The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

H4.SMR/1645-13

"2nd Workshop on Earthquake Engineering for Nuclear Facilities: Uncertainties in Seismic Hazard"

14 - 25 February 2005

Permanent Ground Deplacements
Secondary Seismic Effects

P. Labbe'

EDF, SEPTEN
France

IAEA/ICTP Workshop on
Earthquake Engineering for Nuclear Facilities - Uncertainties in Seismic Hazard Assessment

Permanent ground displacements Secondary seismic effects

Trieste, Italy, 14 – 25 February 2005

Unit 14 , Pierre Labbé

Contents of the Presentation

- Settlement under static loads
- Settlement under seismic input motions
- Liquefaction hazard

Settlement under static load

Settlement under static load

- **IMMEDIATE SETTLEMENT**

$$s_i = C\, q\, B\, \frac{1 - \nu^2}{E} = \frac{C}{2}\, q\, B\, \frac{1 - \nu}{G}$$

C: coefficient accounting for shape and flexibility of the foundation

q: equivalent uniform stress

B: characteristic dimension of the footing

ν: Poisson's coefficient (= 0,5 for saturated cohesive soils)

E: Young's modulus (undrained modulus for clays)

for a rigid circulate foundation: C = $\frac{\pi}{4}$, B = diametre

Settlement under static load

- **WATER IN SOIL**
- **Soil versus continuum:**

$$\sigma = u + \sigma'$$

σ : stress in the continuum

u : pore pressure

σ' : effective stress (carried by the soil solid)

remark : $\tau' = \tau$

Settlement under static load

- **WATER IN SOIL**
  - Darcy's Law: $v_x = -k \frac{\partial h}{\partial x}$

sand: $10^{-4} > k > 10^{-6}$ m/s

clay: $10^{-8} > k > 10^{-10}$ m/s

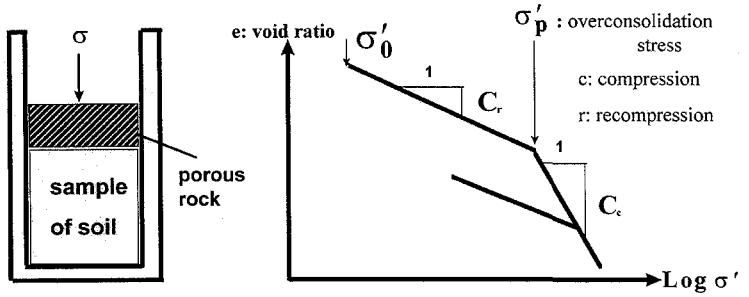
v_x : discharge velocity

$\frac{\partial h}{\partial x}$: hydraulic gradient, $h = \frac{u}{\rho_w g} + z$ (low velocity)

k : permeability

Settlement under static load

- OEDOMETRIC TEST



σ is increased step by step

- beginning of a step: $u = \sigma$, $\sigma' = 0$
- end of a step : $u = 0$, $\sigma' = \sigma$

Settlement under static load

- **CONSOLIDATION SETTLEMENT**

$$s_c = H_0 \frac{\Delta e}{1 + e_0}$$ H_0 is the thickness of the layer

Δe is obtained from the oedometric curve:

$$\Delta e = C_r \log\left(\frac{\sigma'_p}{\sigma'_0}\right) + C_c \log\left(\frac{\sigma'}{\sigma'_p}\right) \qquad 0{,}1 < C_c < 3$$

$$OCR = \frac{\sigma'_p}{\sigma'_0}$$: Over Consolidation Ratio

OCR > 1 : Over Consolidated soil
OCR = 1 : Normally consolidated
OCR < 1 : Under consolidated : $u > u_{hydrostatic}$ (Mexico City)

Settlement under static load

A street in Mexico City

Settlement under static load

- **RATE OF CONSOLIDATION SETTLEMENT**

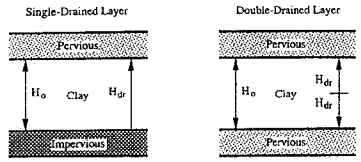
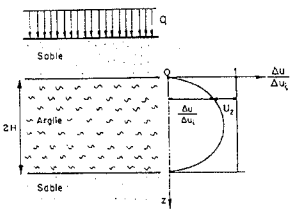


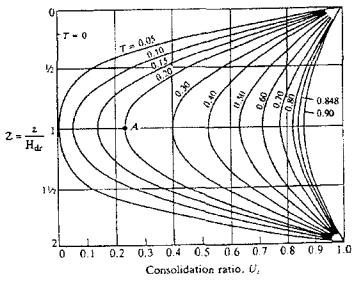
FIGURE 18.5 Boundary drainage conditions for the consolidation problem.

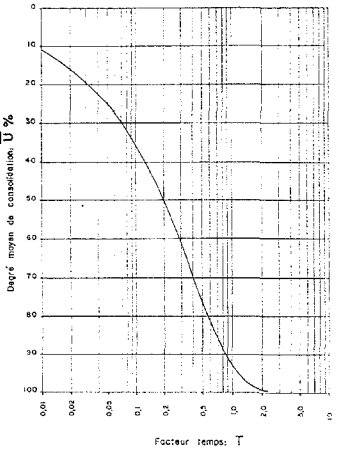


$$T = \frac{(1+e_o)}{\rho_w g}\frac{k}{a}\frac{t}{H_{dr}^2} \quad ; \quad a = -\frac{de}{d\sigma'_v}$$

Settlement under static load

- **RATE OF CONSOLIDATION SETTLEMENT** (cont.)





