Evaluation of DM Columns from Seismic Tests

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LECTURE SERIES AND WORKSHOPS ON GEOTECHNICAL ENGINEERING IN PRACTICE

Contents of Presentation

- SCPT Down-hole Guidelines
- Nordic Dry Mixed-in-Place Method
- Importance of Column Stiffness
- Seismic Field Testing
- Stress-strain behaviour of soils
- Stress-strain behaviour of columns
- Example of seismic tests in clay and column

Seismic Testing can measure soil properties by listening….

ISSMGE TC 10 - SCPT Procedure to Measure Shear Wave Velocity

Seismic cone downhole procedure to measure shear wave velocity - a guideline prepared by ISSMGE TC10: Geophysical Testing in Geotechnical Engineering

Procédé séismique de downhole de cône à la vitesse d'ondes de cisaillement de mesure - une directive a préparé par ISSMGE TC10 : Essai géophysique dans la technologie géotechnique

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ABSTRACT

The International Society for Soil Mechanics and Geotechnical Engineering, Technical Committee No 10: Geophysical Testing in Geotechnical Engineering has as part of its brief the task of drafting guidelines for geophysical techniques where no other national or international standards or codes of practice exist. This document is the first of these guidelines and concerns the use of the Seismic Cone to measure downhole seismic wave propagation.

Contents of SCPT Guidelines

Seismic cone downhole procedure to measure shear wave velocity - a guideline prepared by ISSMGE TC10: Geophysical Testing in Geotechnical Engineering

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RÉSUM

La Société Internationale de Mécanique des Sols et de la Géotechnique
technologie géotechnique a en tant qu'élément de son dossier le charge
où aucune autre norme ou recueil d'instructions nationale ou internatio
concerne l'utilisation du cône séismique de mesurer la propagation séis

1 INTRODUCTION

This document is to provide guidance to practitioners and procurers on downhole seismic wave measurement using a seismic cone penetrometer. The guideline has been prepared by ISSMGE TC10: Geophysical Testing in Geotechnical Engineering and is a supplement to the International Reference Test Procedure (IRTP) for the electric Cone Penetration Test (CPT) and the Cone Penetration Test with Pore pressure (CPTU) as produced by the ISSMGE TC16. The document therefore follows, and should be used with, the CPT IRTP (1999).

The addition of a seismic sensor (usually a geophone but may be an accelerometer or seismometer) inside the barrel of a standard electric CPT is termed a Seismic Cone Penetrometer Test (SCPT) (Robertson et al, 1986). Such a sensor allows the measurement of the arrival of vertically propagating seismic body waves, generated from a source on the ground surface, in addition to the usual cone parameters that are used for detailed stratigraphic logging.

There are two types of seismic body waves, Pressure or Compression waves (P waves) as well as Shear waves (S waves) and seismic sensors react to both. The P wave always arrives first. In soils below the ground water table the P wave typically travels 2 or more times faster than the S wave, so separation of the two body waves is easy. Above the water table, however, the difference is small and separation of P and S waves may be very difficult, requiring specialized techniques. However the most significant difference between P and S waves is that S waves are reversible. Therefore using a source that can produce shear waves of opposite polarity facilitates the identification of S waves.

Since shear waves travel through the skeletal structure of the soil at very small strains, one can apply simple elastic theory to calculate the average elastic small strain shear modulus, over the length interval of measurement, as the mass density times the square of the shear wave velocity. Thus, the shear wave ve-

Shear beam: Beam that forms part of the downhole seismic shear wave Source that is impacted by a Hammer to maximize S waves and minimize P waves.

Source: Device that, when activated, generates polarised shear waves that propagate into the ground. (A basic source will include a loaded Shear Beam, Hammer and a Trigger to activate the data recording equipment).

Trigger: Device attached to either the Shear Beam or the Hammer to initiate the data recording equipment at the instant the Shear Beam is struck by the Hammer.

3 METHODOLOGY

During a pause in cone penetration, a shear wave can be created at the ground surface that will propagate into the ground on a hemi-spherical front and a measurement made of the time taken for the seismic wave to propagate to the seismometer in the cone. By repeating this measurement at another depth, one can determine, from the signal traces, the interval time and so calculate the average shear wave velocity over the depth interval between the seismometers. A repetition of this procedure with cone advancement yields a vertical profile of vertically propagating shear wave velocity. Figure 1 shows 2 alternative schematic arrangements of the SCPT, and Figure 2 shows a typical arrangement of the surface shear wave source.

4 EQUIPMENT

The general arrangement of equipment is shown in Figures 1 and 2.

Seismometer: The seismometer will typically have a natural frequency of less than 28 Hz and must fit inside the cone barrel. The seismometer must be mounted firmly in the cone barrel with the active axis in the horizontal direction and the axis alignment indicated on the outside of cone body. The cone barrel at the location of the seismometer should be of a greater diameter than the sections immediately below the location of the seismometer to ensure good acoustic coupling between the cone barrel and the surrounding soil.

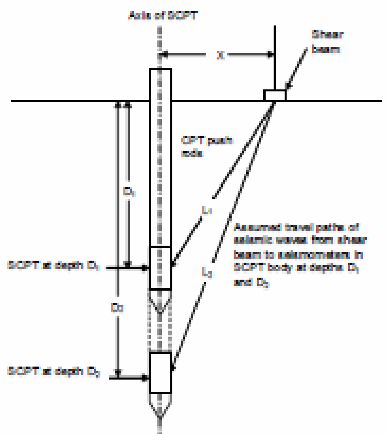

Figure 1a: Schematic diagram of the seismic cone test with required dimensions, D_1, D_2, and X.

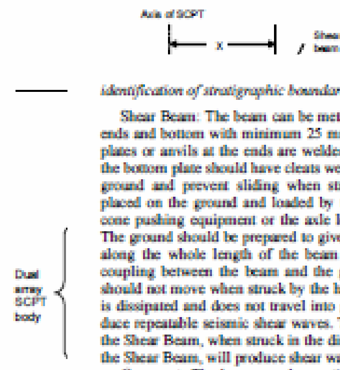

Figure 1b:
required di

Comme
array in t
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signals, wo
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wave arriv
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Figu
beam

identification of stratigraphic boundaries.

Shear Beam: The beam can be metal or wood encased at the ends and bottom with minimum 25 mm thick steel. The strike plates or anvils at the ends are welded to the bottom plate and the bottom plate should have cleats welded to it, to penetrate the ground and prevent sliding when struck. The shear beam is placed on the ground and loaded by the levelling jacks of the cone pushing equipment or the axle load from vehicle wheels. The ground should be prepared to give good continuous contact along the whole length of the beam to ensure good acoustic coupling between the beam and the ground. The Shear Beam should not move when struck by the hammers otherwise energy is dissipated and does not travel into ground and does not produce repeatable seismic shear waves. The anvils, on the ends of the Shear Beam, when struck in the direction of the long axis of the Shear Beam, will produce shear waves of opposite polarity.

Comment: The beam can be continuous (approximately 2.4 m long) i.e. greater than the width of a vehicle or equipment used to load the beam and 150 mm wide or alternatively can be two shorter beams placed and loaded so that the anvils oppose and can be struck by the hammers to produce shear waves of opposite polarity. Care must be taken to position the beams and strike direction to maximise S waves and minimise the production of P waves.

Heavy hammer(s): Heavy hammer(s) with head mass of between 5 to 15 kg to strike the plate or anvil on the end of the shear beam in a direction parallel to the long axis of the shear beam and the active axis of seismometer.

Comment: Two fixed axis hammers, one to strike each end of the beam in the specified directions, will significantly speed up the operation and give controllable and consistent source output. A typical setup is shown in Figure 2.

Data recording equipment: The recording equipment can be a digital oscilloscope, a P.C. with installed A/D board and oscilloscope software or a commercial data acquisition system such as a seismograph. The data recording equipment must be able to record at 50 µs (microsecond) per point interval, or faster, to ensure clear uncorrupted signals and to start the logging of the seismometer outputs using an automatic trigger. An analogue anti aliasing filter should be used to avoid corruption of signal frequencies above the device limits. Commercial data recording equipment usually include amplifiers and signal filters to help enhance recorded signals. The effect of these processes on the recorded signals must be considered before their use. For example filtering can cause phase shift of signals and amplification is usually limited to a frequency range. In either case the signals may not be directly comparable.

Comment: Experience has shown that there is a significant advantage to record the unprocessed data and then the effect of filtering and processing can be assessed during post processing. Most modern acquisition equipment allows the viewing of filtered signals during acquisition (to assess quality and repeatability) but saves the data un-filtered. Most modern acquisition equipment allows signal stacking to improve signal to noise ratio.

Trigger: The trigger can be fixed to the hammer head or the beam. The trigger is required to be very fast (less than 10 microsecond reaction time) and repeatable. When the hammer hits the shear beam, the electrical reaction of the trigger activates the trigger circuit that outputs to the signal recording equipment. A typical trigger circuit is given in Campanella & Stewart (1992). A seismic trigger mounted on the beam may be used if it is fast enough, repeatable and delay time is checked and known or a contact trigger that works the instant contact is made between the hammer and the anvil.

Comment: The use of 2 arrays of seismometers set in the cone barrel a fixed distance apart, say 0.5m or 1.0m, (termed a dual array seismic cone, see Figure 1b) would enable the travel time of the shear wave to be measured between the seismometers from the same source activation thereby avoiding possible errors from selection of signal from different source activation, the speed of the trigger, and the accuracy of distance from the source to the receivers from successive pushes of the drive rods to each depth. In this case the seismometers must have identical response characteristics (natural frequency, calibration and damping). However if signals are to be stacked, that is the signals from successive source activations added together to improve signal to noise ratio, the trigger time must be repeatable.

5 TEST PROCEDURES

At the start of the SCPT, the body of the cone should be rotated until the axis of a seismometer is parallel to the long axis of the shear beam.

a) The cone is pushed into the ground, monitoring the inclination of the cone barrel during the push.

