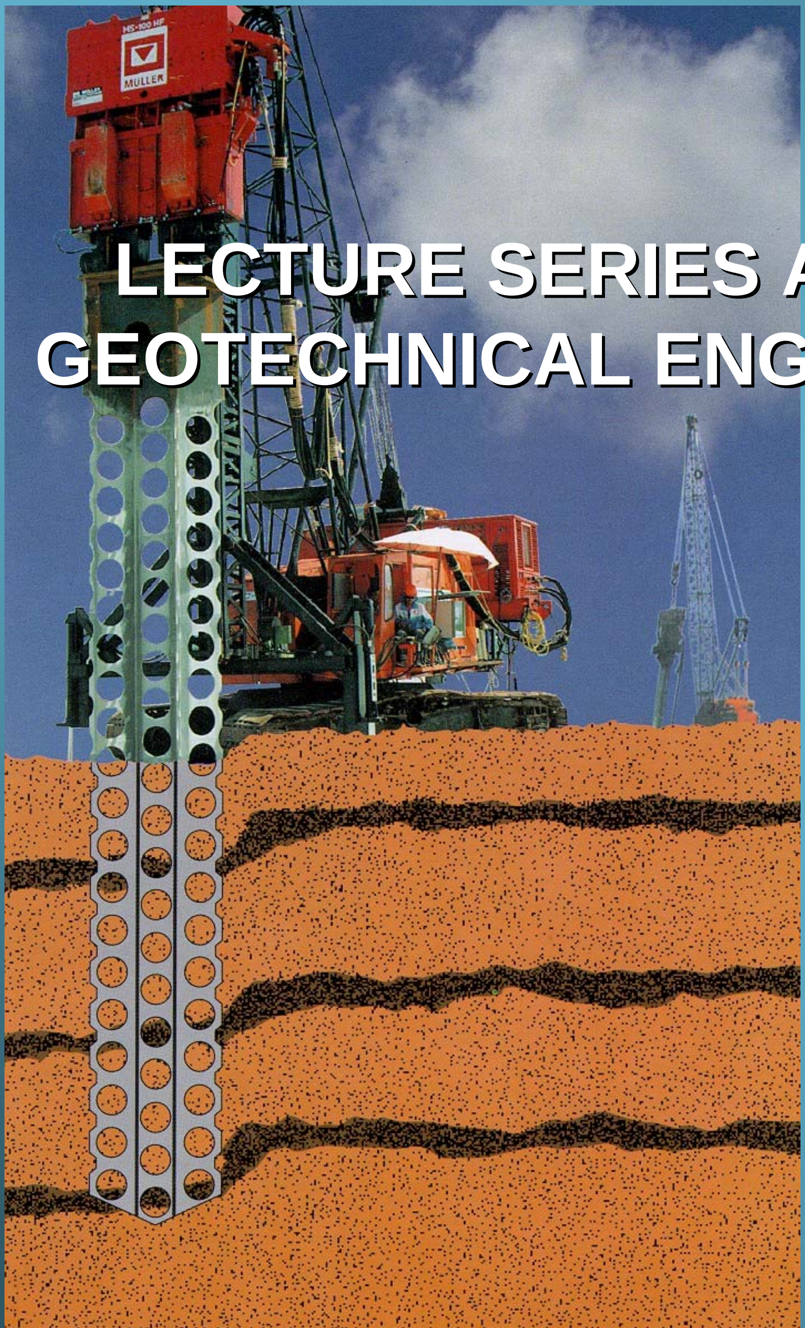


LECTURE SERIES AND WORKSHOPS ON GEOTECHNICAL ENGINEERING IN PRACTICE

Deep Vibratory Compaction

K. Rainer Massarsch

Geo Engineering AB

Sweden

Overview of Presentation

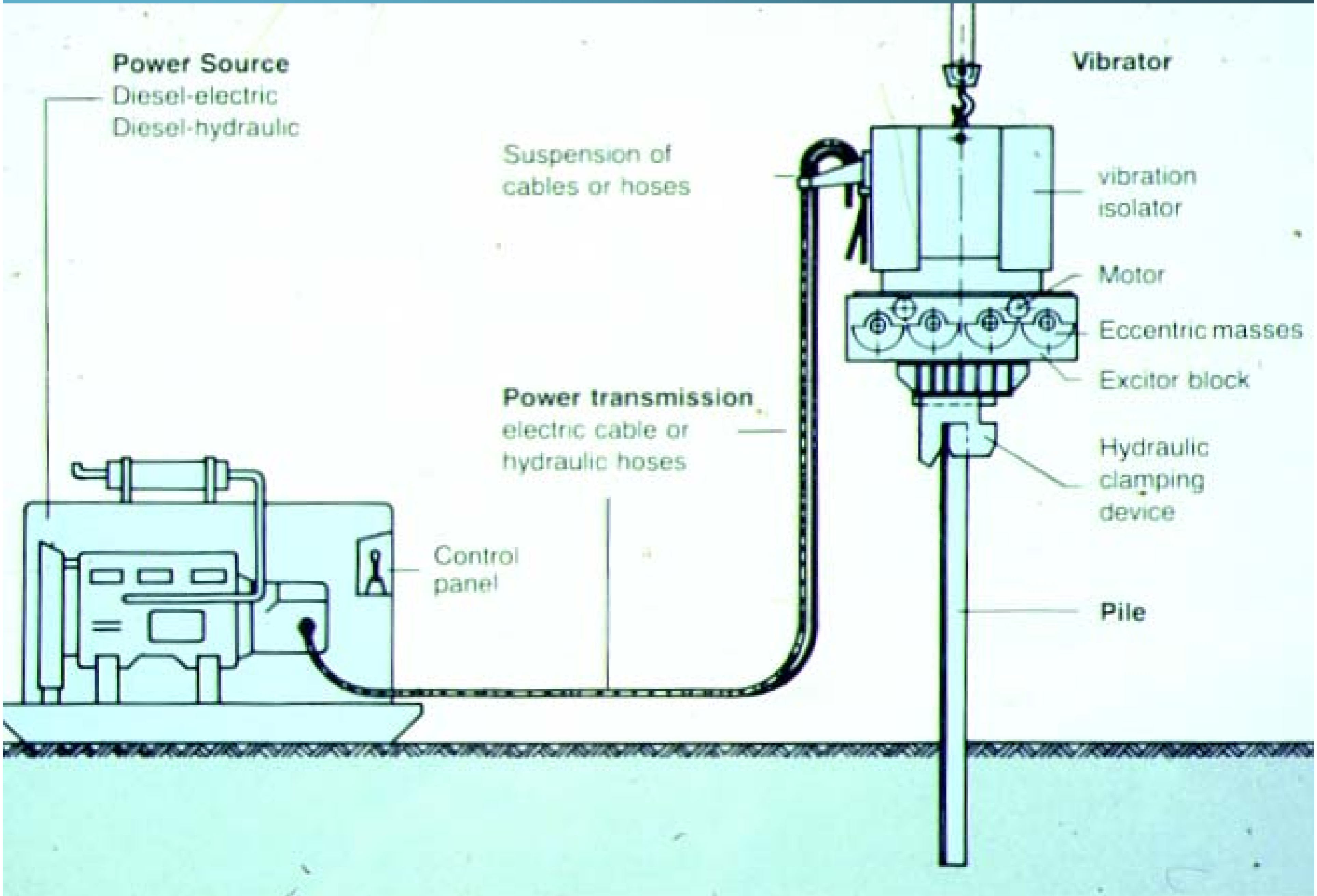
- **Vibratory compaction methods**
- **Case history – Hong Kong**
- **Aspects of Vibratory Compaction**
  - Importance of vibration frequency
  - Probe-soil interaction
  - Horizontal stresses
  - Overconsolidation effect
  - Change of in-situ stresses
- Process Design
- Performance Design
  - Settlements
  - Soil Stiffness
  - Liquefaction
- Conclusions

Tubes and Nails

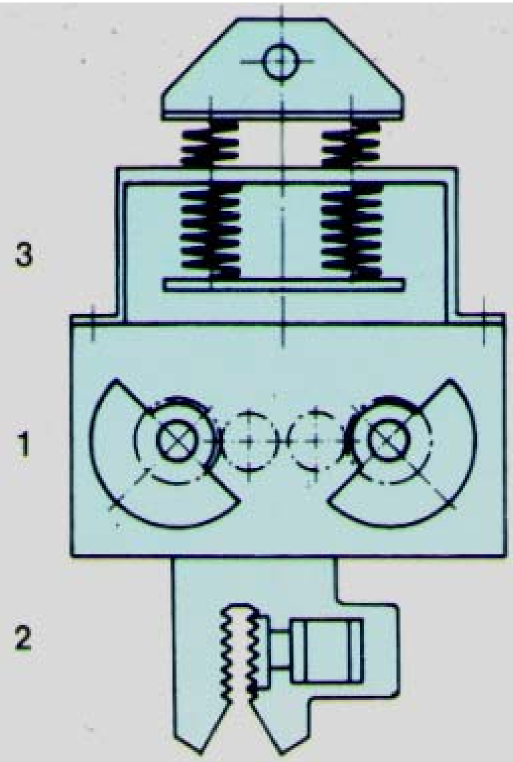
Vibro Wing


KIN SUN

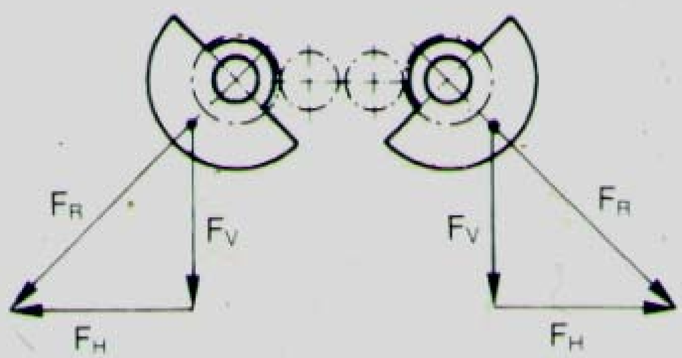

MESSMANN
LIEBHERR



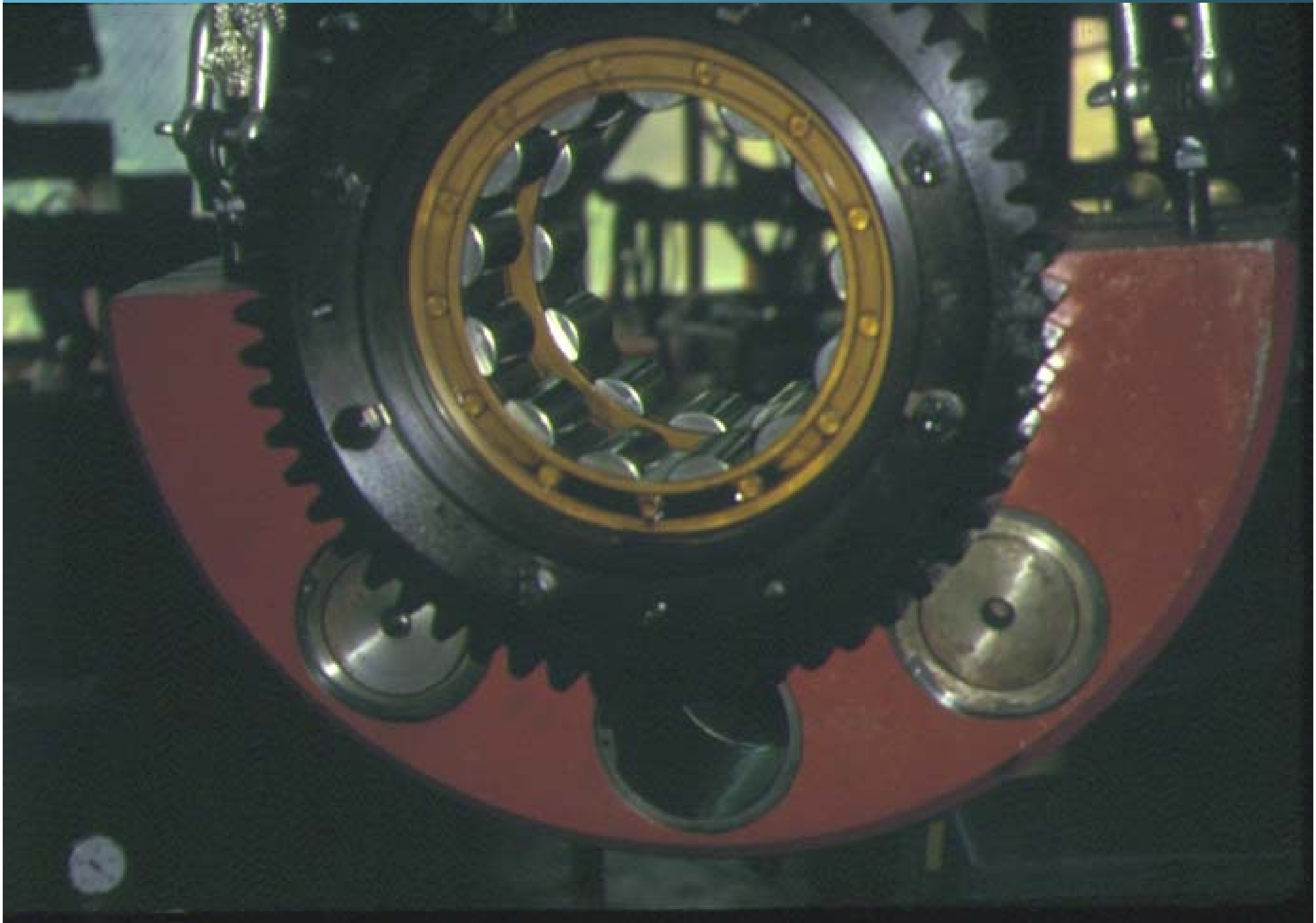
Power Source
Diesel-electric
Diesel-hydraulic
Suspension of
cables or hoses
Vibrator
vibration
isolator
Motor
Eccentric masses
Excitor block
Power transmission
electric cable or
hydraulic hoses
Hydraulic
clamping
device
Control
panel
Pile

