STATIC AND SEISMIC PILE FOUNDATIONS DESIGN
CASE HISTORIES

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TOPICS

1. Introduction
2. Limit States
3. Design Methods
4. Geotechnical Characterisation
5. Experimental Models
6. Serviceability Limit States
7. Guadiana Bridge
8. New Tagus Bridge
9. Conclusions

LIMIT STATES

- Loss of overall stability
- Bearing resistance failure
- Uplift or insufficient resistance of pile
- Failure in ground due transverse loading
- Structural failure
- Combined failure in ground and in structure
- Excessive settlement
- Excessive heave
- Excessive lateral movements
- Unacceptable vibrations

If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties

Advancement of Learning

Francis Bacon

DESIGN METHODS

- **Design by calculation: analytical and numerical model**
- **Design by prescriptive measures: involves conventional and conservative rules**

DESIGN METHODS

- Design by load tests and experimental models
  - differences in ground conditions
  - time effects
  - scale effects

DESIGN METHODS

- Design by observational method
  - limits of acceptable behaviour
  - range of possible behaviour
  - plan of monitoring
  - response time of the instruments
  - plan of contingency actions

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INSTRUMENTED PILES

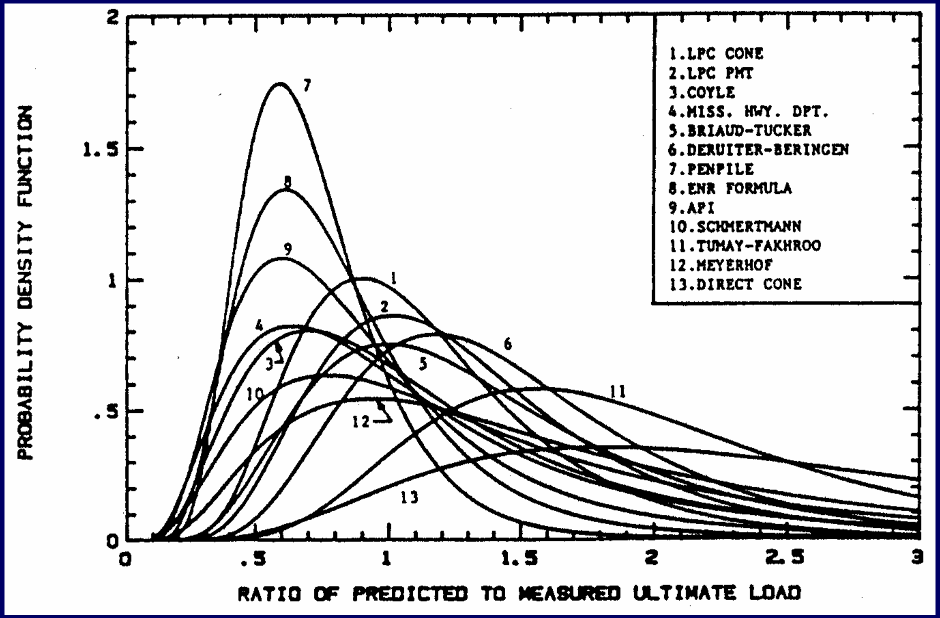


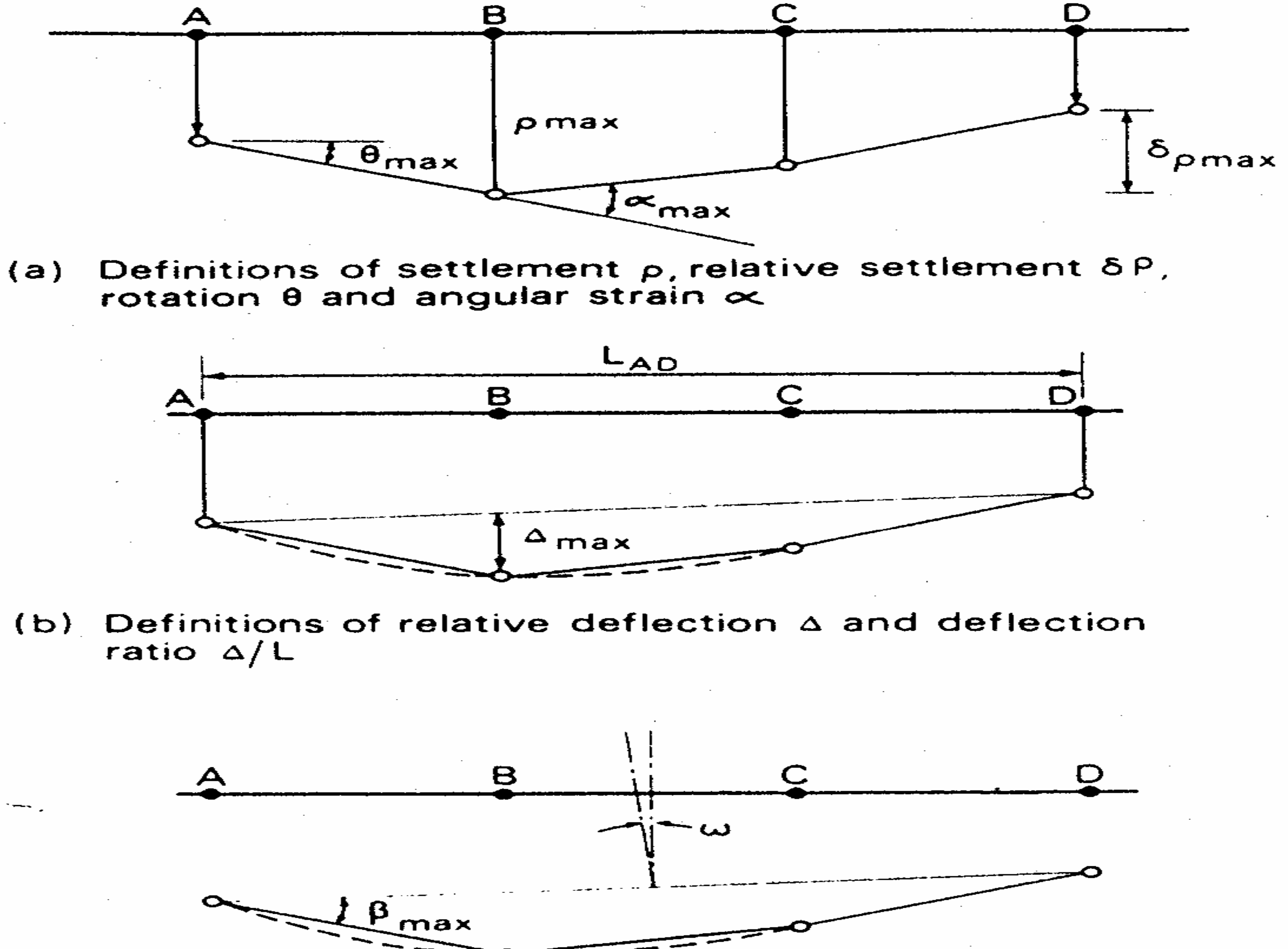
Table 1 - Field tests

Test	Parameters for stress state					Strength Parameters			Parameters for deformation		
	γ	I_d	K_o	OCR	S	S_u	c	ϕ	E	G_{max}	M
CPTU	x	x	x	x	x	x	x	x	x		x
SPT		x			x	x	x	x	x		x
Vane shear			x	x	x	x	x		x		
Pressiometer			x			x	x	x	x		
Penetrometer						x	x	x	x		
Dilatometer	x	x		x		x		x	x	x	x

Table 2 - Laboratory tests

Test	Strength Parameters			Deformation Parameters		
	S_u	c	ϕ	E	G_{max}	M
Direct shear		x	x			
Uniaxial compaction				x		
Triaxial	x	x	x	x		
Odometer						x

Fig 2 - Definition of foundation movements



(a) Definitions of settlement ρ, relative settlement δρ, rotation θ and angular strain α

(b) Definitions of relative deflection Δ and deflection ratio Δ/L

(c) Definitions of tilt ω and relative rotation (angular distortion) β

Table 5 - Allowable deformations

A – Concrete buildings and reinforced walls					
Allowable values for rotations	Skempton and MacDonald (1956)	Meyerhof (1956)	Polshin et Tokar (1957)	Bjerrum (1963)	EC7 (1994)
Structural Damages and cracks on walls	1/150 1/300	1/250 1/500	1/200 1/500	1/150 1/500	1/150 1/300

B – Wall without reinforcement			
Deflection ratio Δ/L	Meyerhof (1956)	Polshin & Tokar (1957)	Burland & Wroth (1975)
Deformation ∪	1/2500	L/H<3 1/3500 to 1/2500; L/H>5 1/2000 to 1/1500	1/2500 L/H = 1 1/1250 L/H = 5
Deformation ∩	–	–	1/5000 L/H = 1 1/2500 L/H = 5

Table 9 - Damages categories in buildings

Damage category	Degree of severity	Description of damage
0	Negligible	Hairline cracks 0,1 mm
1	Very light	Fine cracks ,easily treated
2	Light	Cracks easily filled
3	Moderate	Cracks required some opening
4	Severe	Extensive repair working involving breaking and replacement
5	Very Severe	Major repair involving partial or complete rebuilding

Table 10 - Categories of damages in buildings

Category of damage	Degree of severity	Limiting tensile strain (%)
0	Negligible	0 - 0,05
1	Very slight	0,05 - 0,075
2	Slight	0,075. 0,15
3	Moderate	0,15 - 0,3
4 to 5	Severe to very severe	>0,3

Table 11 - Key attributes of different types of piles tests

	Integrity Testing	High-Strain Dynamic Testing	Kinetic Testing	Static Testing
Mass of Hammer (Kg)	0.5 – 5	2,000 – 10,000	2,000 – 5,000	N/A
Pile Peak Strain (istr)	2 – 10	500 – 1,000	1,000	1,000
Pile Peak Velocity (mm/s)	10 – 40	2,000 – 4,000	500	10^{-3}
Peak Force (kN)	2 – 20	2,000 – 10,000	2,000 – 10,000	2,000 – 10,000
Force Duration (ms)	0.5 – 2	5 – 20	50 – 200	10^{7}
Pile Acceleration (g)	50	500	0.5 – 1	10^{-14}
Pile Displacement (mm)	0.01	10 – 30	50	>20
Relative Wave Lenght	0.1	1.0	10	10^{8}

