REVIEW OF FRENCH "FOREVER" PROJECT

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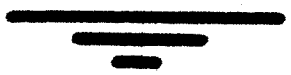
Projet National : Renforcement des sols par micropieux

"FOREVER"

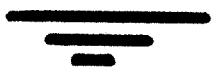
FRENCH NATIONAL RESEARCH PROJECT

Prof. François SCHLOSSER. TERRASOL Consulting Co.

Prof. Roger FRANK. CERMES (ENPC - LCPC)



1. MAIN ASPECTS
2. PRESENT DESIGN
3. RESEARCH PROGRAM
4. SLIDES , if time allows...



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MAIN ASPECTS OF THE RESEARCH

① SINGLE MICROPILES

Settlement estimation

Horizontal forces (calibration chamber, centrifuge, full scale measurements)

Buckling

Durability

Seismic behaviour

② GROUPS OF MICROPILES

Mechanical interaction (vertical forces)

Horizontal forces

Effect of the pile cap

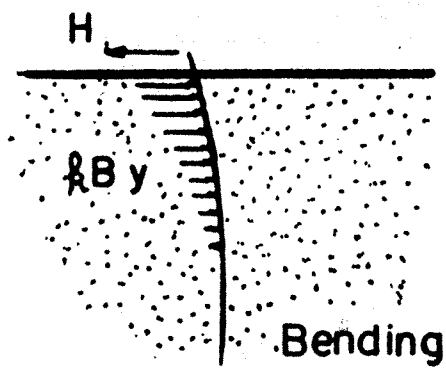
③ NETWORKS OF MICROPILES

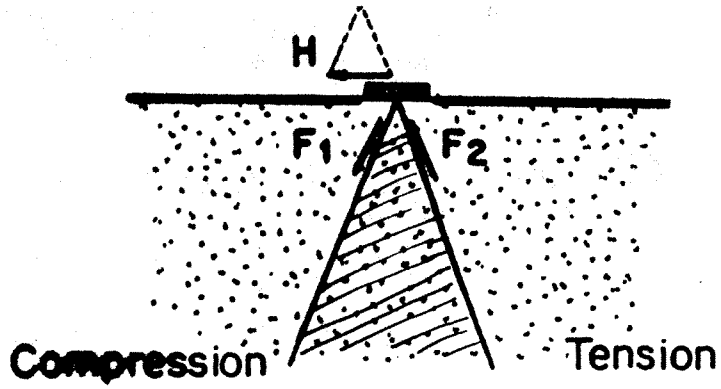
Experimental behaviour (calibration chamber, shear box, full scale instrumentations) under forces.

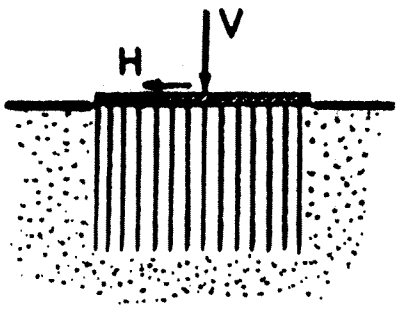
Modelization and theoretical studies

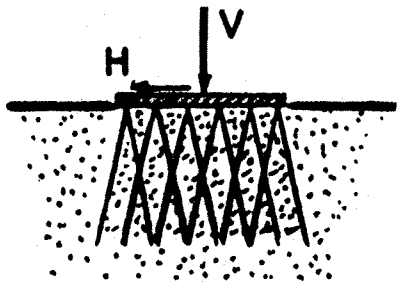
Desing method for groups and networks

MICROPILES : STRUCTURAL EFFECT









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MAIN GOALS OF THE "FOREVER" PROJECT

BEHAVIOUR AND DESIGN

- Deep foundation
- Underpinning
- Slope stabilization
- Settlement reduction

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RESEARCH TOOLS

Monitoring on construction sites

Tests on experimental sites

FULL SCALE

Laboratory models (1g)

Centrifuge models

Numerical modelling

BASIC BEHAVIOUR + PARAMETRIC STUDY

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PRESENT DESIGN OF MICROPILES

① Bearing capacity

② Overall stability (slope stabilization)

Numerical

TRADITIONAL DESIGN

COMPRESSION : $Q_u = Q_u^p + Q_u^s$ (tip, Frictional)

TRACTION : $Q_{tu} = Q_u^s$

TIP RESISTANCE

$(Q_u^p = 0 \text{ to } 0.15\, Q_u^s)$

$Q_u^p = S_p \cdot k_p \cdot p_\ell$

k_p =
- 1.2 Gravels and Sands
- 1.6 Clays
- 1.8 Clays and Marls
- 1.5 Altered Rocks