Comment: It is important to know the exact location of the receivers in all three axes and the inclinometer in the cone barrel will give the horizontal component and the depth measuring system of the CPT the vertical component.

b) The penetration of the cone is stopped and the depth to the seismometer/s is recorded. The horizontal offset distance, X, from cone to centre of the shear beam should also be recorded (see Figure 1)

Comment: Typically this procedure is carried out at depths greater than about 2-3m in order to minimize the interference of surface wave effects. If the seismic cone includes a fully operative electric cone then it will be advanced at 2 cm/s and stopped typically at a rod break at 1m intervals or for pore water pressure dissipation tests. If acceptable such stoppages can also be used for downhole seismic wave measurements. Alternatively the seismic cone can be pushed to a predetermined depth at which the shear wave velocities are required and the measurements made. To avoid the possible effects of time between stopping, pushing and making measurements it is advisable to keep this time interval consistent. The horizontal distance, X, between the entry point of the seismic cone and the source should be kept at around 1m. Greater distances will require the effects of curved travel paths, that particularly affect single array SCPT's, to be addressed. It is advisable at the first depth of measurement to monitor the output of the receivers without activating the source to determine the ambient seismic noise in the ground and thereby enable the filtering, as far as possible, the ambient noise. Experience has shown that ambient noise can be reduced by retracting the cone pushing system, so that the drive rods are unloaded and there is no contact between the shear beam system and the cone drive rods through the cone drive vehicle, and the cone driving equipment motors are not running.

c) The shear beam is struck by the hammer and the trigger activates the recording equipment that then displays the time based signal trace received by the seismometer.

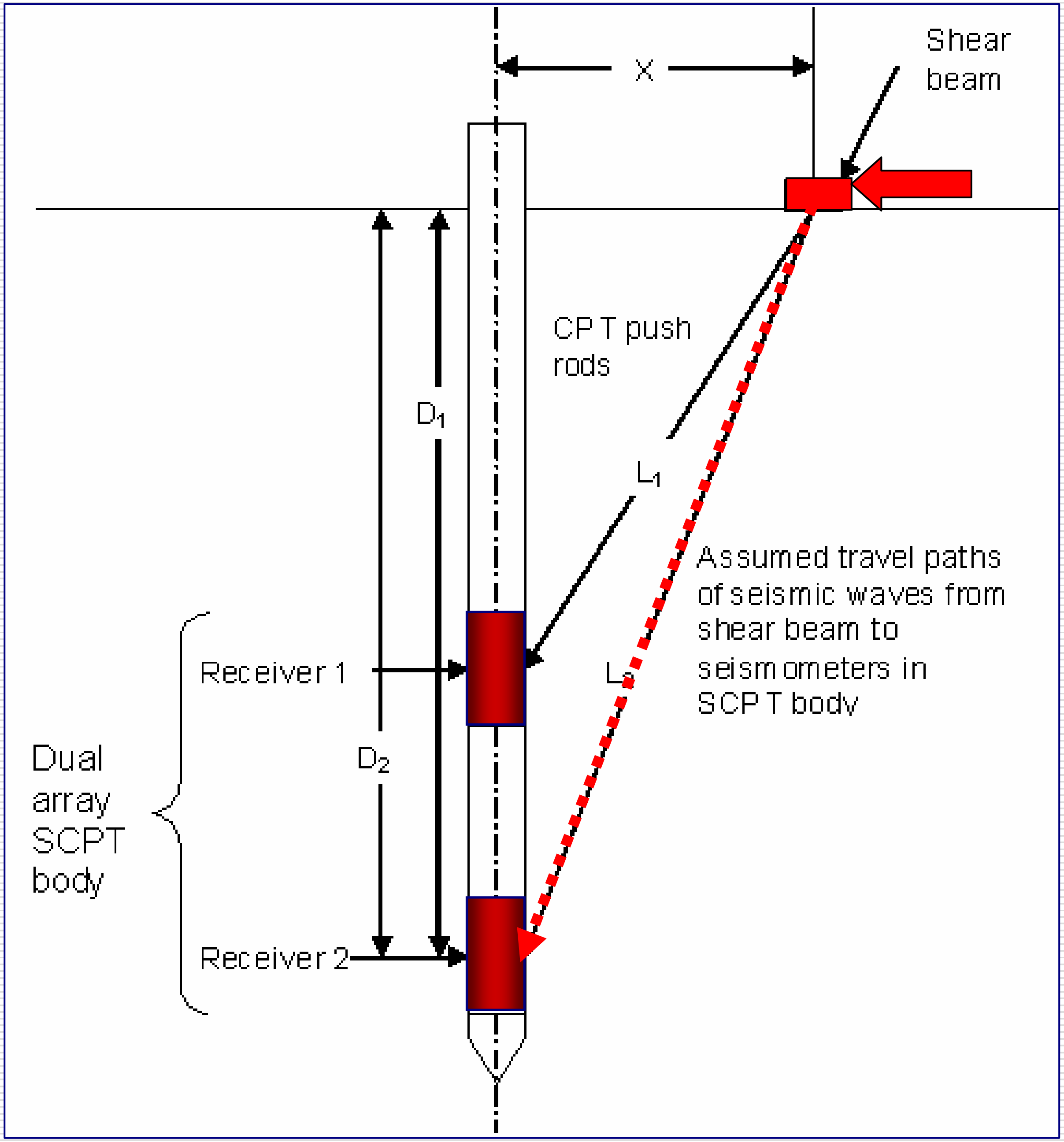
Comment: For quality assurance, it is recommended to reset the trigger and repeat the procedure until a consistent and reproducible trace is obtained. The voltage-time traces should lie one over the other. If they do not, continue repeating until measured responses are identical. In the case of the dual array SCPT the traces from both the seismometers can be displayed together giving a rapid assessment of the shear wave propagation time. If the seismic wave velocity appears too high then there may be a connection between the cone drive system and the seismic cone so allowing the seismic waves to travel through the cone drive rods instead of the ground.

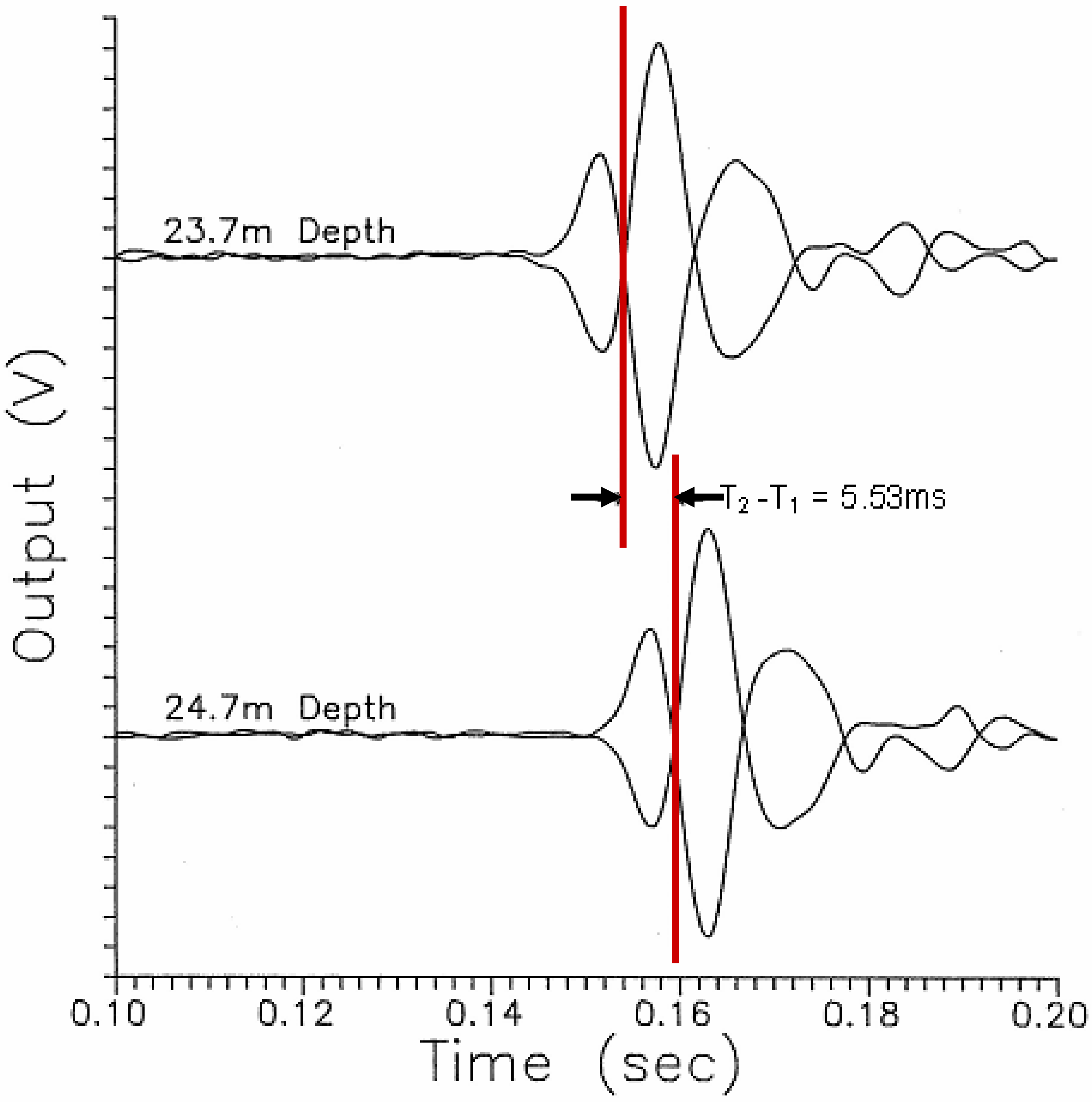
d) The trigger is reset and the shear beam is then struck by the hammer on the opposite end on the other side of vehicle (causing initial particle motion in the opposite direction and a shear wave of opposite polarity) and procedure in step c) is again completed.

