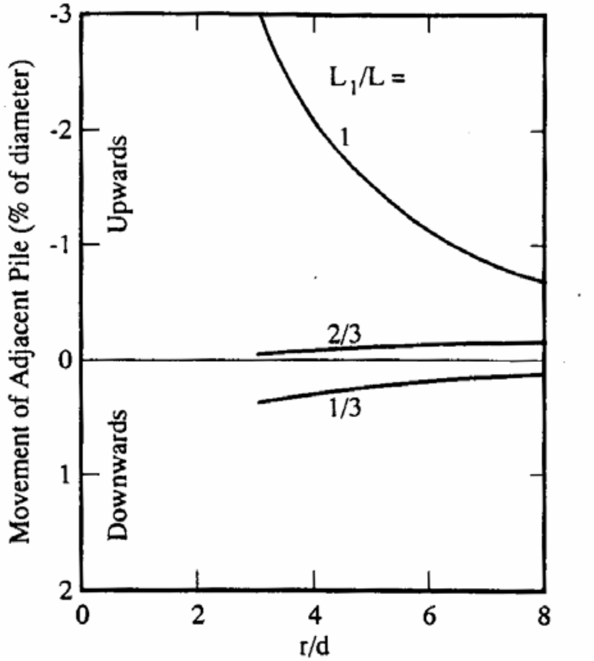


FIG. 10. Computed movements of adjacent pile due to installation of end-bearing pile.

Vertical Force Distribution For Various Levels of Pile Being Installed

Vertical Movement of Existing Pile Head

EFFECTS OF GROUND MOVEMENTS – AXIAL RESPONSE

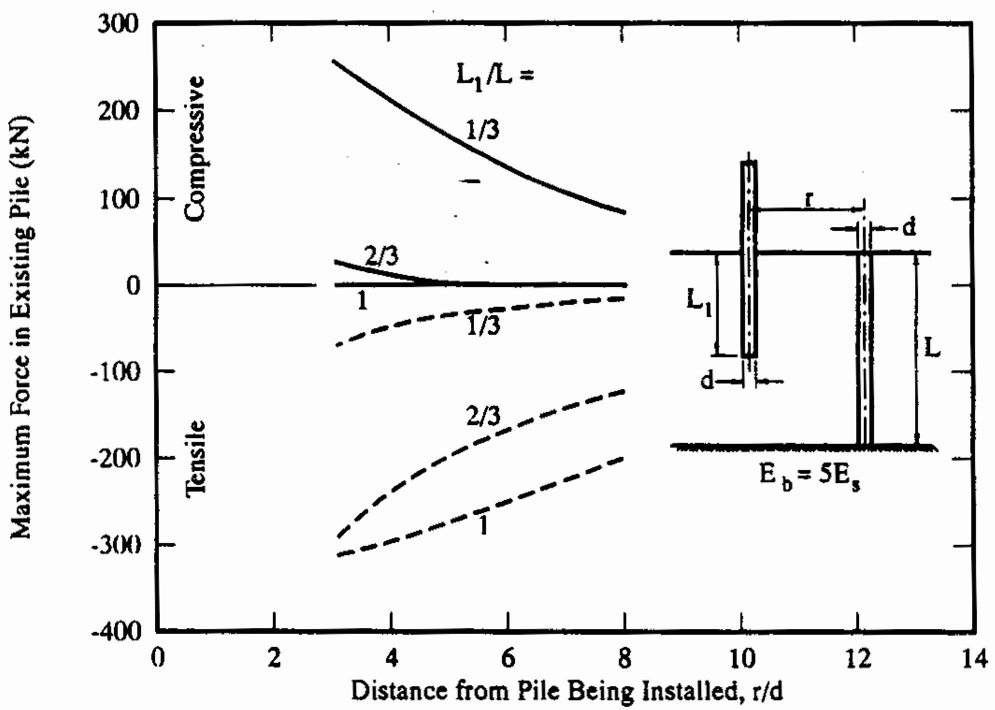


FIG. 9. Maximum compressive and tensile forces induced in existing pile due to driving adjacent end-bearing pile. E_b, Young's modulus of bearing stratum.