$S_p = \frac{\pi}{4} \cdot D_d^2$

p_ℓ = limit pressure at pressuremeter test

FS = 3

FRICTIONAL RESISTANCE

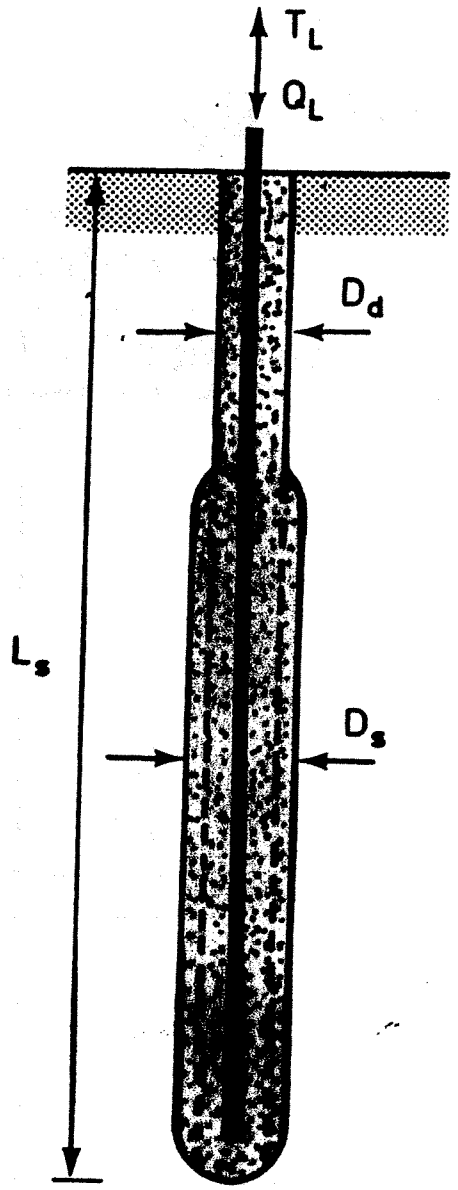
$Q_u^s = \pi . D . L . q_s$

$(D_s = \alpha D_d)$

$q_s = f(p_\ell)$ CHARTS

FS = 2

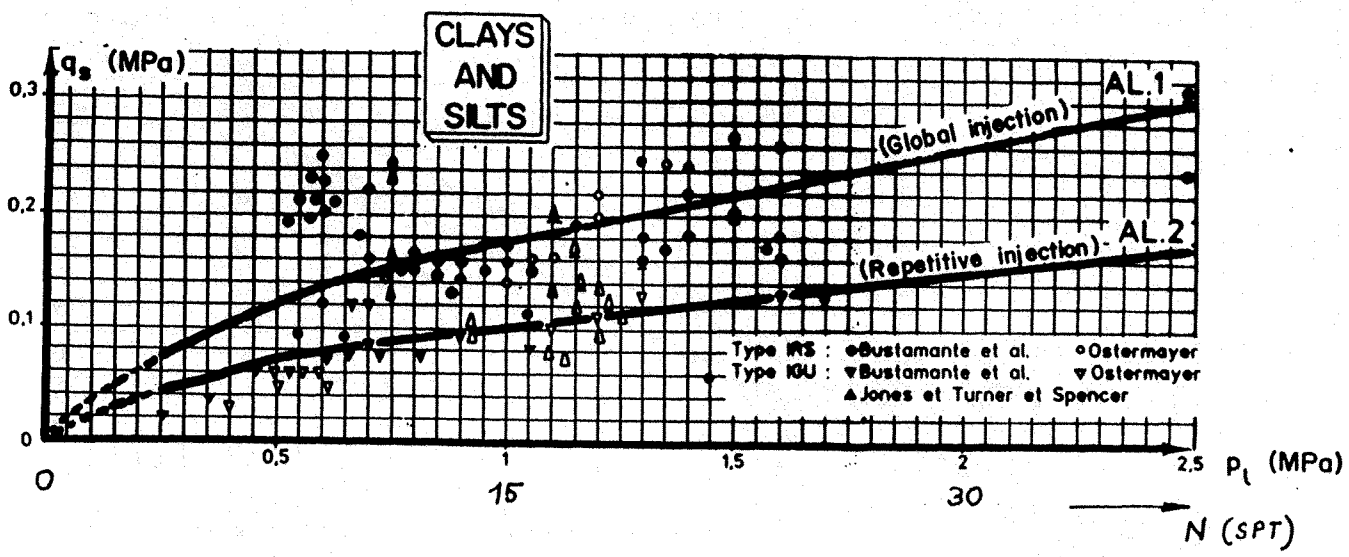
MICROPILE LOAD TESTS ARE RECOMMENDED

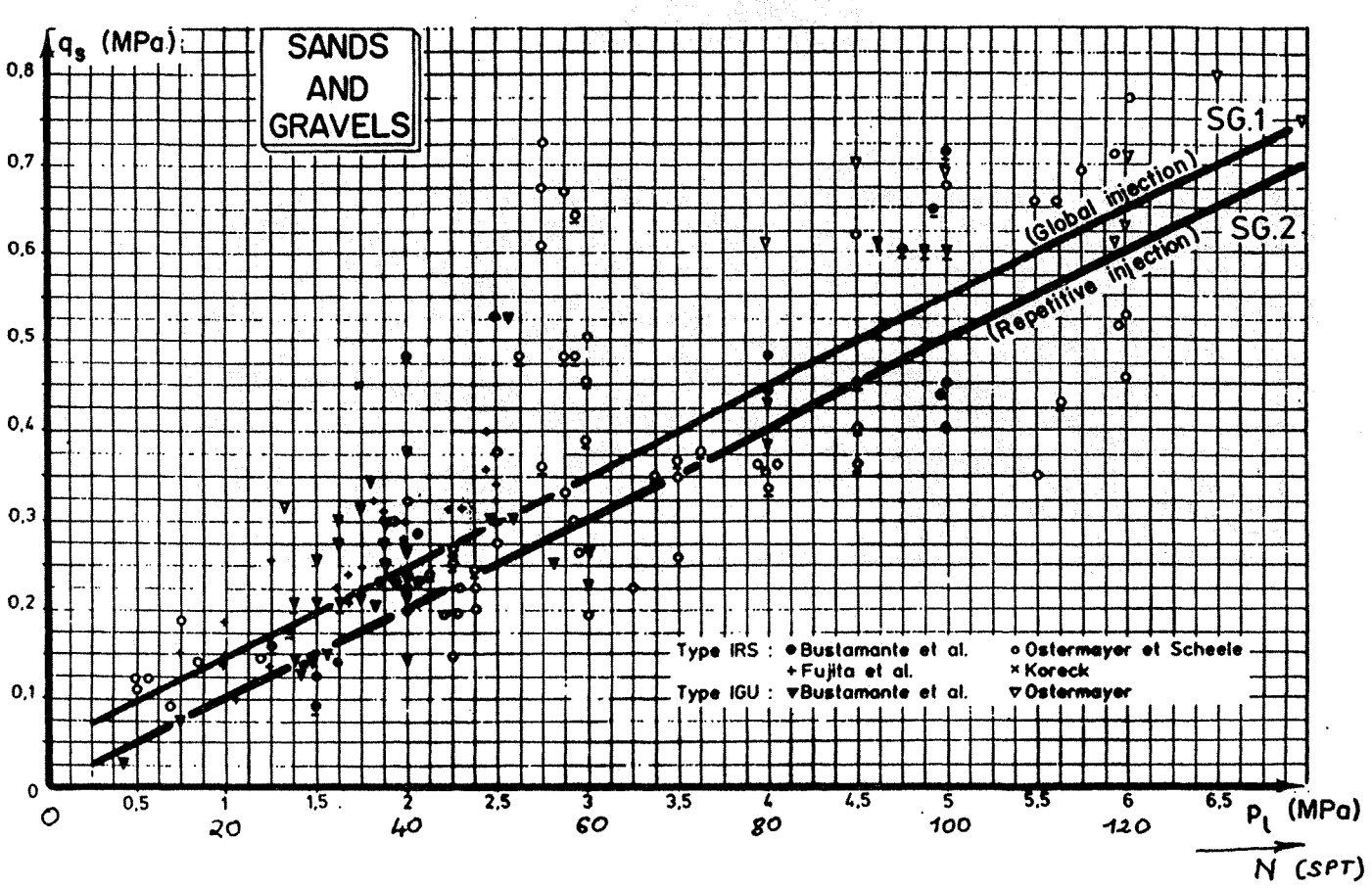


GEOMETRICAL FEATURES OF A MICROPILE

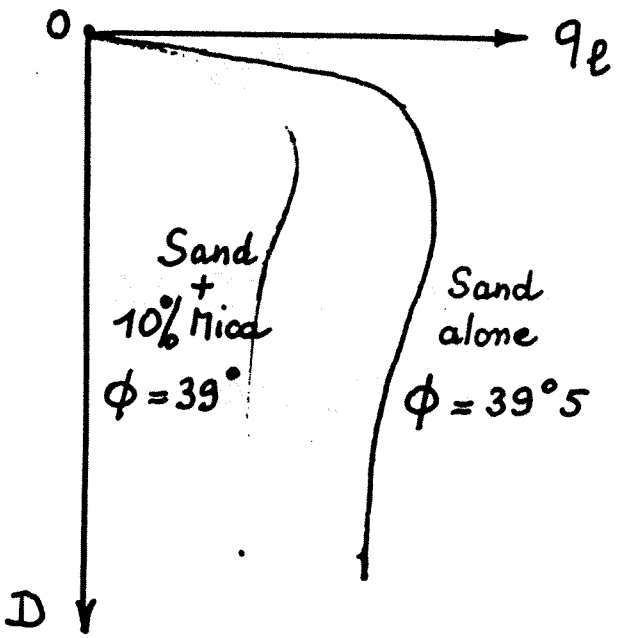
$$D_s = \alpha . D_d$$

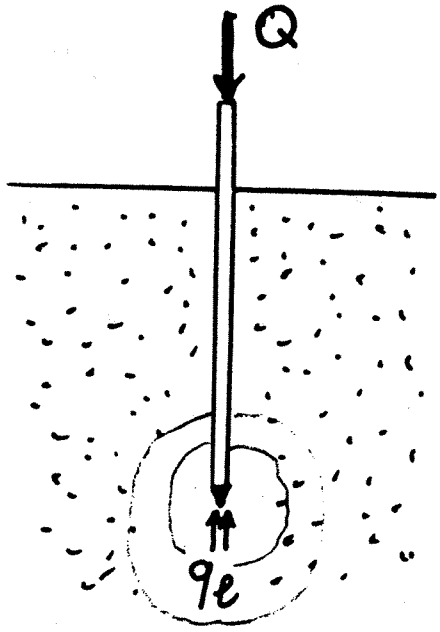
SOILS	α Coefficient	
	Repetitive Injection	Global injection
Gravel	1.8	1.3 to 1.4
Sandy gravel	1.6 to 1.8	1.2 to 1.4
Gravely sand	1.5 to 1.6	1.2 to 1.3
Coarse sand	1.4 to 1.5	1.1 to 1.2
Medium sand	1.4 to 1.5	1.1 to 1.2
Fine sand	1.4 to 1.5	1.1 to 1.2
Silty sand	1.4 to 1.2	1.1 to 1.2
Silt	1.4 to 1.6	1.1 to 1.2
Clay	1.8 to 2	1.2
Marl	1.8	1.1 to 1.2
Marly limestone	1.8	1.1 to 1.2
Chalk	1.8	1.1 to 1.2
Altered rock	1.2	1.1


CLAYS AND SILTS
q_s (MPa)
0,3
0,2
0,1
0
AL.1
(Global injection)
AL.2
(Repetitive injection)
Type IRS : ●Bustamante et al. ○Ostermayer
Type IGU : ▼Bustamante et al. ▽Ostermayer
▲Jones et Turner et Spencer
0,5
1
1,5
2
2,5
p_l (MPa)
0
15
30
N (SPT)


q_s (MPa)
SANDS AND GRAVELS
SG.1
(Global injection)
SG.2
(Repetitive injection)
Type IRS : ● Bustamante et al. ○ Ostermayer et Scheele
+ Fujita et al. × Koreck
Type IGU : ▼ Bustamante et al. ▽ Ostermayer
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
5,5
6
6,5
p_l (MPa)
20
40
60
80
100
120
N (SPT)

TIP RESISTANCE

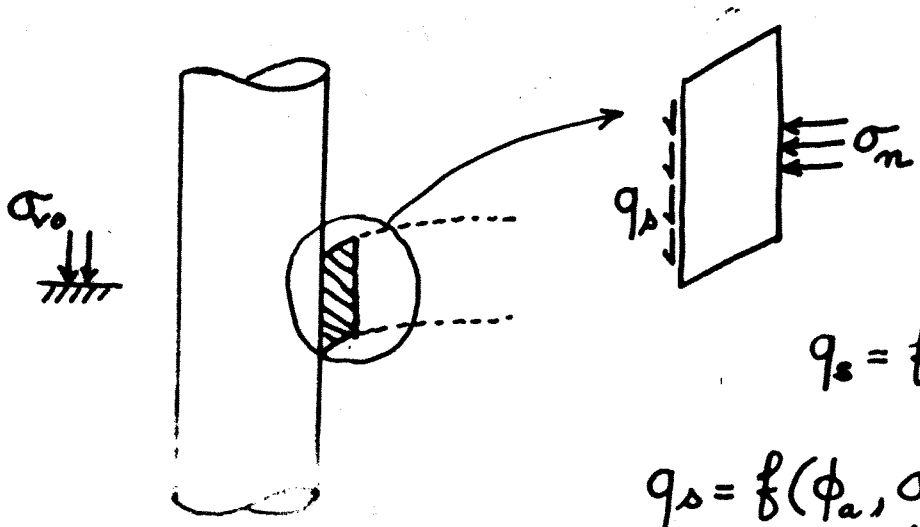




$$q_c = f(\phi)$$

$$p_\ell \longleftrightarrow q_c = f(\phi, E, \ldots)$$

FRICTIONAL RESISTANCE



$$q_s = f(\phi_a) = \tan\phi_a \cdot K_0 \cdot \sigma_z$$

$$q_s = f(\phi_a, \sigma_n, \Delta u, \dot{\varepsilon}, \ldots)$$

ΔV

LIMIT STATE DESIGN

$Q_u = Q_{pu} + Q_{su}$ $\qquad$ $Q_{tu} = Q_{su}$

$Q_c = 0.5\ Q_{pu} + 0.7 Q_{su}$ $\qquad$ $Q_{tc} = 0.7\ Q_{su}$

1 ULTIMATE LIMIT STATE

- COMBINATIONS OF ACTIONS WITH LOAD FACTORS
  - FUNDAMENTAL
  - ACCIDENTAL
- Q_{pu}

$Q_{su} = \pi D d \cdot L_s \cdot q_s$

$$\text{FUNDAMENTAL} : -\frac{Q_{tu}}{1.40} < Q < \frac{Q_u}{1.40}$$

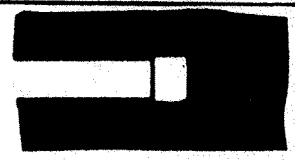
$$\text{ACCIDENTAL} : -\frac{Q_{tu}}{1.20} < Q < \frac{Q_u}{1.20}$$