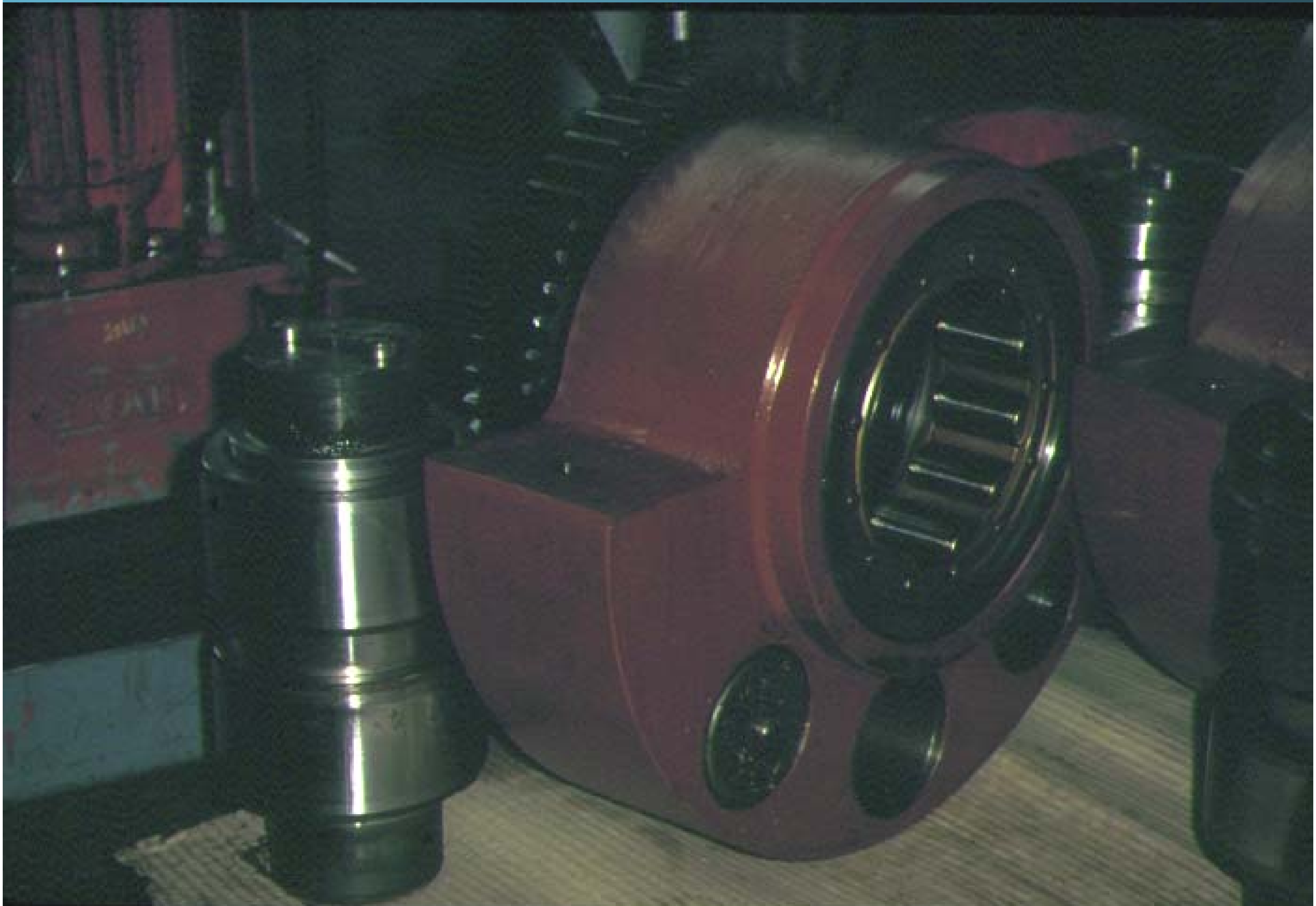


$F_{v\,max.} = M \cdot \omega^2$ M [kgm] ω per sec



Sum of all horizontal centrifugal forces $F_H = 0$






MS-32 HF
MULLER

Resonance Compaction

Vibrator type: Variable frequency

Frequency range: 0 – 33 Hz

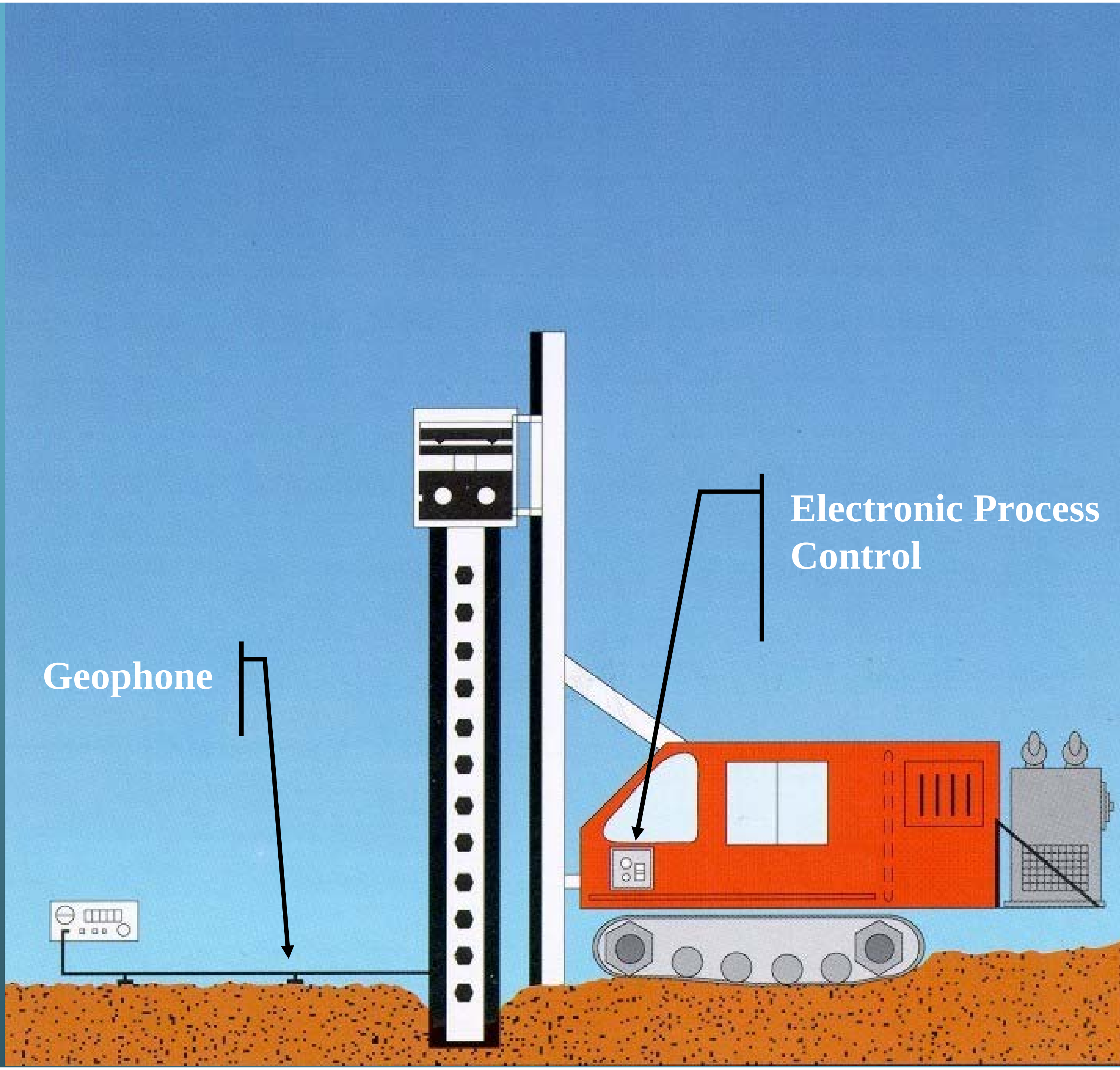
Centrifugal force: max 2 500 kN

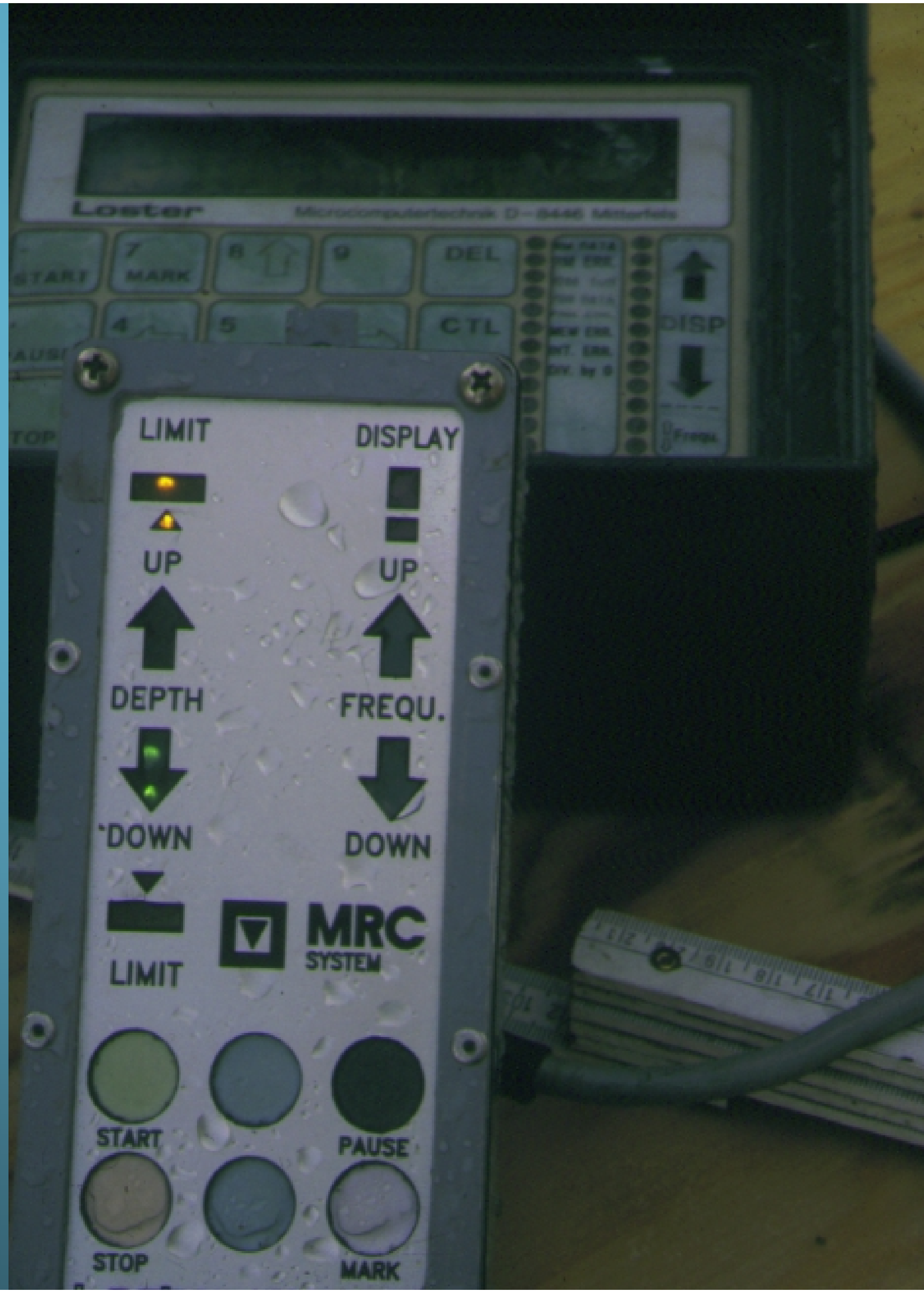
Static moment (torque): 100 kgm

Vibration amplitude: 26 mm

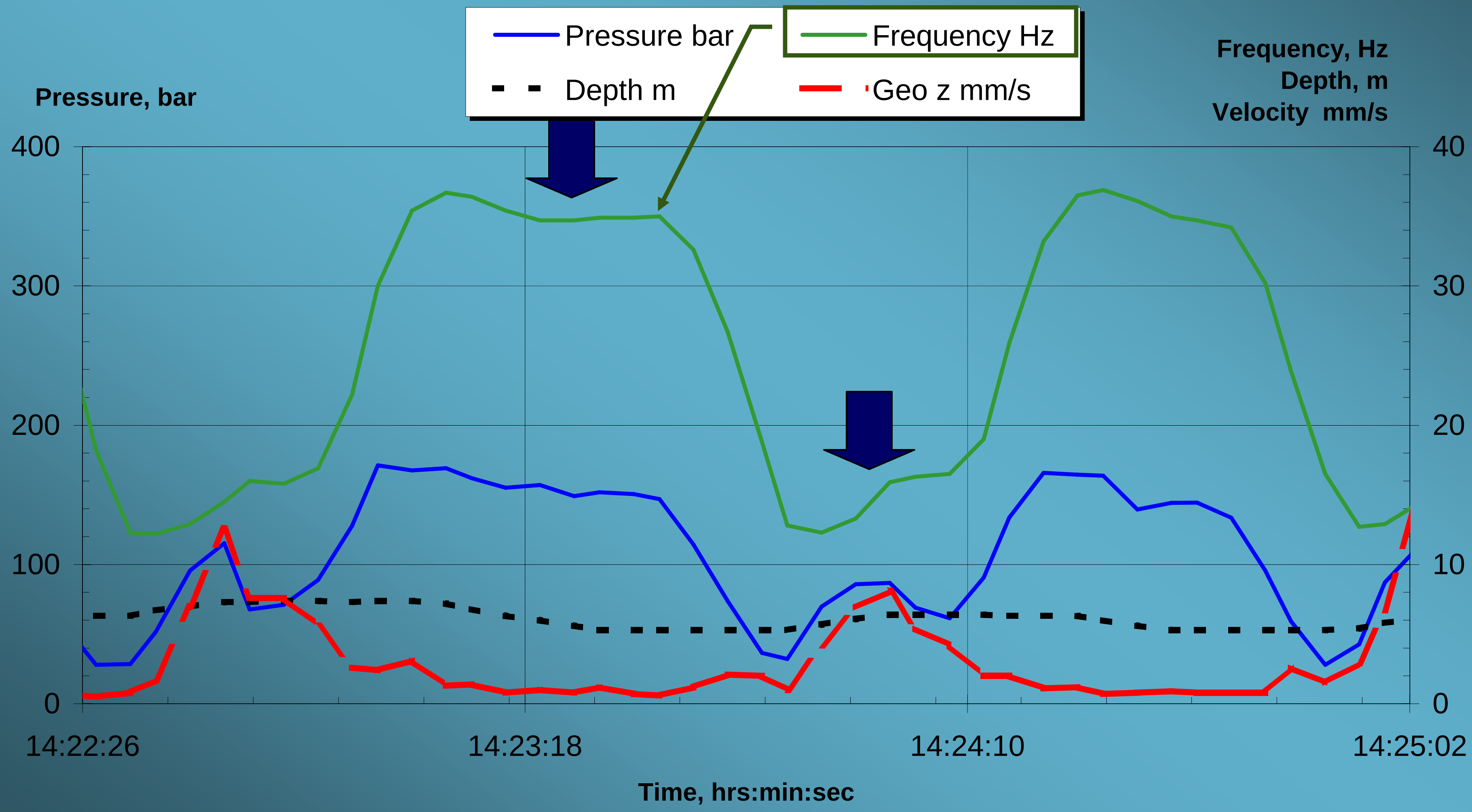
Flexible compaction probe

Electronic process control

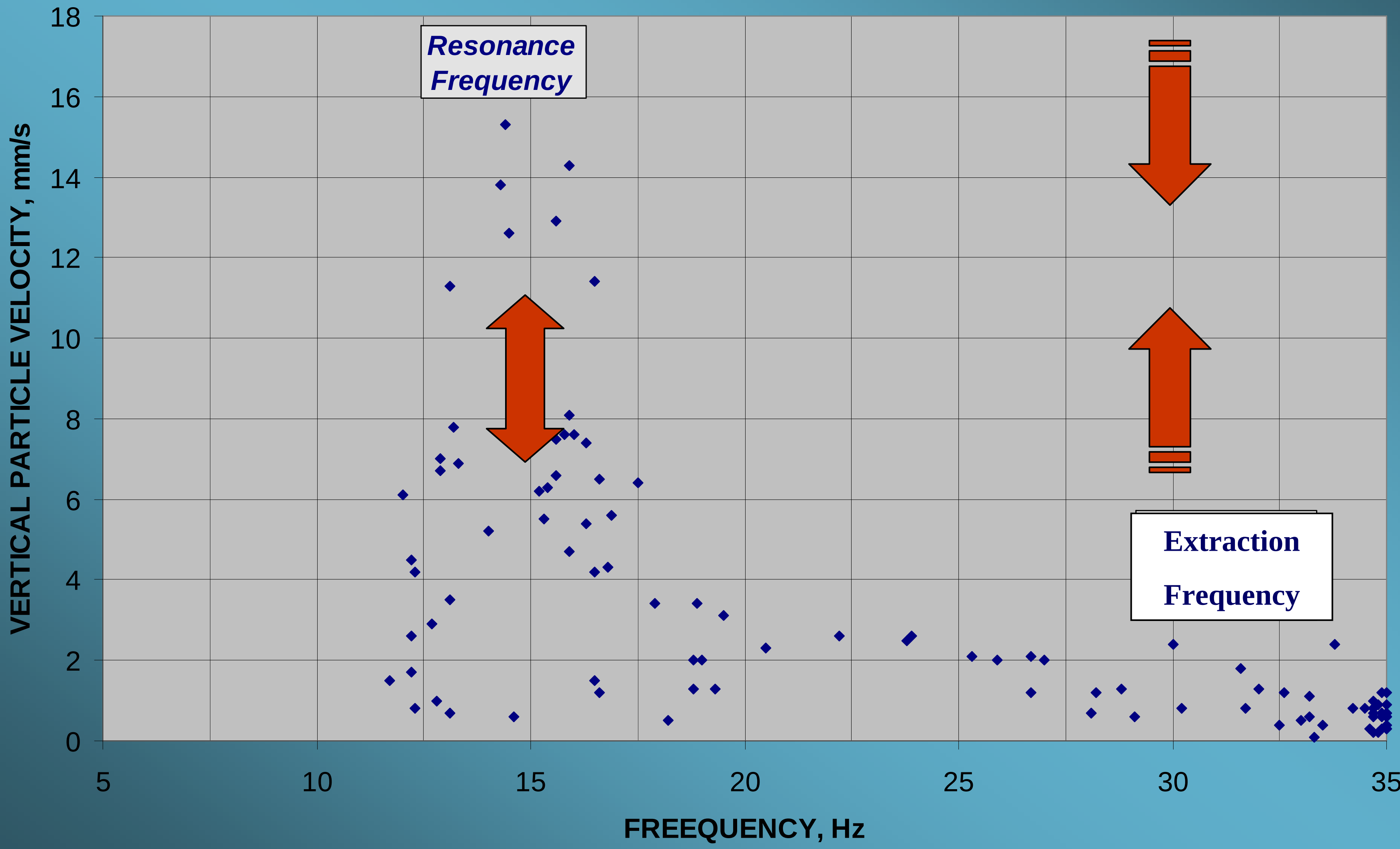

Electronic Process
Control
Geophone

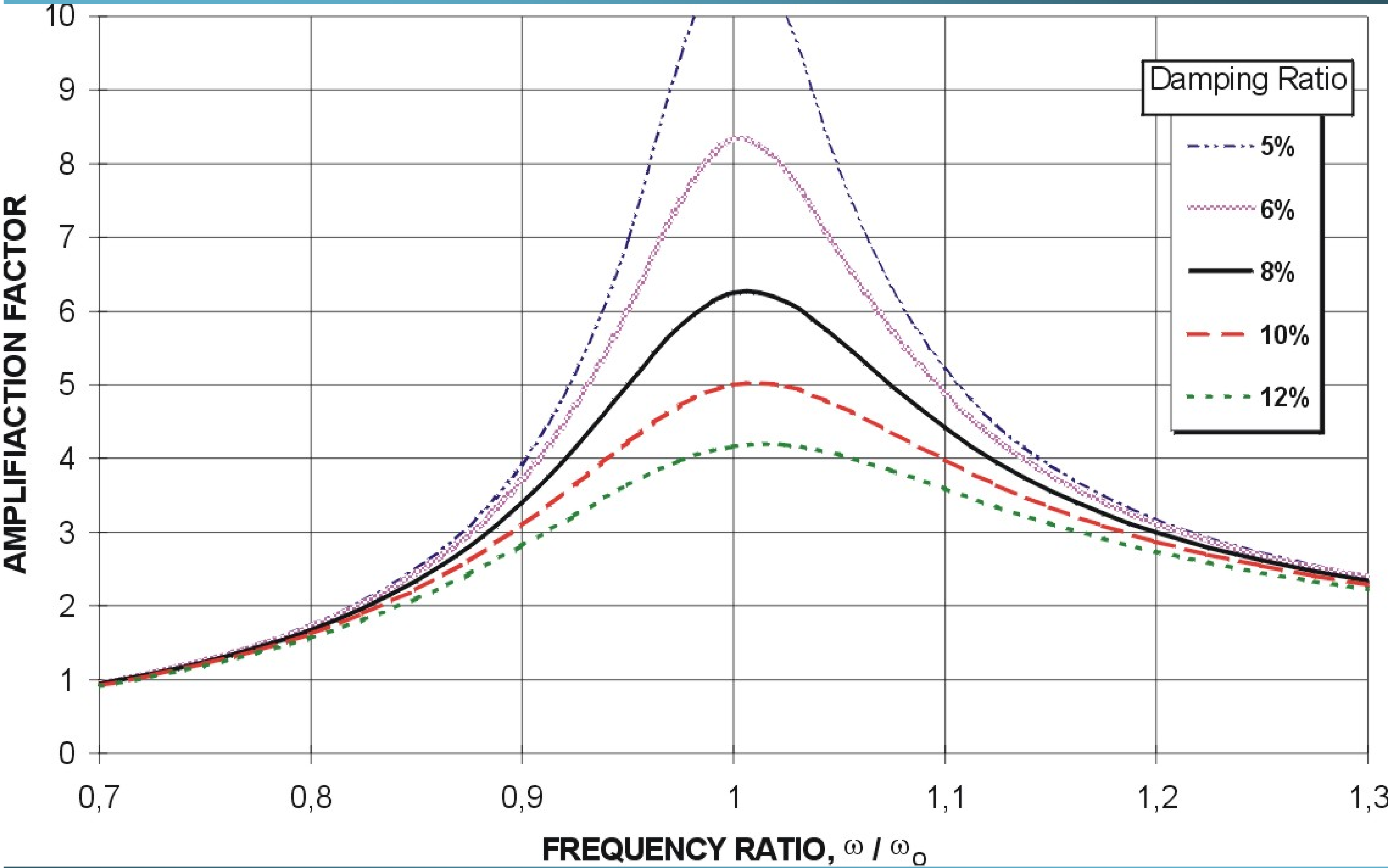

Loster
LIMIT
DISPLAY
UP
UP
DEPTH
FREQU.
DOWN
DOWN
LIMIT
MRC
SYSTEM
START
PAUSE
STOP
MARK
DEL
CTL
DISP

Example of Compaction Monitoring



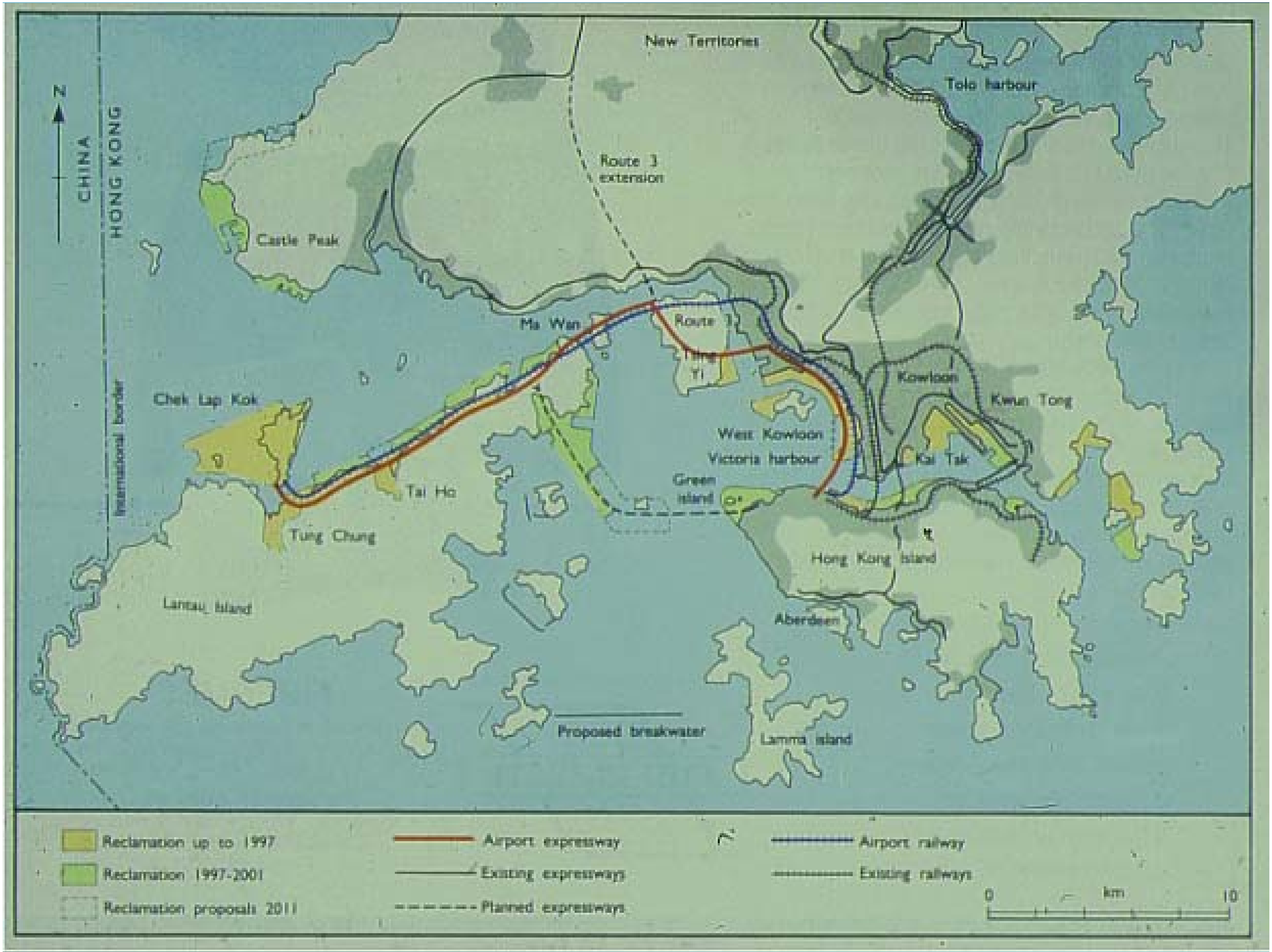
Effect of Vibrator Frequency on Ground Response