Guadiana Bridge

Figure 3 - General view and foundation section

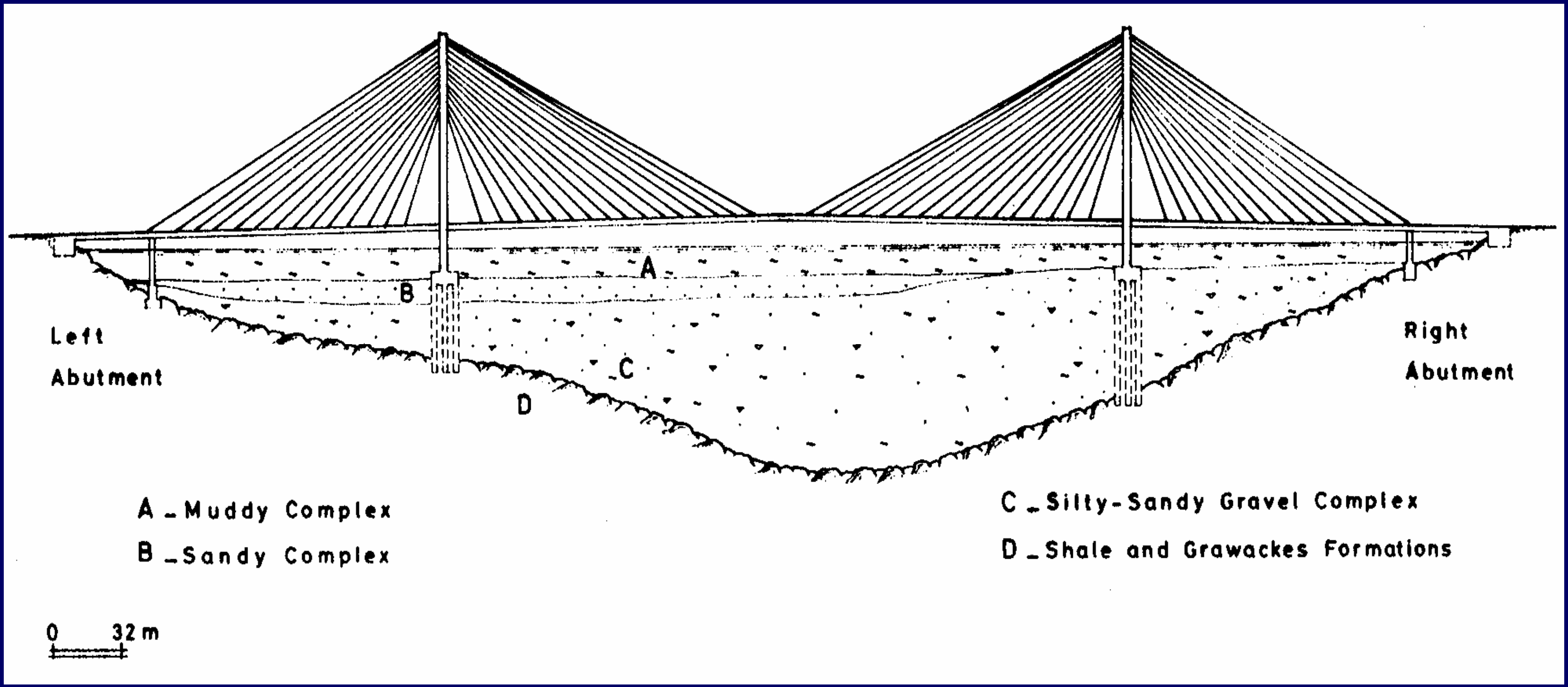


Figure 4 - Displacements of pile head 33

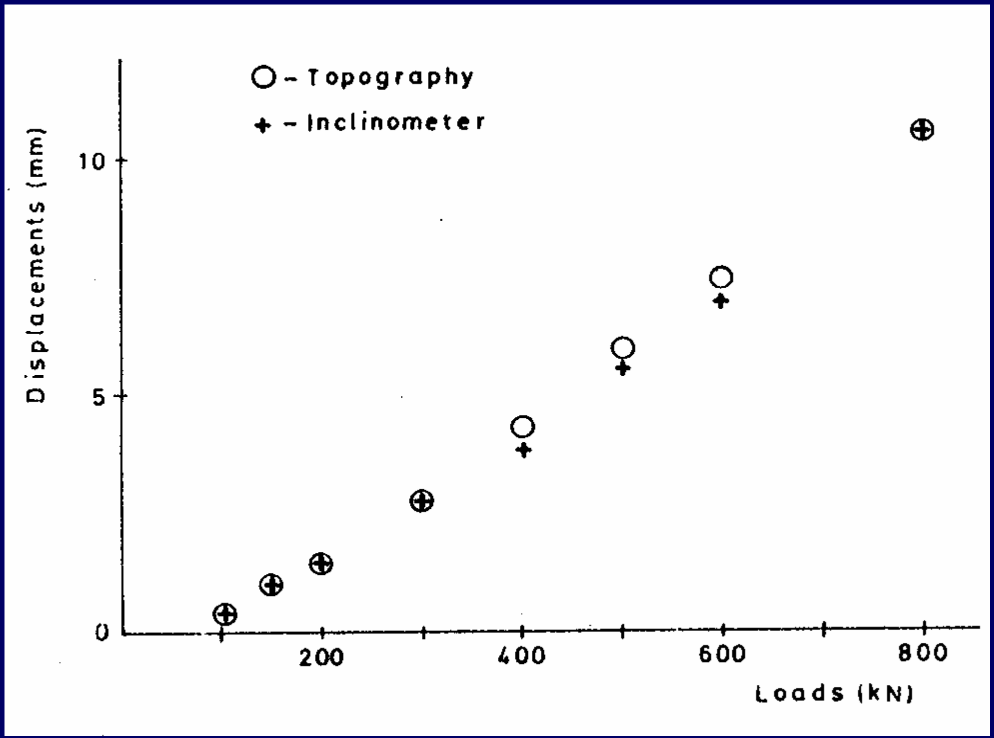


Figure 5 - Distribution of bending moments

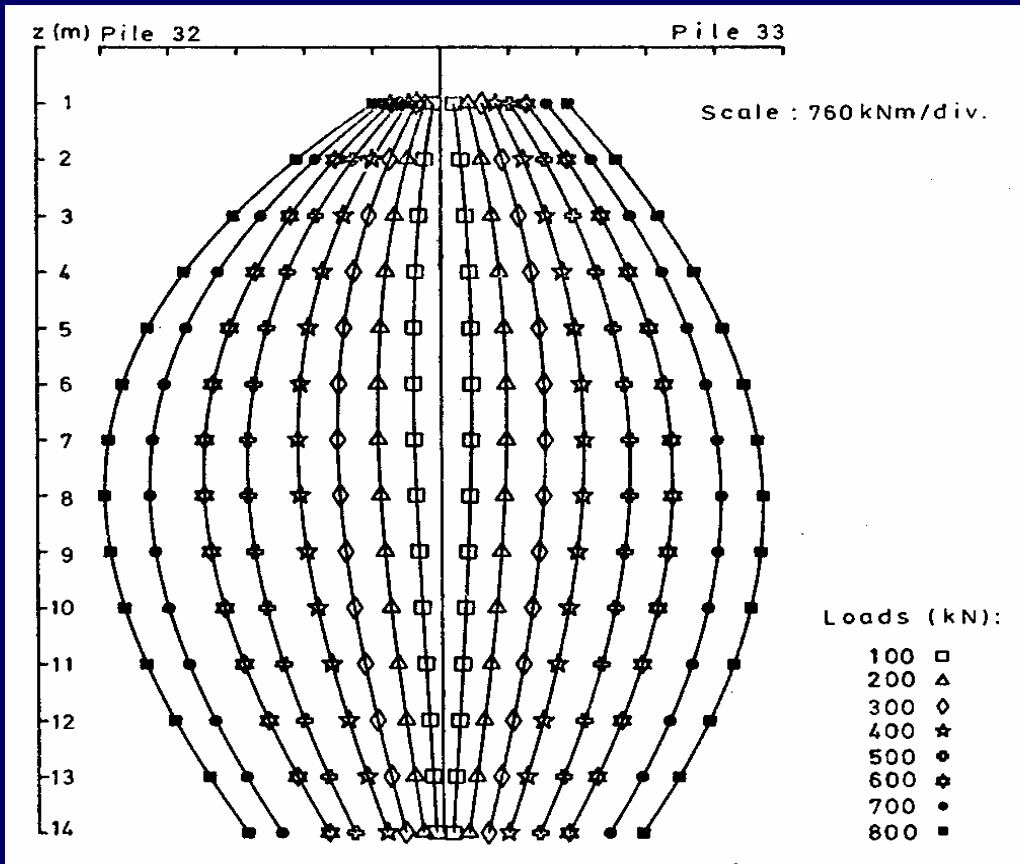


Figure 6 - Recorded of observed strains in piles

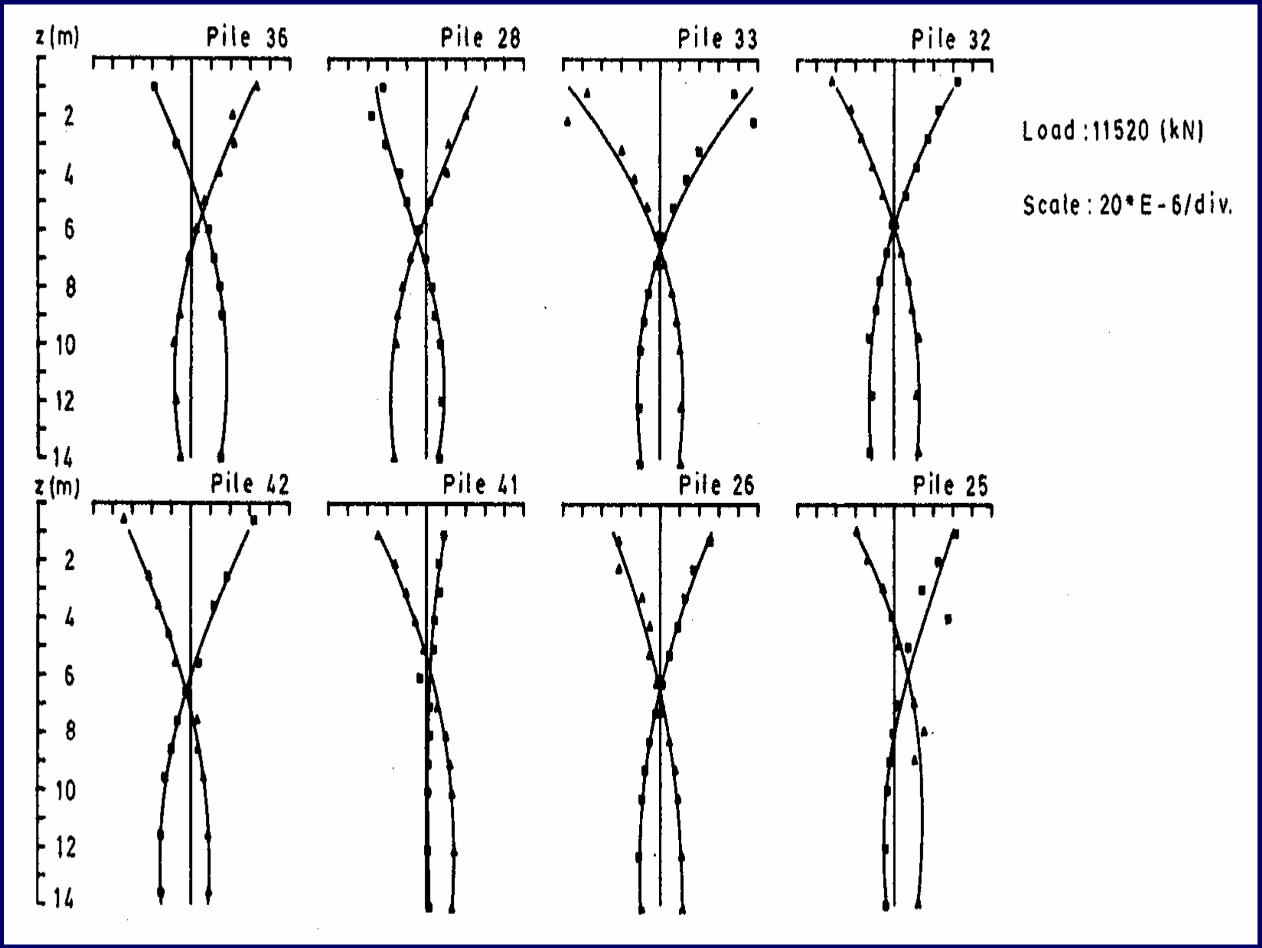


Figure 7 - Distribution of bending moments