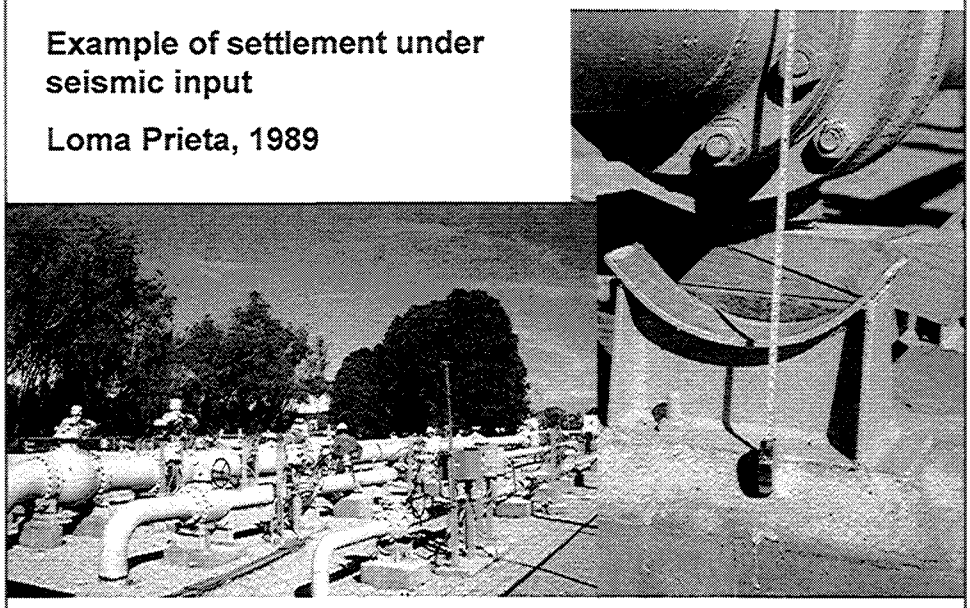
Settlement under static load

- **Example of a clay layer:**
  - **Thickness:** $H = 2.5$ m, $H_{dr} = 1.25$ m
  - **Initial void ratio:** $e_0 = 0.8$
  - **Permeability** $k = 10^{-9}$ m/s
  - **Oedometre :** $C_c = 0.16$
- **Loaded by 10 t / m²** $\sigma = 10^5$ Pa
- **The practically 100% settlement**
  - $T = 2$
  - **is obtained after** 1 year

Settlement under seismic input motion

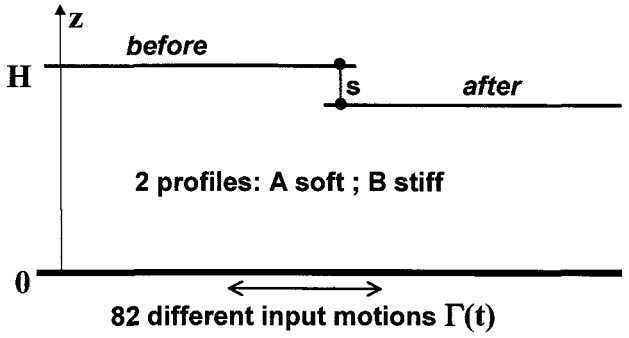
Example of settlement under seismic input

Loma Prieta, 1989



Parametric study of settlement of soil profiles under seismic input motion

1) Purpose of the study



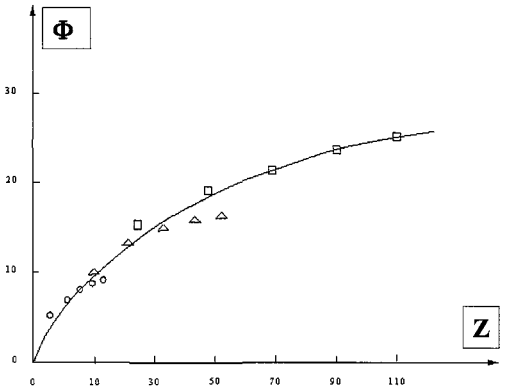
Parametric study of settlement

Soil profiles under consideration

	Profile A	Profile B
Depth H	48 m	9,6 m
$G_{max}(H)$	188 MPa	84 Mpa
$f_1 = \omega_1/2\pi$	1,5 Hz	5,0 Hz
$\rho = 1800$ kg/m^3	$\xi_{max} = 23$ %	
$n_0 = 0,4$	$C_1 = 8,7.10^{-3}$	$C_2 = 2.10^5$