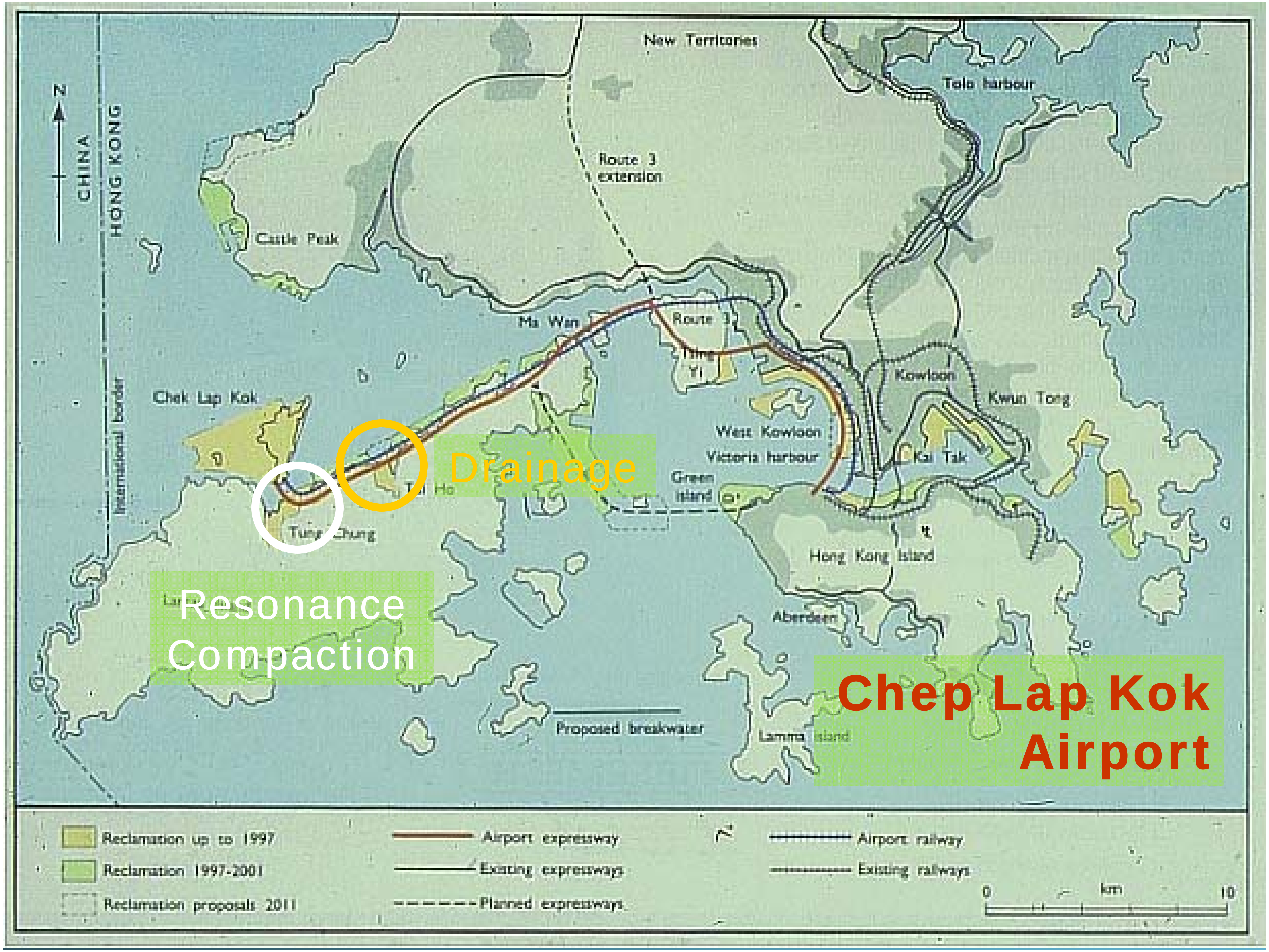


Damping Ratio
5%
6%
8%
10%
12%
AMPLIFIACTION FACTOR
FREQUENCY RATIO, ω / ωo
0
1
2
3
4
5
6
7
8
9
10
0,7
0,8
0,9
1
1,1
1,2
1,3

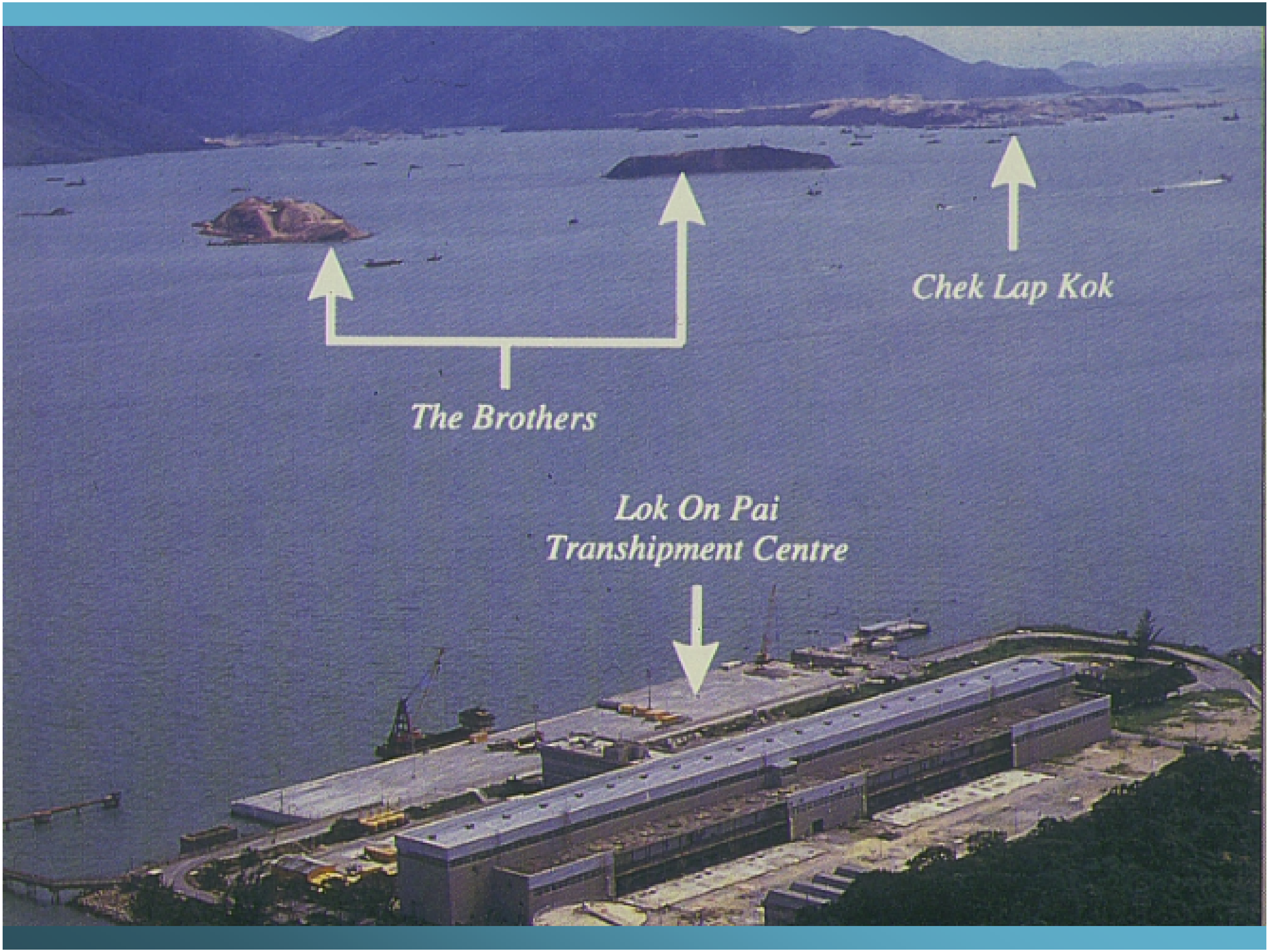

DEEP BAY
NEW TERRITORIES
KOWLOON
Tai Po
TOLO HARBOUR
PORT SHELTER
VICTORIA HARBOUR

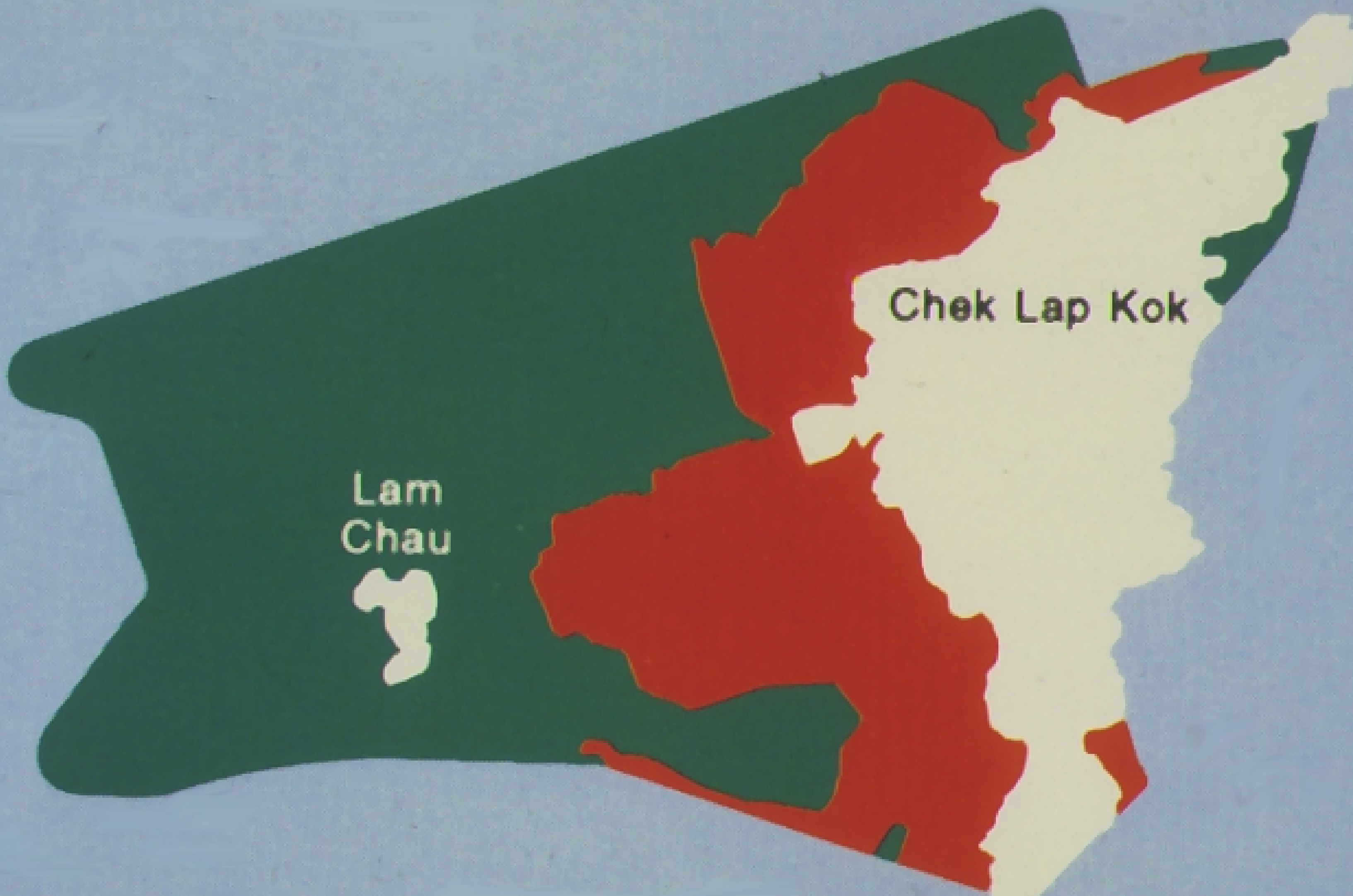


New Territories
Tolo harbour
CHINA
HONG KONG
N
Route 3 extension
Castle Peak
Ma Wan
Route 3
Tsing Yi
Kowloon
Kwun Tong
Chek Lap Kok
International border
West Kowloon
Victoria harbour
Kai Tak
Green island
Tai Ho
Tung Chung
Hong Kong Island
Lantau Island
Aberdeen
Proposed breakwater
Lamma island
Reclamation up to 1997
Reclamation 1997-2001
Reclamation proposals 2011
Airport expressway
Existing expressways
Planned expressways
Airport railway
Existing railways
0
km
10



New Territories
Tolo harbour
CHINA
HONG KONG
N
Route 3 extension
Castle Peak
Ma Wan
Route 3
Tsing Yi
Kowloon
Kwun Tong
Chek Lap Kok
West Kowloon
Victoria harbour
Kai Tak
Green island
Drainage
Tai Ho
Tung Chung
Hong Kong Island
International border
Resonance Compaction
Aberdeen
Chep Lap Kok Airport
Proposed breakwater
Lamma island
Reclamation up to 1997
Reclamation 1997-2001
Reclamation proposals 2011
Airport expressway
Existing expressways
Planned expressways
Airport railway
Existing railways
0
km
10


Chek Lap Kok
The Brothers
Lok On Pai
Transhipment Centre



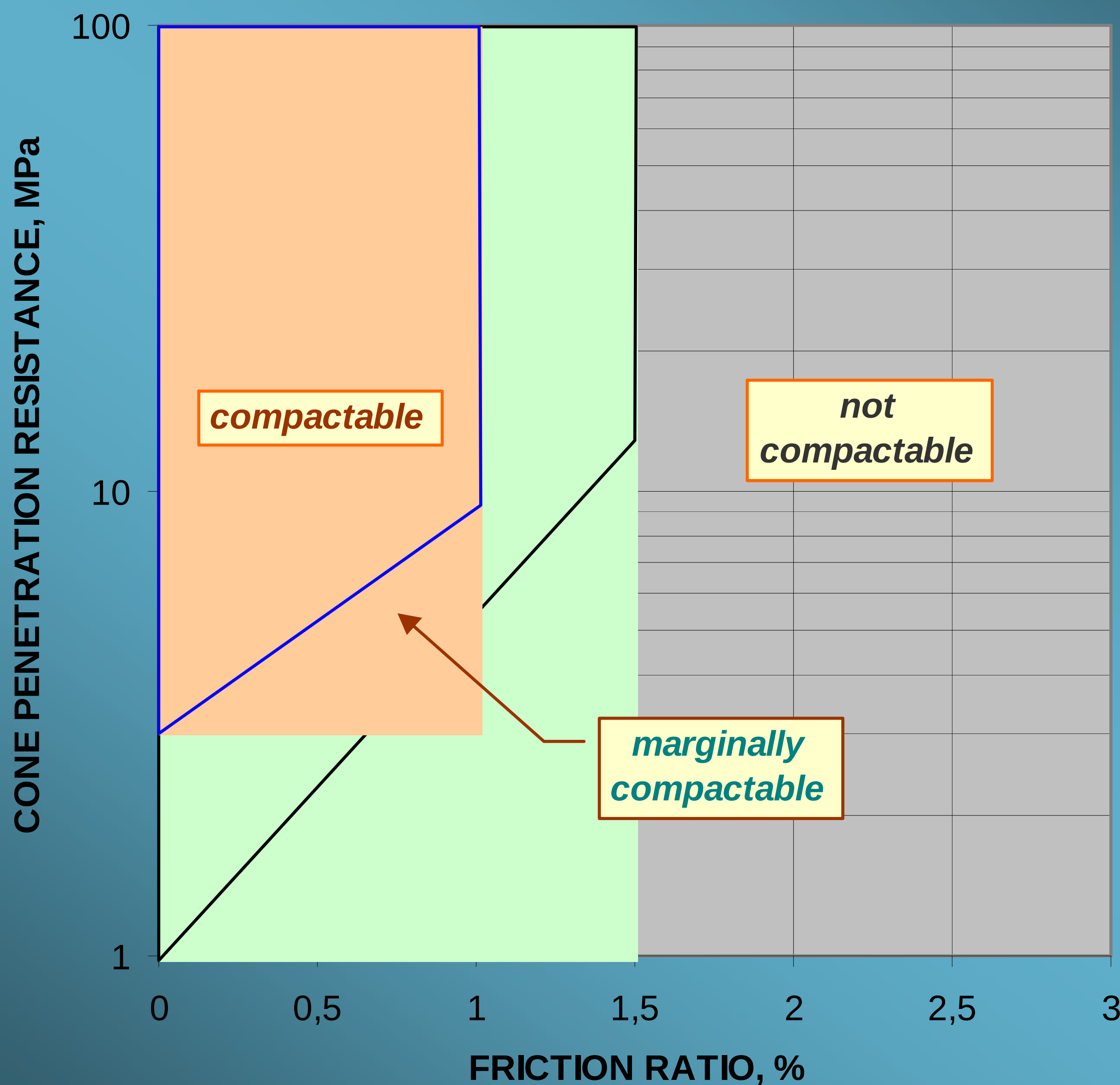
Reclamation at Chek Lap Kok in November 1993