2 SERVICEABILITY STATE

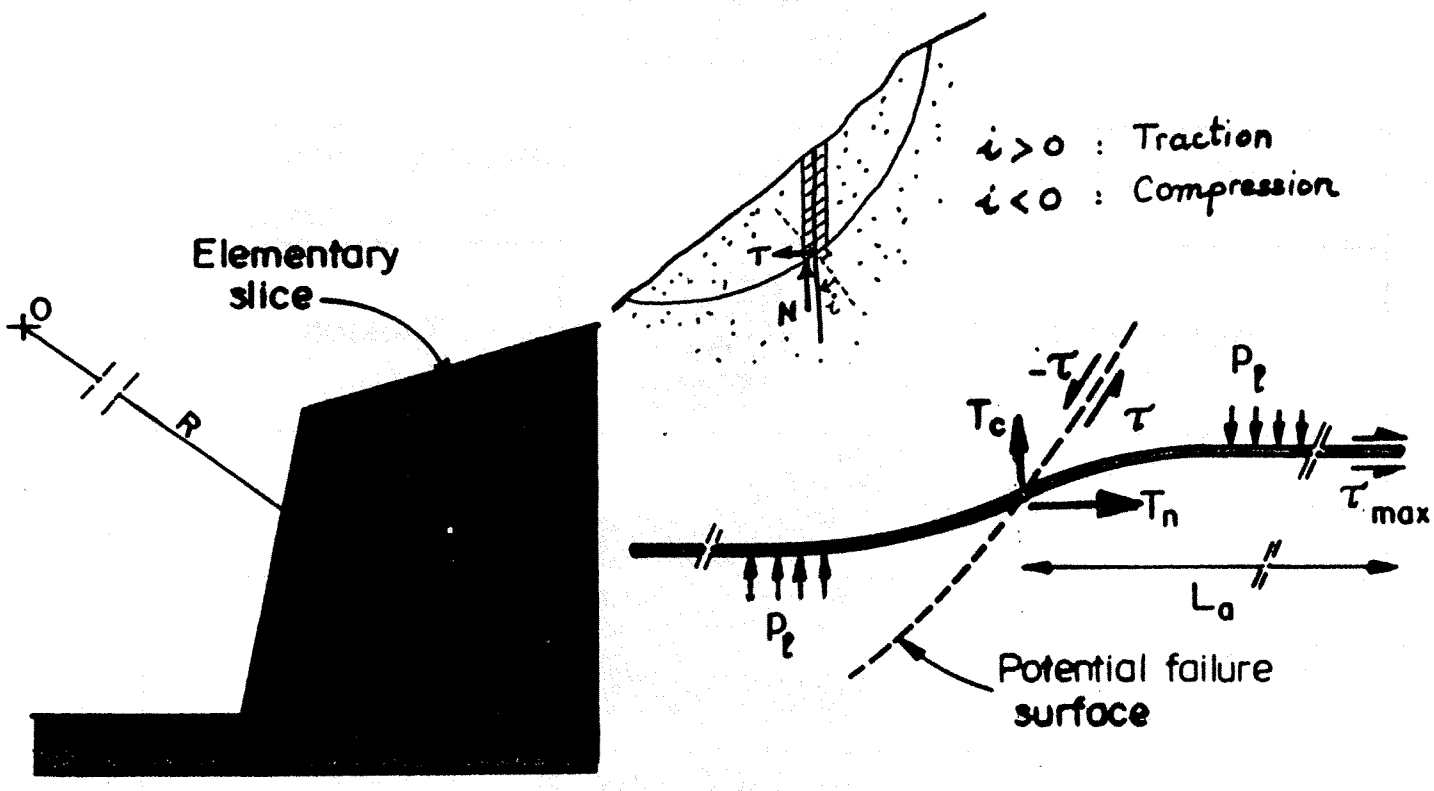
- COMBINATIONS OF ACTIONS WITH LOAD FACTORS
  - RARE
  - FREQUENT
  - QUASI-PERMANENT
- $Q_c = 0.7\ Q_{su}$

$$\text{RARE} : -\frac{Q_{tc}}{1.10} < Q < \frac{Q_c}{1.10}$$

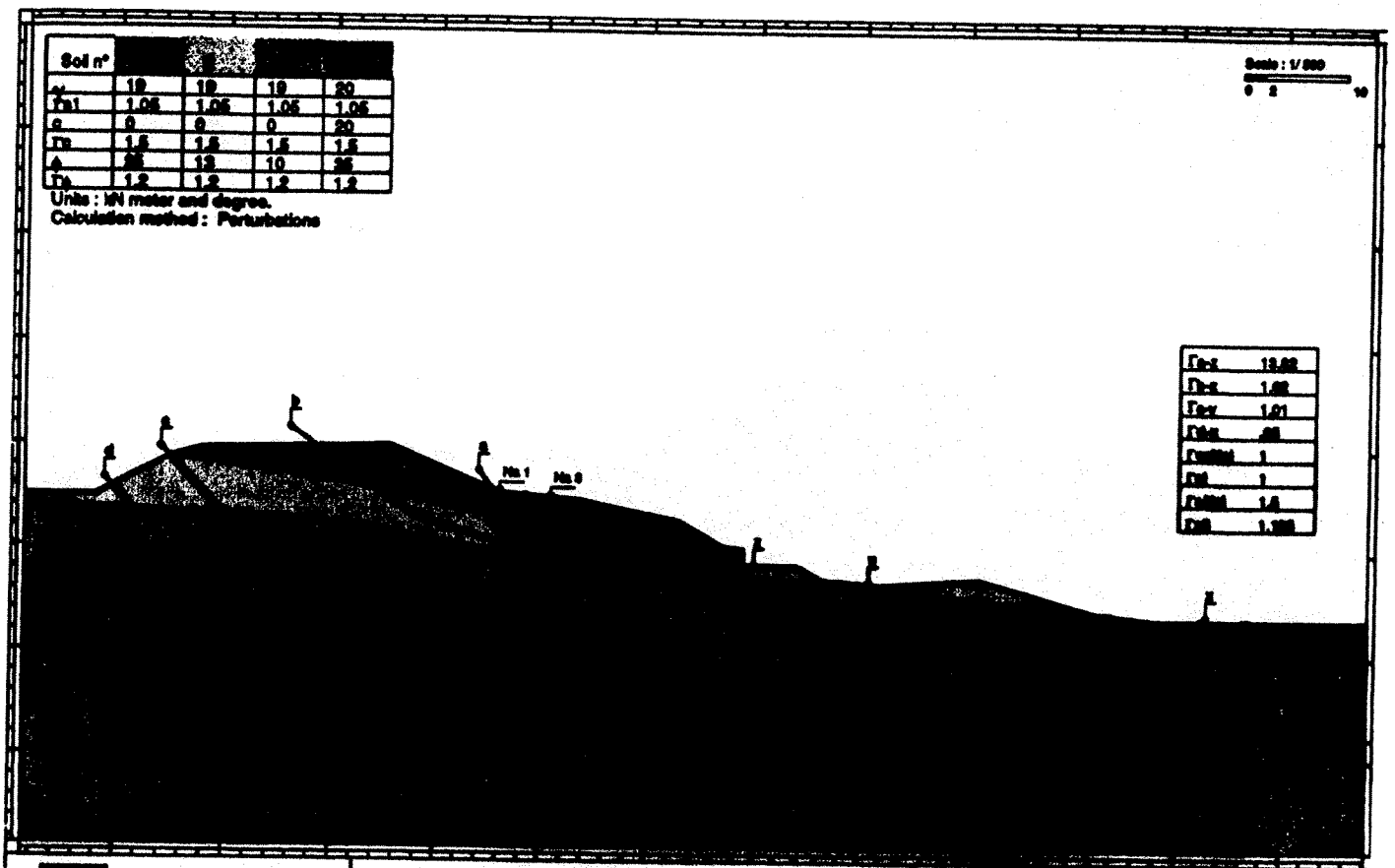
$$\text{QUASI-PERMANENT} : -\frac{Q_{tc}}{1.40} < Q < \frac{Q_c}{1.40}$$