Parametric study of settlement

Sand densification modelling



$$Z = \gamma^2 N / 4$$

$$\Phi = C_1 \ln(1 + C_2 Z)$$

$$\varepsilon = \Phi \, n_0 / (1 - n_0)$$

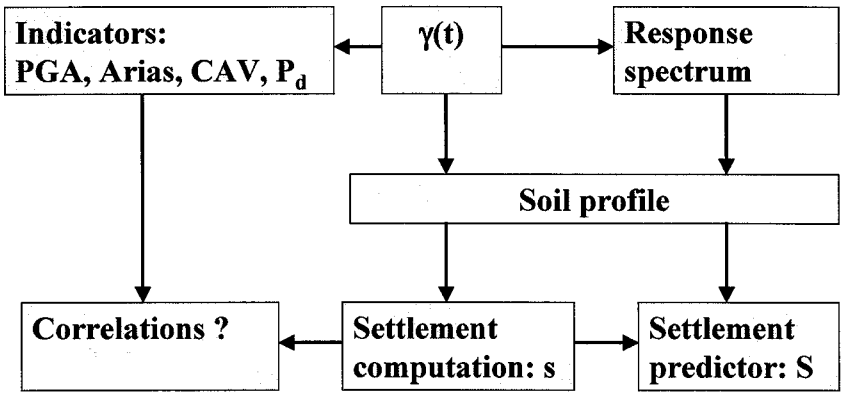
Parametric study of settlement

Seismic input motions considered

82 input motions from 13 earthquakes

- **Magnitudes:** 5.3 - 7.7 (Ken Conuty 1952)
- **P.G.A. :** 0.03 - 0.48 g (Whittier 1987)
- **Strong motion duration:** 2.02 - 58.6 s (El Centro 1956)

Parametric study of settlement



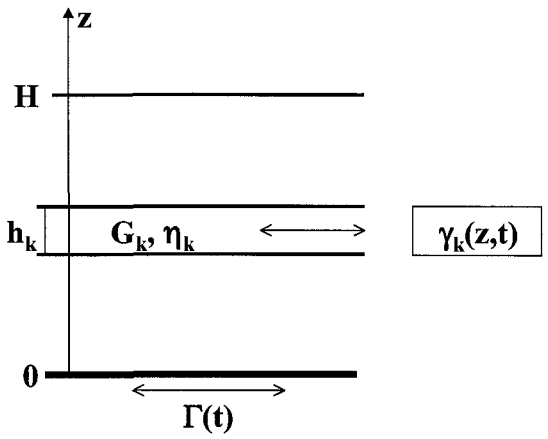
Parametric study of settlement

2) Settlement computation

- Time history analyses of both profiles under the 82 input motions.
  Equivalent linear approach.
- Post treatment of each response to derive the corresponding settlement.