Seismic Cone Downhole Procedure to Measure Shear Wave Velocity

The document is structured to give a minimum standard guideline.

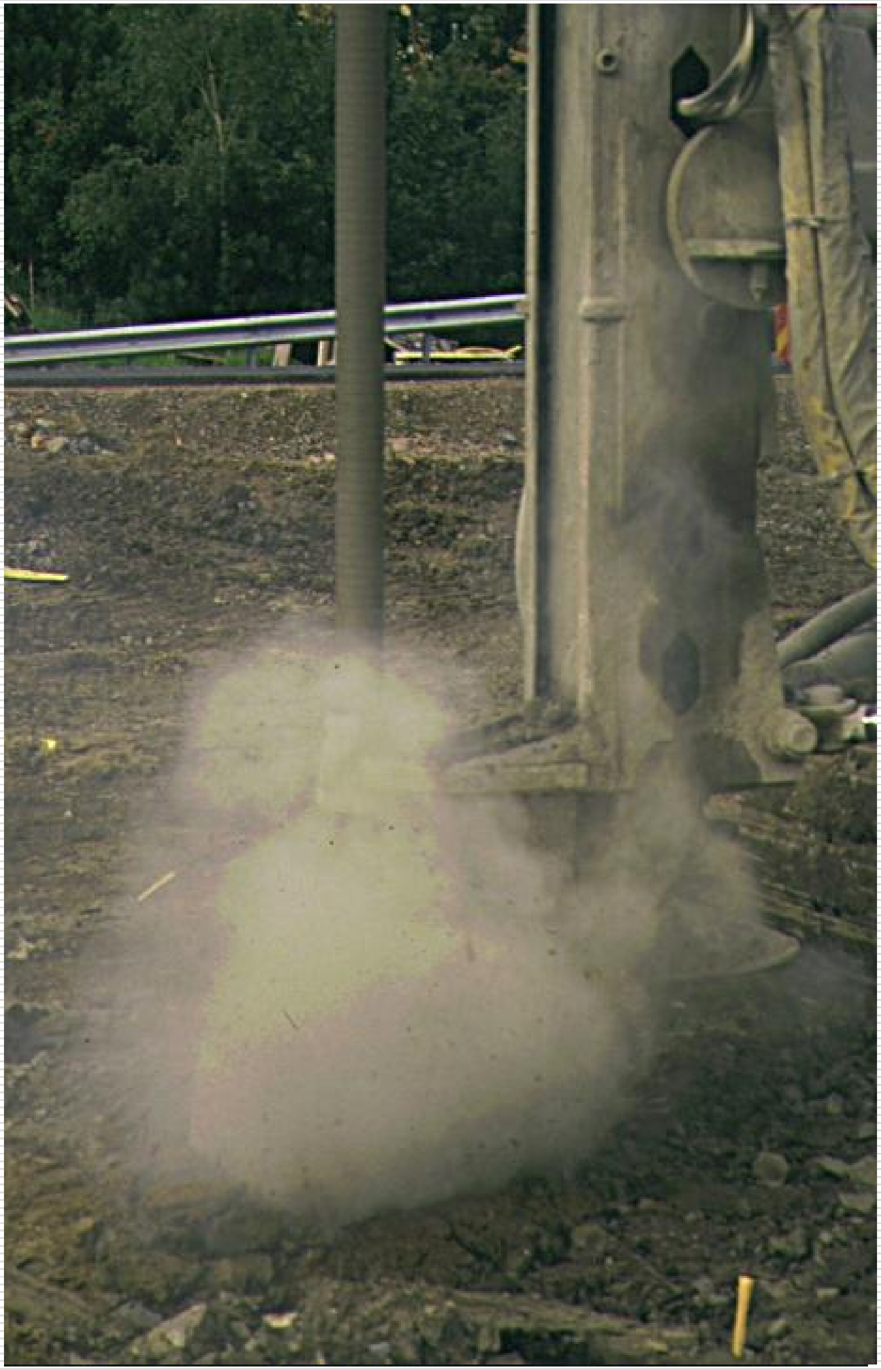
It includes ***comments*** and **additional information** and **enhancements** that can improve the quality of data and/or aid interpretation of the data.

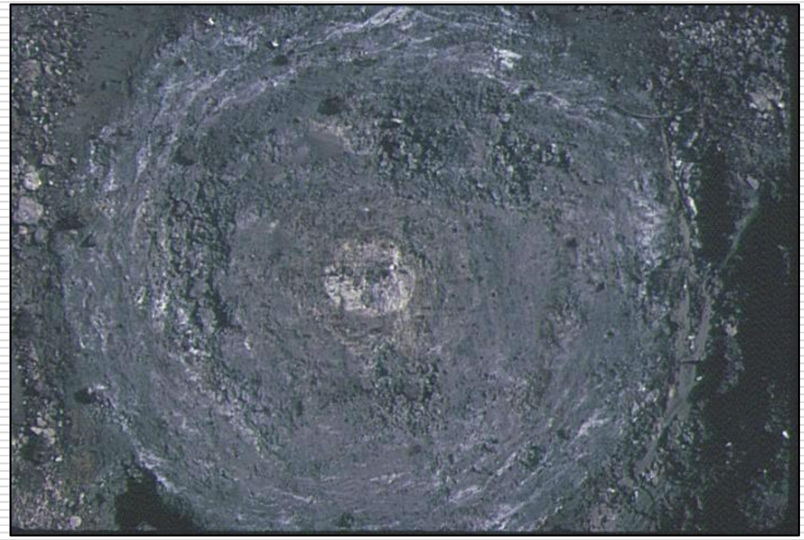

Shear beam
X
CPT push rods
D1
L1
L2
D2
Assumed travel paths of seismic waves from shear beam to seismometers in SCPT body
Receiver 1
Receiver 2
Dual array SCPT body