Maximum Induced Force vs Distance, for Various Levels of Pile Being Installed

EFFECTS OF MULTIPLE PILE INSTALLATION - AXIAL RESPONSE

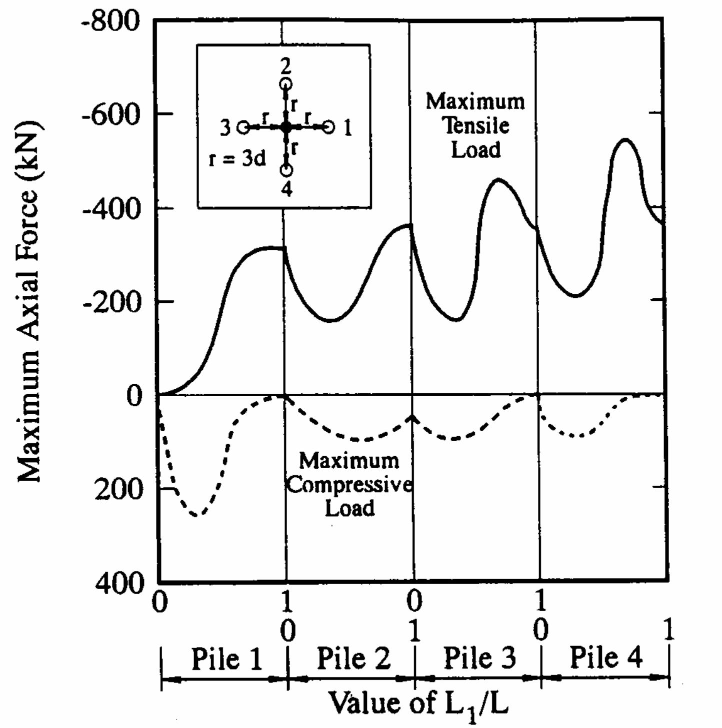


FIG. 11. Maximum forces in pile during installation of four surrounding end-bearing piles.

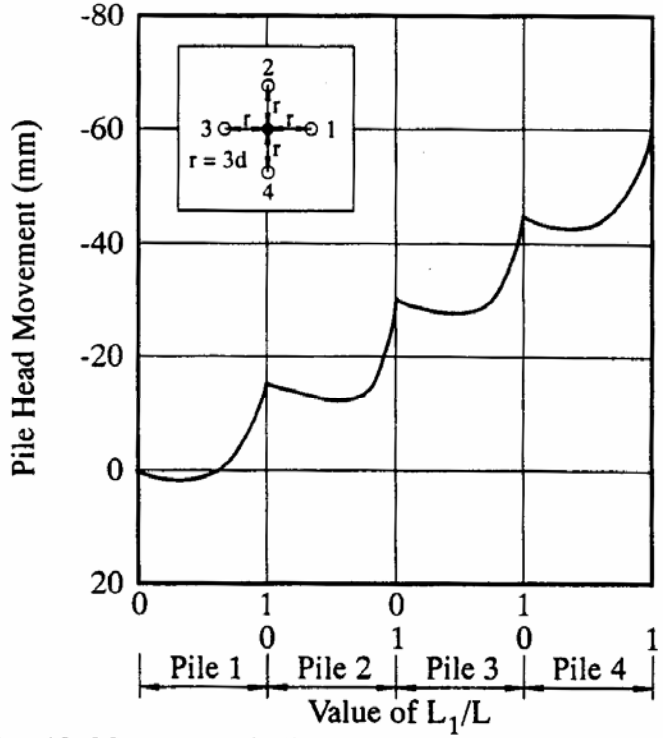


FIG. 12. Movement of pile head during installation of four surrounding end-bearing piles.

Maximum Forces

Maximum Pile Head Movement

EFFECTS OF PILE INSTALLATION – LATERAL RESPONSE

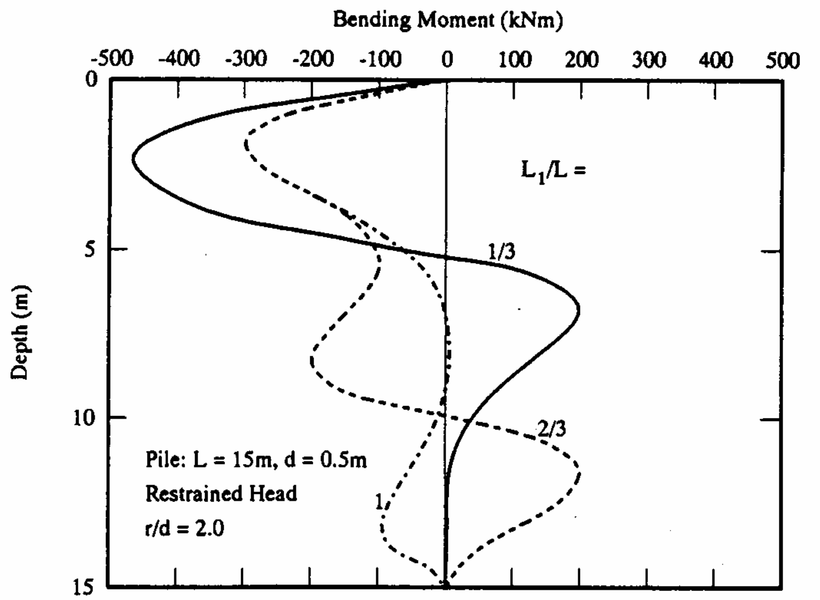


FIG. 14. Computed distributions of bending moment in existing restrained-head pile due to installation of adjacent pile.