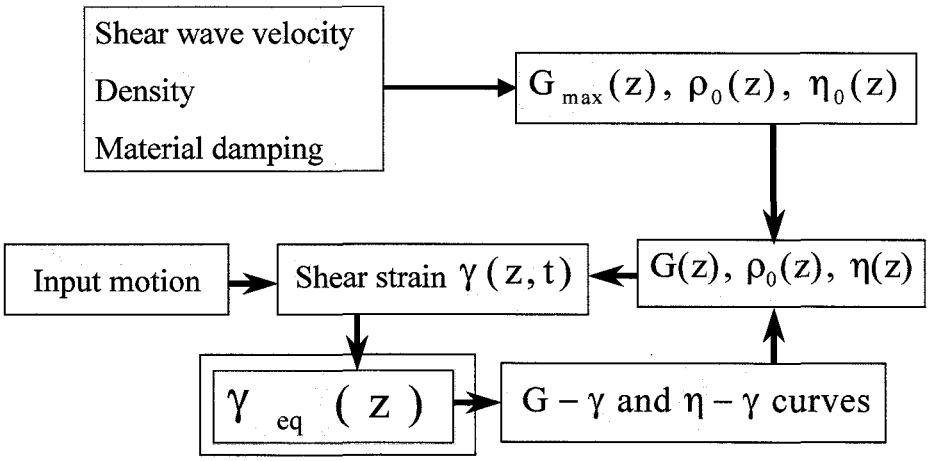
Parametric study of settlement

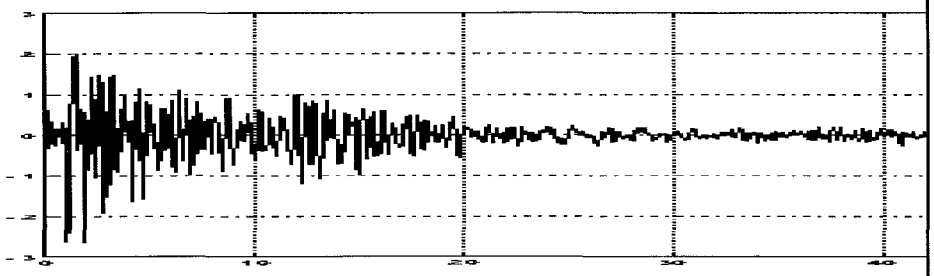
Time history analyses



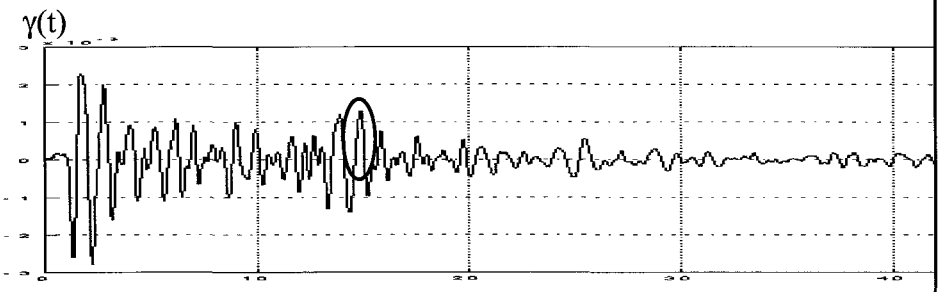
Parametric study of settlement

Linear equivalent profile





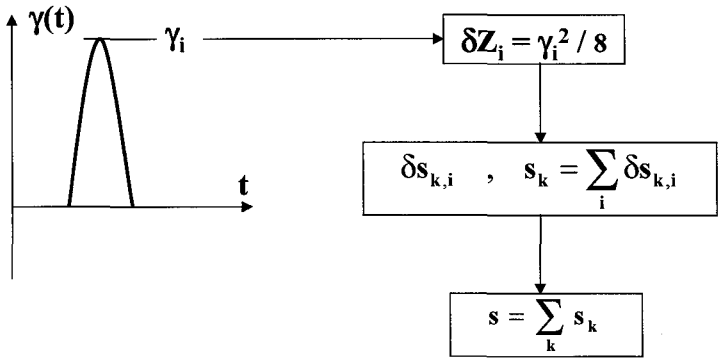
Typical input motion: wide band signal



Typical response: narrow band signal

Parametric study of settlement

Post treatment



Parametric study of settlement

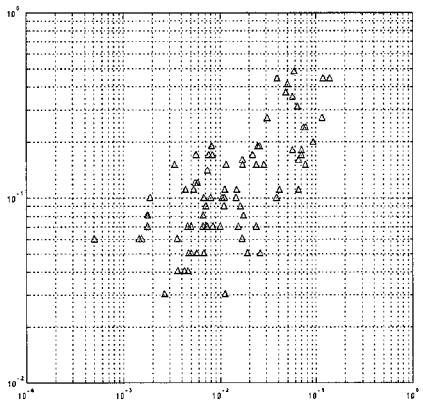
3) Correlations

- PGA
- Arias Intensity
- CAV
- Saragoni's P_d

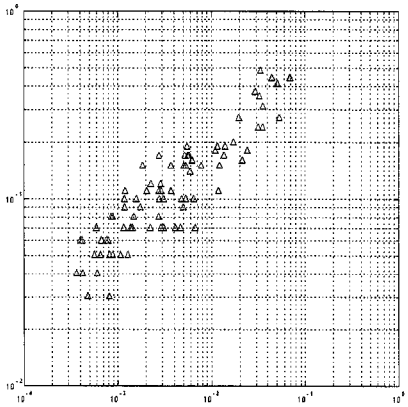
vs settlement

Parametric study of settlement

Correlations pga - settlement



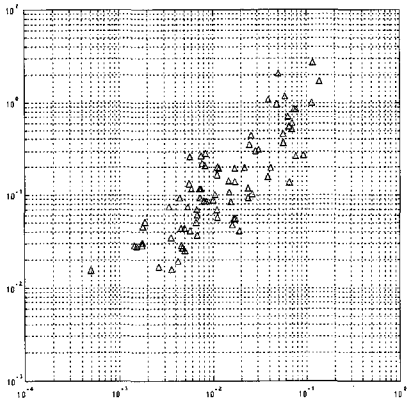
Profile A



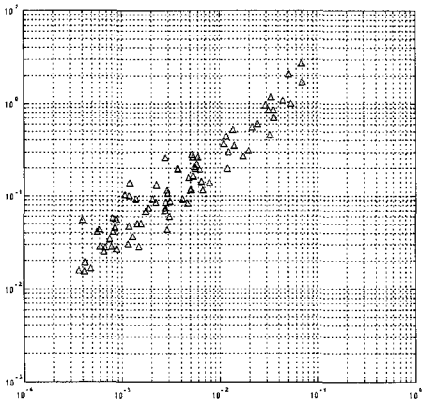