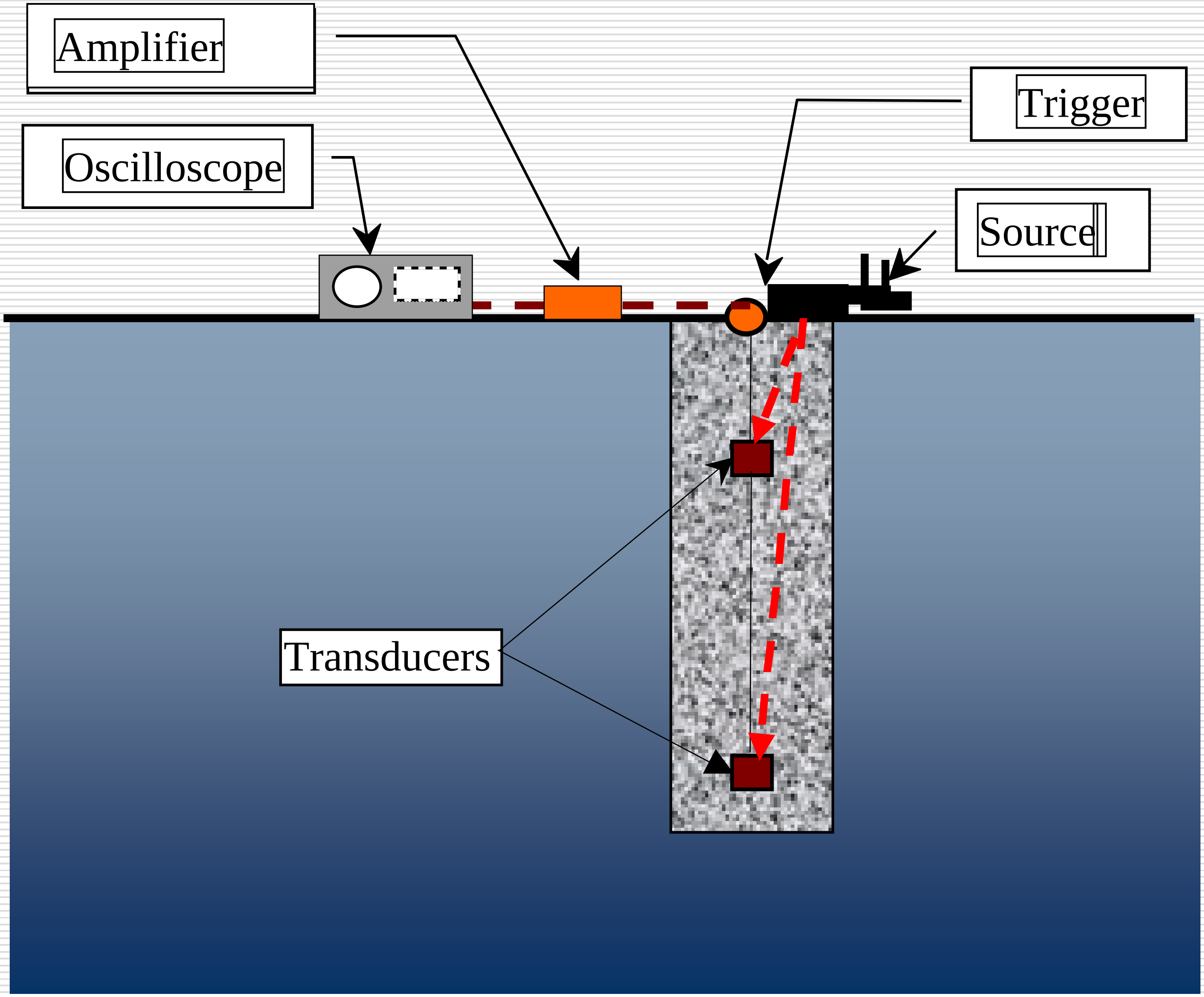
$$V_S = \frac{L_2 - L_1}{T_2 - T_1}$$

Dry Mixed-in-Place Columns, Nordic Countries

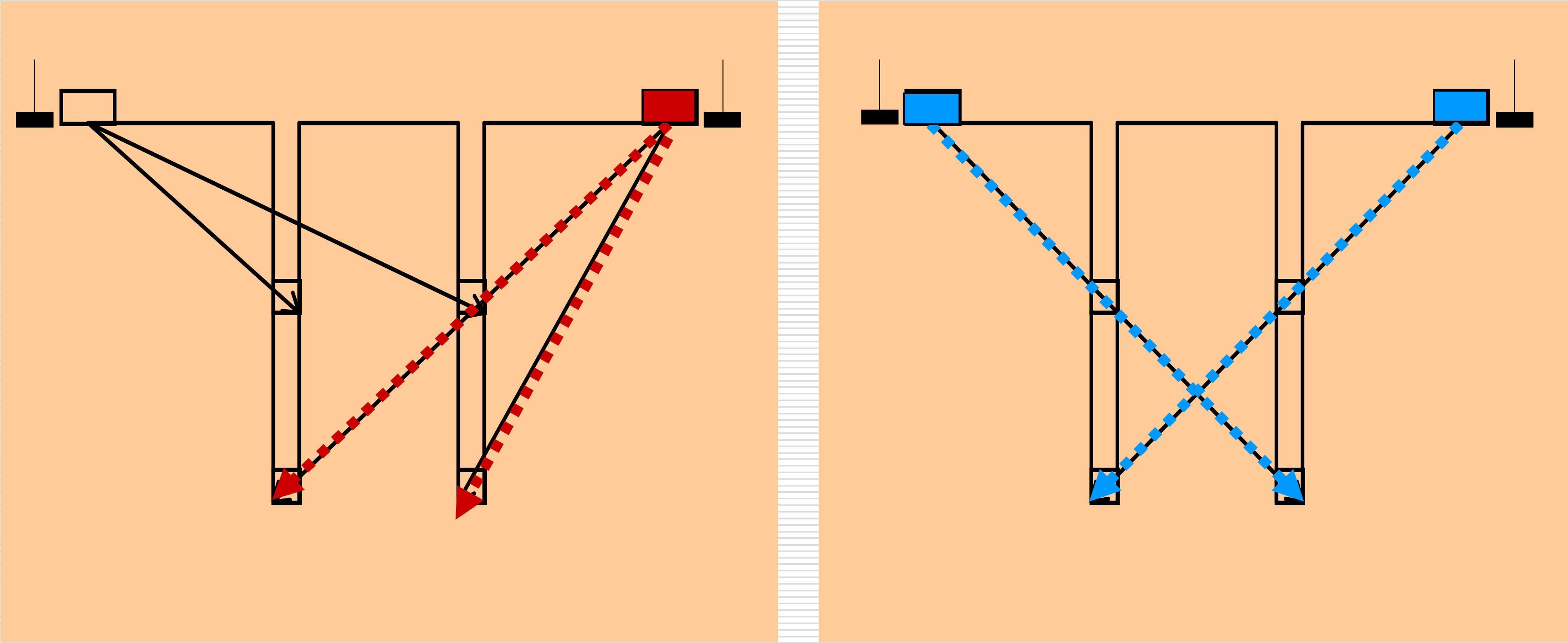



Seismic Downhole Test in Dry Mixed-in-Place Column



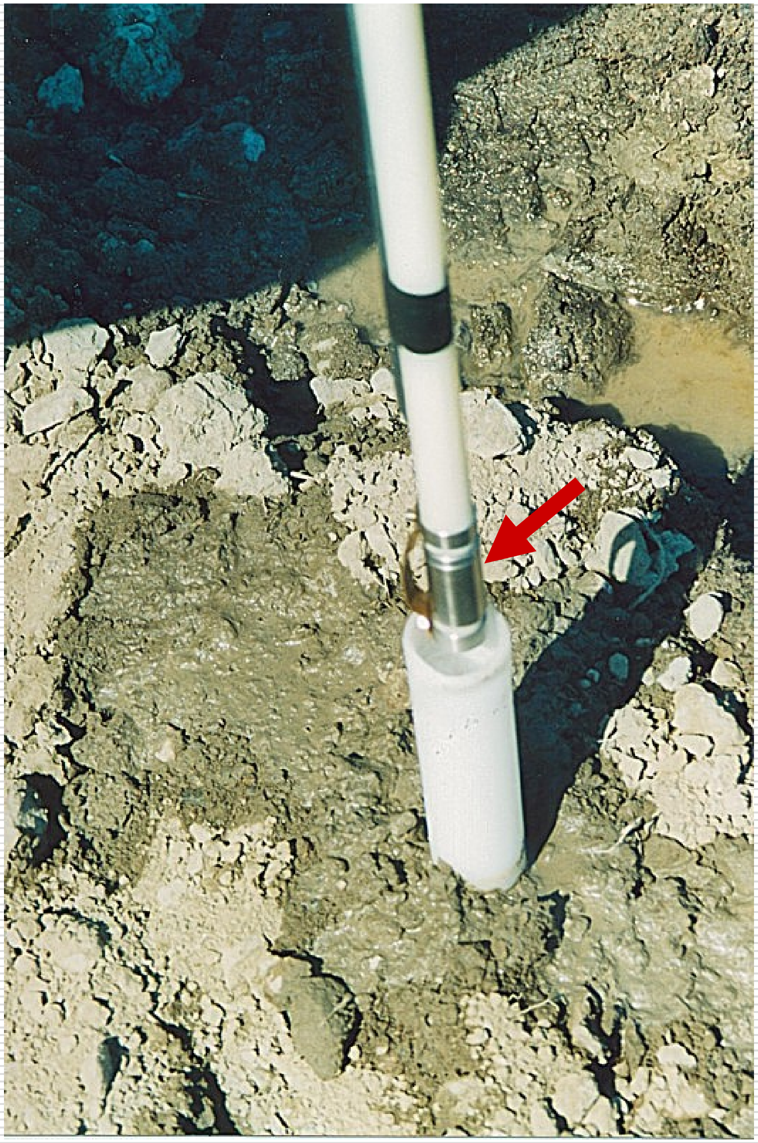
Seismic Tomography

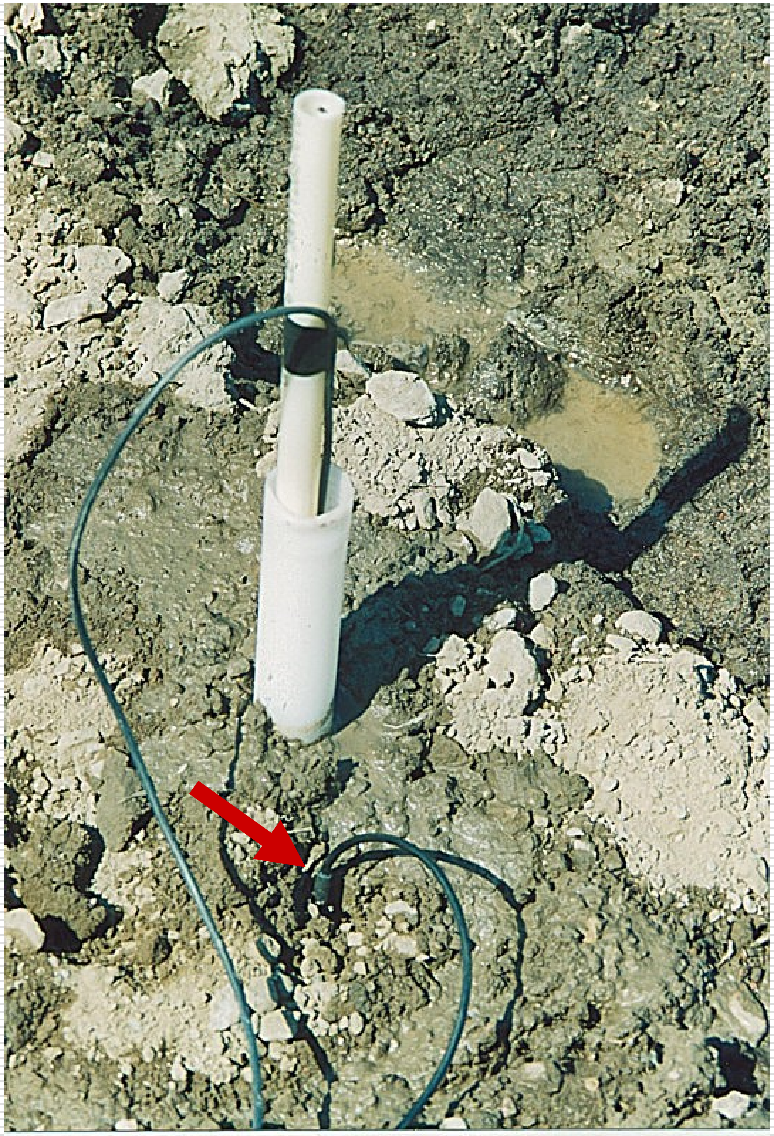


Inclined down-hole measurements with different source locations.