TYPE OF STRUCTURE	PRIMARY FORCES IN THE NAILS
① Retaining structure 	Tension
② Slope stabilization 	Bending
③ Tunnels 	Tension
④ Foundations 	Compression

APPLICATION OF SOIL NAILING



PRINCIPLES OF TALREN STABILITY PROGRAM



TALREN 97 V1.0 of 16/09/97 TERRASOL	STABILIZING AN UNSTABLE SLOPE WITH VERTICAL PILES ULS CALCULATION File : EXEMP17E.tal Proj : EXAMPLES	Study made by :	Figure : 8

SOILS

N°	γ	γsi	c	δe(s)	γq	δ	γδ	re	qs	pl	Ks.δ
1	19	1.05	0	0	1.5	26	1.2	0	0	0	0
2	19	1.05	0	0	1.5	13	1.2	0	0	0	0
3	19	1.05	0	0	1.5	10	1.2	0	0	0	0
4	20	1.05	20	0	1.5	35	1.2	0	0	0	0

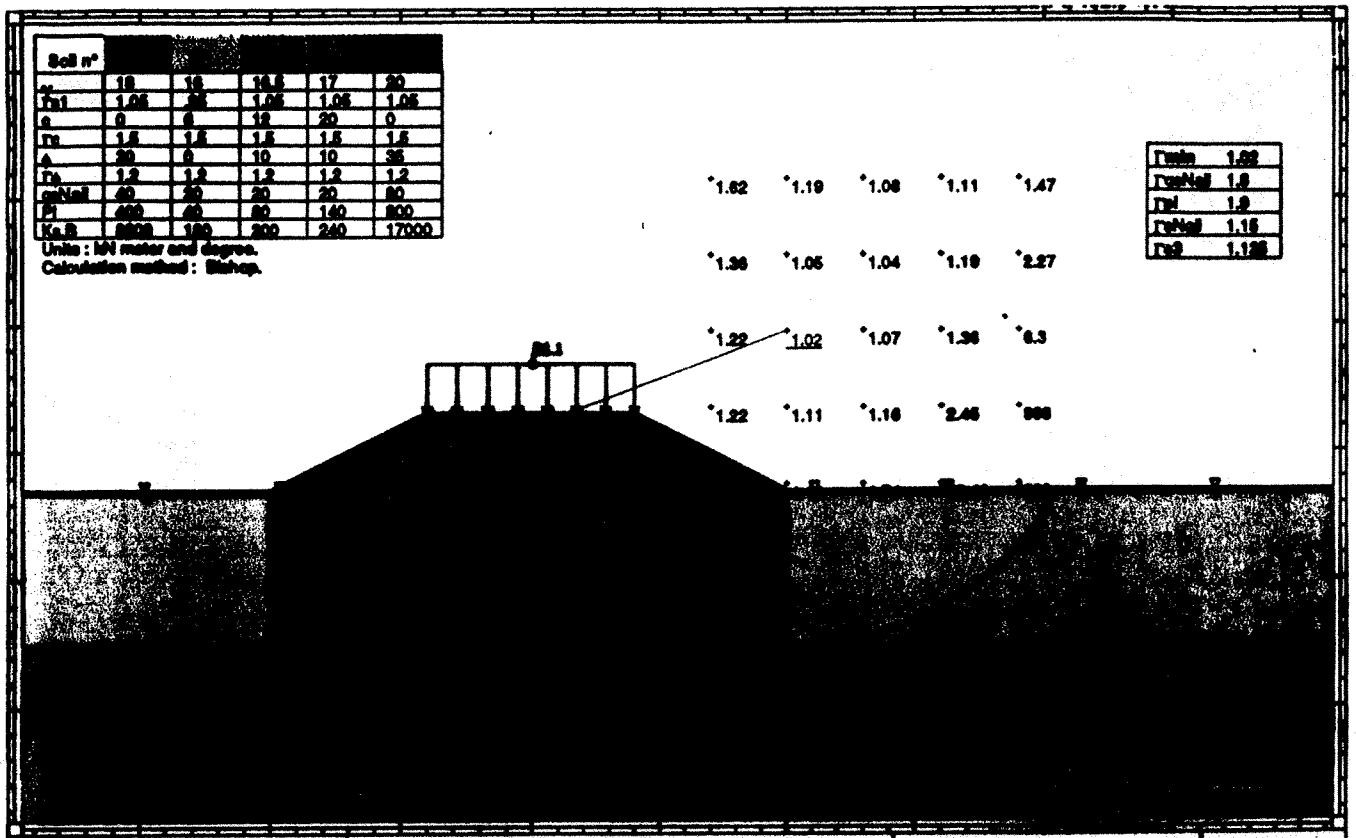
NAILS

N°	Yield st	Spacing	Elev.	Length	Inclin.	D bore	R shear	M plastic	Rigidity	Calc type
Na1	0	2.4	22	16	90	2	540	0	0	Tcal+Simp
Na2	0	2.4	21.75	16	90	2	540	0	0	Tcal+Simp
Na3	0	2.4	21.5	16	90	2	540	0	0	Tcal+Simp

Unit weight of water : 10

Units : kN meter and degrees

Calculation method : Perturbations



TALREN 97
V1.0 of 18/09/97
TERRASOL

EMBANKMENT REINFORCED WITH SUB-VERTICAL MICROPILES
ULS CALCULATION
File : EXEMP18E.tal
Proj : EXAMPLES

Study made by :

Figure : 9

SOILS

N°	γ	γsl	c	φeff(s)	γc	φ	γφ	ru	qp	pl	Ks.B
1	18	1.05	0	0	1.5	30	1.2	0	40	400	8800
2	16	.95	6	0	1.5	0	1.2	0	20	40	180
3	16.5	1.05	12	0	1.5	10	1.2	0	20	80	200
4	17	1.05	20	0	1.5	10	1.2	0	20	140	240
5	20	1.05	0	0	1.5	35	1.2	0	80	800	17000

DISTRIBUTED LOADS

N°	σ1	σ2	γq
Sd1	20	20	1.3

NAILS

N°	Yield st	Spacing	Elev.	Length	Inclin.	D bore	R shear	M plastic	Rigidity	Calc type
Na1	-2220	3	2	13	110	.332	-1110	183	7644	Tcal+Scal
Na2	-2220	3	2	13	95	.166	-1110	183	7644	Tcal+Scal
Na3	-2220	3	2	13	90	.166	-1110	183	7644	Tcal+Scal
Na4	-2220	3	2	13	85	.166	-1110	183	7644	Tcal+Scal
Na5	-2220	3	2	13	70	.332	-1110	183	7644	Tcal+Scal

Unit weight of water : 10
Units : kN meter and degrees
Calculation method : Bishop

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RESEARCH PROGRAM

- Basic problems
- Laboratory and centrifuge testing*
- Experimental site at S^{t} Rémy *
- Numerical modelling

(*) plus slides

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BASIC PROBLEMS OF MICROPILE GEOTECHNICAL STRUCTURES

- Under axial loading
- Under lateral loading
- Buckling
- Seismic loading
- Corrosion