Profile B

Parametric study of settlement

Correlations Arias intensity - settlement



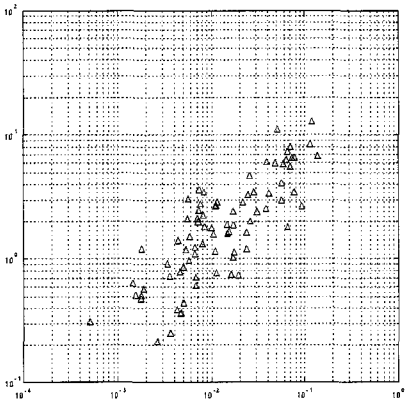
Profile A



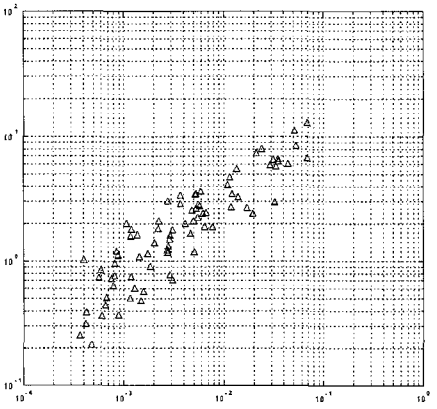
Profile B

Parametric study of settlement

Correlations CAV - settlement



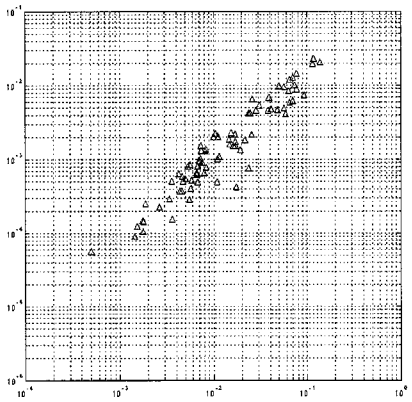
Profile A



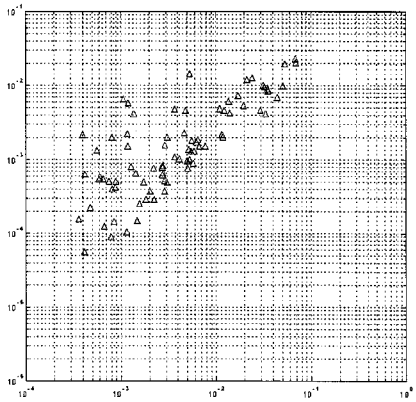
Profile B

Parametric study of settlement

Correlations Saragoni's P_d - settlement



Profile A



Profile B

Parametric study of settlement

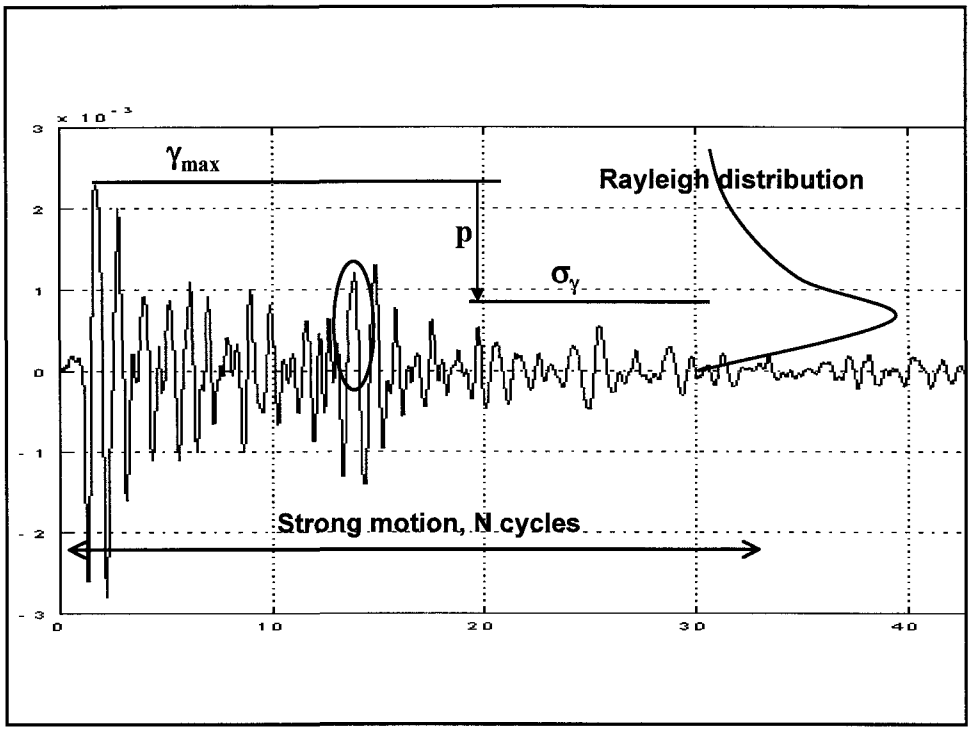
4) Prediction of settlement

- **For each z value, the response of the profile**

  $$\gamma(z,t)$$

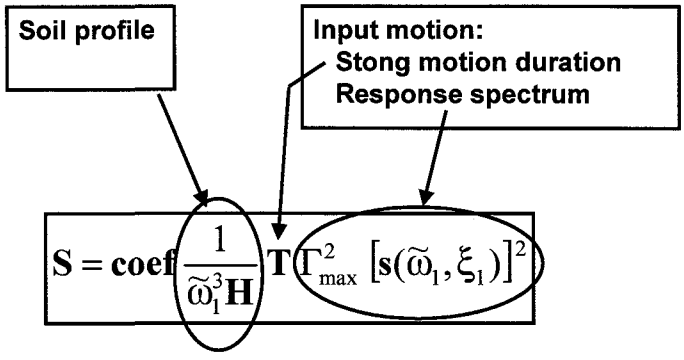
  is regarded as a sample of a narrow banded stochastic process.