Connecting Accelerometer

Insertion of Accelerometer into Measuring Tube

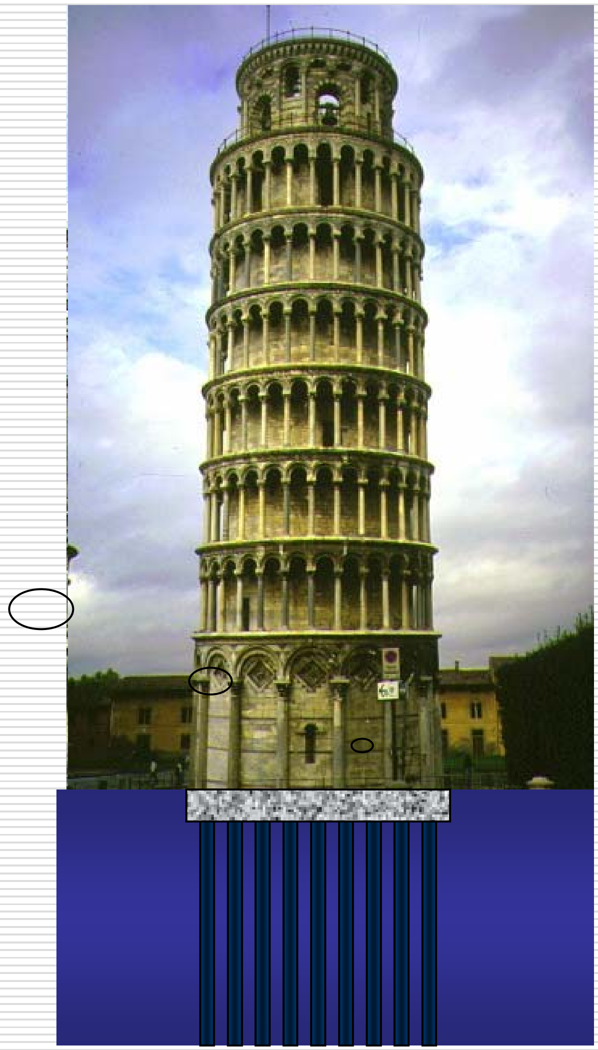




Load Sharing between Soil and Columns

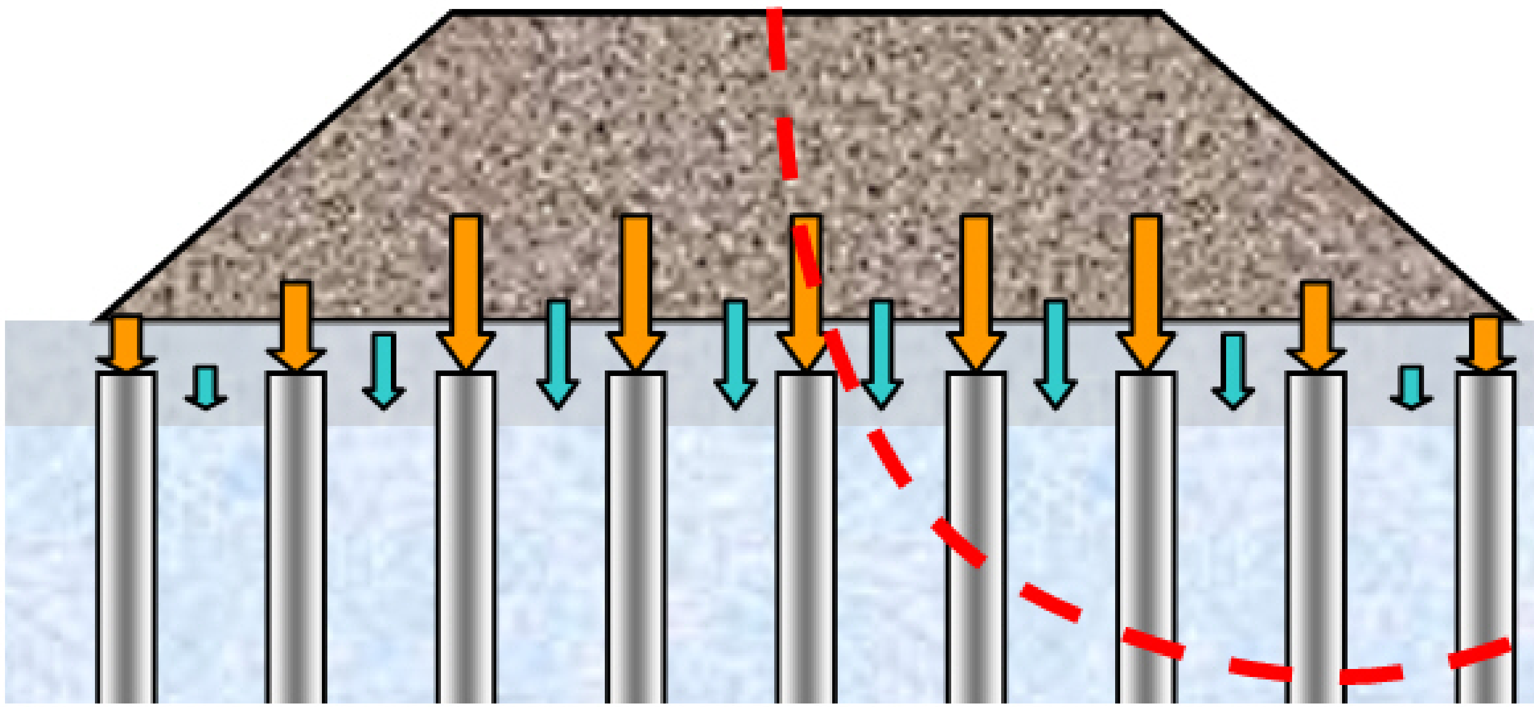
???

- !!!