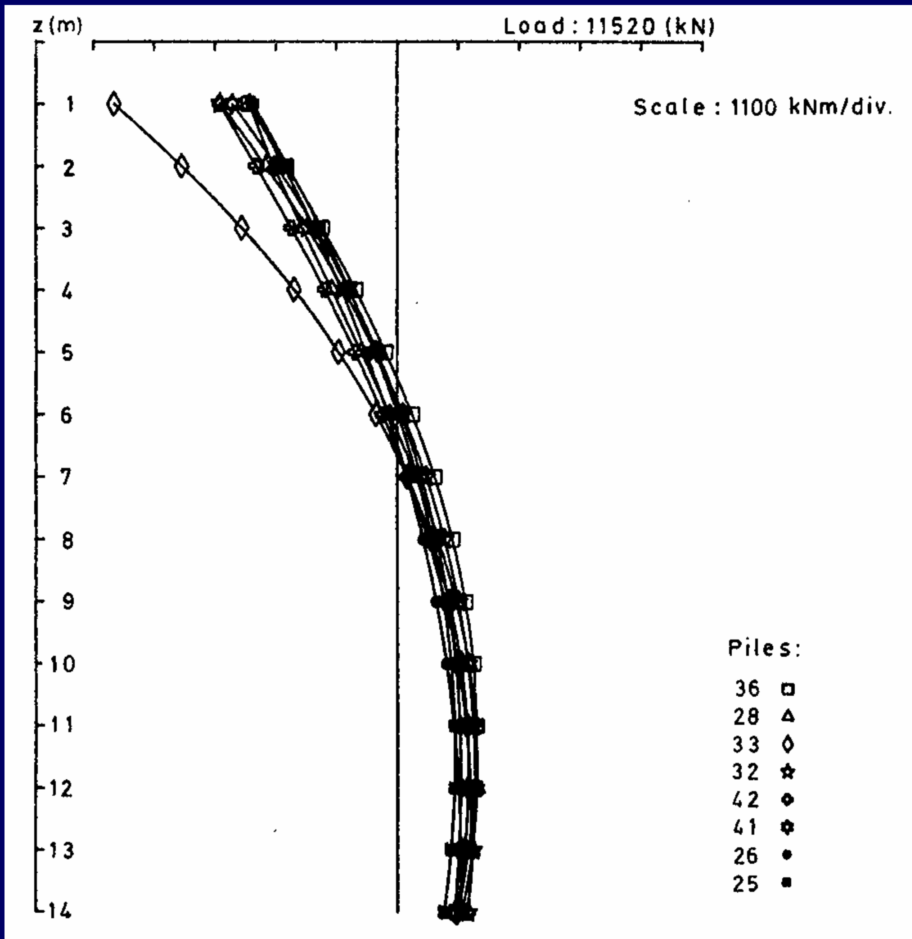
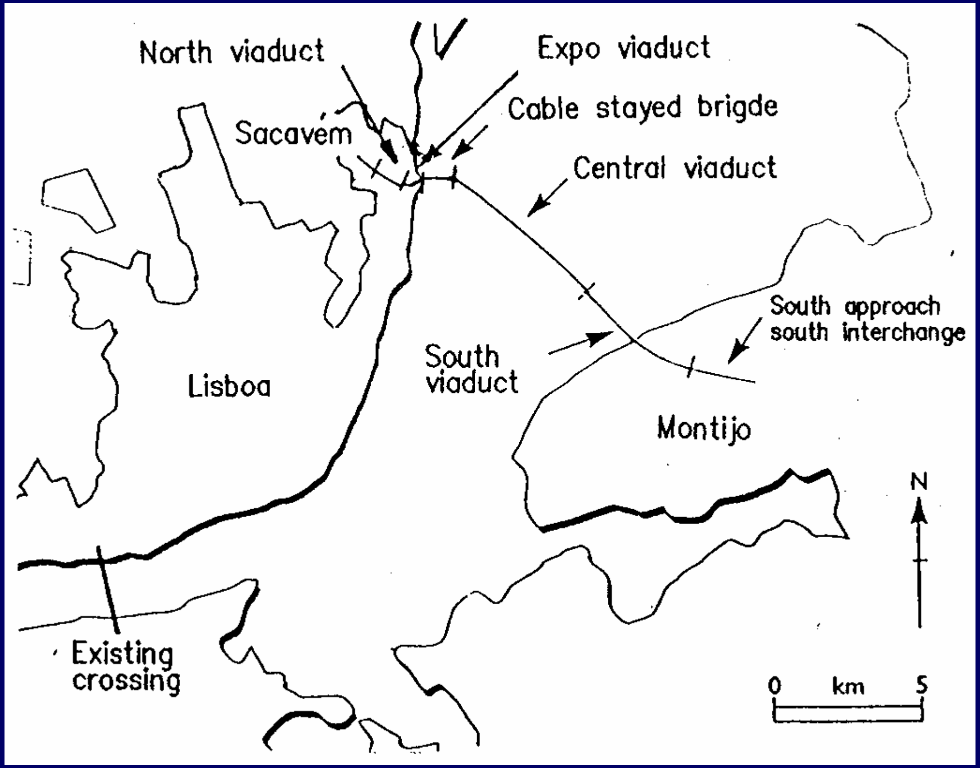


Figure 8 - New Tagus crossing site



New Tagus crossing site

When I was invited to act as Owner Consulting to co-ordinate the Geotechnical Design Team I felt very honoured, but soon became worried

I am very busy
I have already begun with my survey
And I began to write my next error.
Bertolt Brecht