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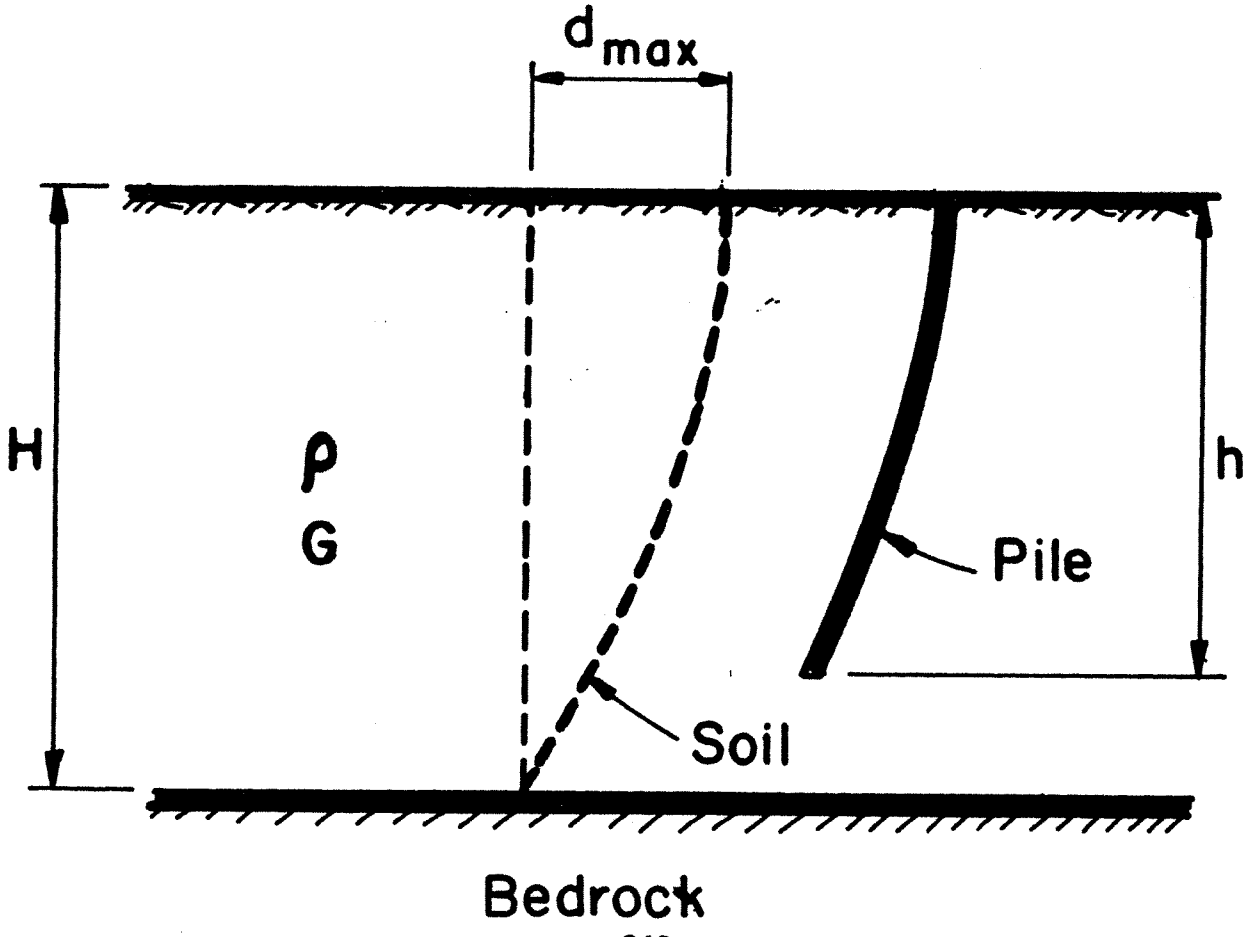
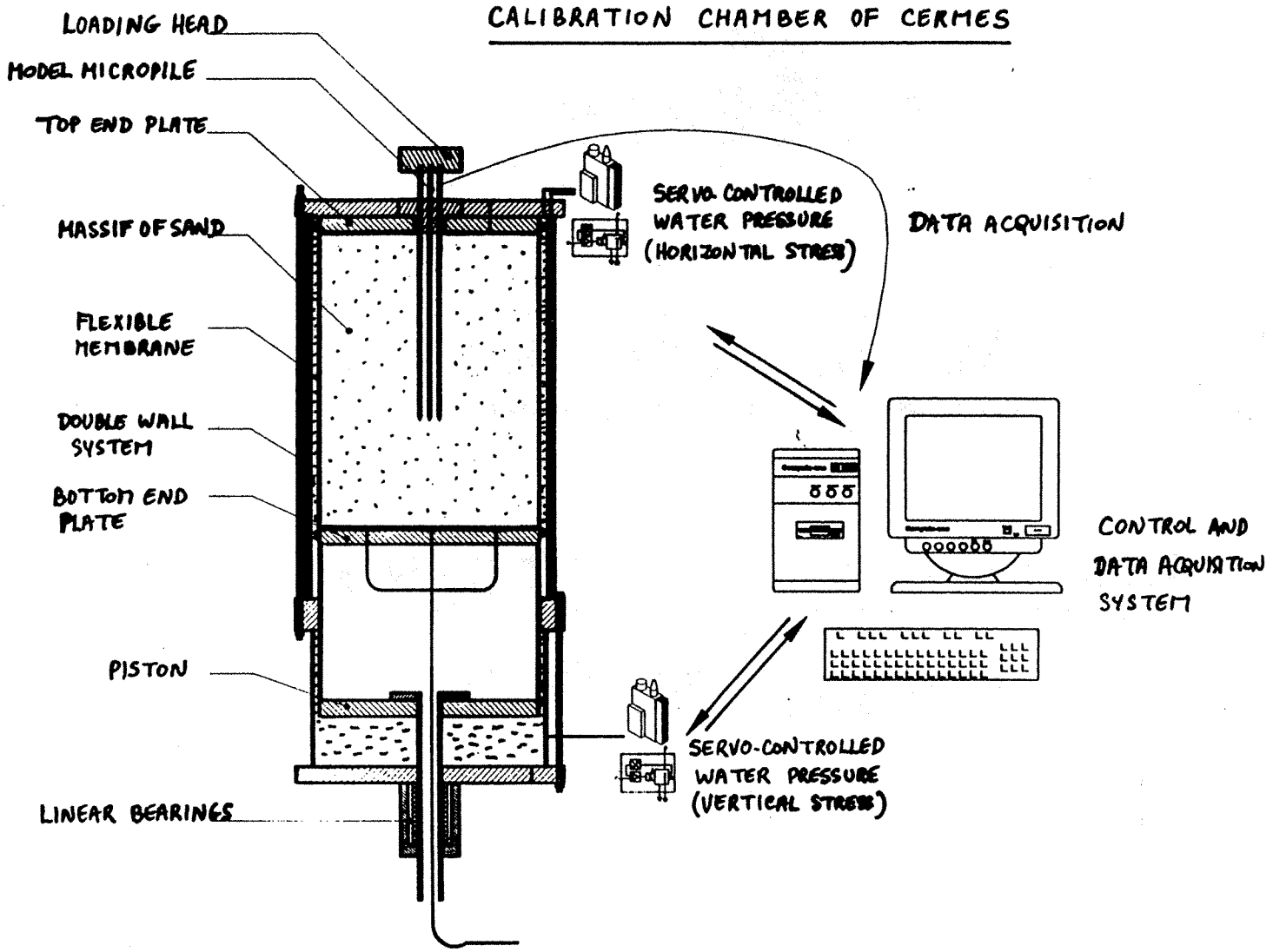
SEISMIC LOADING

Recommendations AFPS 90

Simplified approach




CALIBRATION CHAMBER OF CERMES
LOADING HEAD
MODEL MICROPILE
TOP END PLATE
MASSIF OF SAND
FLEXIBLE MEMBRANE
DOUBLE WALL SYSTEM
BOTTOM END PLATE
PISTON
LINEAR BEARINGS
SERVO-CONTROLLED WATER PRESSURE (HORIZONTAL STRESS)
DATA ACQUISITION
CONTROL AND DATA ACQUISITION SYSTEM
SERVO-CONTROLLED WATER PRESSURE (VERTICAL STRESS)