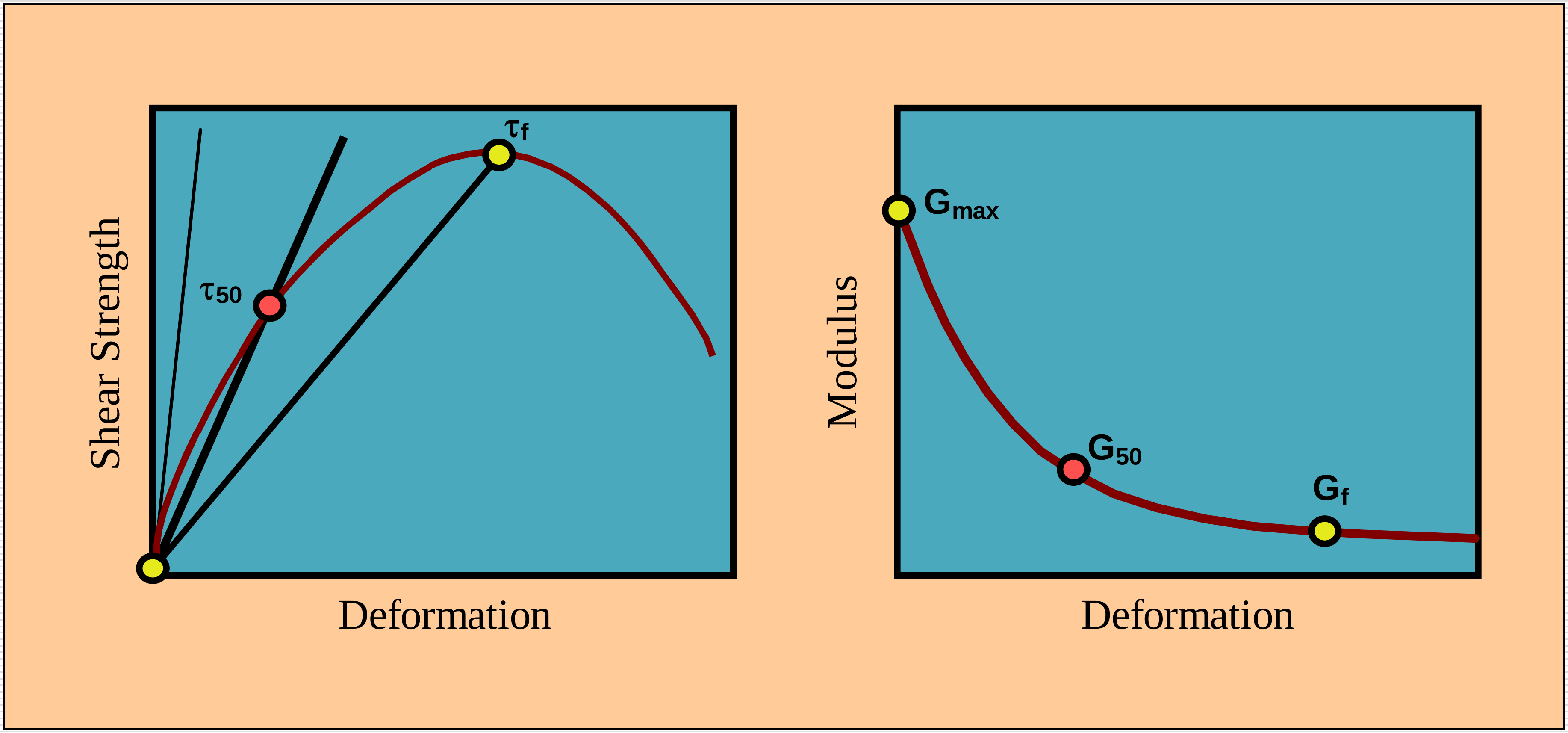


$$\sigma_{col} = \frac{q_0}{(1-a)\frac{M_{soil}}{E_{col}} + a}$$

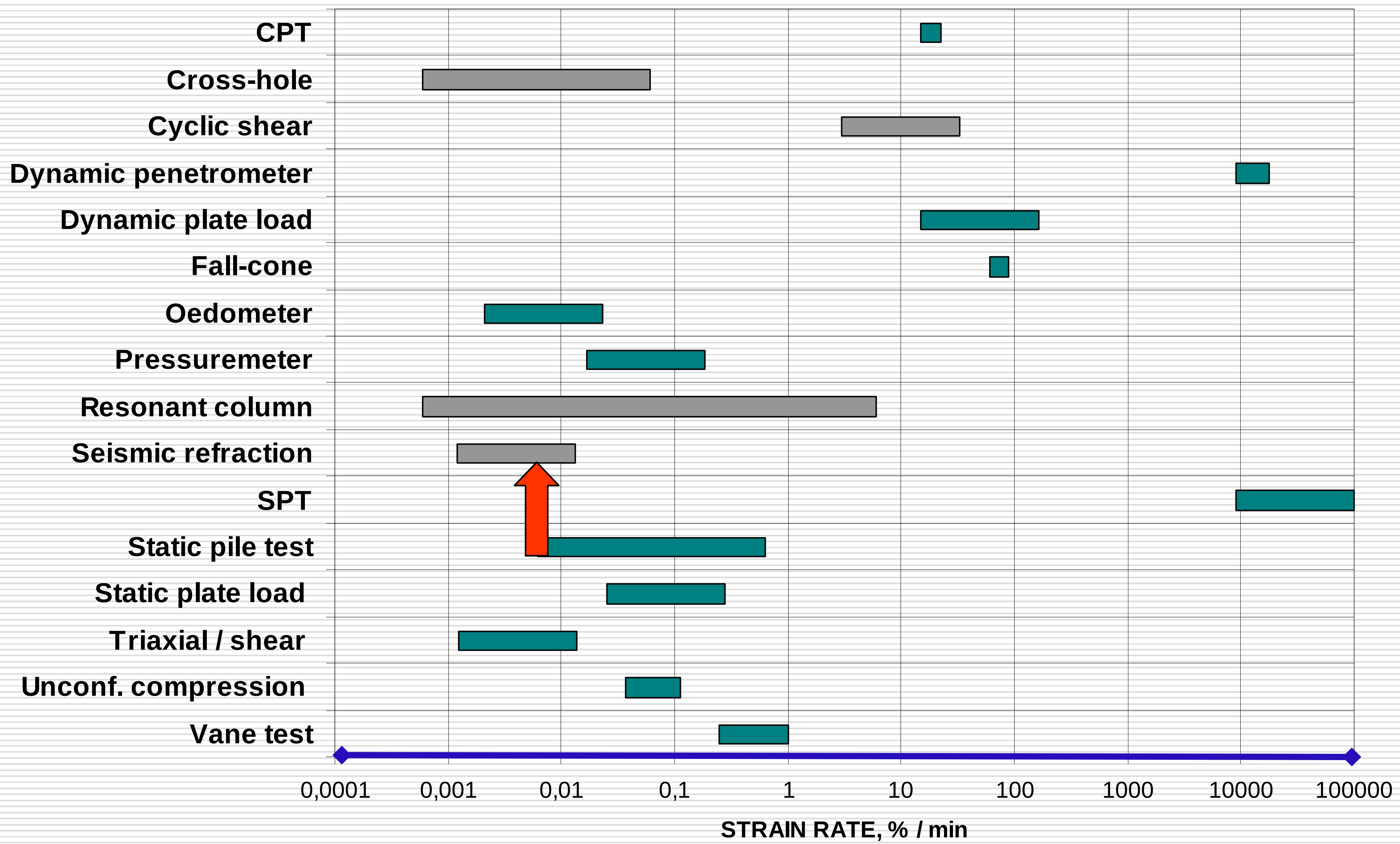
Load transfer from embankment to soil stabilized by columns.



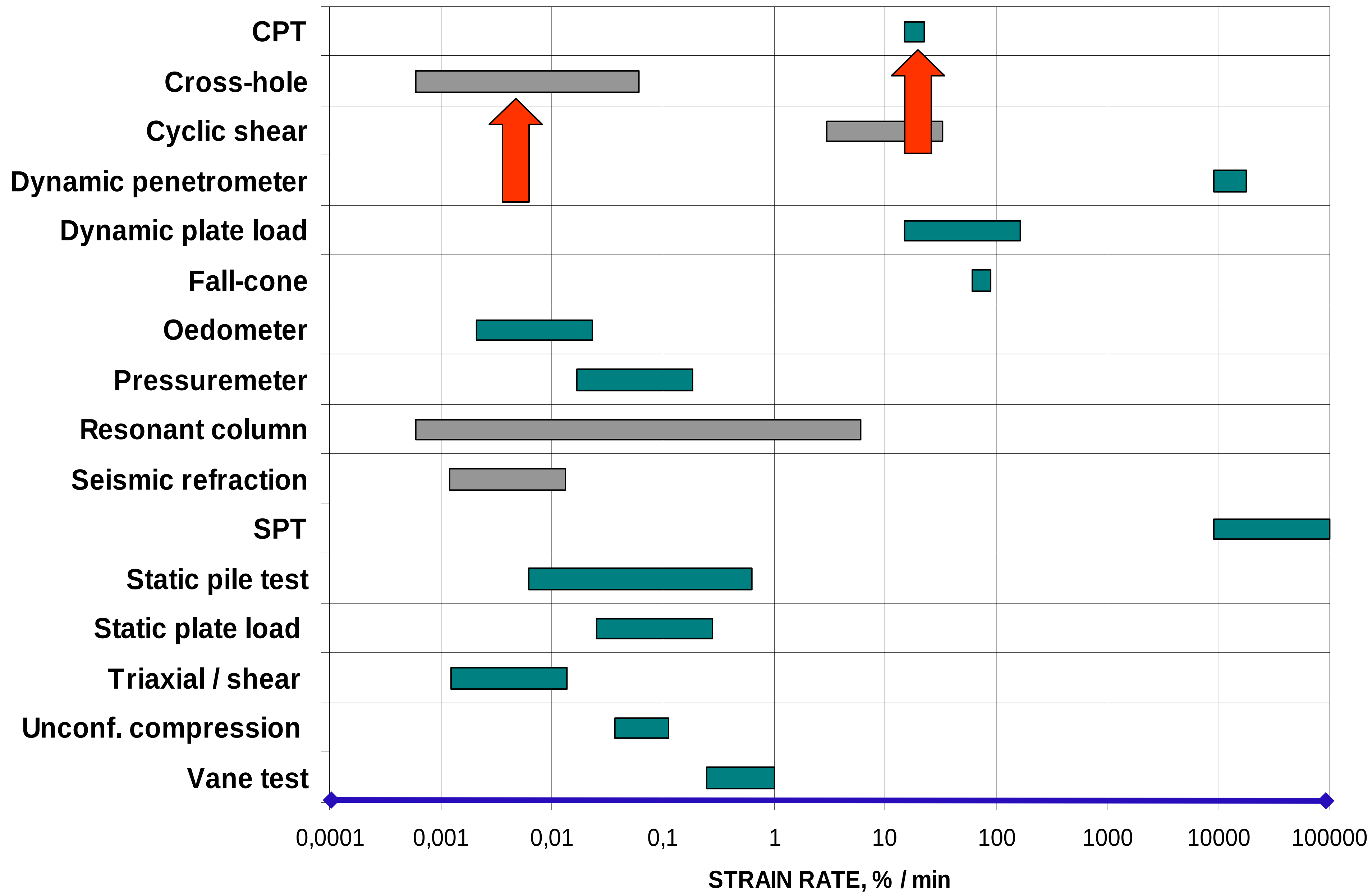
Stress-Strain Behaviour of Soils



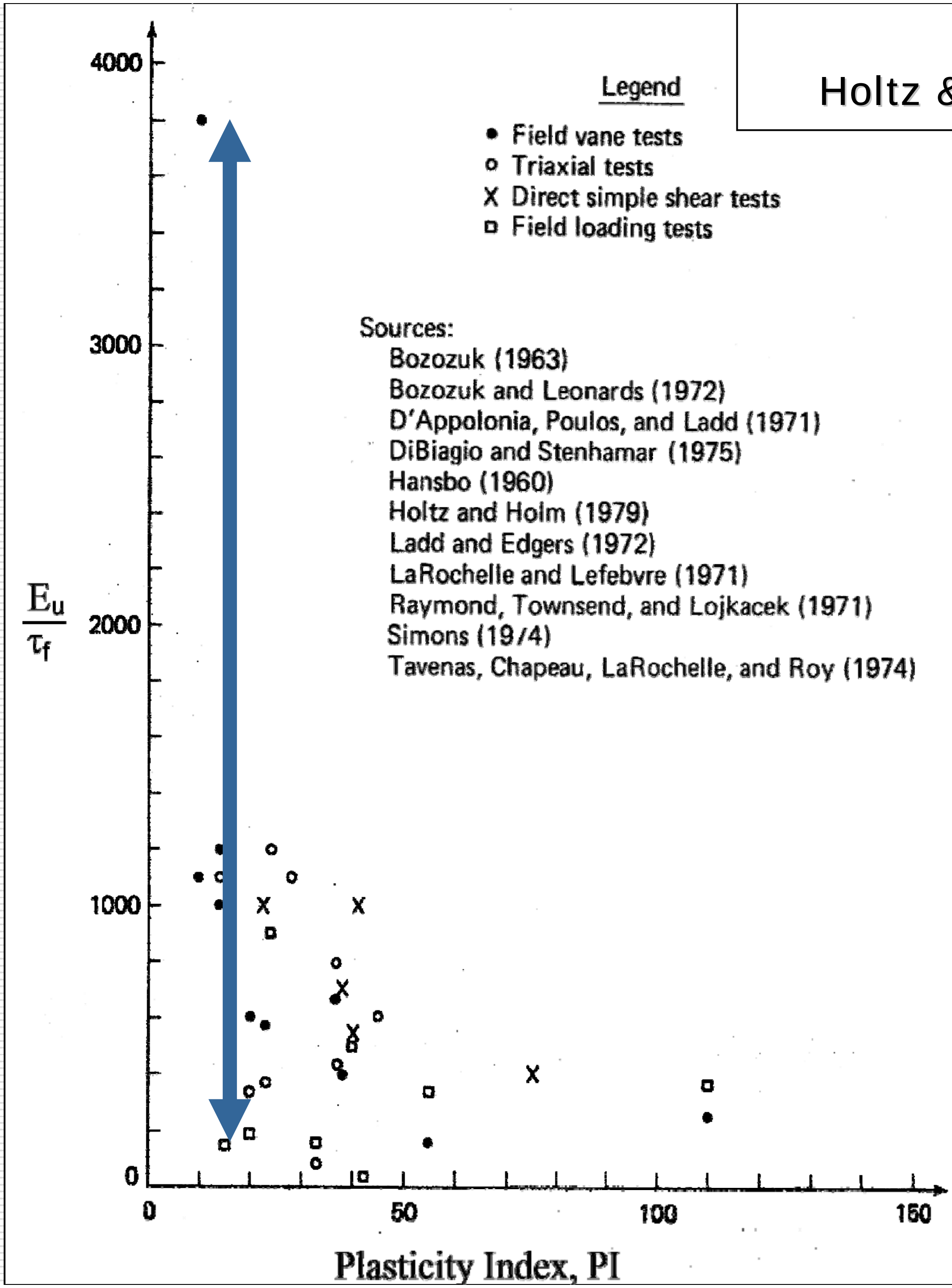
Typical Loading Rate during Testing



Typical Loading Rate During Testing



Holtz & Kovacs (1981)