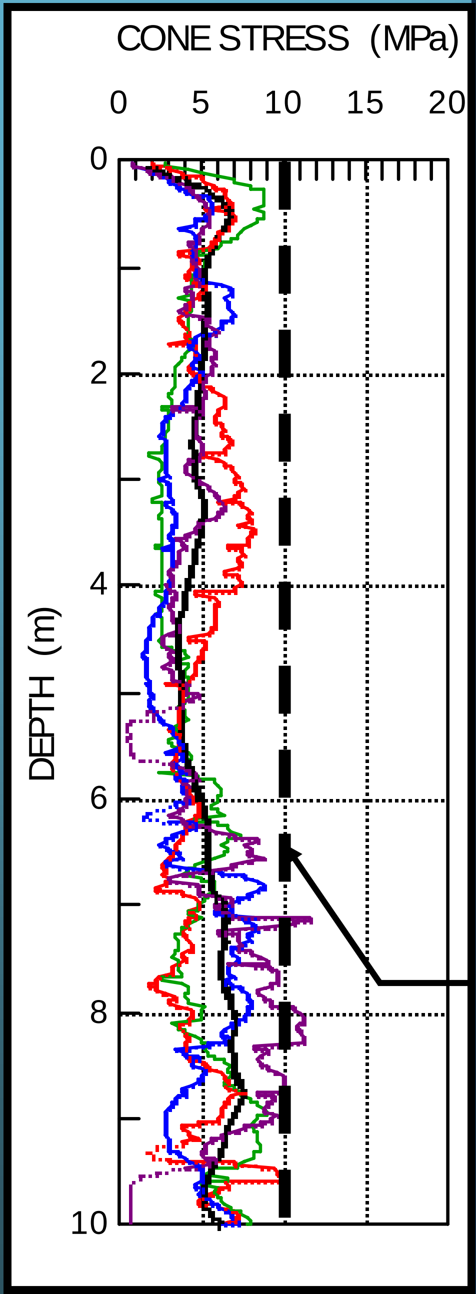
Vibratory Compaction - Yam O

- Hydraulic fill (5 - 15 m thickness)
- Foundation for railway station
- Monitoring of compaction with CPT (electric CPTU with cone, sleeve friction and pore pressure measurements)
- Compaction requirement: 10 MPa (CPT)
- Deep vibratory compaction by MRC method


KATO

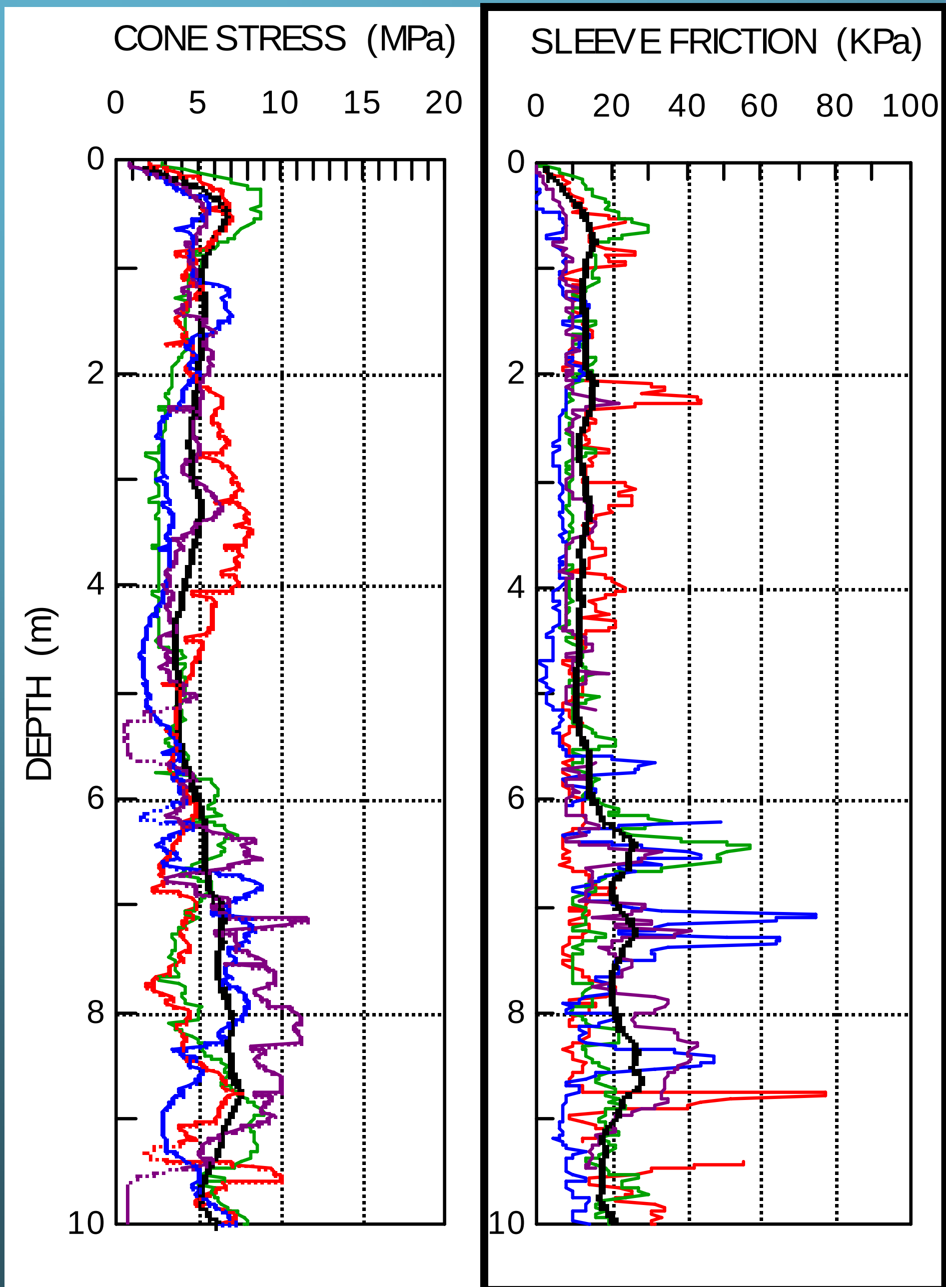
Compactibility of Soils base on CPT





Cone resistance before compaction

Compaction requirement 10 MPa



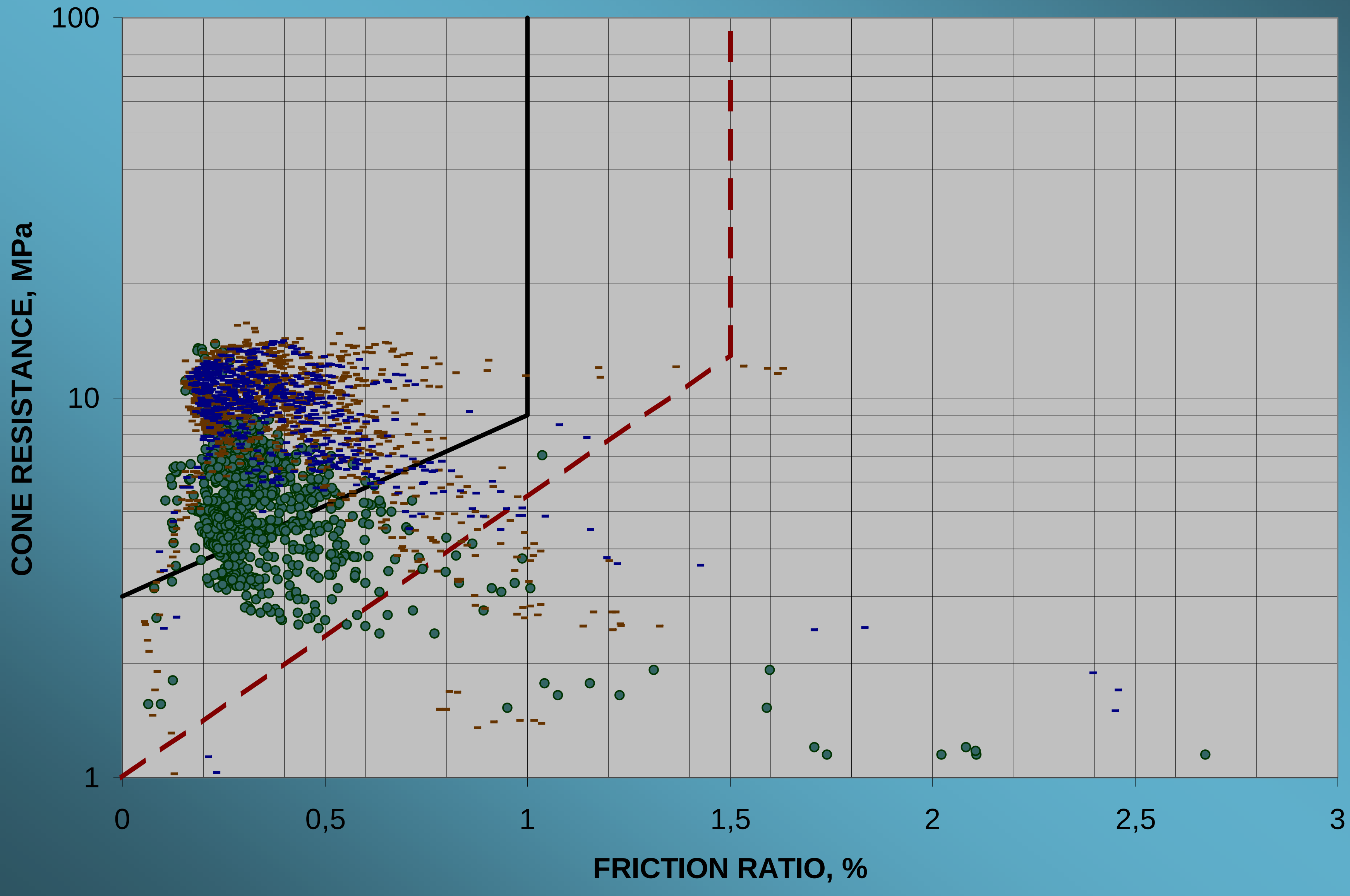
Sleeve resistance before compaction

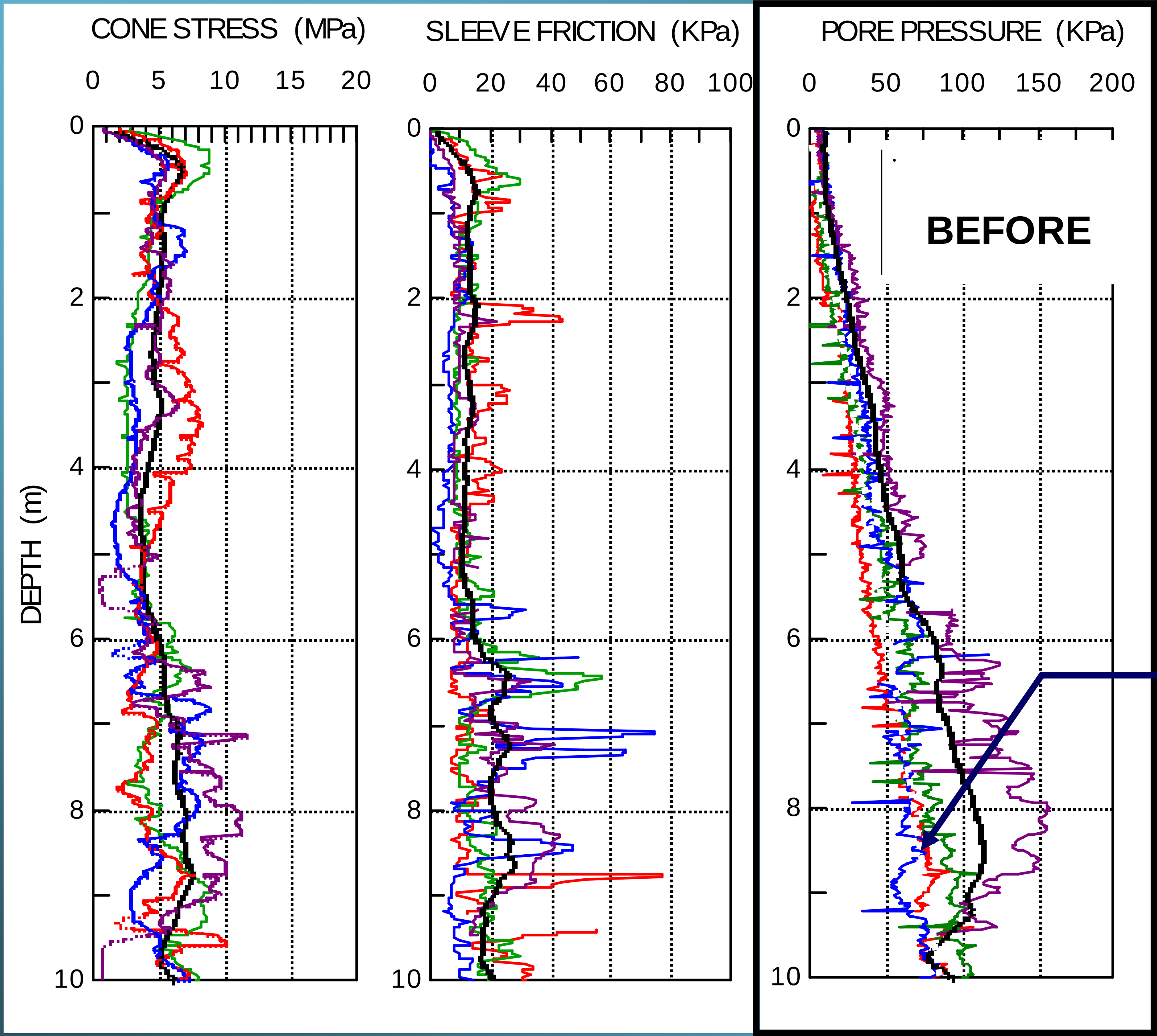
Sleeve Friction

Friction Ratio:

$$F_R = f_s \ / \ q_c \ (\%)$$

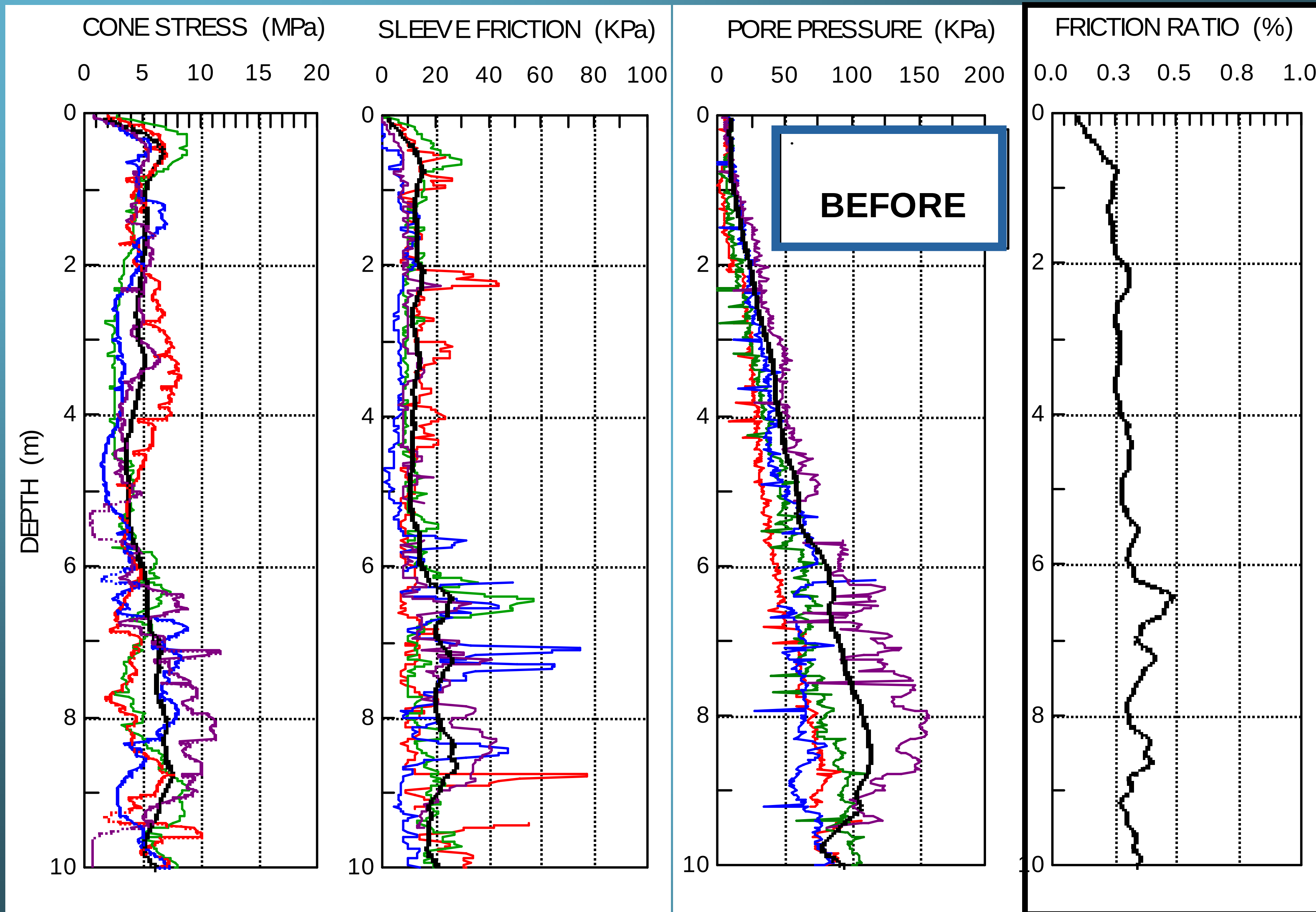
Compaction Efficiency

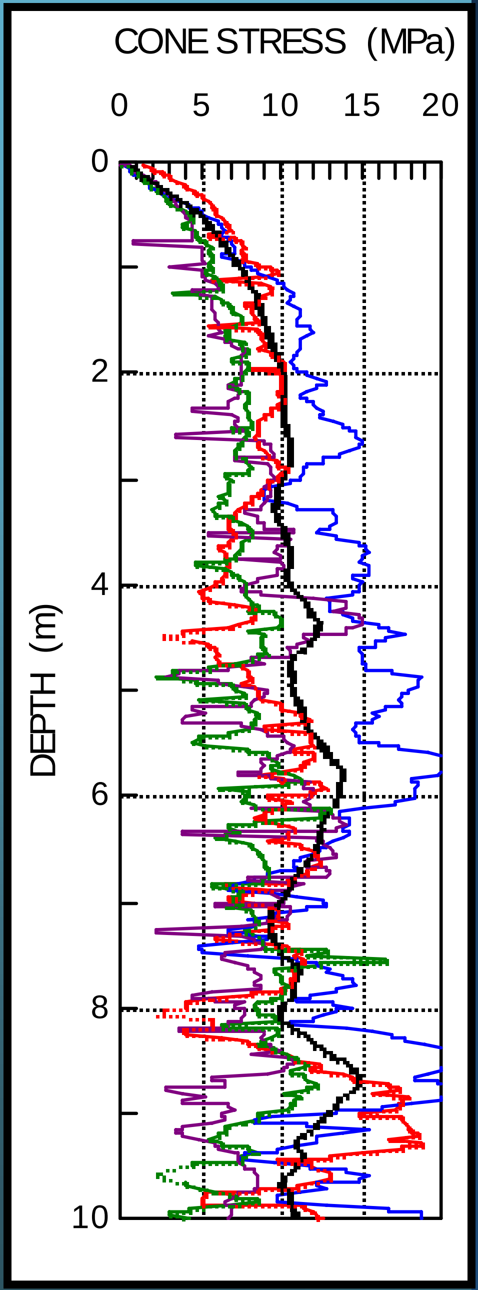




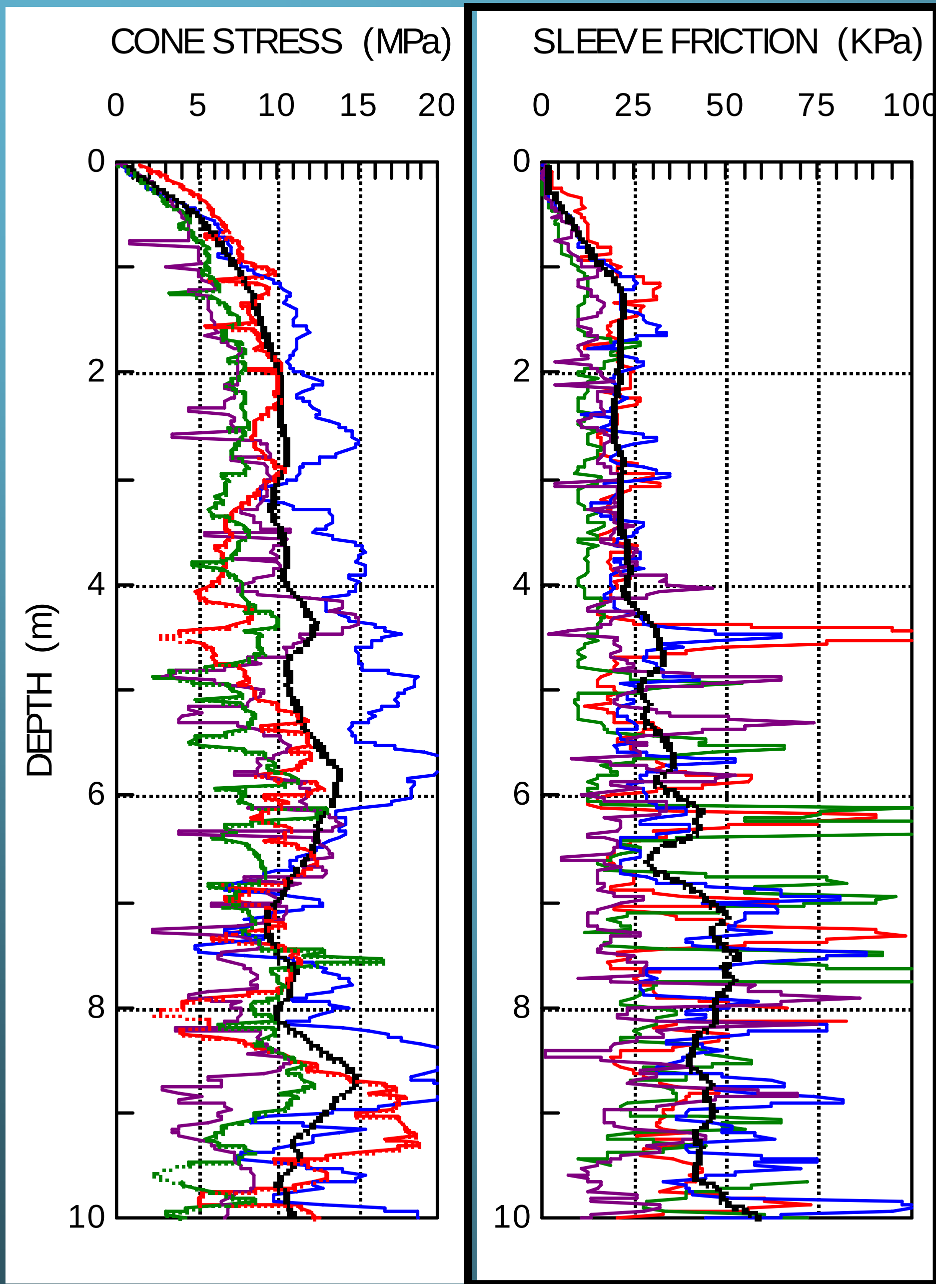
Pore pressure before compaction

Hydrostatic

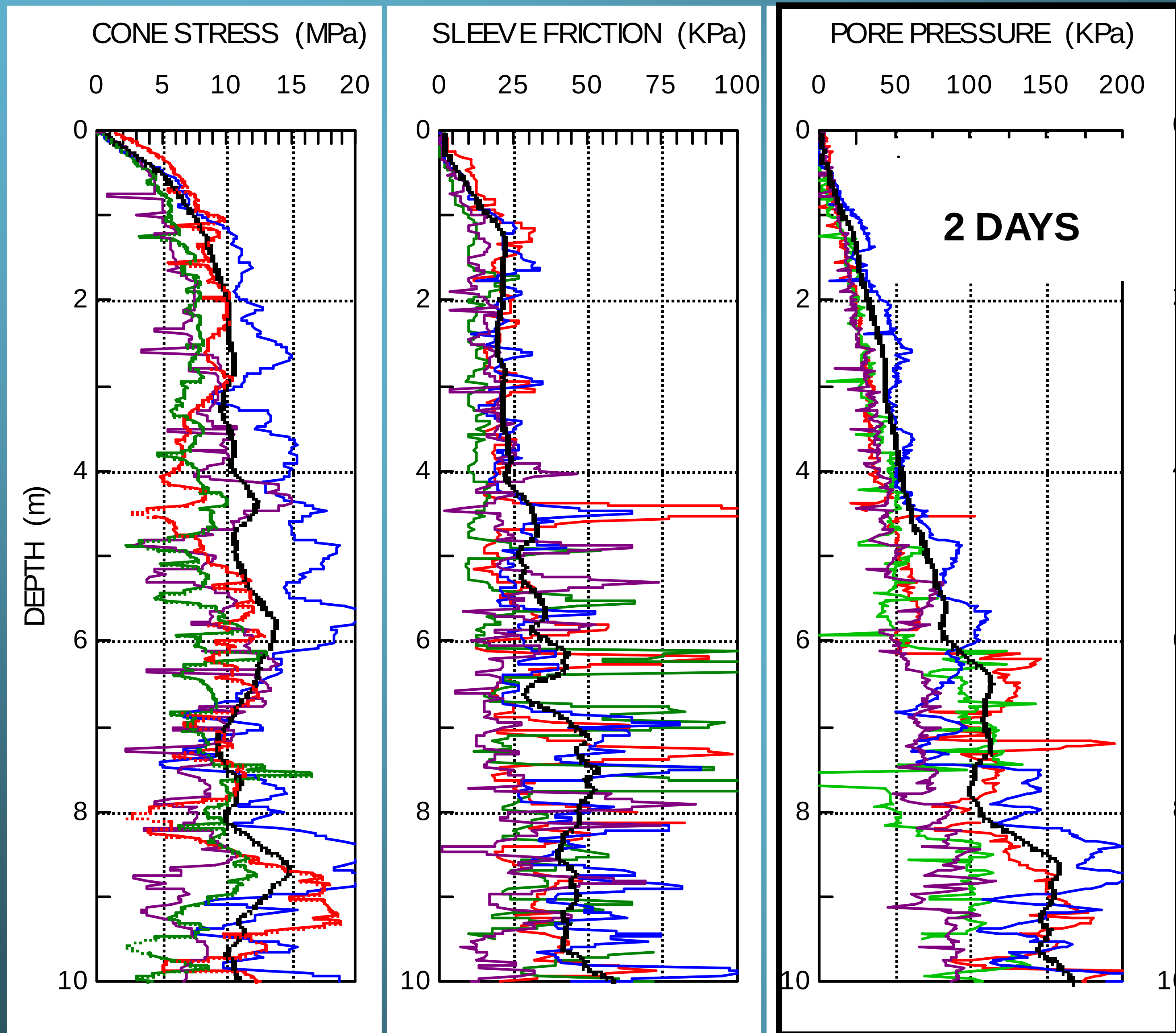

CONE STRESS (MPa)
0 5 10 15 20
SLEEVE FRICTION (KPa)
0 20 40 60 80 100
PORE PRESSURE (KPa)
0 50 100 150 200
FRICTION RATIO (%)
0.0 0.3 0.5 0.8 1.0
DEPTH (m)
0 2 4 6 8 10
BEFORE

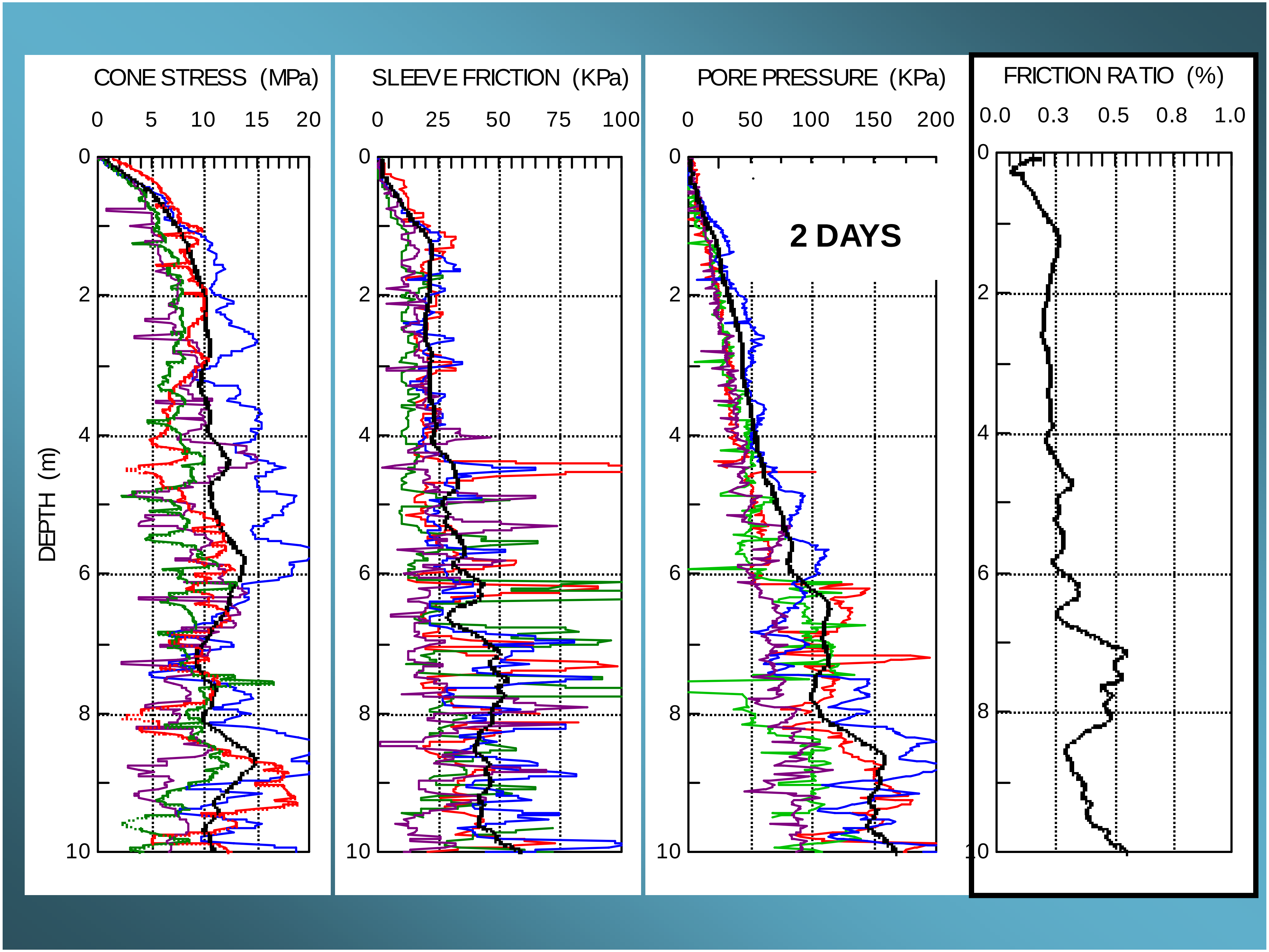


2 DAYS AFTER COMPACTION

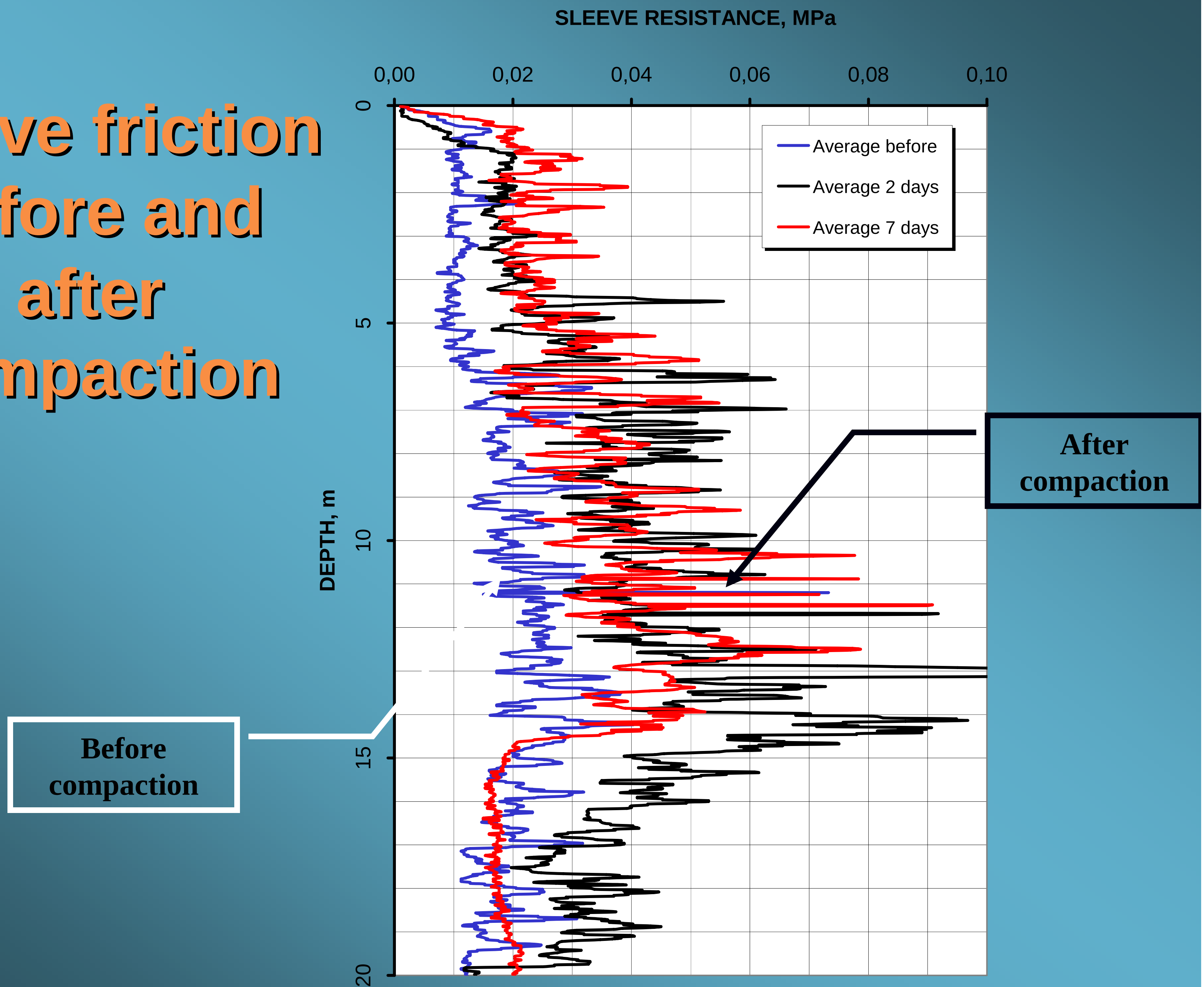


2 DAYS AFTER COMPACTION


CONE STRESS (MPa)
0 5 10 15 20
SLEEVE FRICTION (KPa)
0 25 50 75 100
PORE PRESSURE (KPa)
0 50 100 150 200
2 DAYS
DEPTH (m)
0 2 4 6 8 10


CONE STRESS (MPa)
0 5 10 15 20
SLEEVE FRICTION (KPa)
0 25 50 75 100
PORE PRESSURE (KPa)
0 50 100 150 200
FRICTION RATIO (%)
0.0 0.3 0.5 0.8 1.0
DEPTH (m)
0 2 4 6 8 10
2 DAYS

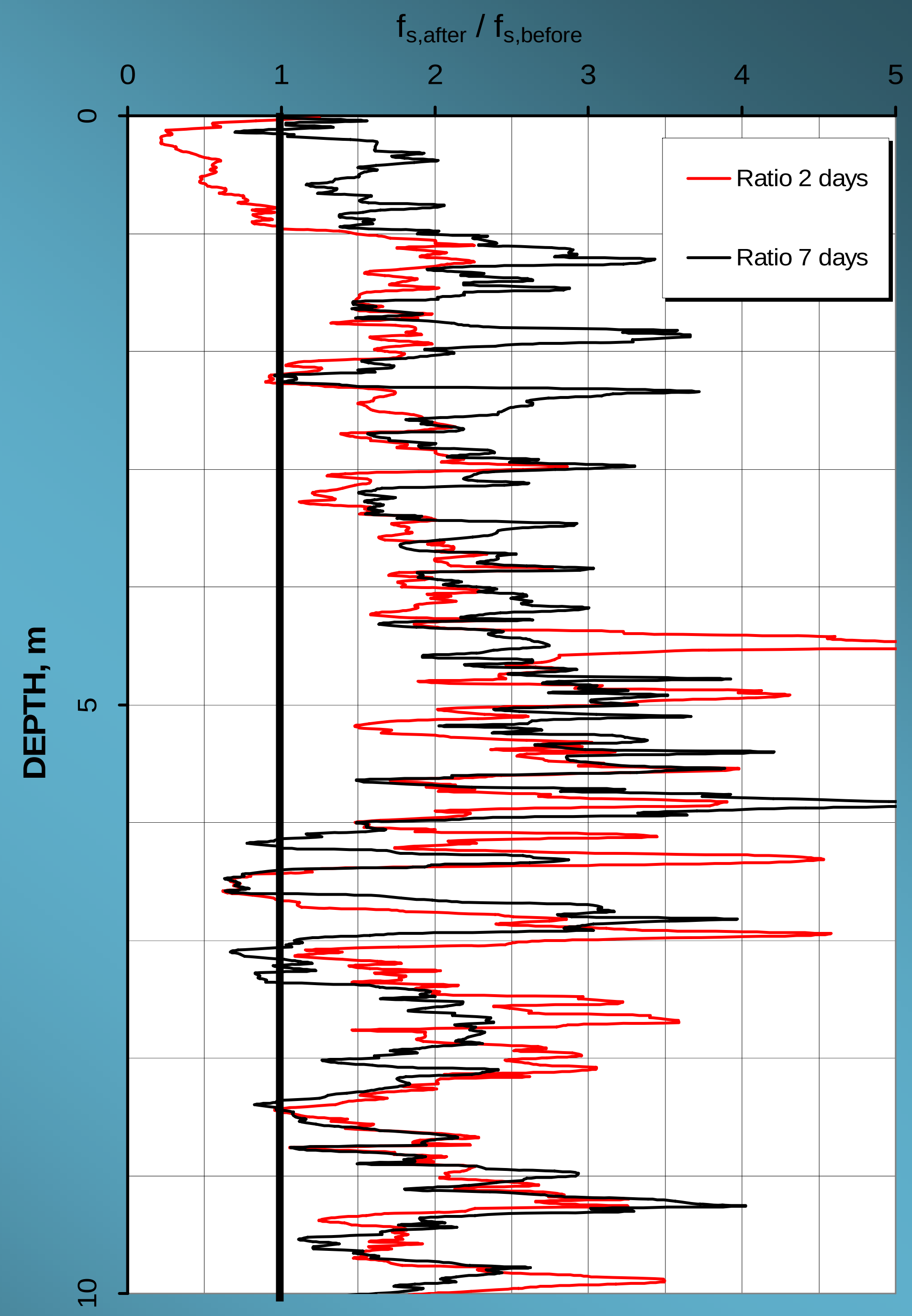
Sleeve friction before and after compaction