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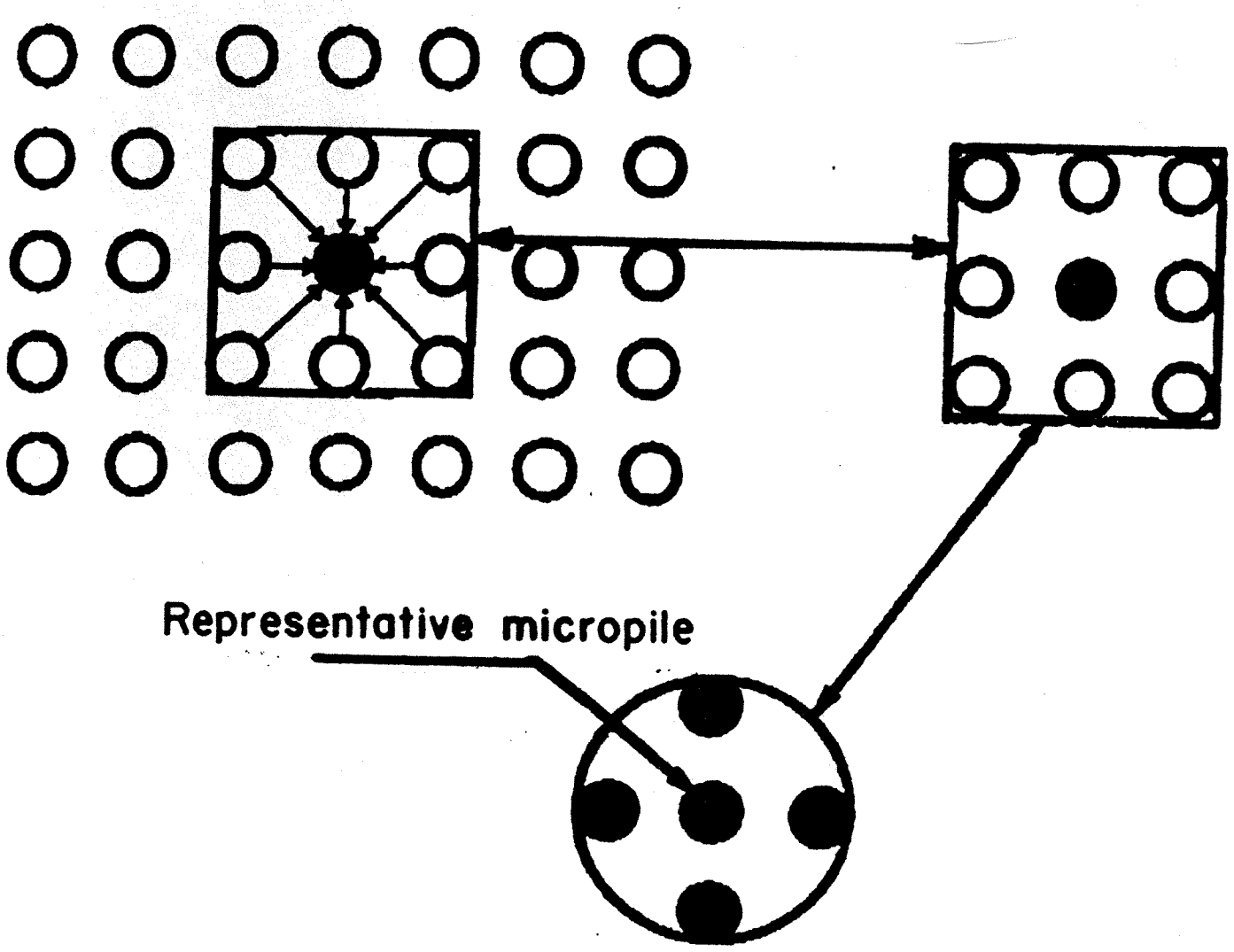
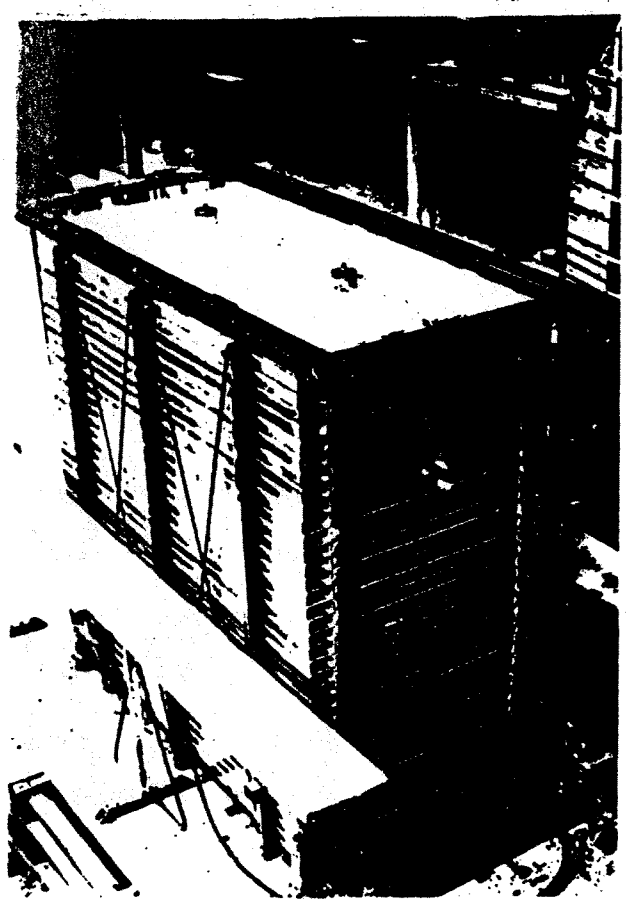
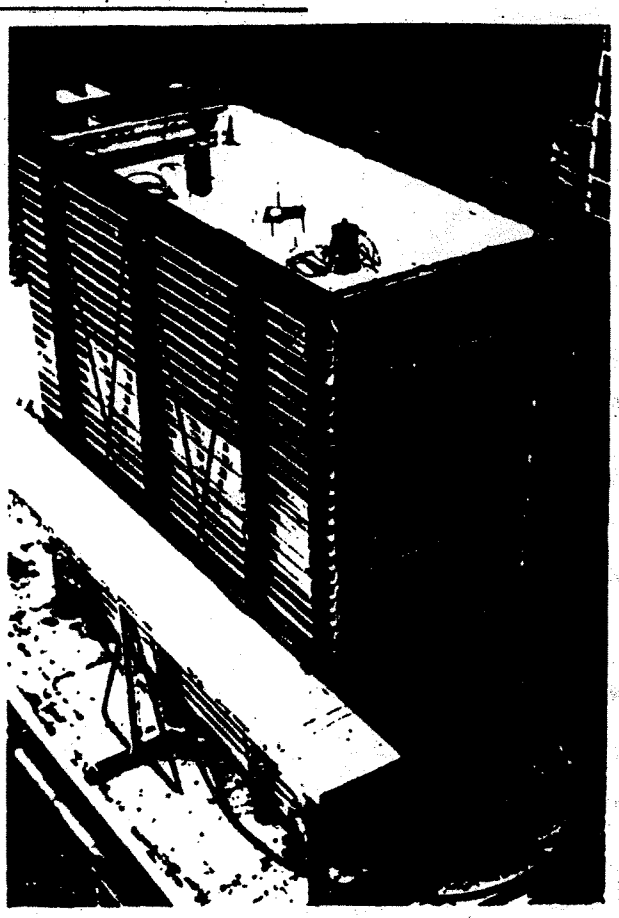


BREAKDOWN OF A MICROPILE GROUP

UNIVERSITY OF CANTERBURY VIBRATING TABLE



Experimental set-up with two 95 mm diameter instrumented models before shaking



View of the set-up after very strong shaking

Dismounting of the set-up after testing

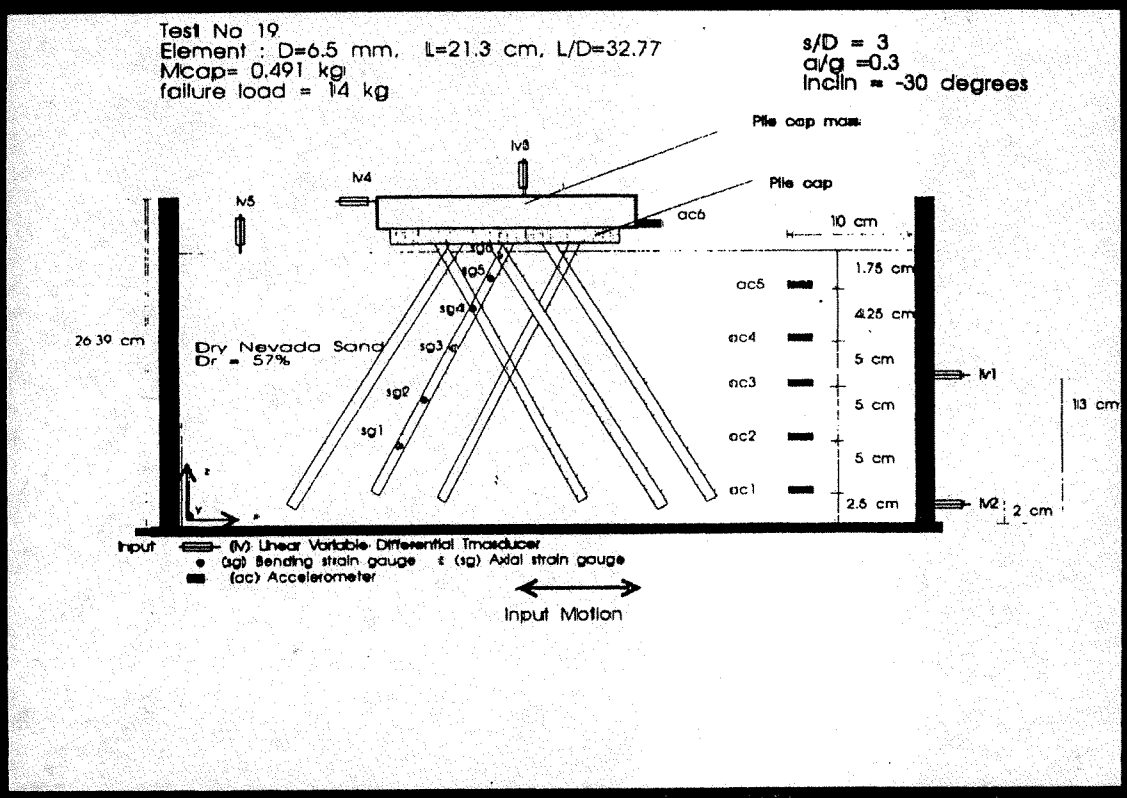
Seismic Behavior of Micropile Systems

OBJECTIVES

PHASE	SOIL TYPE / MICROPILE SYSTEMS	ENGINEERING APPLICATIONS
Phase I	Loose Sand Micropile Groups	Foundation Underpinning Seismic Retrofitting
Phase II	Bi-layers and Silty Clays Micropile Groups	Foundation Underpinning Seismic Retrofitting
Phase III	Micropile Groups Micropile Networks	Prototype Systems Under Selected Range of Loading Conditions
Phase IV	Final Report Seismic Design Guidelines for Micropile Systems	Selected Engineering Applications Loading Conditions and Soil Types