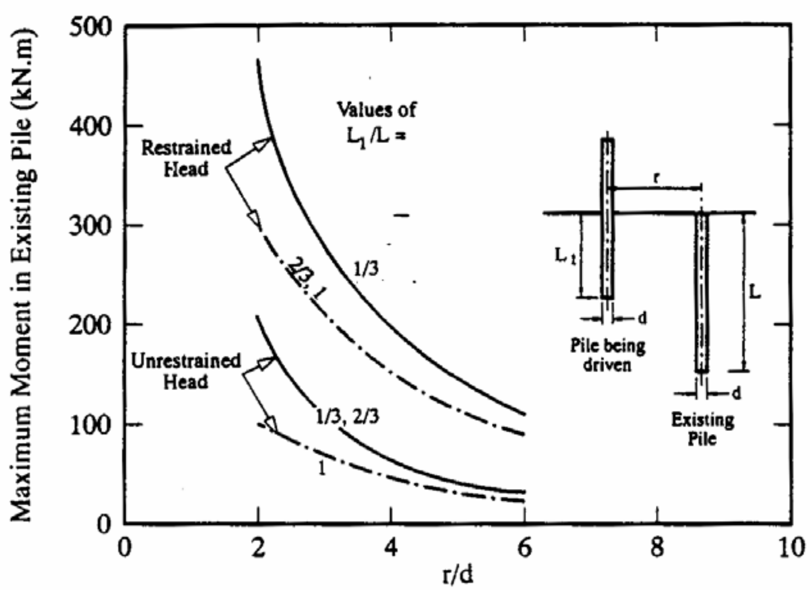


FIG. 15. Influence of pile spacing on maximum moment in pile due to driving of adjacent pile.

Bending Moment Distributions For Various Levels of New Pile

Maximum Pile Moment

EFFECTS OF PILE INSTALLATION – COMPARISONS BETWEEN MEASUREMENT & THEORY

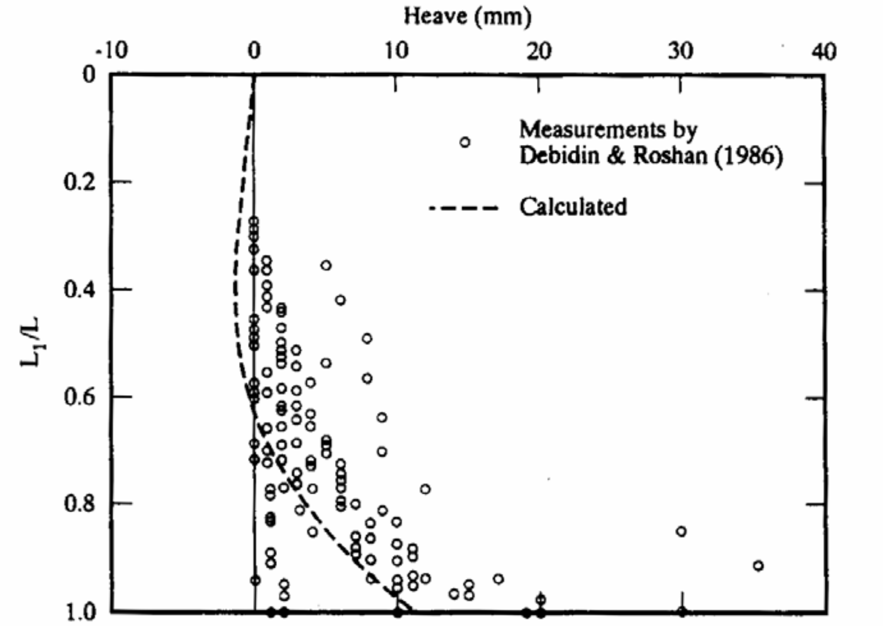


FIG. 17. Comparison between measurement by Debidin and Roshan (1986) and theory.