La Primavera – Sandro Botticelli 1482

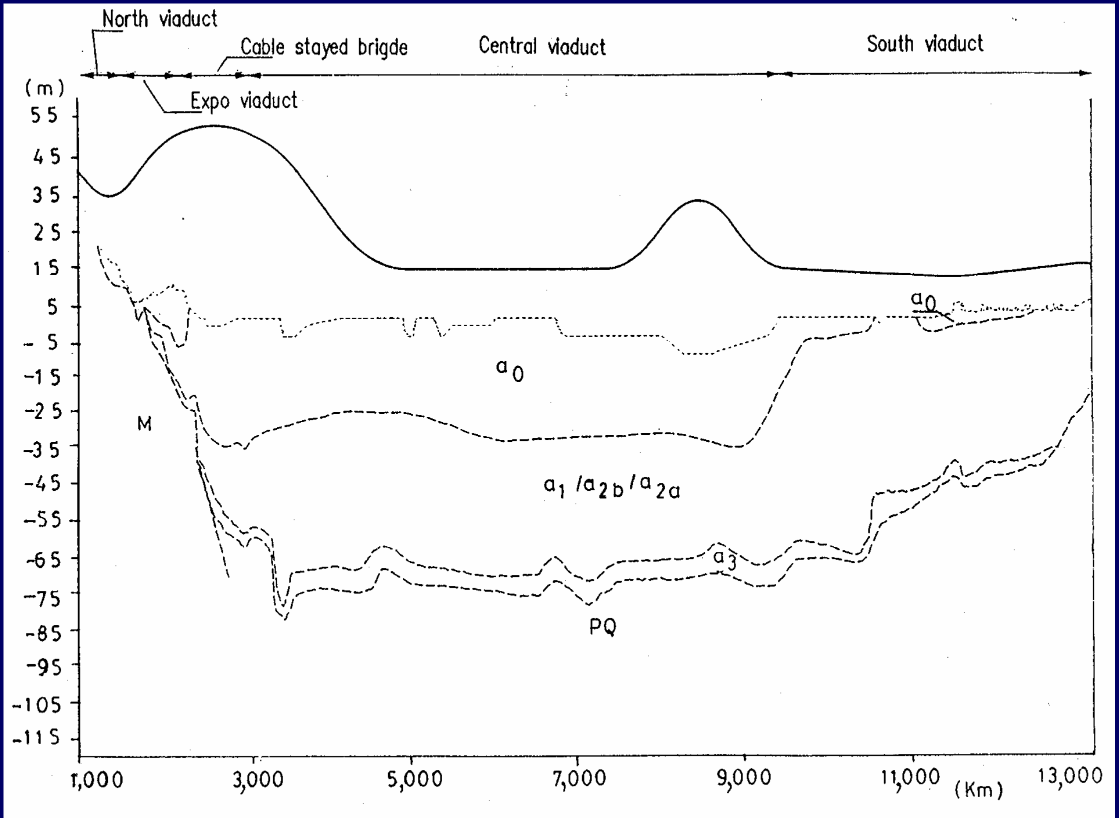
Distribution of Field Tests

TESTS	LNEC / GATTEL	ACE / TEJOPROJECTO	TOTAL
Boreholes	23	91	114
Undisturbed sampling	0	7	7
Self-boring pressuremeter	2	17	19
Vane-shear tests	4	14	18
Crosshole	1	10	11
PCPT	4	108	112
Seismic cone	0	6	6

Distribution of Laboratory Tests

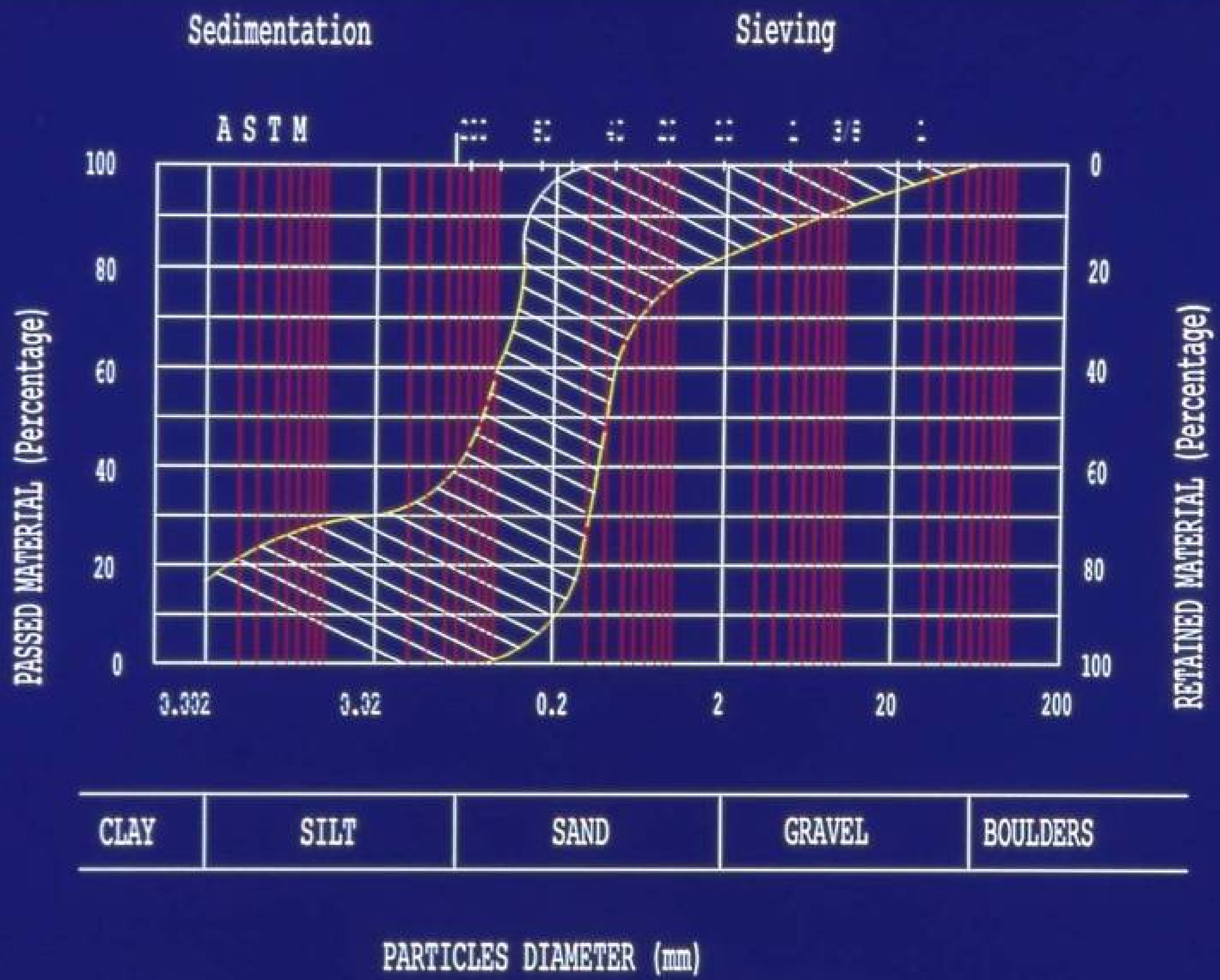
TESTS	LNEC / GATTEL	ACE / TEJOPROJECTO	TOTAL
Identification	25	206	231
Sieve curves	25	204	229
Odometer	4	56	60
Triaxial	6	52	58
Cyclic simple shear	0	12	12
Direct shear	0	13	13
Permeability	0	24	24
Chemical	0	12	12
Resonant column	0	6	6
Cyclic triaxial	0	6	6
Torsional-shear density	0	3	3
Particle density	0	12	12