FOREVER - Cooperative Research Program

Soil Reinforcement



Typical Micropile Configuration Tested in the Centrifuge

Hamburg, 97

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TESTING WITH THE LCPC CENTRIFUGE AT NANTES

- **Buckling of micropiles**

- **Laterally loaded micropiles**

  (p, y) experimental curves + comparison with PILATE

- **Groups of micropiles**

  efficiency coefficients

  $\varnothing$ = 8mm at 40 g $\Longrightarrow$ $\varnothing$ = 32 cm

- **Simple networks (pairs of micropiles)**

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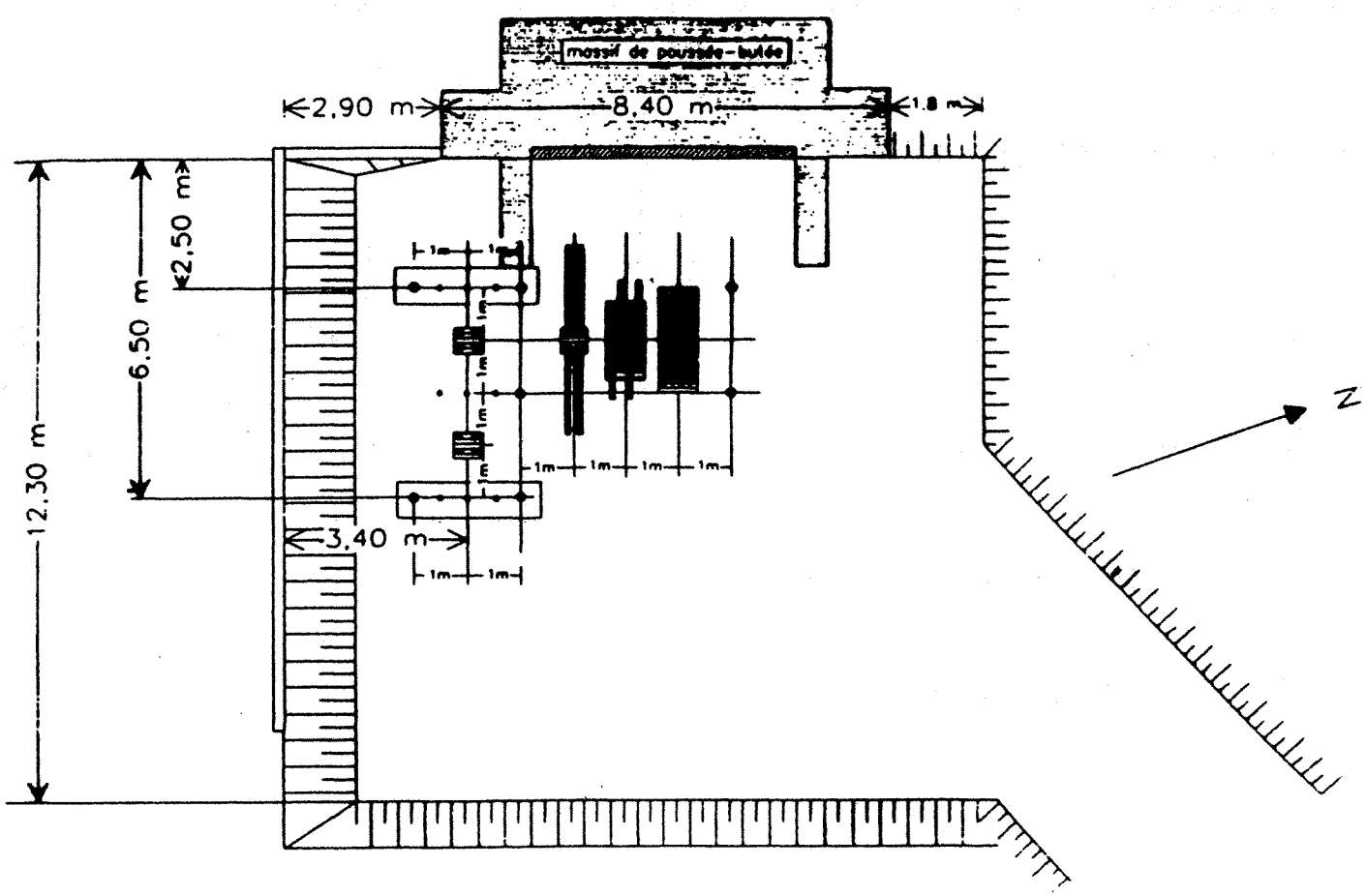
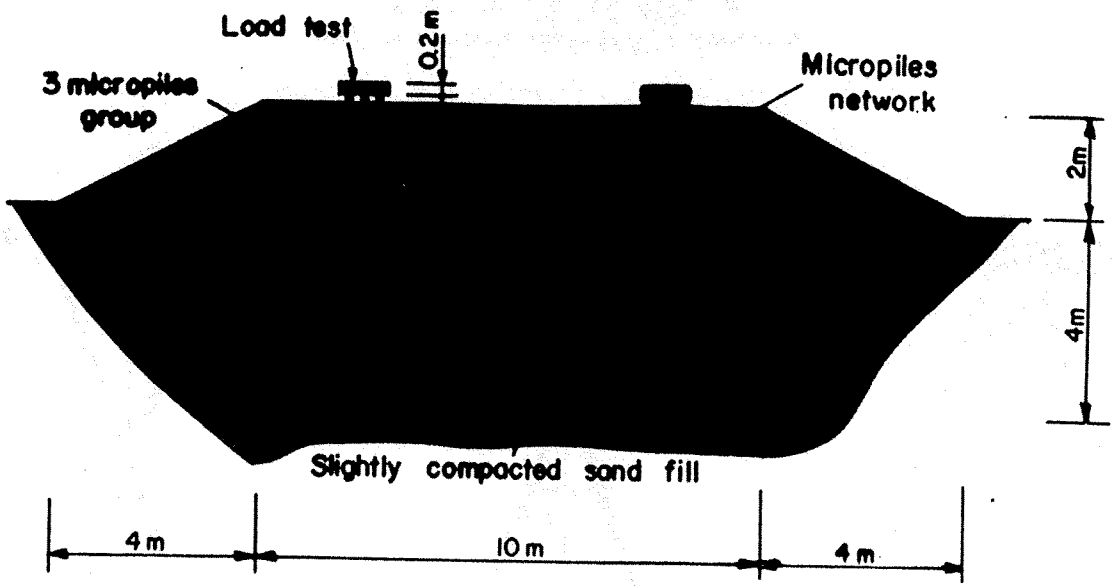


GENERAL ARRANGEMENT OF THE EXPERIMENTAL SITE OF S^{t} REMY



FOREVER - MICROPILES

(Cross - section of the experimental site)

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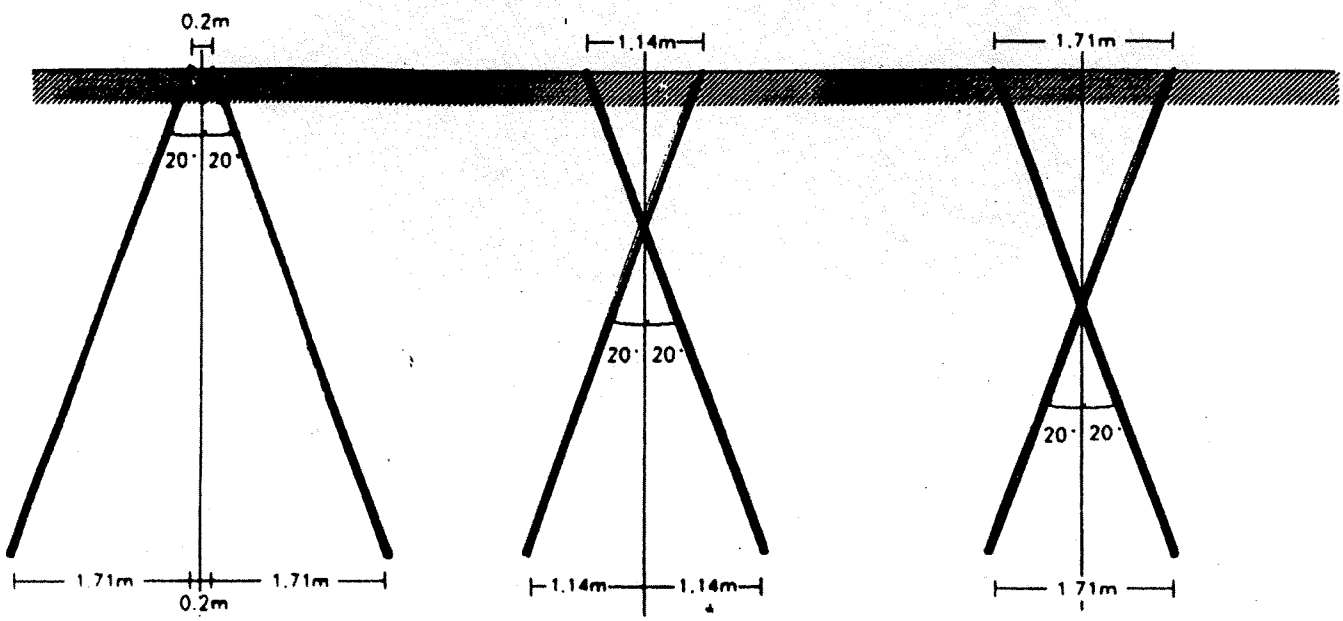
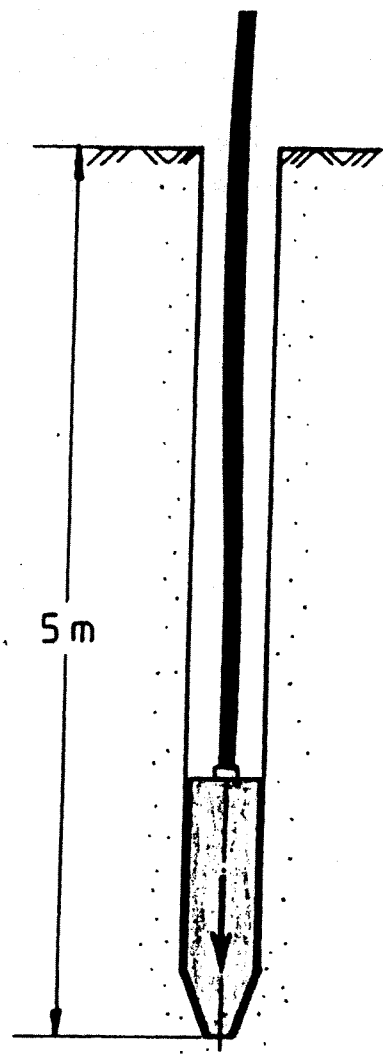
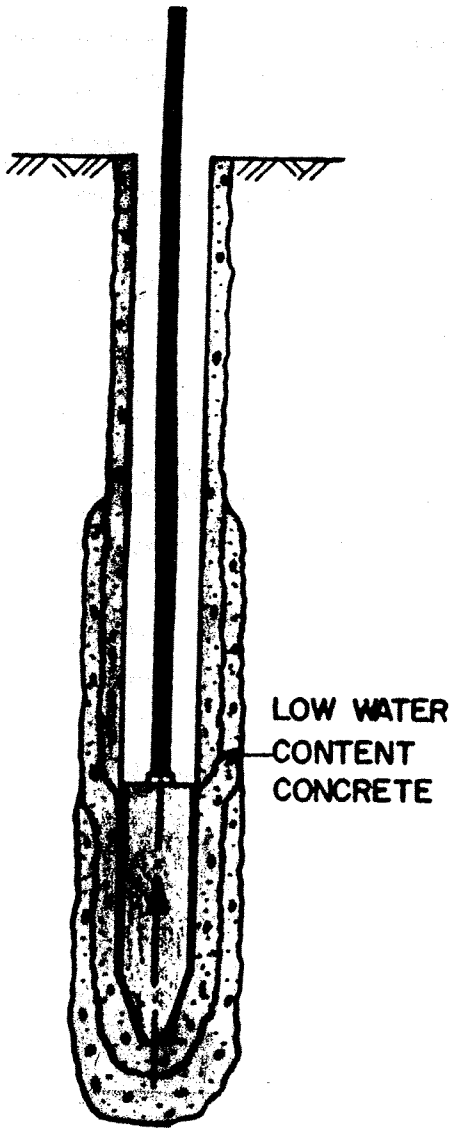