- **Information about the number and magnitude of cycles is derived.**
- **A prediction of settlement is calculated.**



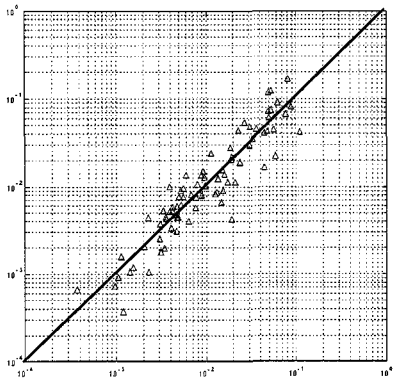
Parametric study of settlement

Settlement predictor

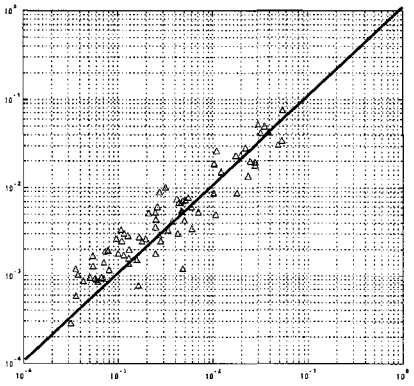


Parametric study of settlement

Performance of the predictor



Profile A



Profile B

Parametric study of settlement

Conclusions

	Profile A	Profile B	A and B
PGA	0,72	0,90	0,70
Arias	0,76	0,94	0,74
C.A.V.	0,80	0,88	0,75
Pd	0,94	0,86	0,83
Predictor	0,81	0,90	0,85

Correlation factors

Parametric study of settlement

Conclusions

	Lubiatowo Dr » 60 %	Kozienice Dr » 50 %
PGA	0,62	0,72
Arias	0,63	0,77
C.A.V.	0,67	0,76
Pd	0,72	0,84
Predictor	0,83	0,84

Correlation factors on A and B with other materials

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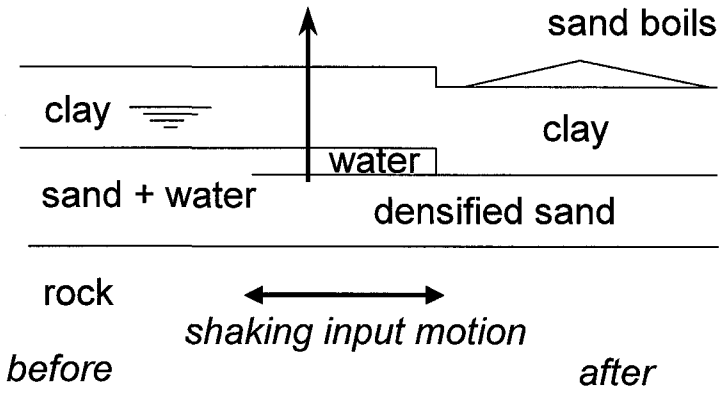
Liquefaction