Figure 9 - Simplified geological profile

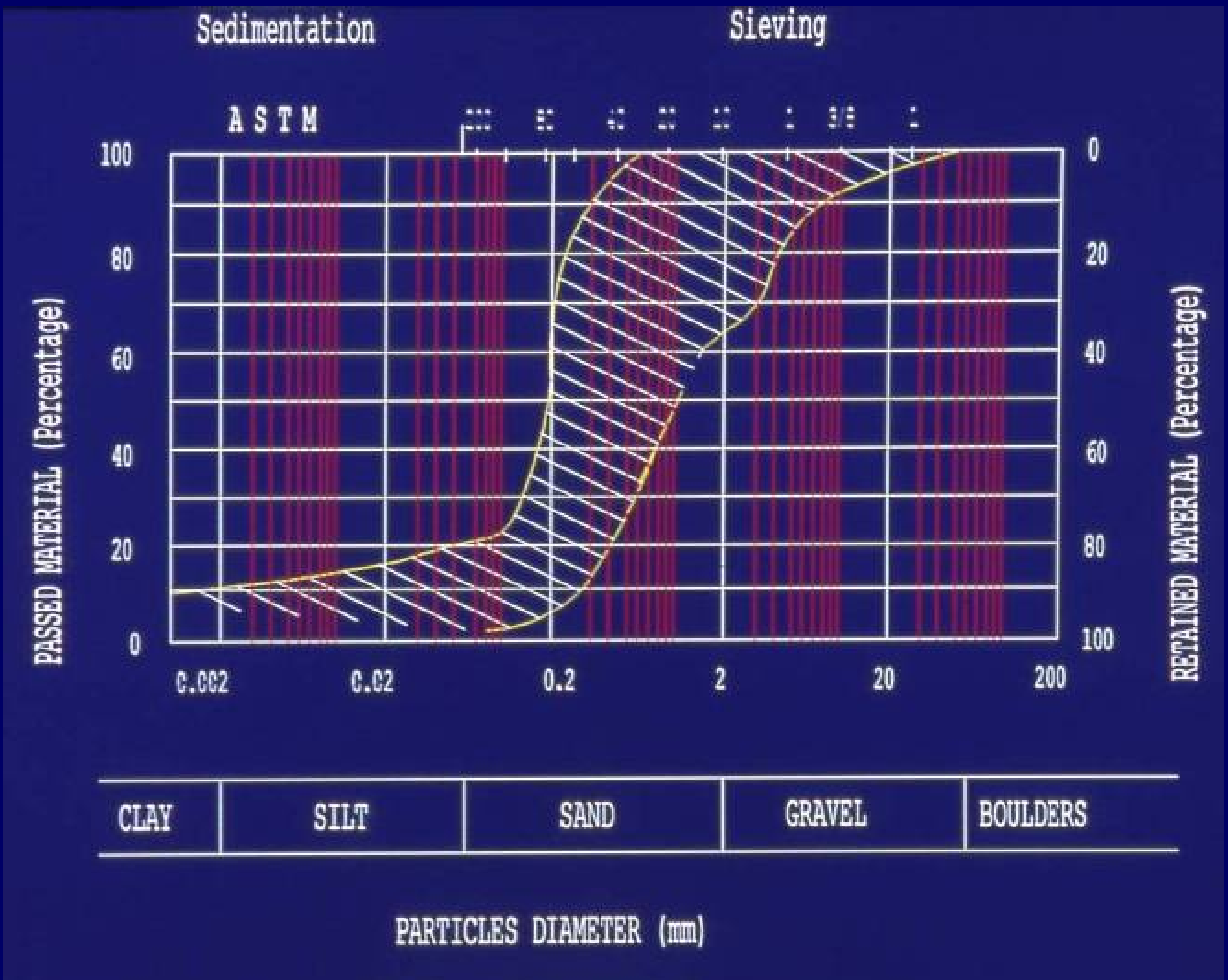


Liquefaction Assessment

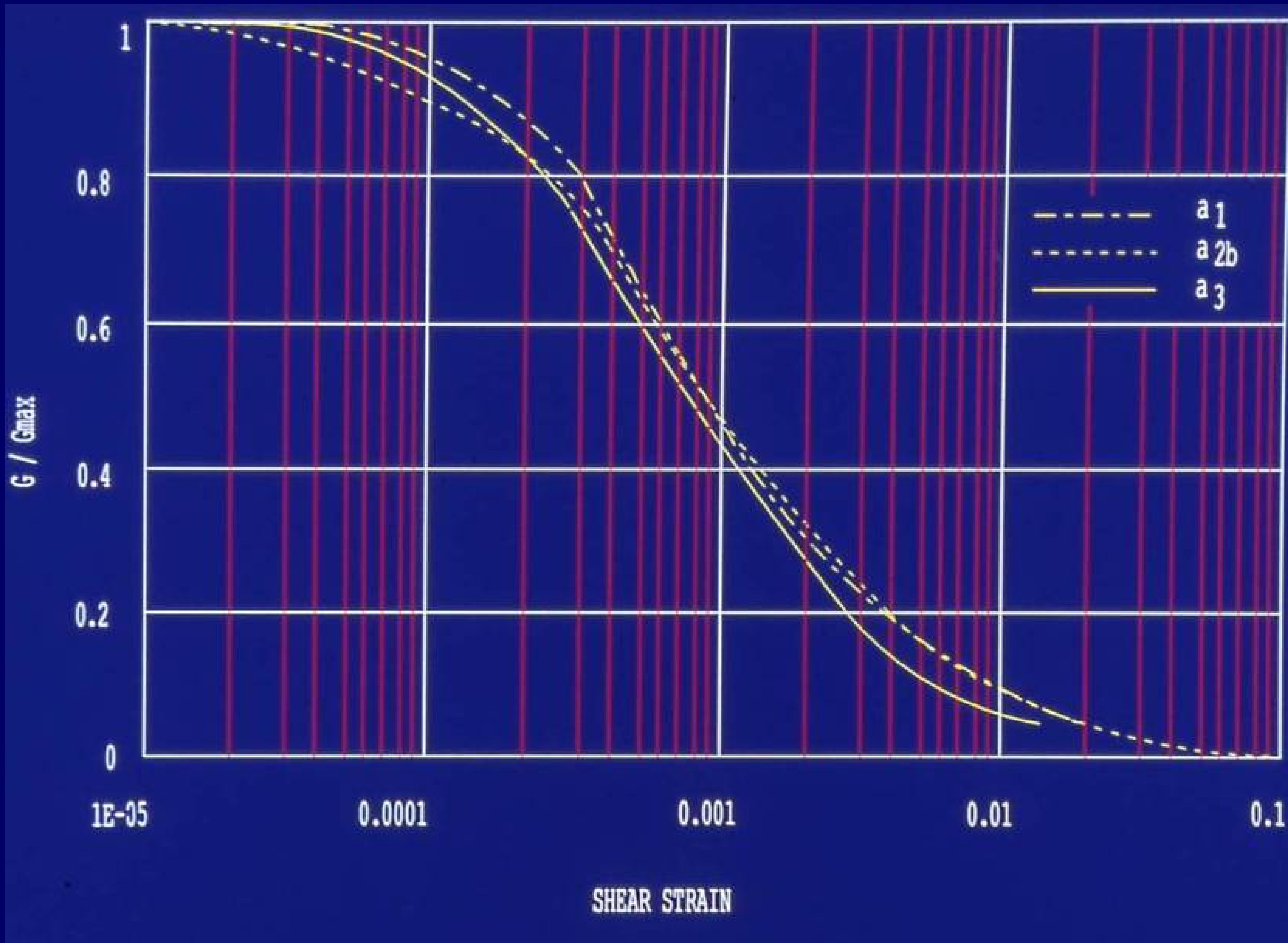
- SPT Tests
- CPT Tests
- Seismic Tests



Sieve curves for material a_1



Sieve curves for material a_{2b}



G / Gmax
1
0.8
0.6
0.4
0.2
0
1E-05
0.0001
0.001
0.01
0.1
SHEAR STRAIN
a 1
a 2b
a 3

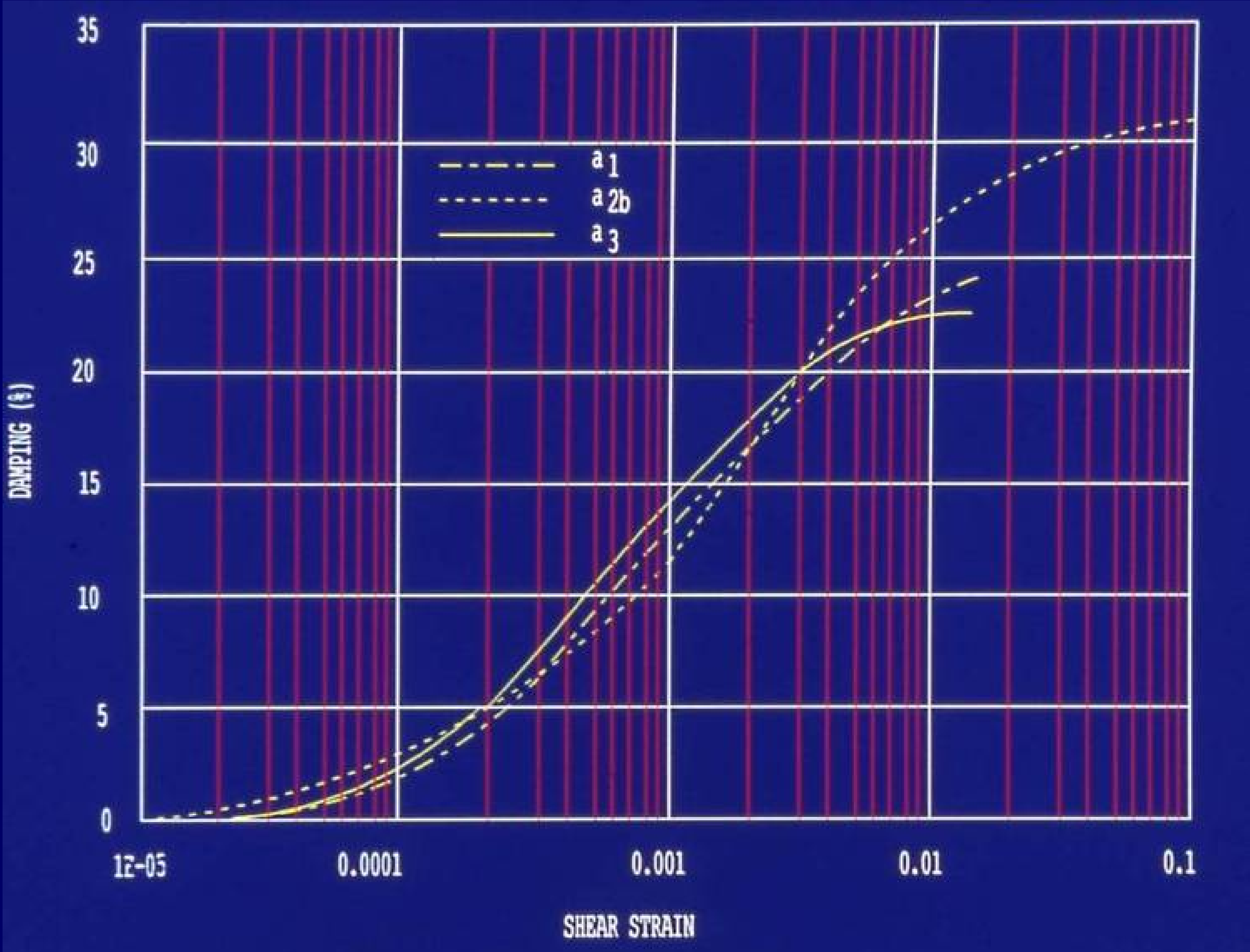
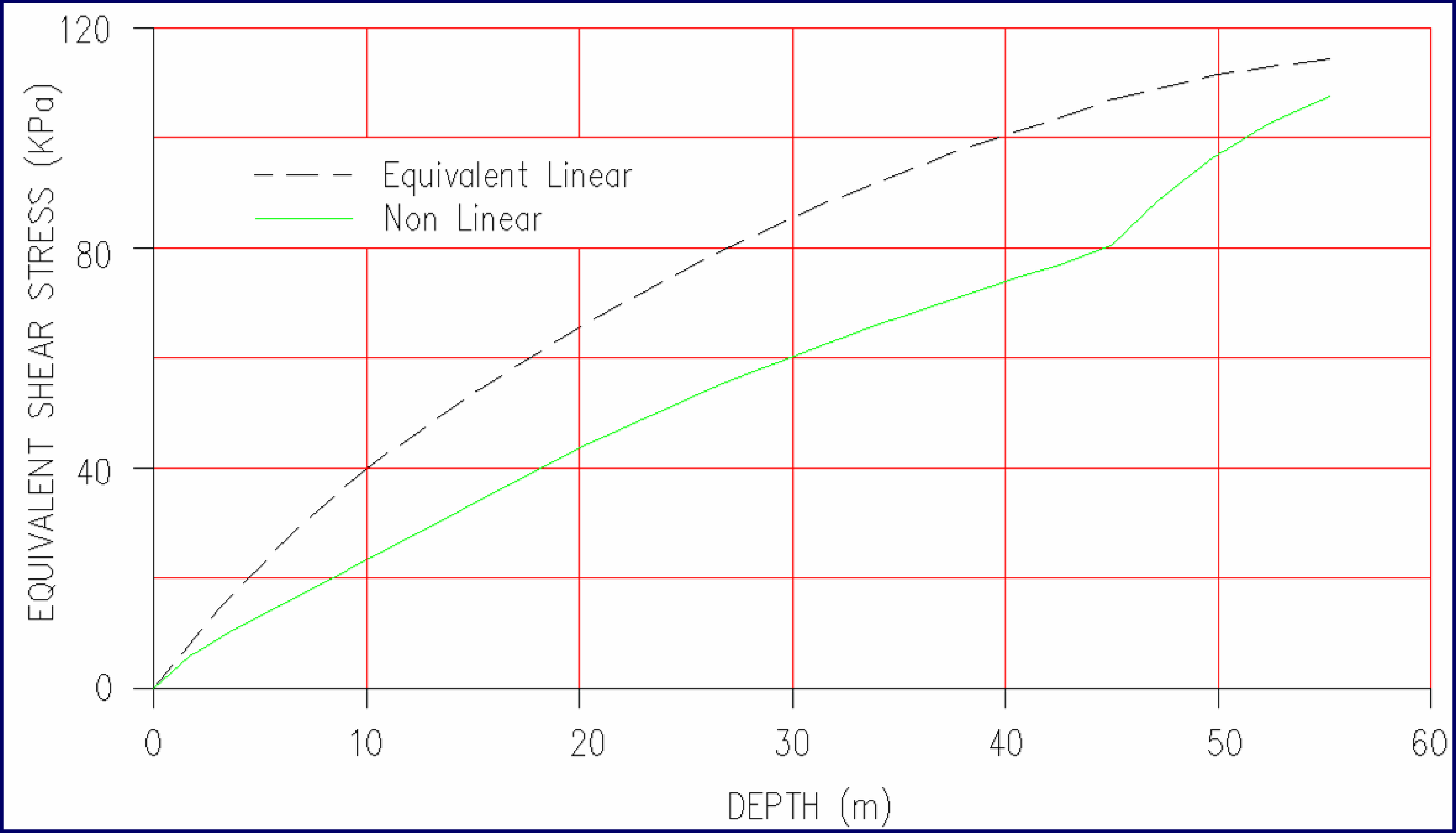