Determination of Small-Strain Soil Modulus from Seismic Test

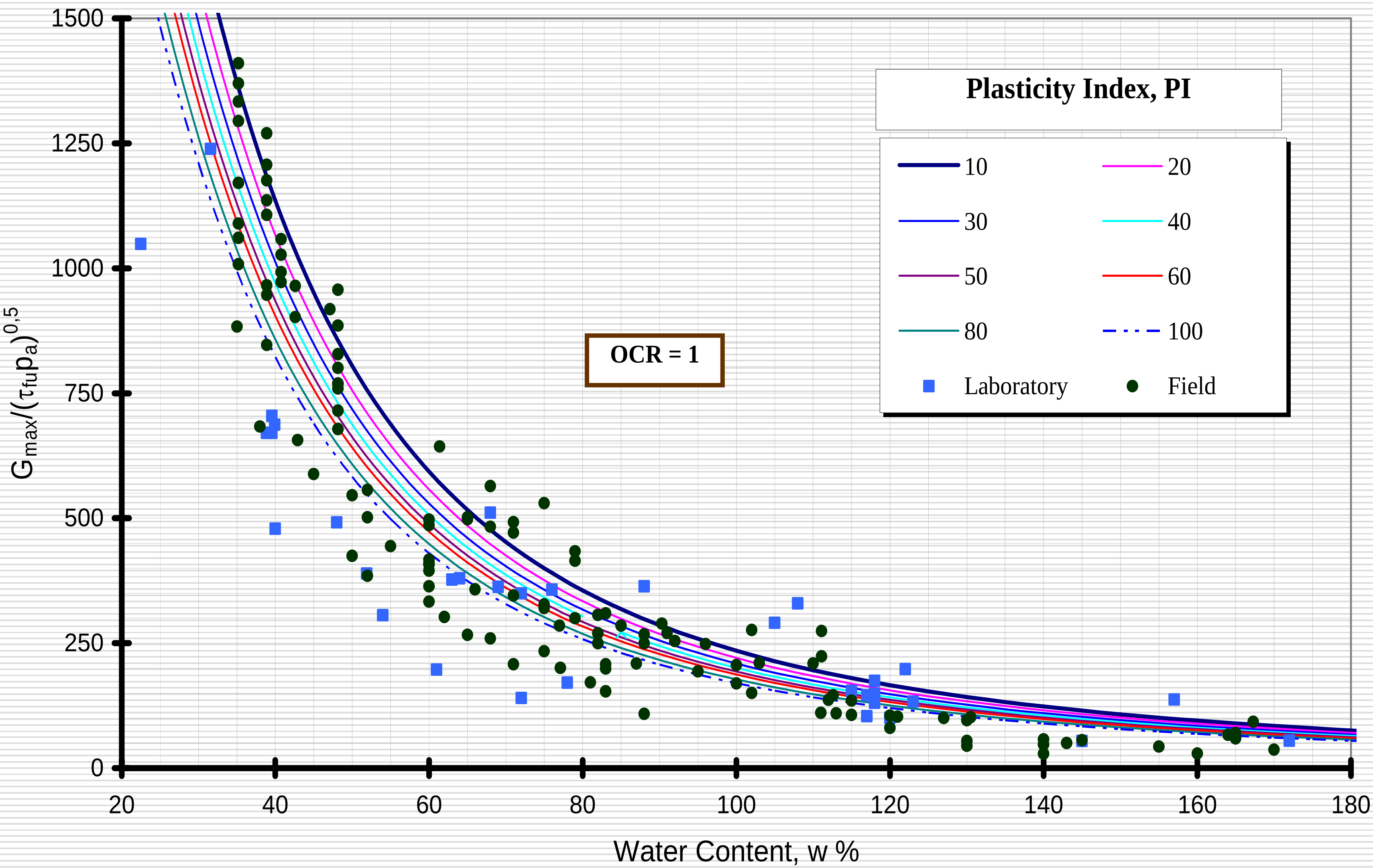
Small-Strain
Shear Modulus

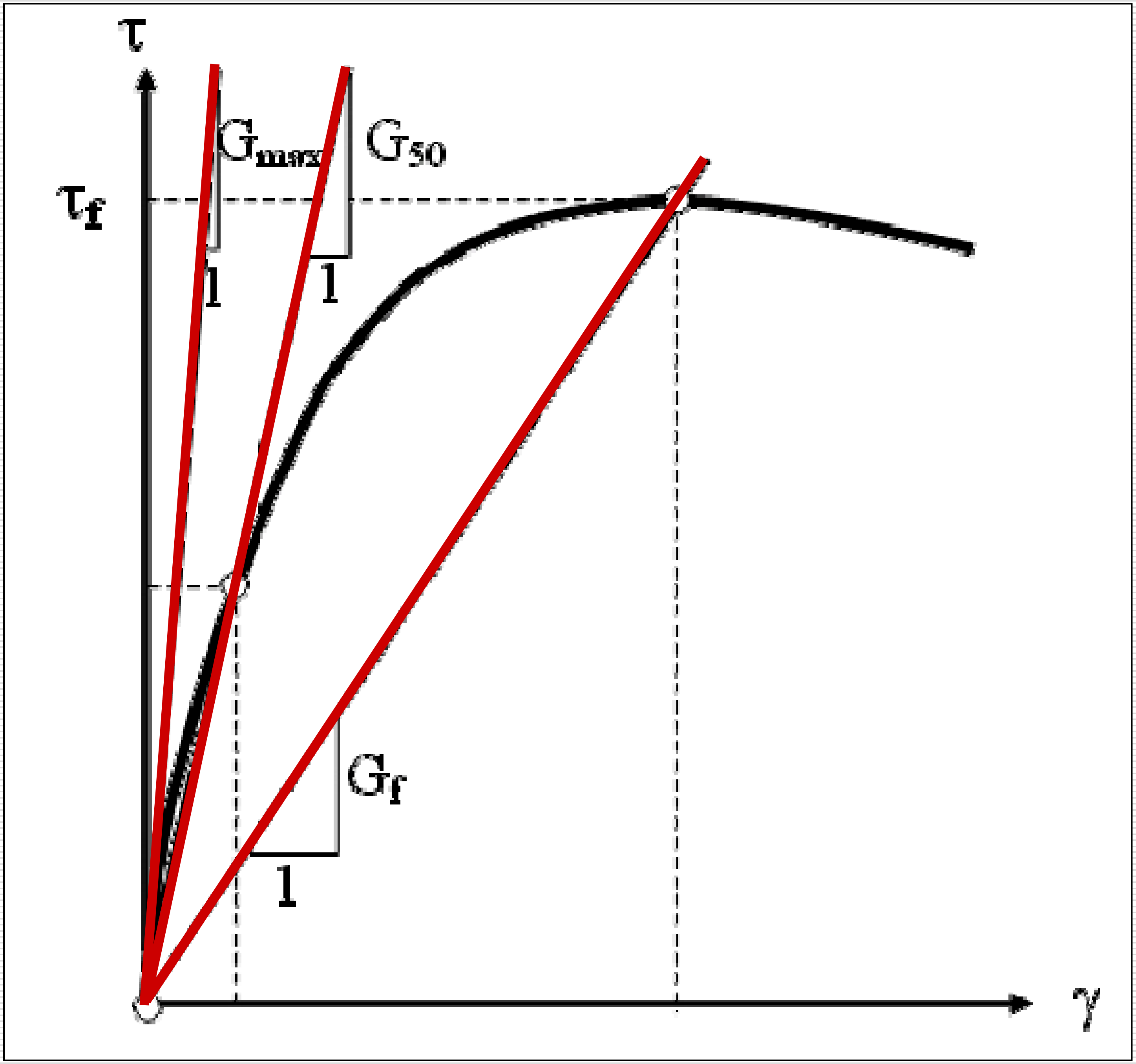
$$G_{\max} = \rho\, C_S^2$$

Confined Modulus

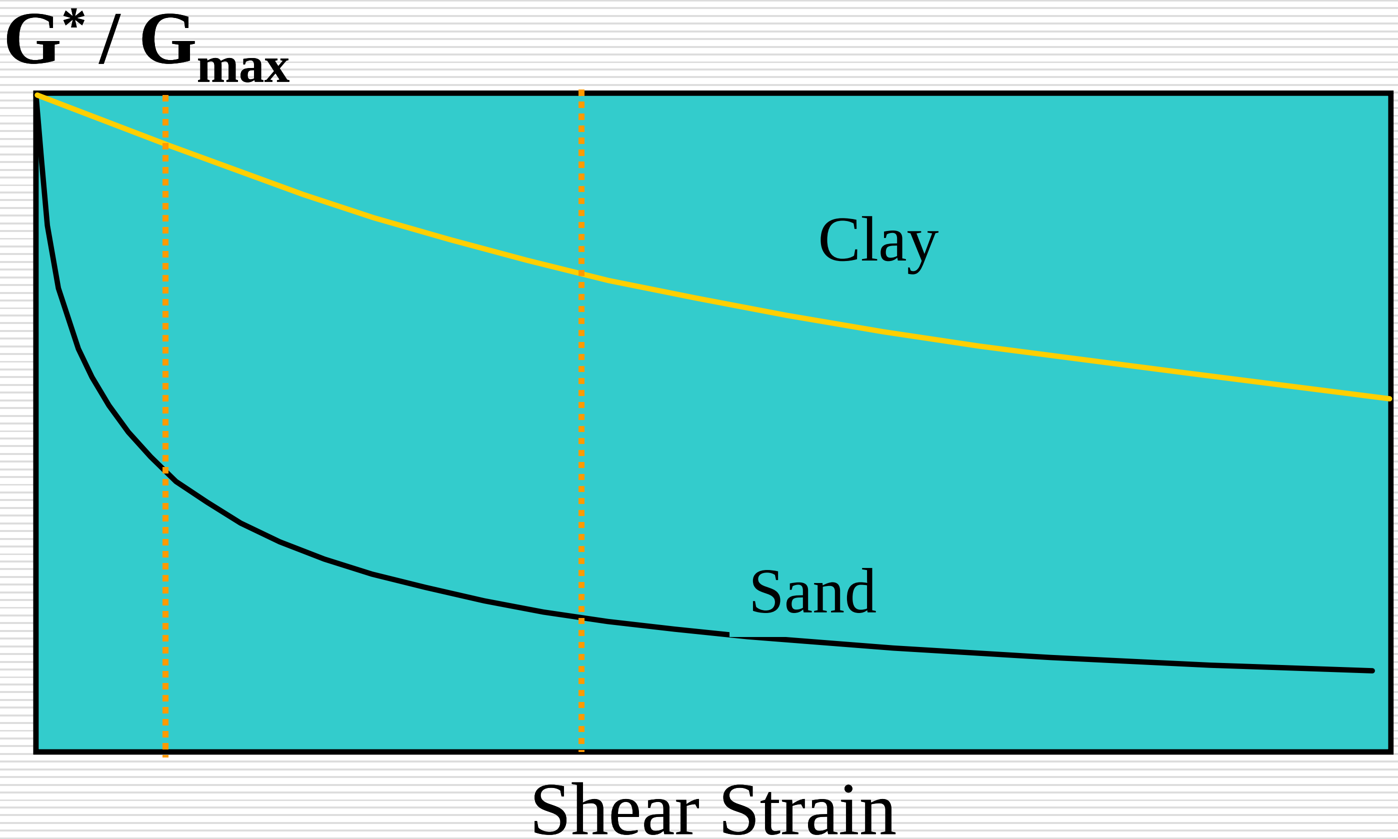
$$M_{\max} = \rho\, C_P^2$$