Liquefaction

- **What is liquefaction?**



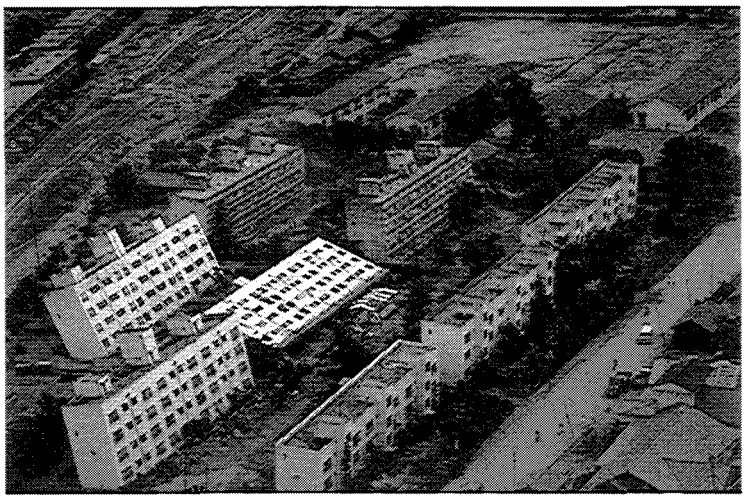
Liquefaction

Ceyhan Misis, Turkey, 1998

Liquefaction

San Francisco 1906

Liquefaction
Nigata, 1964



Liquefaction

Nigata, 1964,
Sand boils

Liquefaction
San Fernando dam, 1971

Liquefaction
San Fernando dam, 1971

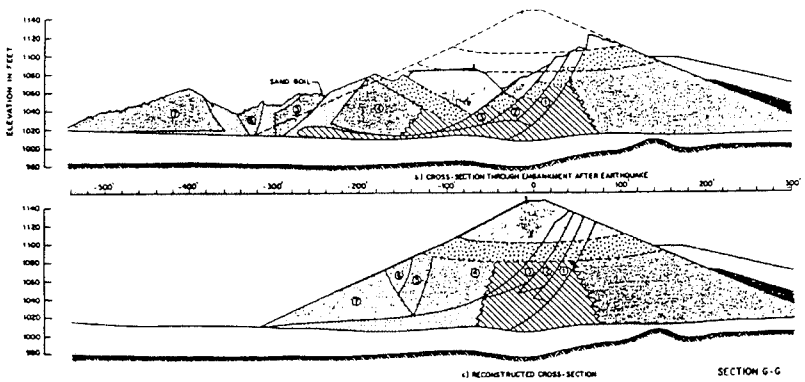
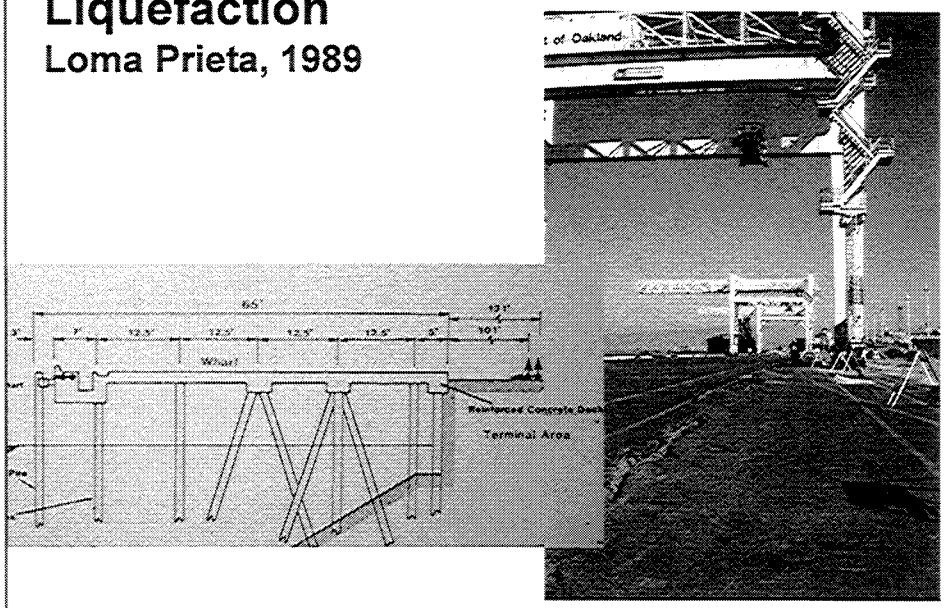


Figure 1.20. *Recomposition du glissement du barrage de San Fernando*

Liquefaction
Loma Prieta, 1989



Liquefaction
Kobe, 1995

Liquefaction

Adapadzari, Ismit earthquake, 1999

Liquefaction

Assessment of the liquefaction potential

IAEA Safety Guide

- **Empirical approach**
- **Conventional approach**
- **Sophisticated approach**

Liquefaction

Assessment of the liquefaction potential

Empirical correlation

Inputs are estimates of shear stress and SPT or CPT results. The potential evaluation is based on empirical observations (experience feedback)

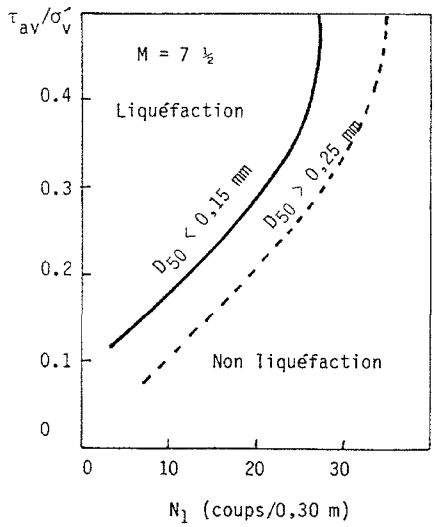


Fig. IV-5.9. Corrélation entre comportement des sites (sables limoneux $D_{50} < 0,15$ mm) et résultat SPT (TOKIMATSU et al., [IV-103]).
Correlation between field performance (silty sands $D_{50} < 0.15$ mm) and SPT (TOKIMATSU and al., [IV-103]).

Liquefaction

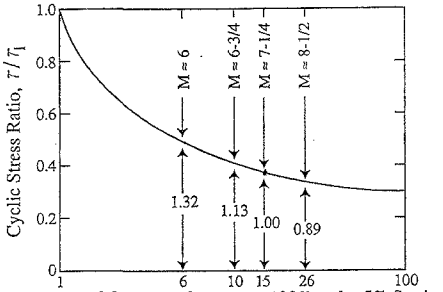
Assessment of the liquefaction potential

Conventional approach

- **Experimental characterization of cyclic strength in each layer.**
- **Selection of a set of appropriate accelerograms.**
- **Computation of the soil profile response. The stress histories are transformed into numbers of equivalent uniform cycles.**
- **Comparison of the cyclic strength characteristic with the computed equivalent cycles.**