Figure 6 Damping curves

Models

- Total Stress Model Shake Program
- Effective Stress Model Dynaflow Program



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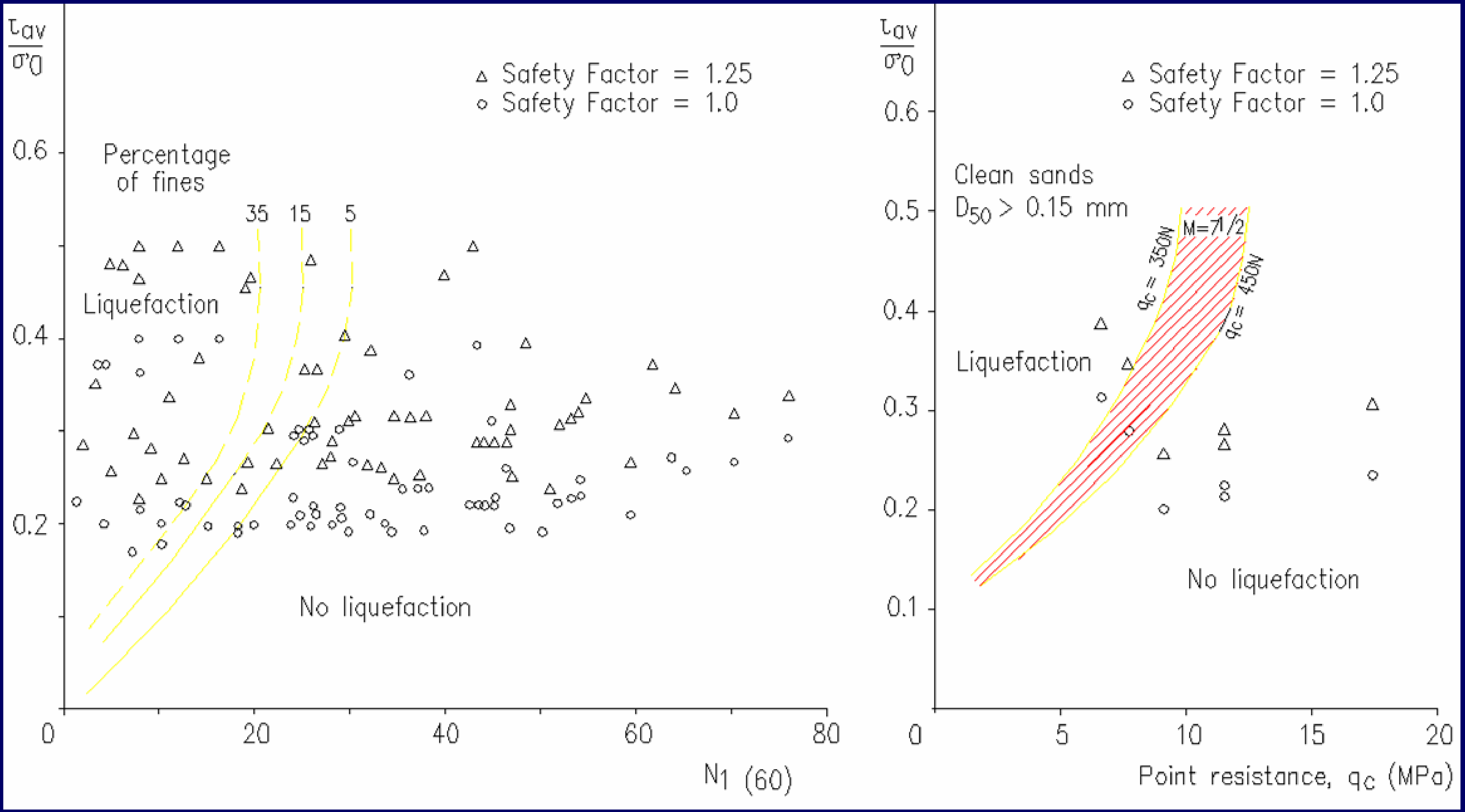

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Sieve Characteristics of the Materials

Structure	Material a_1			Material a_{2b}		
	F_n (%)	D50 (mm)	NCG	F_n (%)	D50 (mm)	NCG
Main Bridge	17.8	0.13	4	-	-	-
Central Viaduct	15.9	0.14	16	10	0.4	18
South Viaduct	11.2	0.14	29	2.8	0.7	4

Cable Stayed Bridge
Evaluation of Liquefaction Potential Material a1

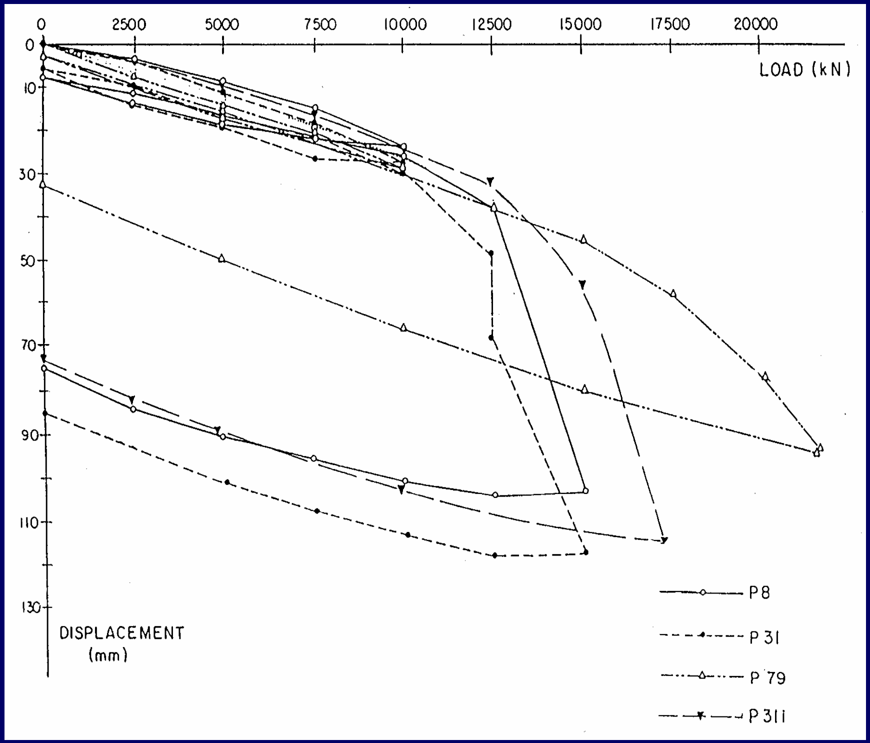
(1) Pier	(2) No. of Borehole or CPT	(3) Depth (m)	(4) Thickness (m)	(5) N_m	(6) $(q_c)_m$ (MPa)	(7) σ'_o (kPa)	(8) C_N	(9) N_1 (60)	(10) $(q_c)_1$ (MPa)	(11) $\tau_{equiv.}$ (kPa)	(12) τ/σ'_o	(13) τ/σ'_ox 1.1	(14) τ/σ'_ox 1.25	(15) Ref.	(16) Remarks
PS	BD/PS	34.2-38.2	4.0	52	-	338	0.58	30	-	53	0.16	0.17	0.20	13	N.L
PS	CPTD/PS	33.5-38.0	4.5	-	8.5	324	0.44	-	3.7	48	0.15	0.16	0.19	14	N.L
PS	B/PS	34.5-35.3	0.8	14	-	311	0.61	9	-	45	0.14	0.16	0.18	15	L
PS	B/PS	35.3-36.7	1.4	45	-	324	0.59	27	-	48	0.15	0.16	0.19	16	N.L
PS	B/PS	36.7-38.8	2.1	20	-	338	0.58	12	-	53	0.16	0.17	0.20	17	L
PS	BU/PS	31.8-36.0	4.2	23	-	306	0.61	14	-	44	0.14	0.16	0.18	18	N.L
PS	BU/PS	37.7-39.7	2.0	31	-	342	0.56	17	-	53	0.15	0.17	0.19	19	N.L
PS	CPTU/PS	31.8-36.0	4.2	-	7.5	306	0.46	-	3.45	44	0.14	0.16	0.18	20	N.L
PS/P4	B/PS-P4	33.5-38.5	5.0	48	-	315	0.59	28	-	47	0.15	0.16	0.19	21	N.L
PS/P4	B/PS-P4	38.5-41.5	3.0	26	-	356	0.55	14	-	58	0.16	0.18	0.20	22	N.L
P4	CPT/P4	33.5-45.0	11.5	-	8.5	347	0.44	-	3.74	54	0.16	0.17	0.19	23	N.L
P5	CPT/P5	34.0-44.0	10.0	-	9	351	0.44	-	3.96	55	0.16	0.17	0.20	24	N.L
P6	B/P6	33.0-38.0	5.0	51	-	324	0.59	30	-	48	0.15	0.16	0.19	25	N.L
P6	B/P6	38.0-42.0	4.0	58	-	360	0.55	32	-	59	0.16	0.18	0.20	26	N.L
P6	B/P6	42.0-46.0	4.0	43	-	396	0.53	23	-	66	0.17	0.18	0.21	27	N.L