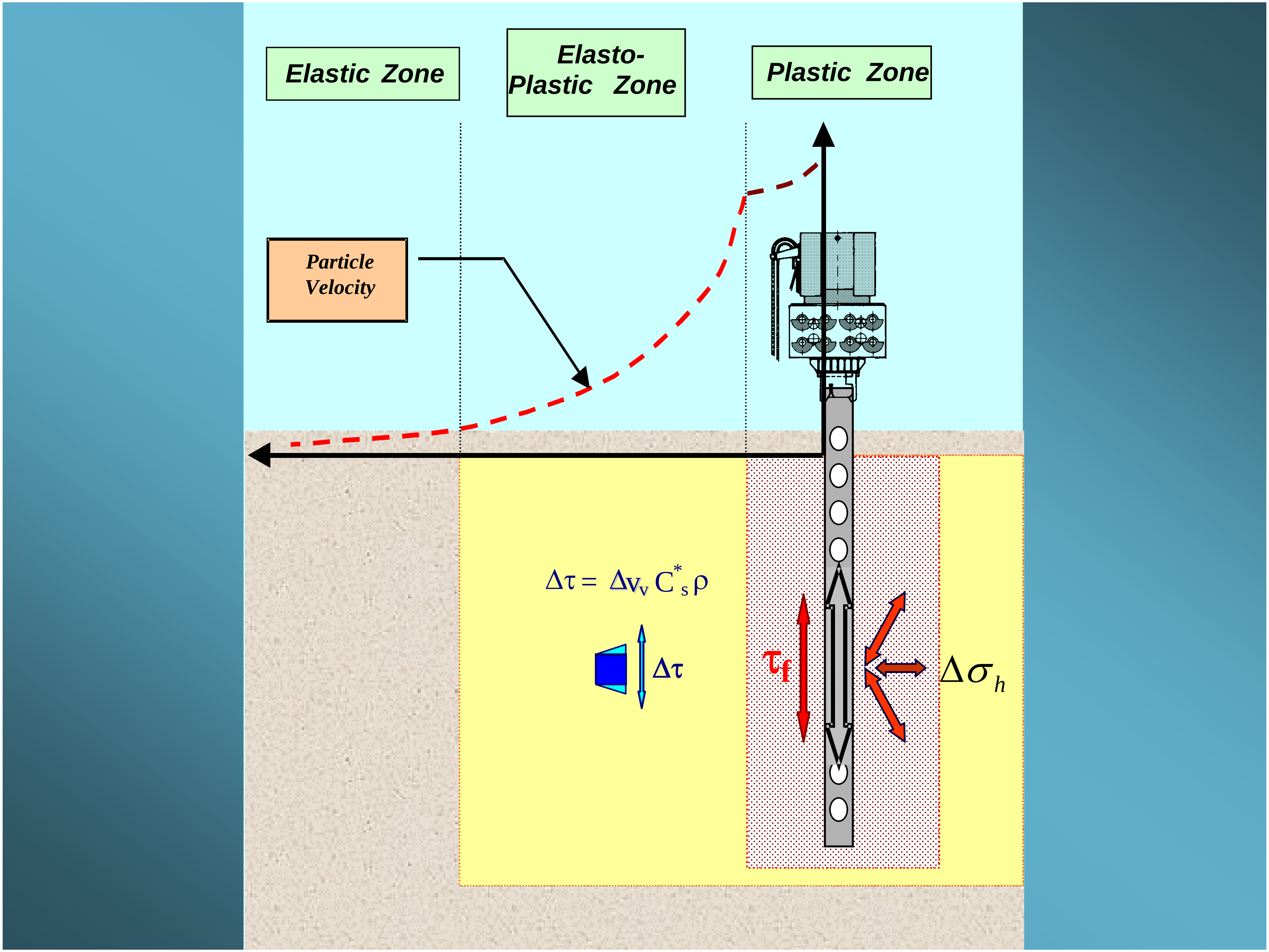


Sleeve friction ratio after vs. before compaction

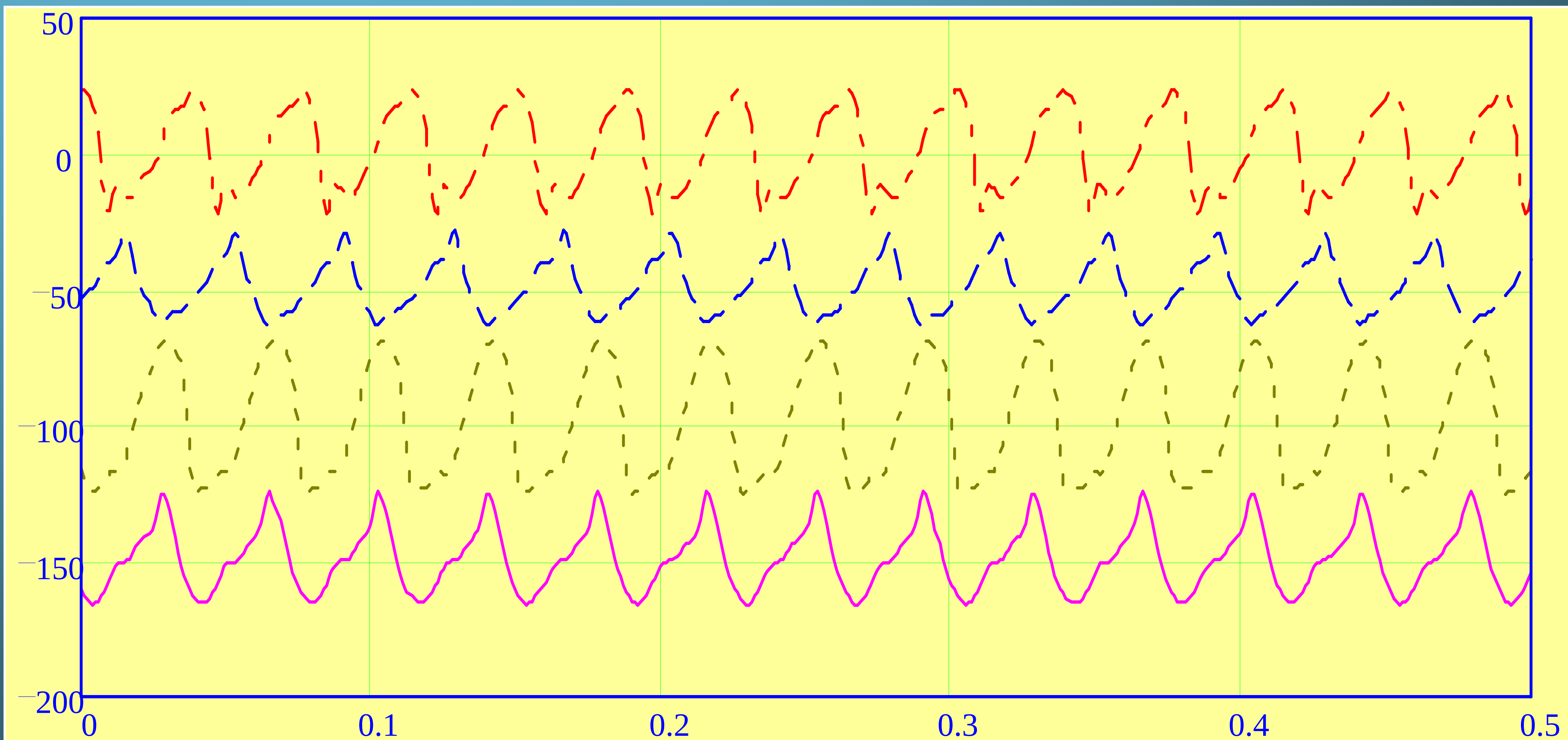
Estimation of increase in lateral earth pressure due to compaction

$$\frac{K_{01}}{K_{00}} = \frac{f_{s1}\ \tan\left(\phi'_{a0}\right)}{f_{s0}\ \tan\left(\phi'_{a1}\right)}$$




Elastic Zone
Elasto-Plastic Zone
Plastic Zone
Particle Velocity
$\Delta\tau = \Delta v_v C^*_s \rho$
$\Delta\tau$
τ_f
$\Delta\sigma_h$

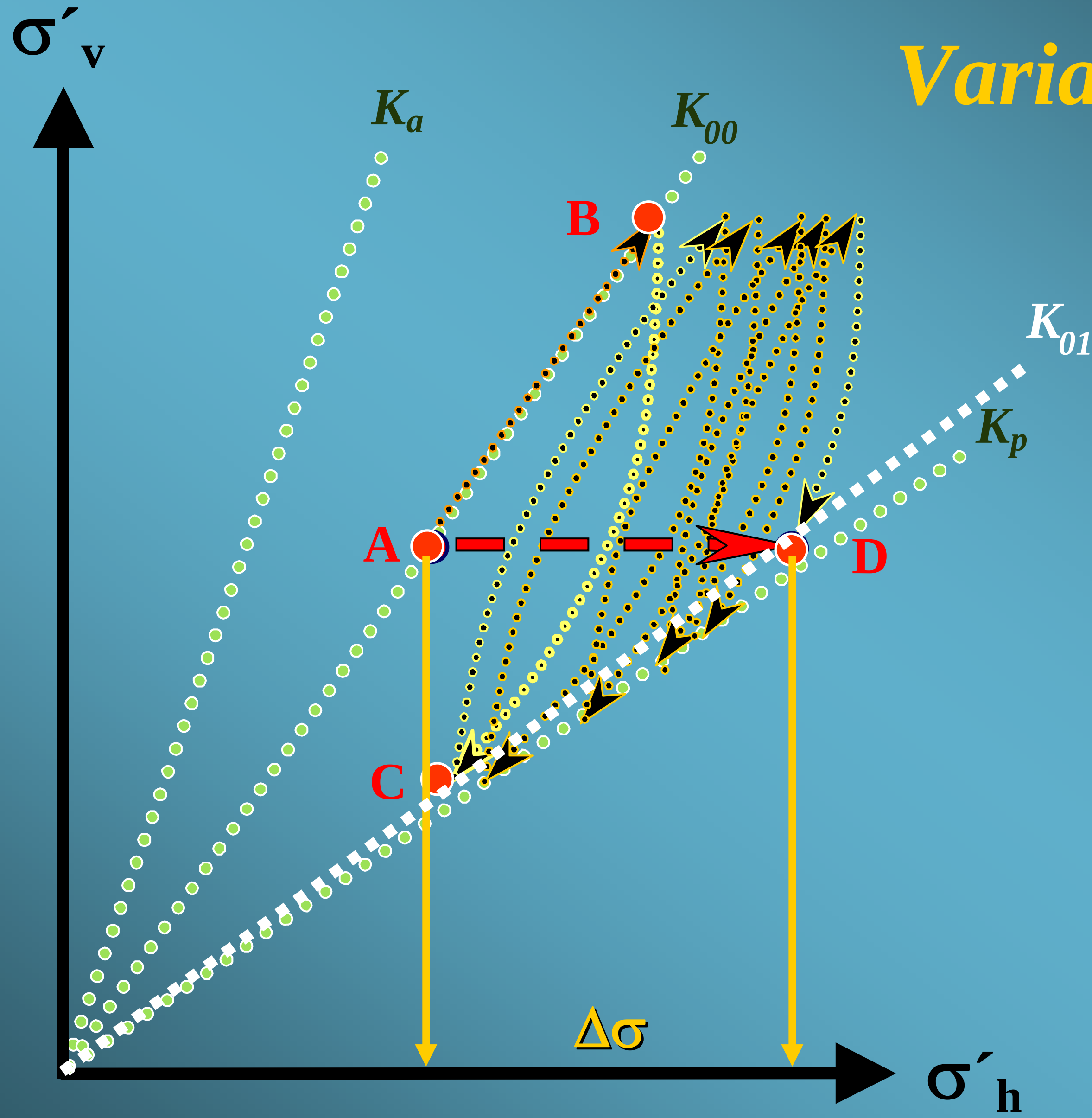
Measurement of horizontal ground vibration

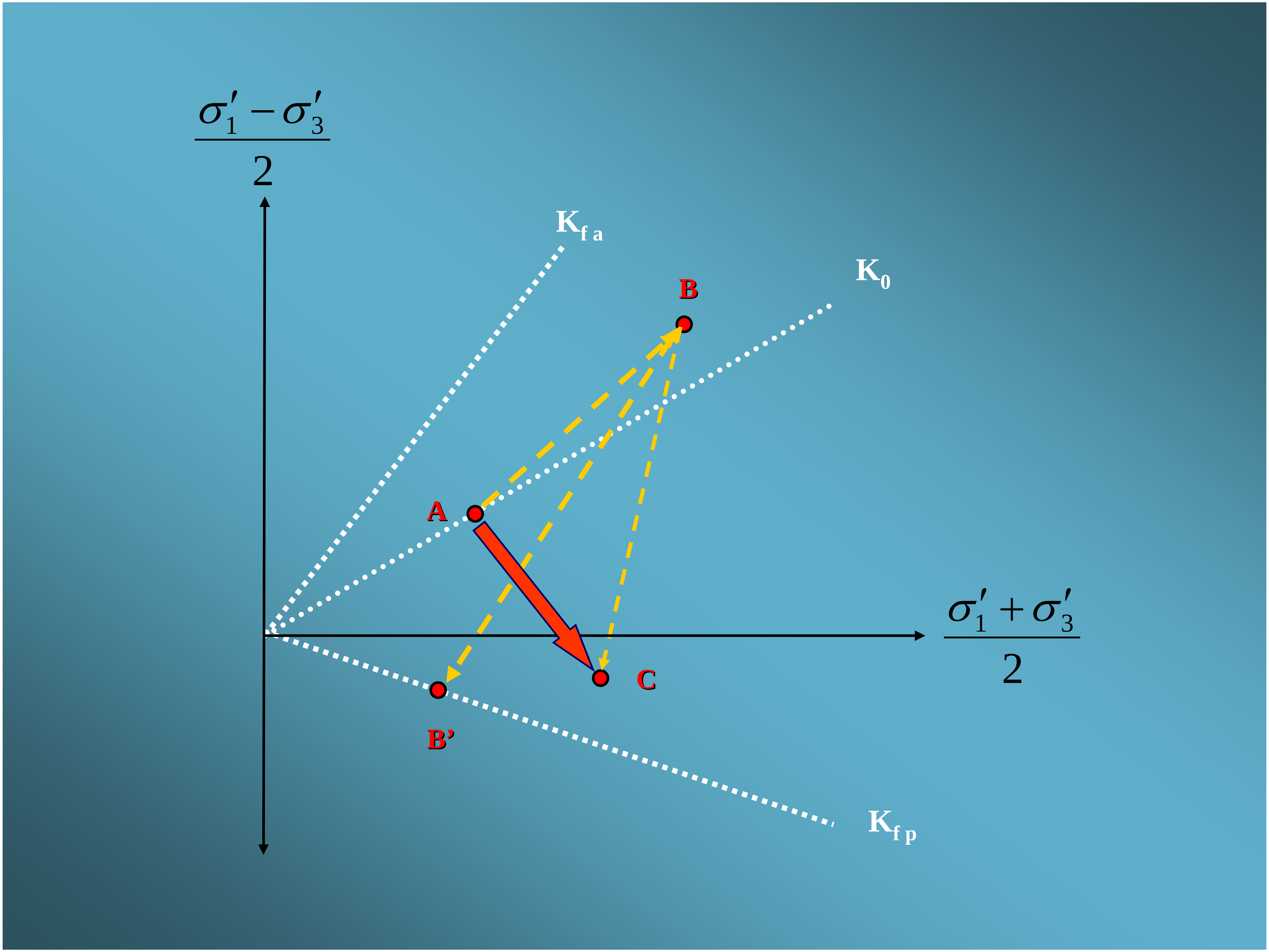


LEGEND

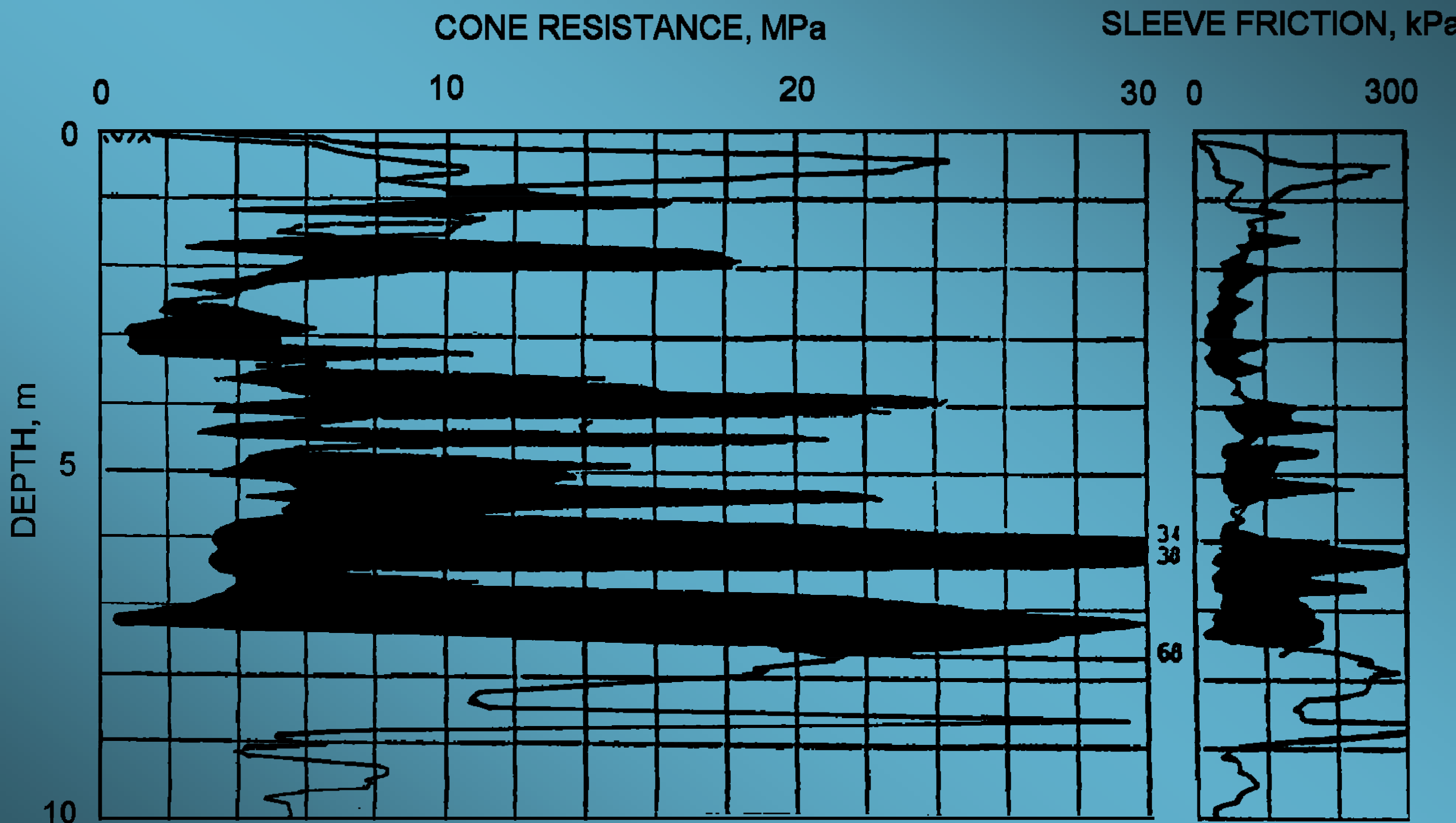
Channel 1: Horizontal surface geophone (mm/s)
Channel 2: Horizontal underground geophone (mm/s) Depth: 1.65 m
Channel 3: Horizontal underground geophone (mm/s) Depth: 3.55 m
Channel 4: Horizontal underground geophone (mm/s) Depth: 5.05 m