Liquefaction

Liquefaction potential, conventional approach

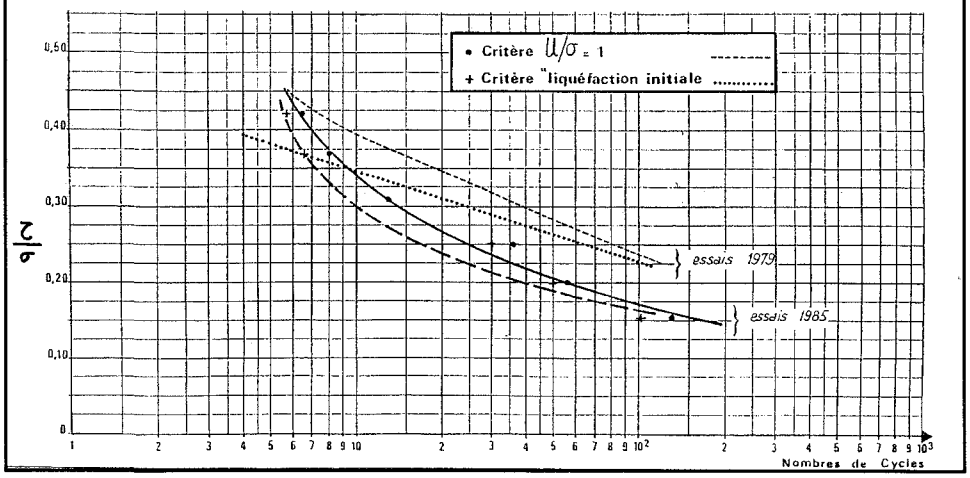


Representative Relationship Between CSR and Number of Cycles To Cause Liquefaction and (After Seed and Idriss, 1982)

Magnitude, M (1)	Seed and Idriss (1982) (2)	Idriss 1990 (3)	Ambraseys (1988) (4)
5.5	1.43	2.20	2.86
6.0	1.32	1.76	2.20
6.5	1.19	1.44	1.69
7.0	1.08	1.19	1.30
7.5	1.00	1.00	1.00
8.0	0.94	0.84	0.67
8.5	0.89	0.72	0.44

Liquefaction

Liquefaction potential, conventional approach Example on a site



Liquefaction

Liquefaction potential, sophisticated approach

In sophisticated analytical approaches a constitutive model of soil is incorporated in the non-linear step –by step analysis to evaluate directly the buildup of pore pressure and the dynamic ground response.

In this sophisticated analysis, the liquefaction potential can be directly assessed according to chosen seismic input motions in terms of the buildup of pressure or the development of strain.

However, the results may be quite variable owing to different input motions, constitutive models and other parameters, and the final assessment should be made in consideration of the extent of variability.

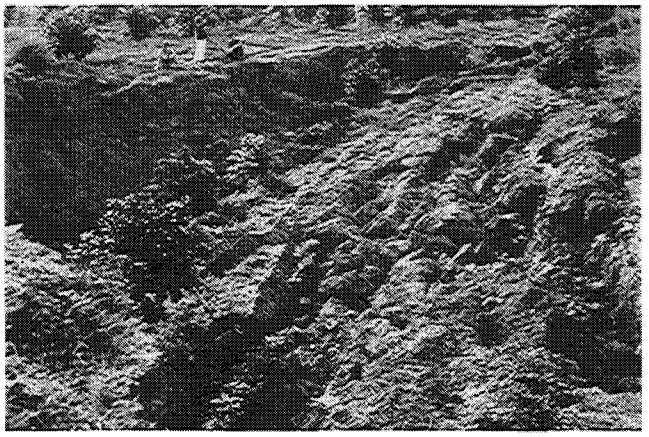
Landslides

Landslides

Loma Prieta, California, USA, 1989

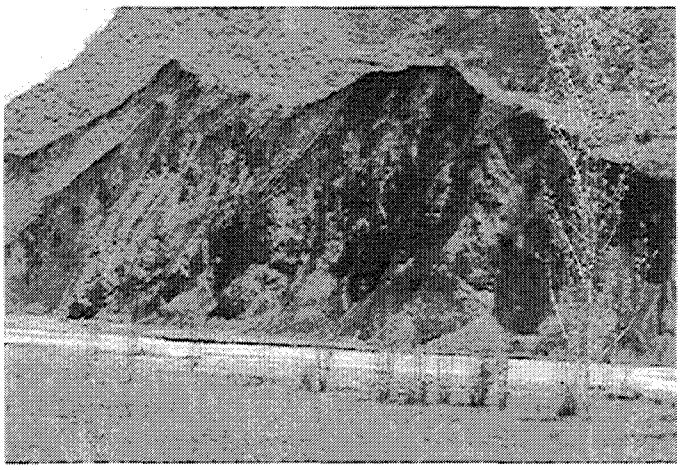
Landslides

Ceyhan-Misis, Turkey, 1998



Landslides

Bingol, Turkey, 2003



Landslides

Nigata, Japan, 2004

Summary and recommendations

- In the settlement of clay soils under static loads, water plays a crucial role.
- Settlement under seismic input motion is seldom considered as it should be. A reasonable prediction of seismically induced settlements is possible.
- Liquefaction of sand under seismic input is a frequent phenomenon that should be considered with care. Its assessment is still a matter of expertise.
- In settlement and liquefaction assessment, the magnitude of the ground motion plays a prominent role, however the duration effect is not negligible.
- Large uncertainties should be considered in assessments of settlement and liquefaction.