FULL SCALE TESTS ON SIMPLE NETWORKS AT S^{t} REMY



BORING BY SOIL DISPLACEMENT



RAISING OF THE HAMMER
AFTER SEVERAL PASSES

R-SOL TYPE MICROPILE

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NUMERICAL MODELLING OF GROUPS AND NETWORKS OF MICROPILES WITH THE USE OF t-z AND p-y CURVES

Determination of t - z and p - y curves

Seismic soil displacement

ISOLATED MICROPILES

Introduction of installation effects

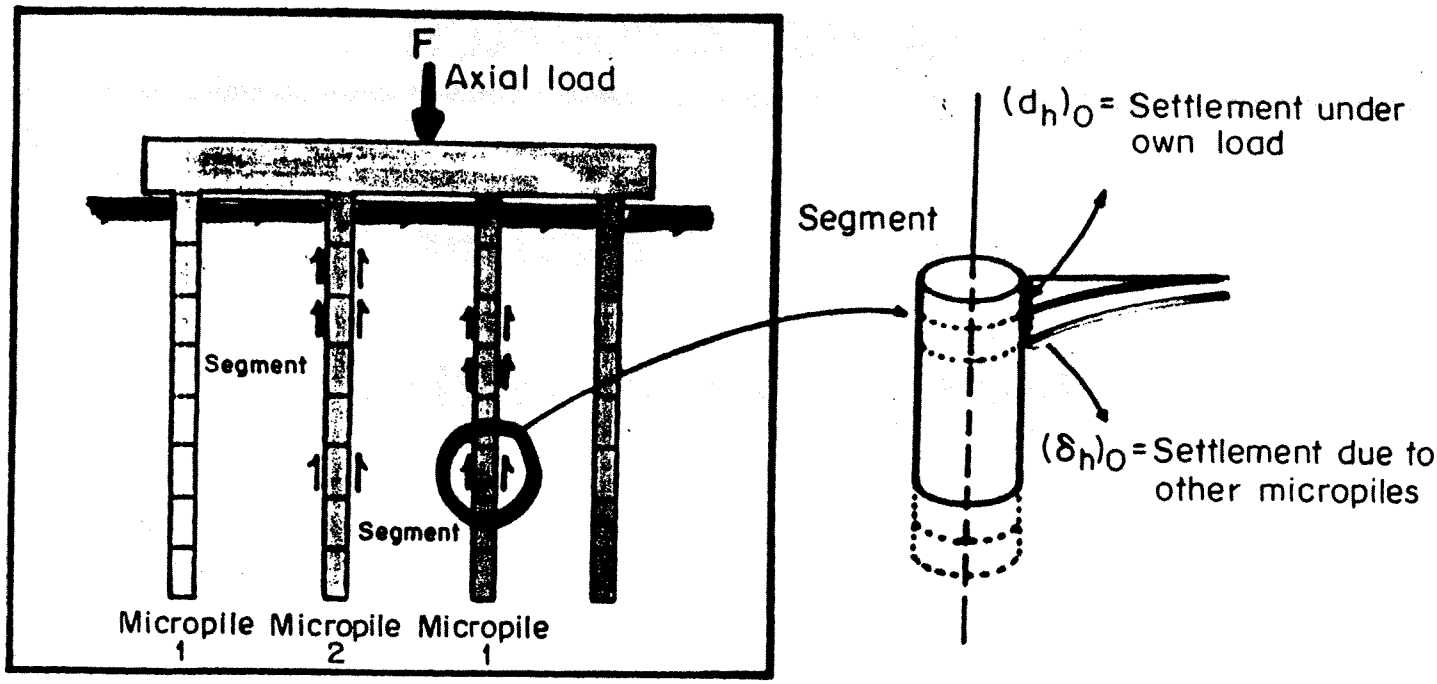
Micropile - soil - micropile interaction (efficiency coefficient)

GROUP OF MICROPILES

Various raking angles of micropiles

Interlocking effects

NETWORKS OF MICROPILES


F
Axial load
Segment
Segment
Micropile 1
Micropile 2
Micropile 1
Segment
$(d_h)_O$ = Settlement under own load
$(\delta_h)_O$ = Settlement due to other micropiles

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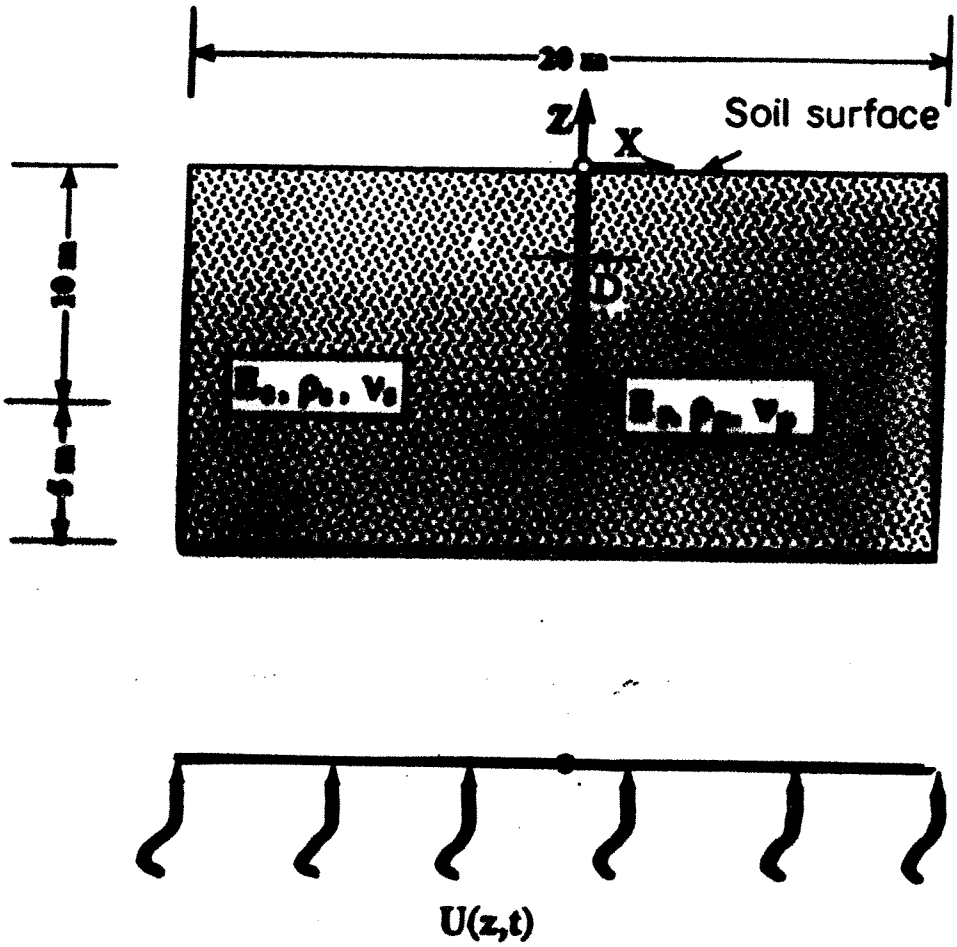
NUMERICAL MODELLING OF GROUPS AND NETWORKS OF MICROPILES BY CONTINUUM APPROACH

F.E.M calculations

Homogeneisation methods



F.E.M. CALCULATION OF WAVE PROPAGATION IN A CONTINUUM CONTAINING A MICROPILE