Summary Table
Liquefaction Susceptible Zones

Structure	Material a_1			Material a_{2b}		
	Treated Values	Piers Zones Susceptible to Liquefaction	Percentage	Treated Values	Piers Zones Susceptible to Liquefaction	Percentage
Expostion Viaduct	7	0	0	6	1	17
Main Bridge	27	2	7	24	1	4
Central Viaduct	291	19	7	333	14	4
South Viaduct	90	20	22	43	0	0
TOTAL	415	41	10	406	16	4

Vertical pile load tests

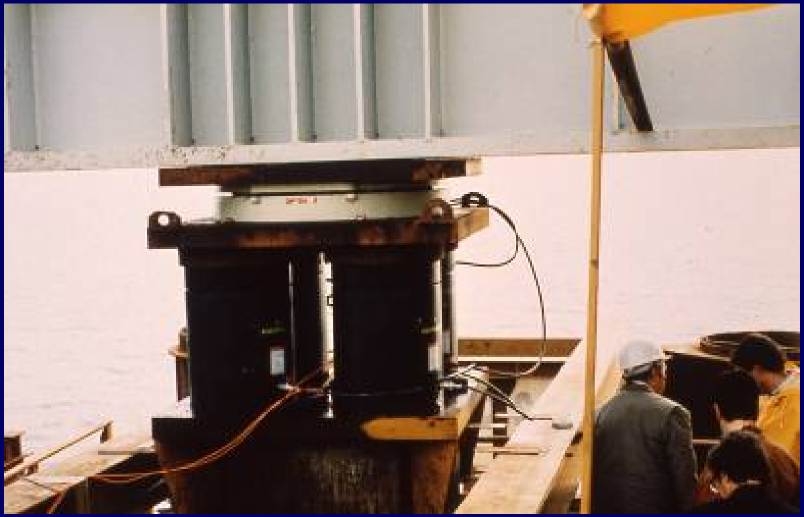
Figure 10 - Load settlements curves



Vertical pile load tests

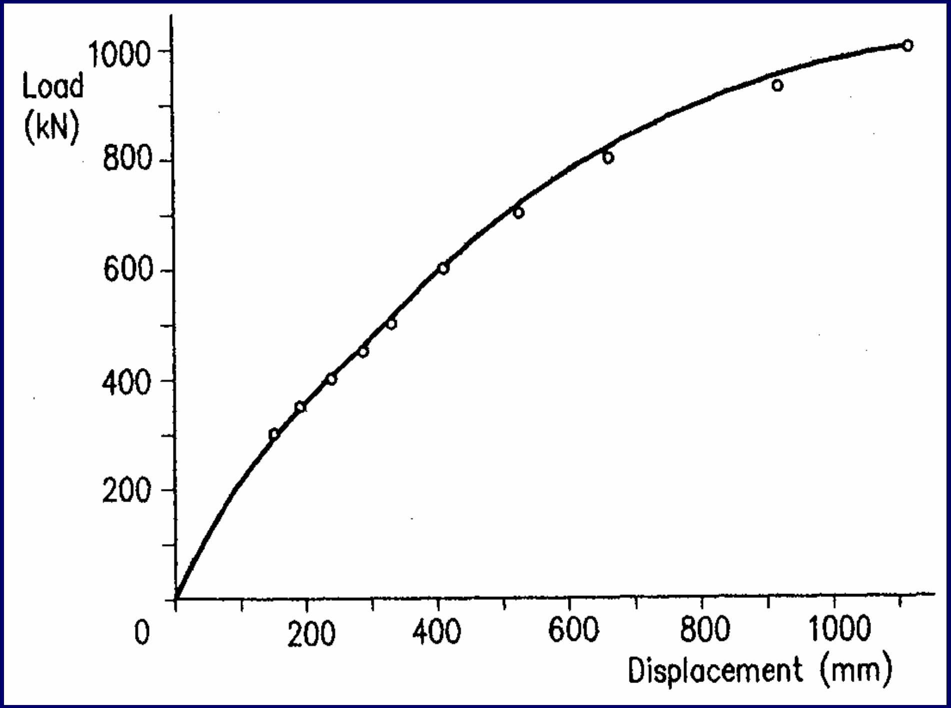
Table 13 - Failure Loads

P8		P31		P79		P31i
m	p	m	p	m	p	m
15	20.3	15	21.4	>21.15 24.5	>22.7	>17.5
m – measured			p – predicted loads in MN			



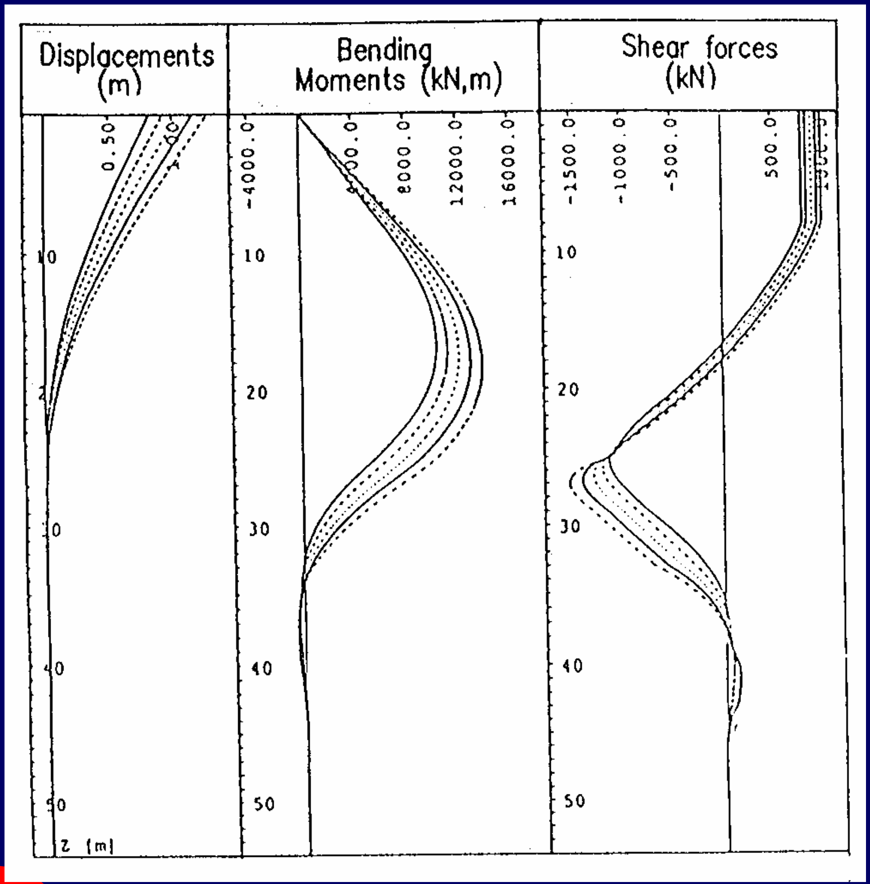
Horizontal pile load tests

Figure 11 - Measured load displacement curve



Horizontal pile load tests

Figure 12 - Computed values for piles displacements, bending moments and shear forces