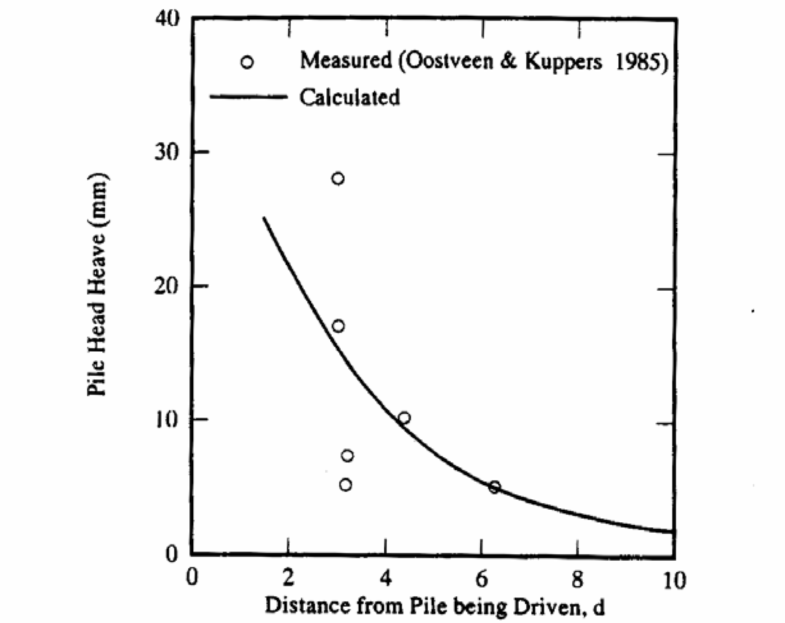


FIG. 18. Measured and predicted pile head heave due to pile driving. Penetration of pile being driven is approx. 5 m.

Head Vertical Movement For Various Levels of New Pile

Vertical Head Movement vs Distance from New Pile

EFFECTS OF PILE INSTALLATION – COMPARISONS BETWEEN MEASUREMENT & THEORY

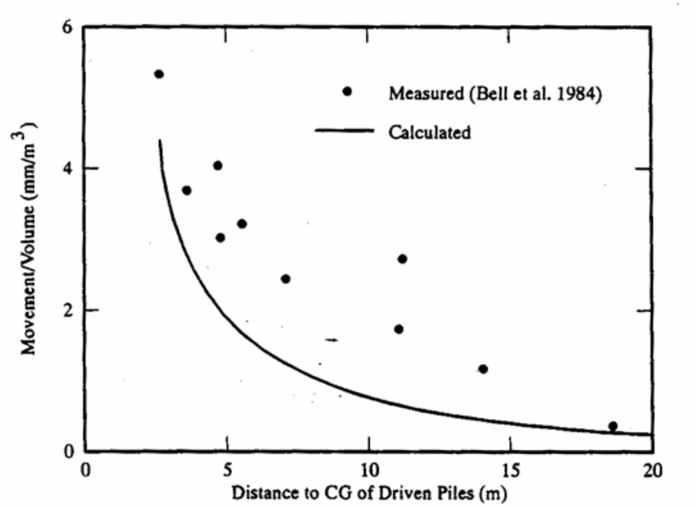


FIG. 22. Distance–movement relationships for Los Angeles Harbour project. CG, centre of gravity.

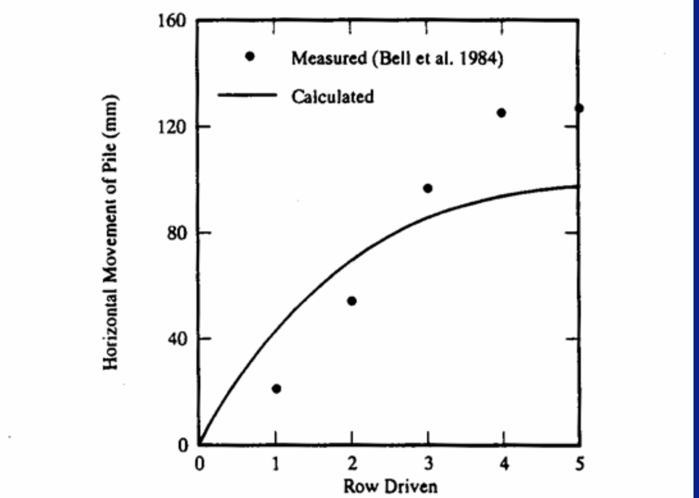


FIG. 23. Horizontal movement of pile due to driving of pile rows, Los Angeles Harbour project.

Head Vertical Movement vs Distance from New Piles

Lateral Head Movement vs Number of Pile Rows Driven