Cyclic Stress Variations during Vibratory Compaction





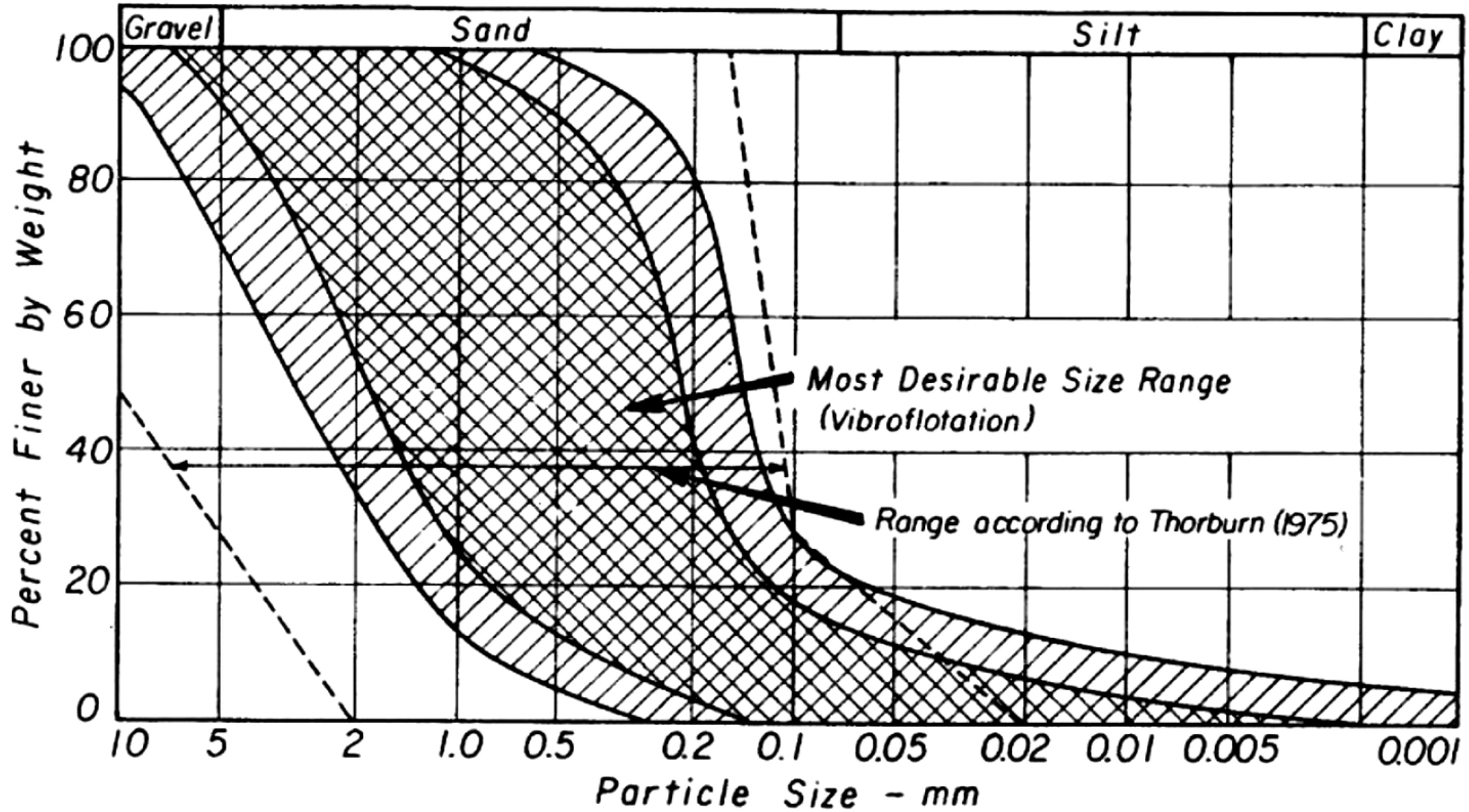
$\frac{\sigma_1' - \sigma_3'}{2}$
K_{fa}
K_0
B
A
$\frac{\sigma_1' + \sigma_3'}{2}$
C
B'
K_{fp}

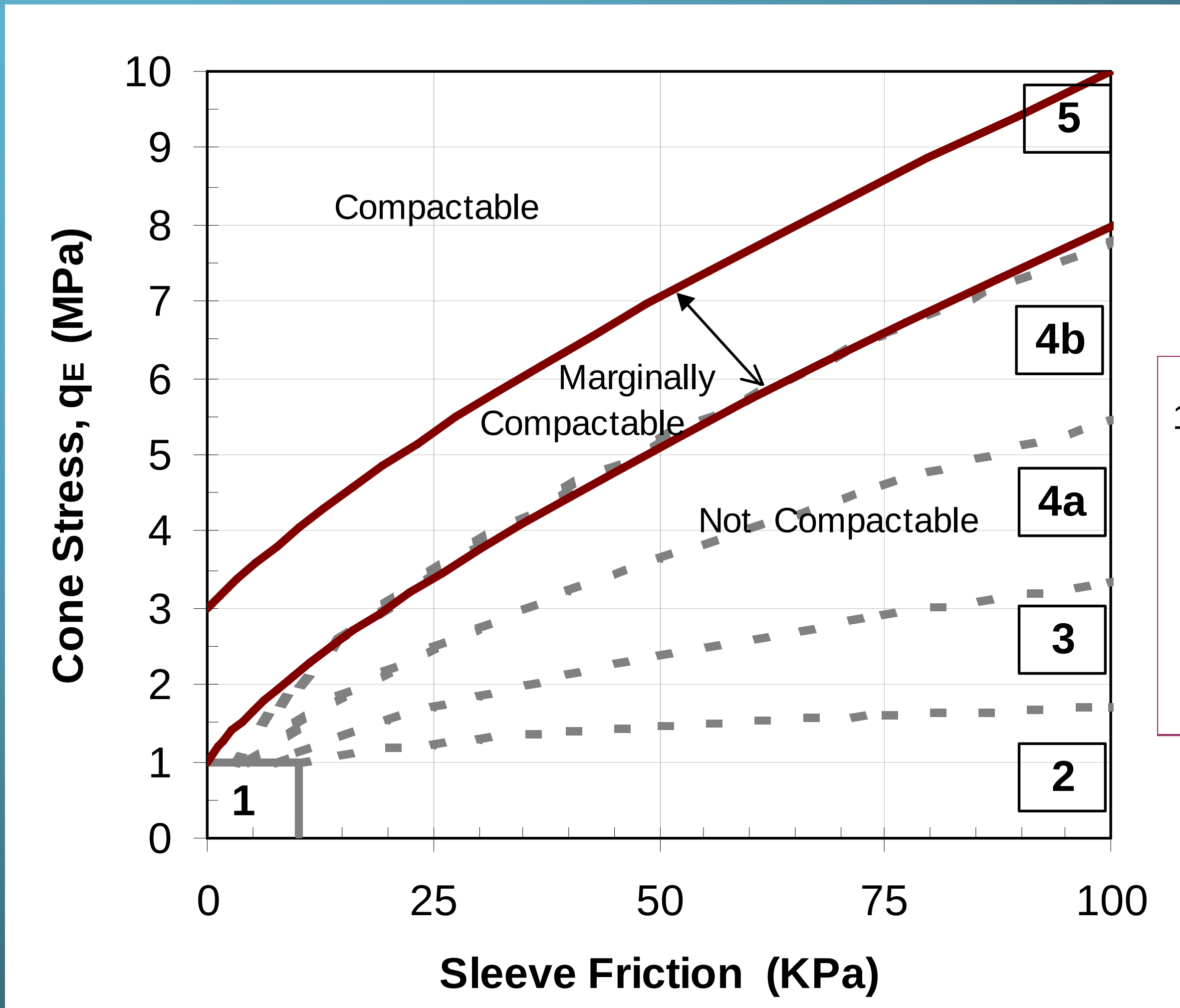


CONE RESISTANCE, MPa
SLEEVE FRICTION, kPa
0
10
20
30
0
300
DEPTH, m
0
5
10
34
38
68

Observations

- Compaction methods can have different mechanisms – vertical & horizontal vibration
- Operating frequency affects compaction process
- Cone resistance and sleeve resistance increase during compaction
- Cyclic horizotal stress variations during driving
- Increase in static horizontal stresses
- Compaction causes pre-loading effect
- **Experience from vibratory compaction - can be applied to pile/sheetpile driving!**


Gravel
Sand
Silt
Clay
100
80
60
40
20
0
Percent Finer by Weight
Most Desirable Size Range
(Vibroflotation)
Range according to Thorburn (1975)
10
5
2
1.0
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.001
Particle Size - mm



1 = Very Soft Clays or Sensitive and/or Collapsible Soils
2 = Clay and/or Silt
3 = Clayey Silt and/or Silty Clay
4b = Sandy Silt and Silt
4a = Fine Sand and/or Silty Sand
5 = Sand to Sandy Gravel

Fig. 1 Soil classification for deep compaction according to Massarsch (1994) with soil type boundaries according to Eslami-Fellenius (1997; 2000)

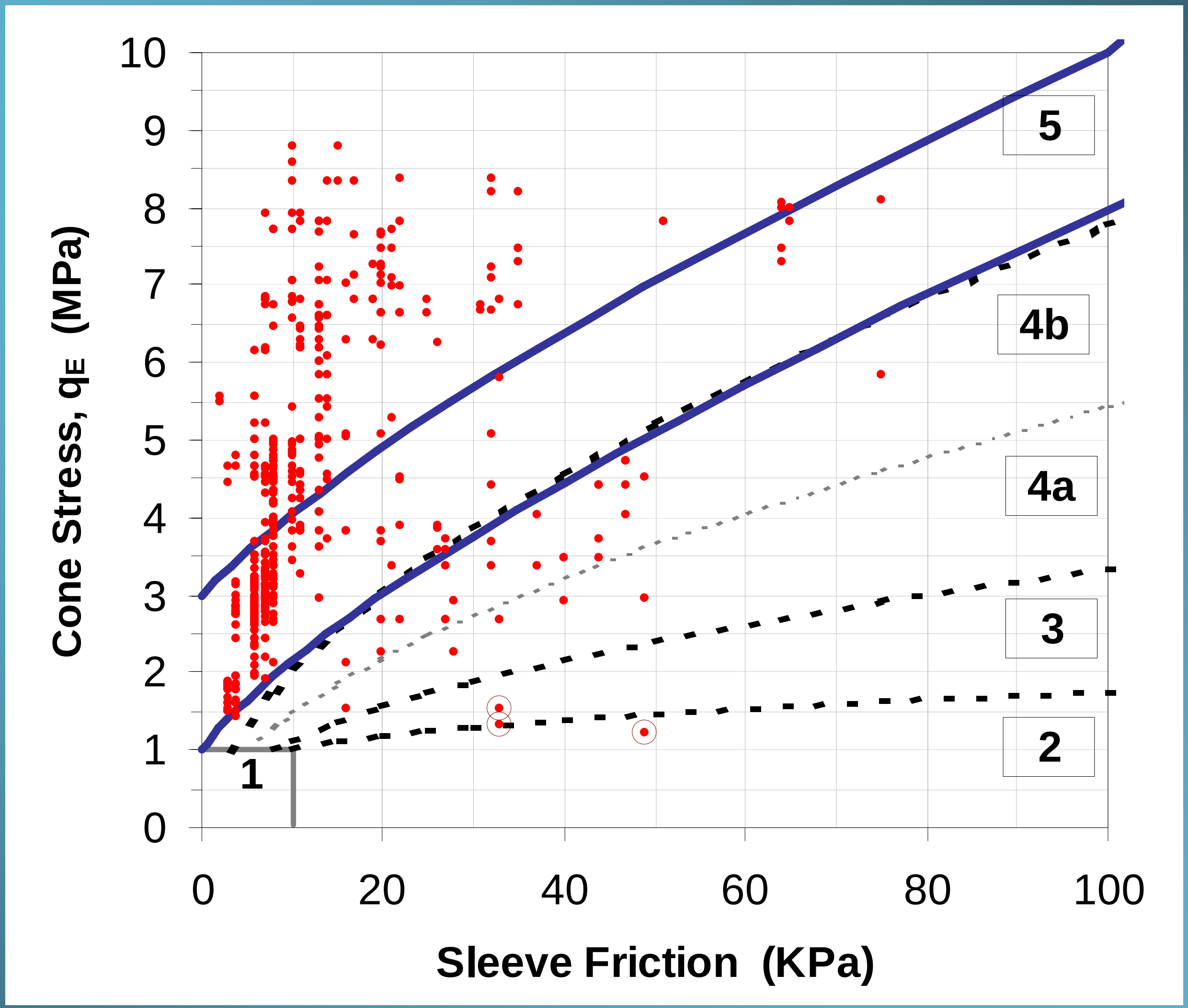
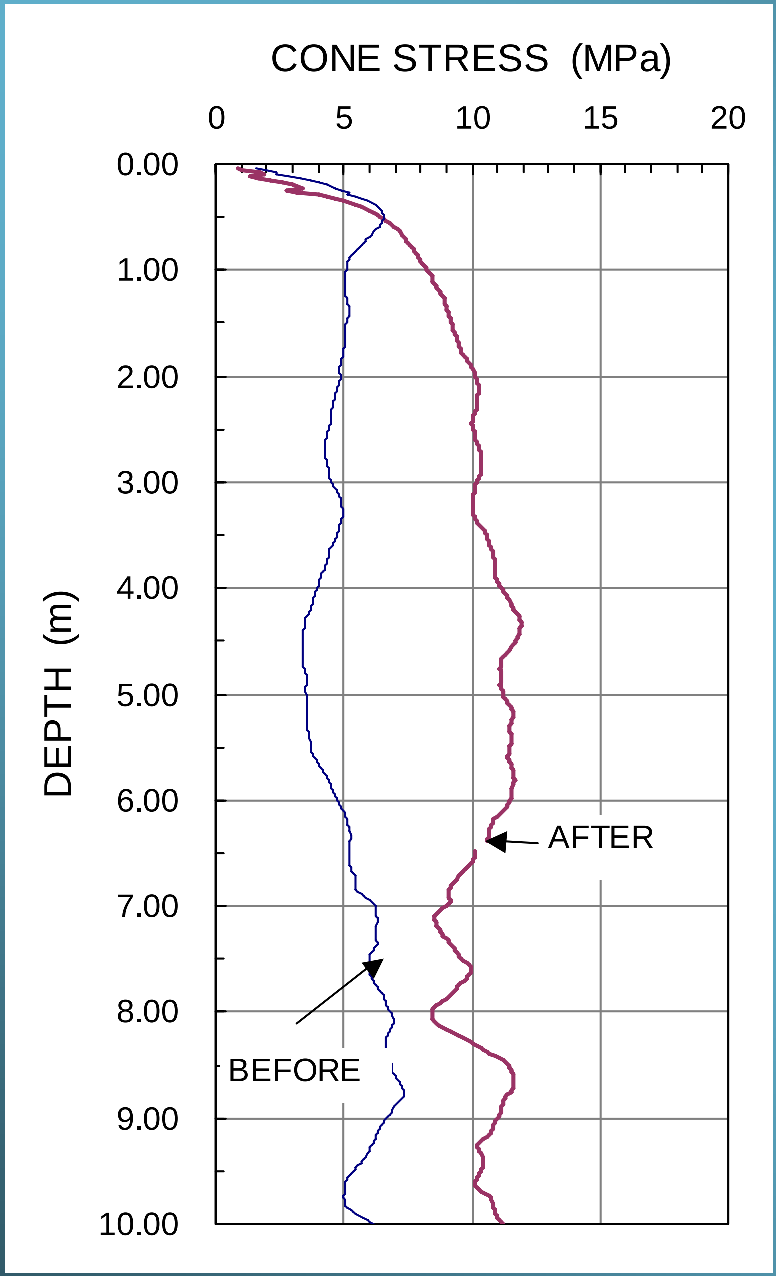
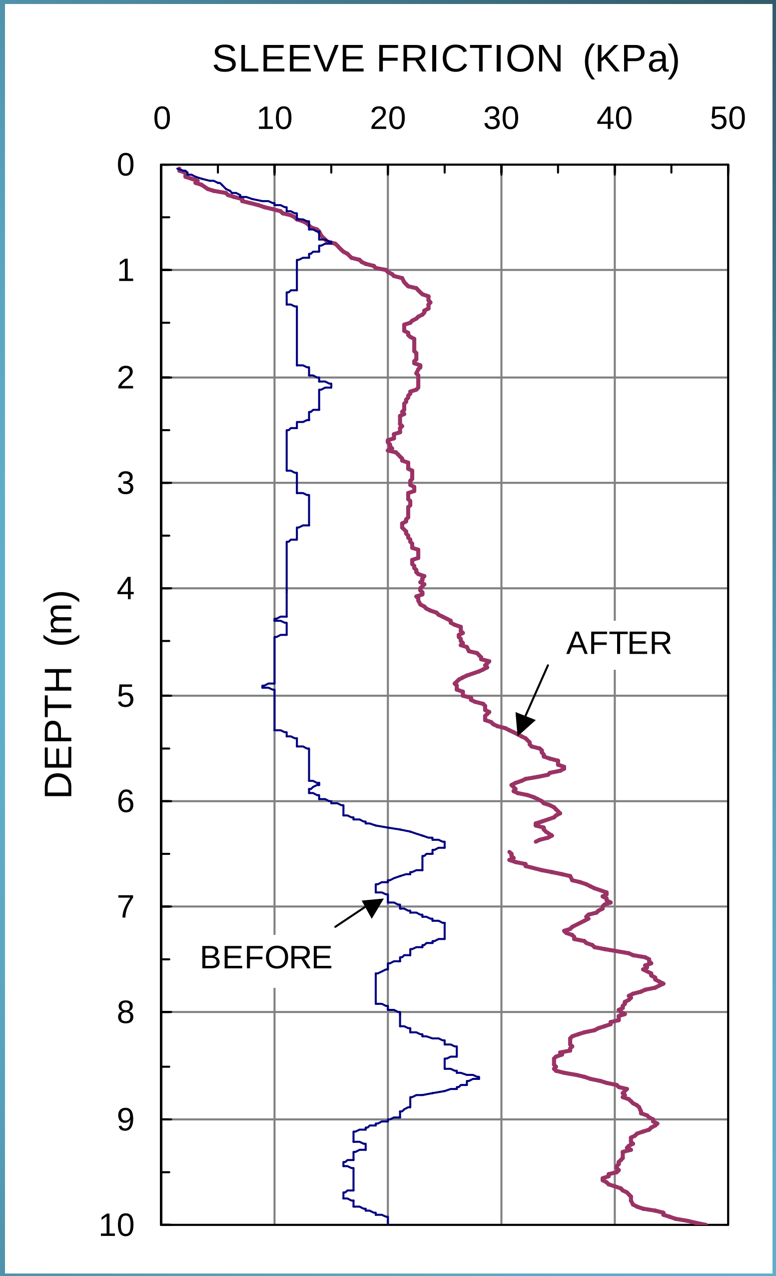


Fig. 3 The CPT data plotted in the Fig. 1 type chart


CONE STRESS (MPa)
0
5
10
15
20
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
DEPTH (m)
AFTER
BEFORE