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Dynamic pile load tests

Shaker

Velocity transducers

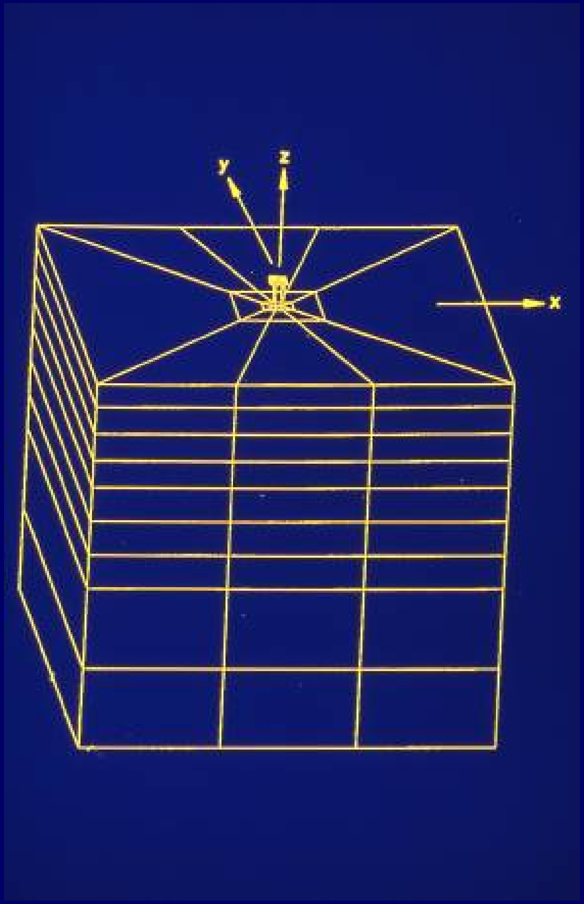
Dynamic pile load tests

Shaker

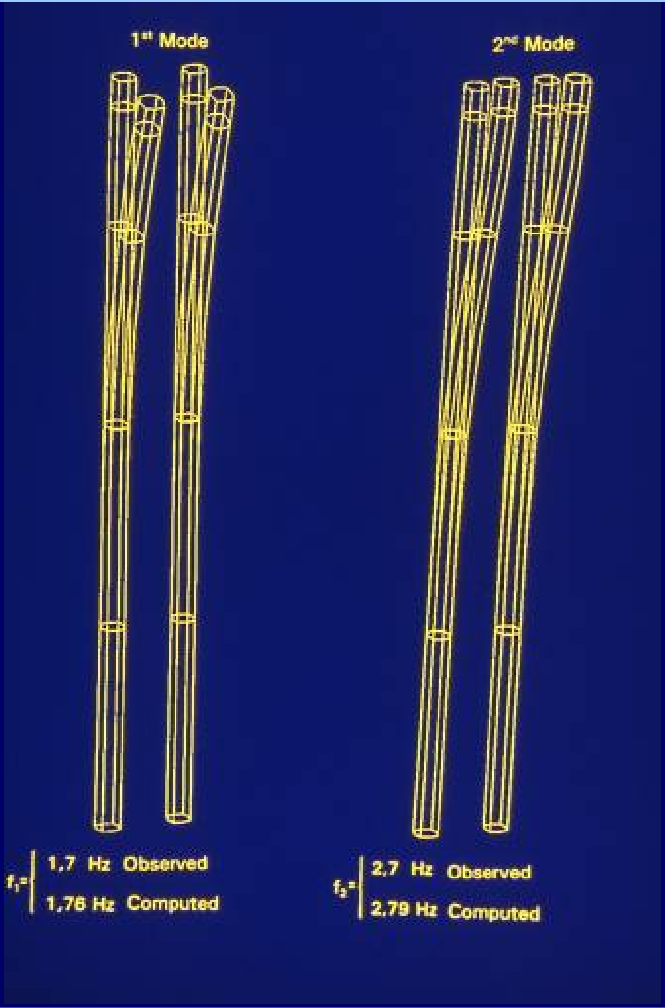
Accelerometers

Dynamic pile load tests

Finite element mesh

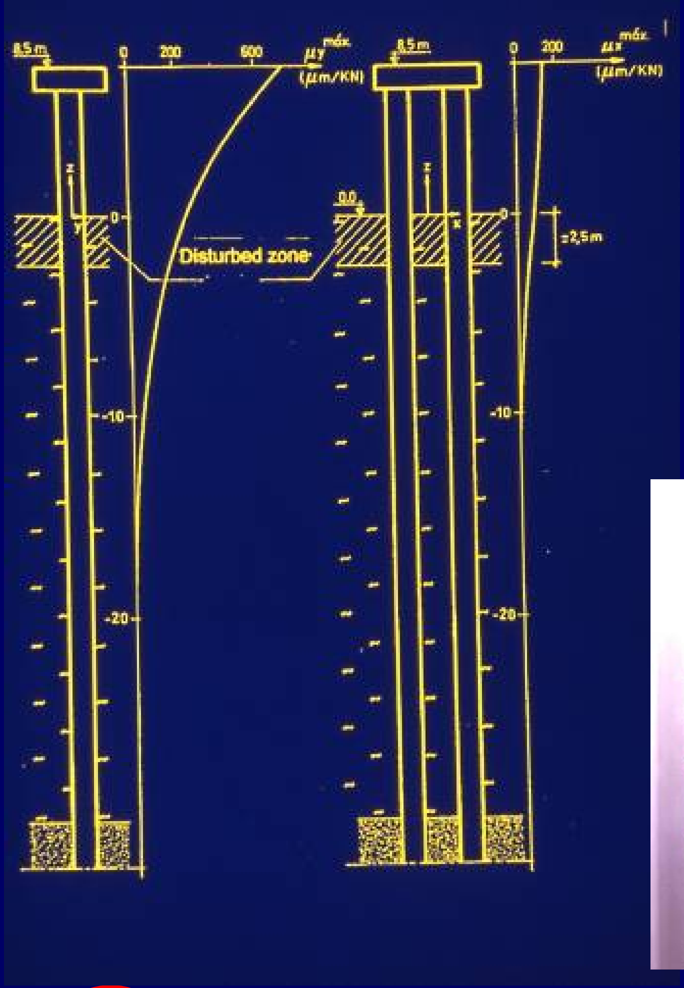


First two vibration modes

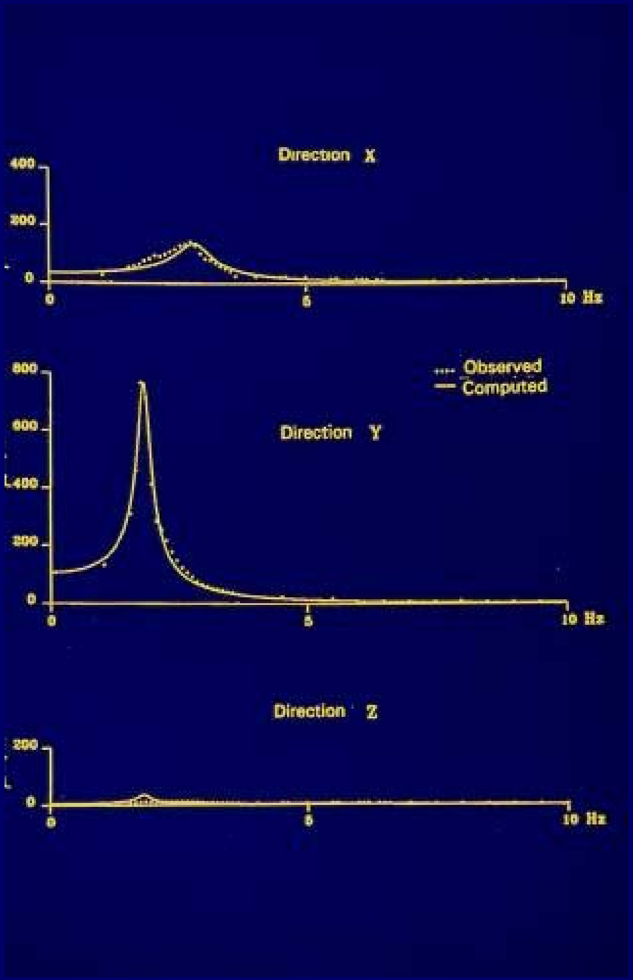


Dynamic pile load tests

Variation of maximum displacement



Displacement transfer function



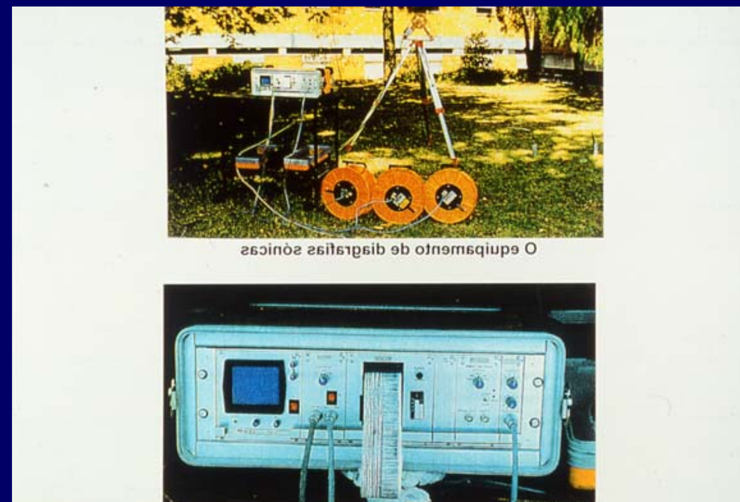
RECEPTION TESTS FOR PILES

TV camera

Core sampling

Sonic tests

Sonic diagraphy tests



Monitoring during Construction and Long Term

- Validation of design criteria and calibration of mental model
- Analysis of bridge behaviour during his life
- Corrective measures for the rehabilitation of the structure
- Cumulative experience for future studies

Superstructure Measurements

- Deck displacements
- Piers rotations and deformations
- Deck and stays temperatures
- Air temperature, relative humidity and wind speed
- Seismic and wind induced accelerations
- Force stays

Infrastructure Measurements

- Pile head displacements
- Horizontal displacements along the piles shaft
- Strain distribution of the piles
- Seismic accelerations

WARNING LEVELS

- Warning level 1 - no interruption of traffic
- Warning level 2 - limitation of traffic
- Warning level 3 - interruption of traffic
- Warning level 4 - decision concerning the traffic

INSPECTIONS

- Reference situation - detail inspection
- Daily inspections
- Annual inspection
- Five year inspection

CONCLUSIONS

- Design situations shall be verified that no relevant limit state is exceeded
- Limit states shall be verified by one or a combination of the following methods: by design by calculation, design by prescriptive measures, design by load tests, experimental models and observational method
- None of existing procedures for calculating pile capacity is reliable
- For design purposes field tests with instrumented piles are highly recommended
- Load tests performed in Guadiana bridge and New Tagus bridge for design purposes have shown the advantages to calibrate the design parameters and to assess the suitability of the construction method

MY VISION - LESSONS FOR TOMORROW

1. Further discussion in recent codes related performance based design and allowable displacements for the 2 levels of seismic action.

2. Vulnerability is associated with the degree of loss or the potential loss and integrates the range of opportunities that people face in recovery. Resilience is a measure of the system`s capacity to absorb recover from a hazardous event

MY VISION - LESSONS FOR TOMORROW

•3. The recognition of a better planning, early warning, quality of evacuation for extreme events. Plato (428-348 BC) in the Timaeus stressed that destructive events that happened in the past can happen again, and for prevention and protection we should followed Egyptians example and preserve the knowledge through the writing.

•4. The none recognition for the engineers work is lacking since the past, e.g. the Egyptian King Cheops has his name linked with the great pyramid, a master piece engineer work, but the history does not record the name of the engineer.

•5. Interaction with the Owners, Decision Makers, Society and General Public and to explain that the concern for man and fate has been always the core interest of the engineer profession.

•6. The engineers should have competence, devotion and honesty.

•7. The Engineers should enjoy the activities during the day, but only by performing those that will allow to sleep at the night. .

MY VISION - LESSONS FOR TOMORROW

8. Contribution of Voltaire and the book Candide published in 1759, after the Lisbon earthquake (1755), for the change from the intellectual optimism and potential fatalism that is a necessary condition for the construction of future scenarios in a reliability and risk analysis context.

- **9. It is important to narrow the gap between the university education and the professional practice, and remember that Theory without Practice is a Waste, but Practice without Theory is a Trap. Kant has stated that *Nothing better that a good theory,* but following Seneca *Long is the way through the courses, but short through the example..***
- **10. 7 Pillars of Engineering Wisdom: Precedents, Practice, Principles, Prudence, Perspicacity, Professionalism and Prediction.**

HYPPOCRATES

- The Art is long
- The Life is short
- Experience is fallacious
- And Decision is difficult