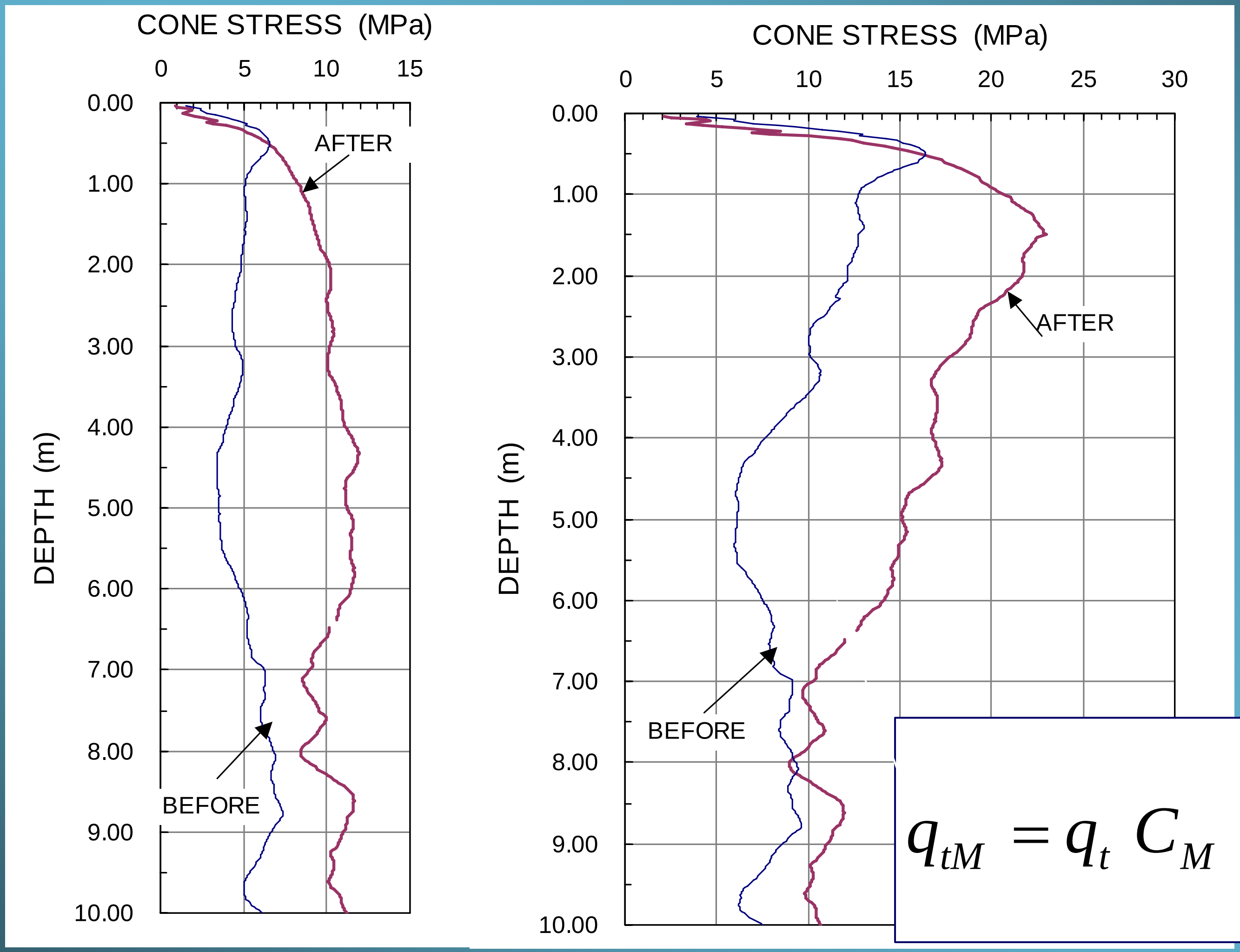

SLEEVE FRICTION (KPa)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
DEPTH (m)
AFTER
BEFORE

Settlement Estimation
Tangent Modulus Method

Correlation of soil modulus with stress-adjusted cone resistance

$$M_t = \frac{d\sigma}{d\varepsilon} = m\,\sigma_r \left(\frac{\sigma'_v}{\sigma_r}\right)^{(1-j)}$$

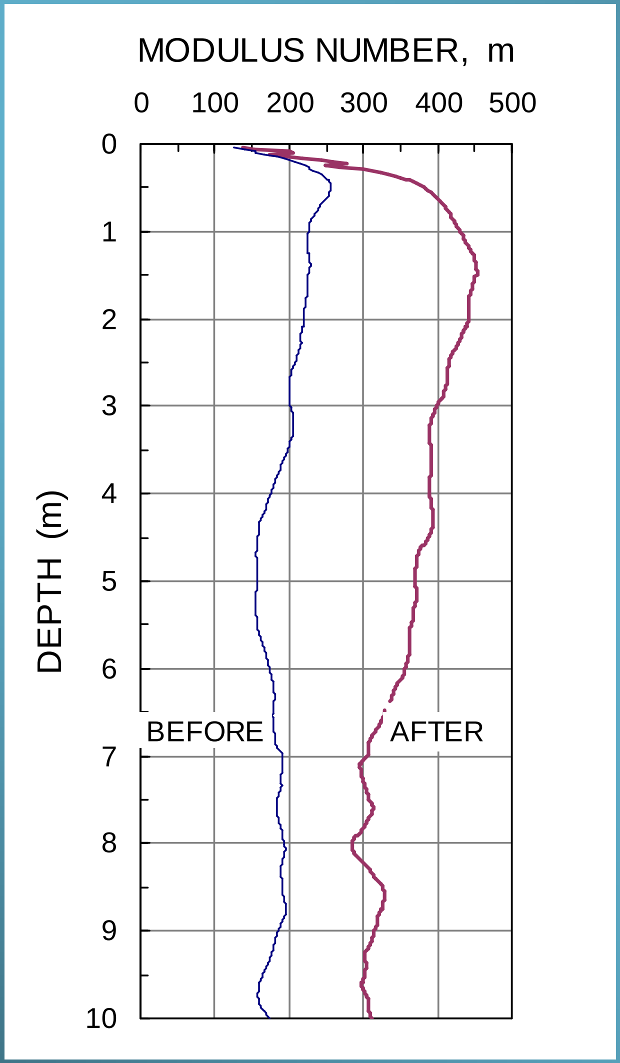
$$\varepsilon = \left(\frac{2}{m}\right)\left[\sqrt{\frac{\sigma'_1}{\sigma_r}} - \sqrt{\frac{\sigma'_0}{\sigma_r}}\right]$$



$$q_{tM} = q_t\, C_M = q_t \left(\frac{\sigma_r}{\sigma'_m}\right)^{0.5}$$

Fig. 5 Filtered average values of cone stress from before and after compaction

Unadjusted **in the left diagram and** adjusted for depth **in the right diagram**



$$m = a\left[\left(\frac{q_t}{(\sigma'_r\,\sigma'_v)^{0.5}}\right)\left(\frac{3}{1+K_0}\right)^{0.5}\right]^{0.5}$$

a = an empirical modulus modifier that depends on soil type

COMPACTION RESULTS

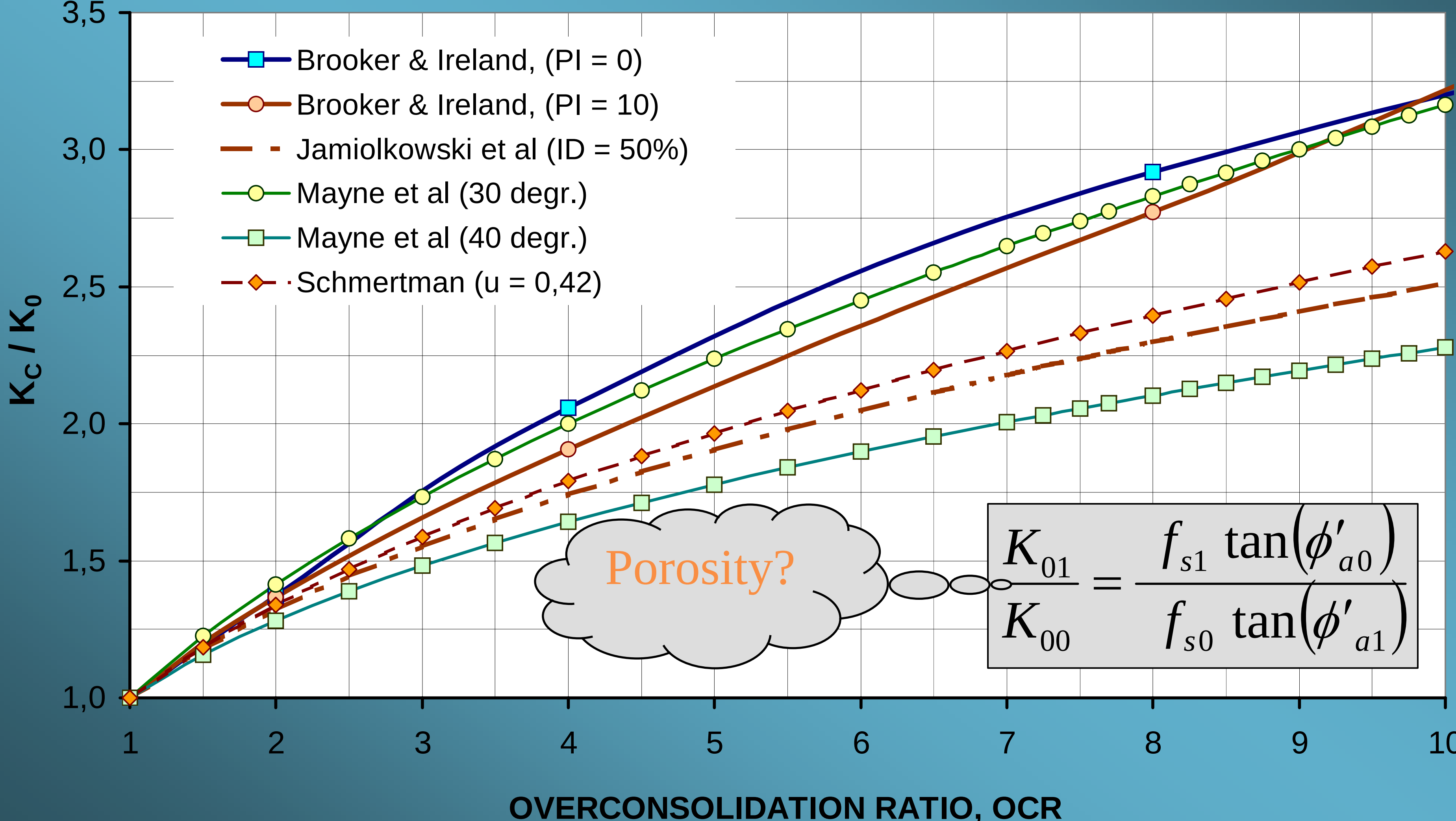
An about doubling of the modulus number and an increase of the OCR from about 1 to about 5.

Fig. 6 Janbu modulus number, m, before and after compaction

$$m = a\sqrt{\frac{q_M}{\sigma_r}}$$

Soil Type	Correction factor, a
Silt, organic soft	7
Silt, loose	12
Silt, medium dense	15
Silt, dense	20
Sand, silty loose	20
Sand, loose	22
Sand, compact	28
Sand, dense	35
Gravel, loose	35
Gravel, dense	45

$K_C / K_0 = OCR^m$



$$\frac{K_{01}}{K_{00}} = \frac{f_{s1}\tan\left(\phi'_{a0}\right)}{f_{s0}\tan\left(\phi'_{a1}\right)}$$

Settlement Assessment
Yam O, Hong Kong

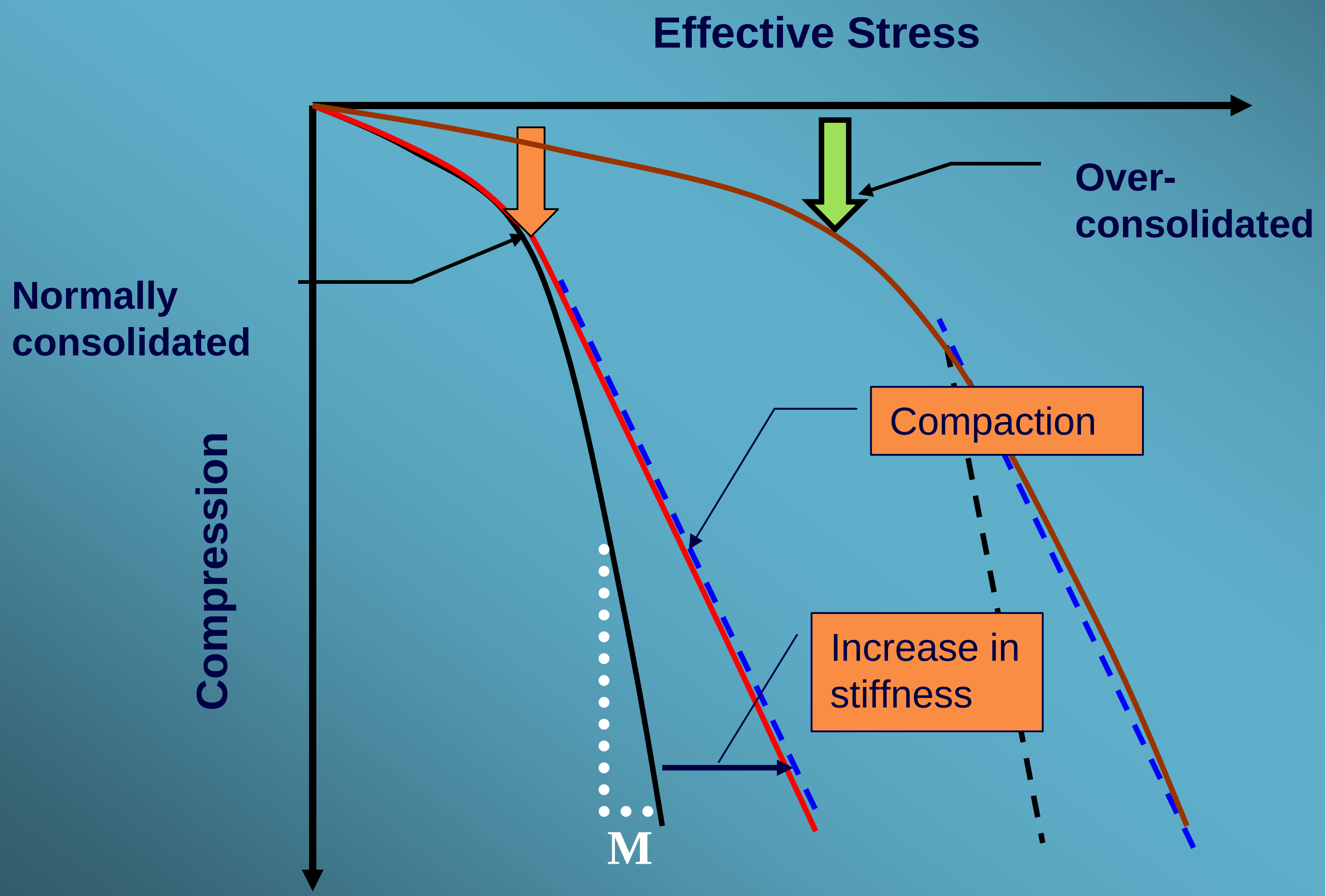
- **10 m wide square slab**
- **Foundation stress: 300 kPa**
- **Modulus number**

  Before compaction: m = 250 – 180

  After compaction: m = 450 – 300

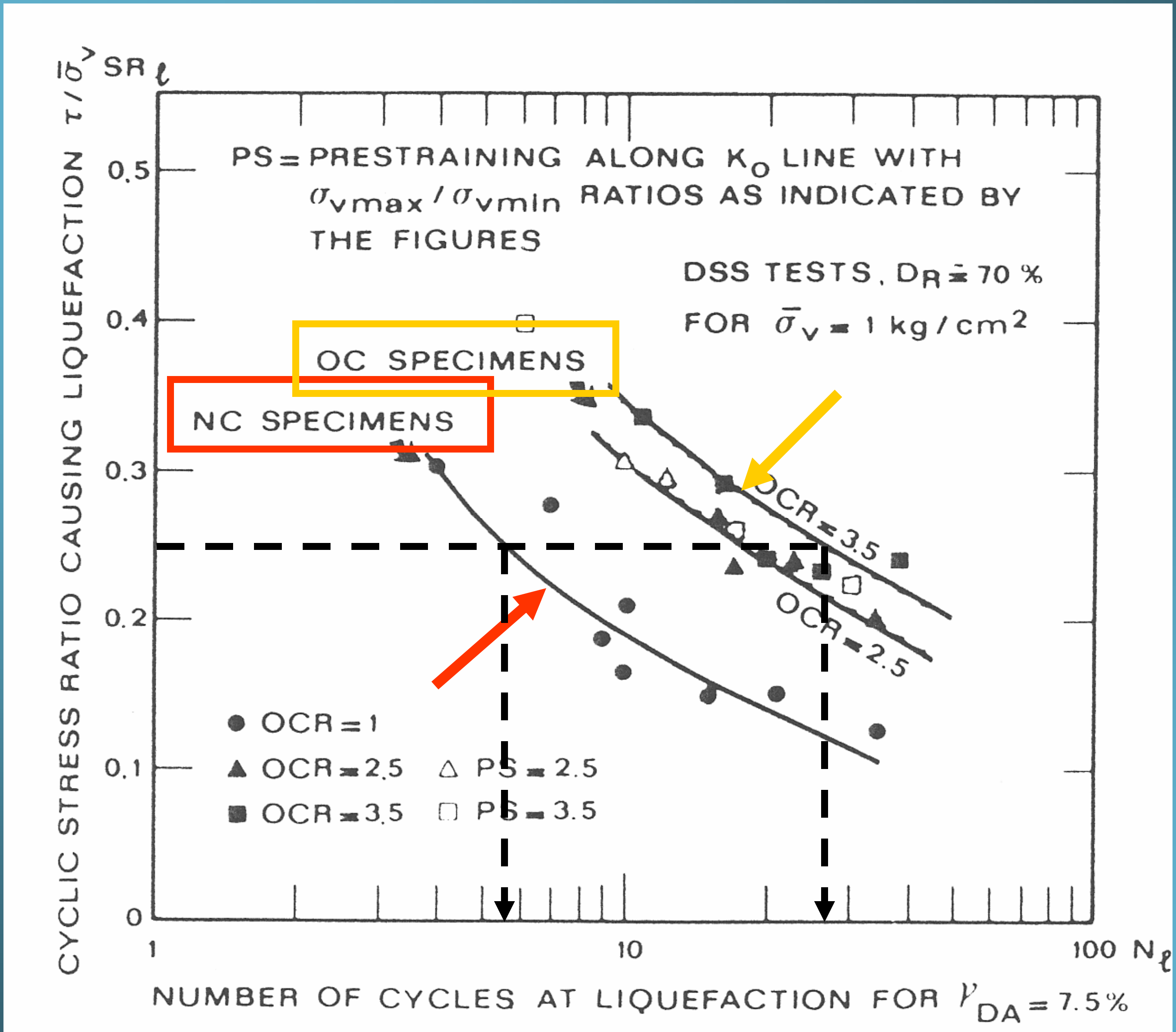
- ✓ **Settlement before compaction: 60 mm (100%)**
- ✓ **Settlement after compaction (increase of modulus only): 35 mm (58%)**
- ✓ **Settlement after compaction (increase of modulus and preconsolidation): 20 mm (30%)**

Increase of Soil Stiffness & Pre-consolidation



Soil Compaction causes Overconsolidation!

Effect of OCR on Liquefaction



Conclusions

- Compaction efficiency can be assessed from cone resistance and sleeve friction
- Cone resistance and sleeve resistance increase during compaction
- Cone resistance should be corrected with respect to effective confining pressure
- Change of stress field due to compaction
- Compaction causes pre-consolidation effect – important for settlement estimation
- Lateral stress increase reduces liquefaction hazard