$$\frac{G_{\max}}{\sqrt{\tau_{fu} p_a}} = \frac{625}{\left[0.3 + 0.7\left(w_n \frac{\rho_s}{\rho_w}\right)\right]^2} OCR^k \sqrt{\frac{1 + 2K_0}{3(0.0029PI + 0.13)}}$$

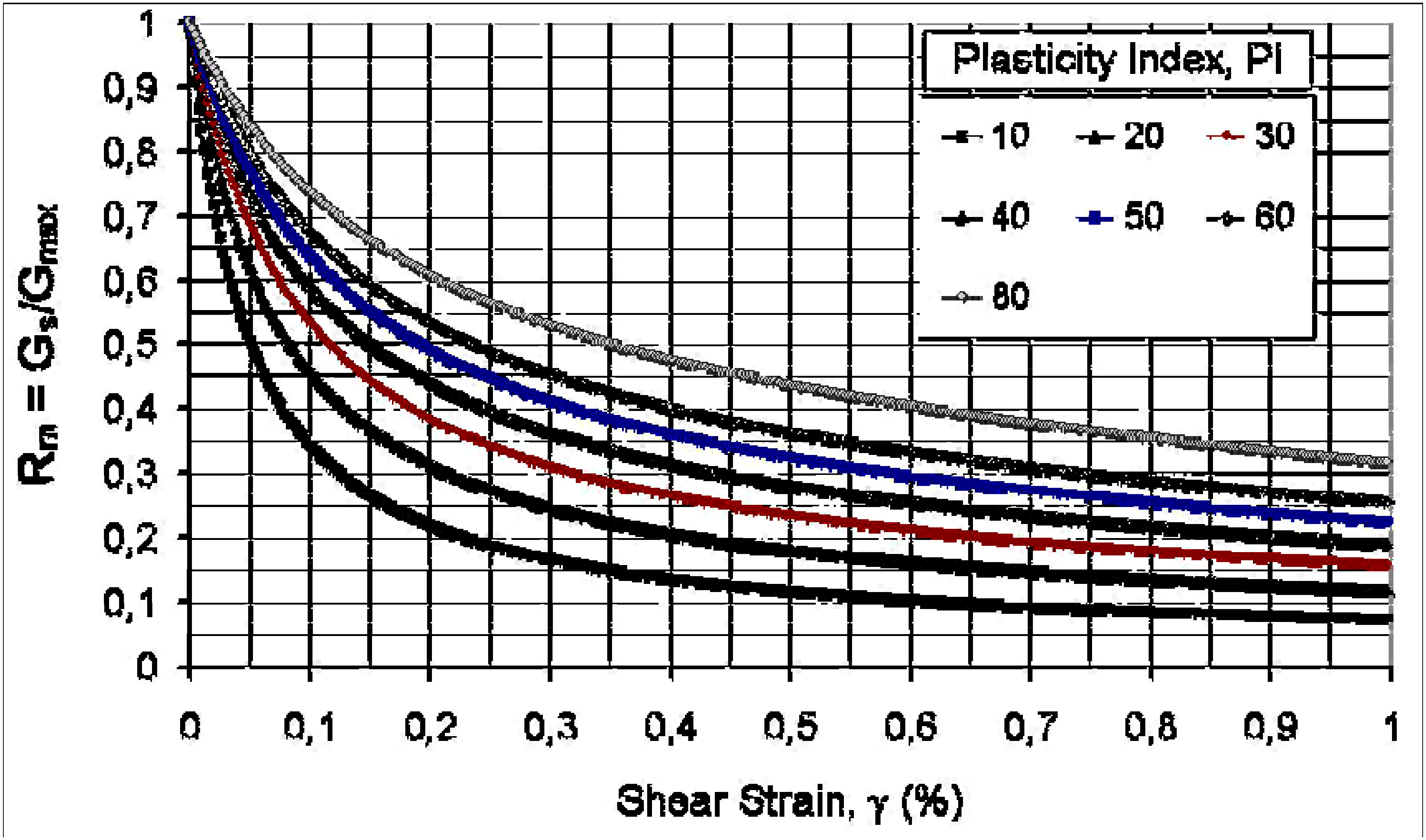



τ
G_{max}
G_{50}
τ_f
1
1
G_f
1
γ

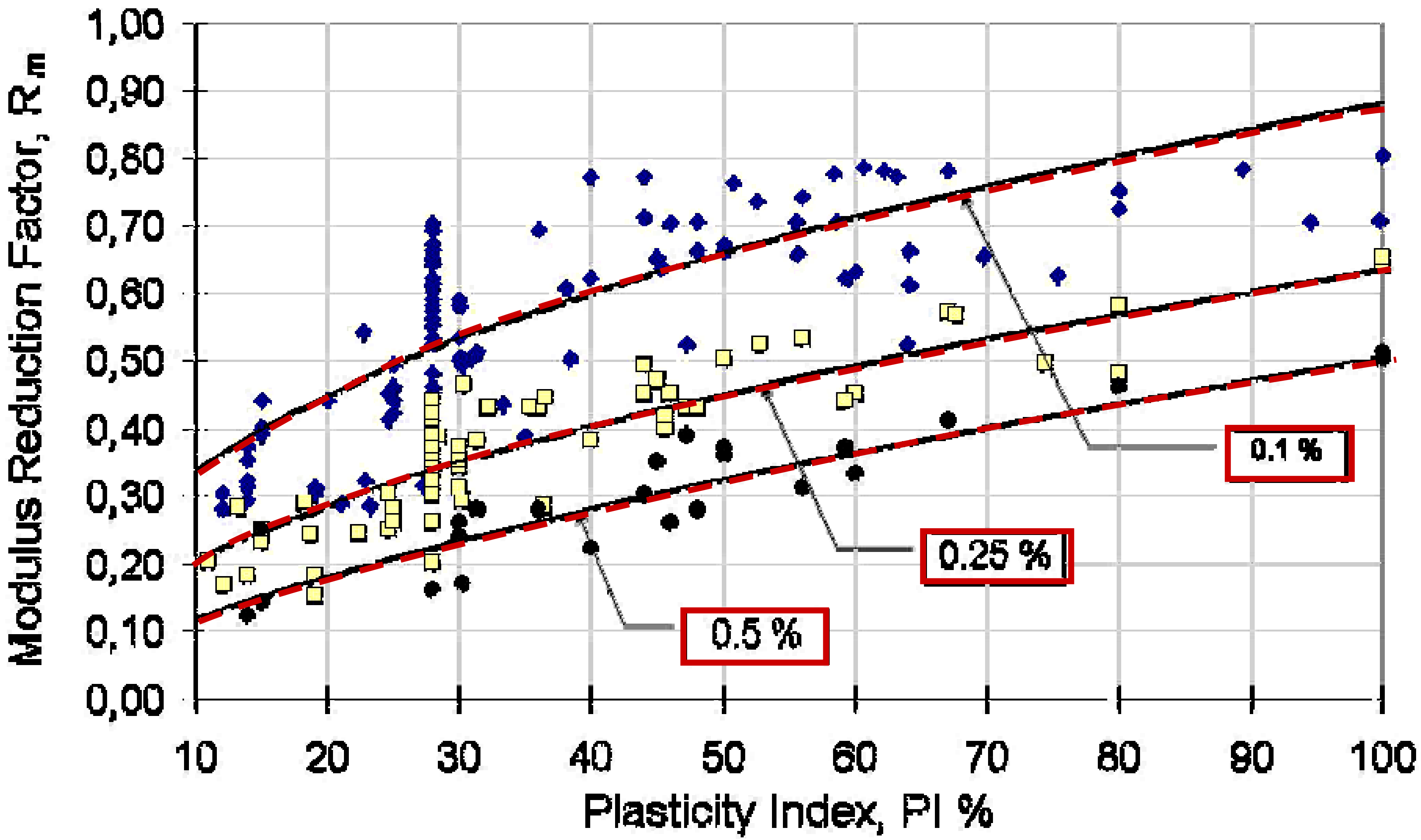
Reduction of Shear Modulus with Strain

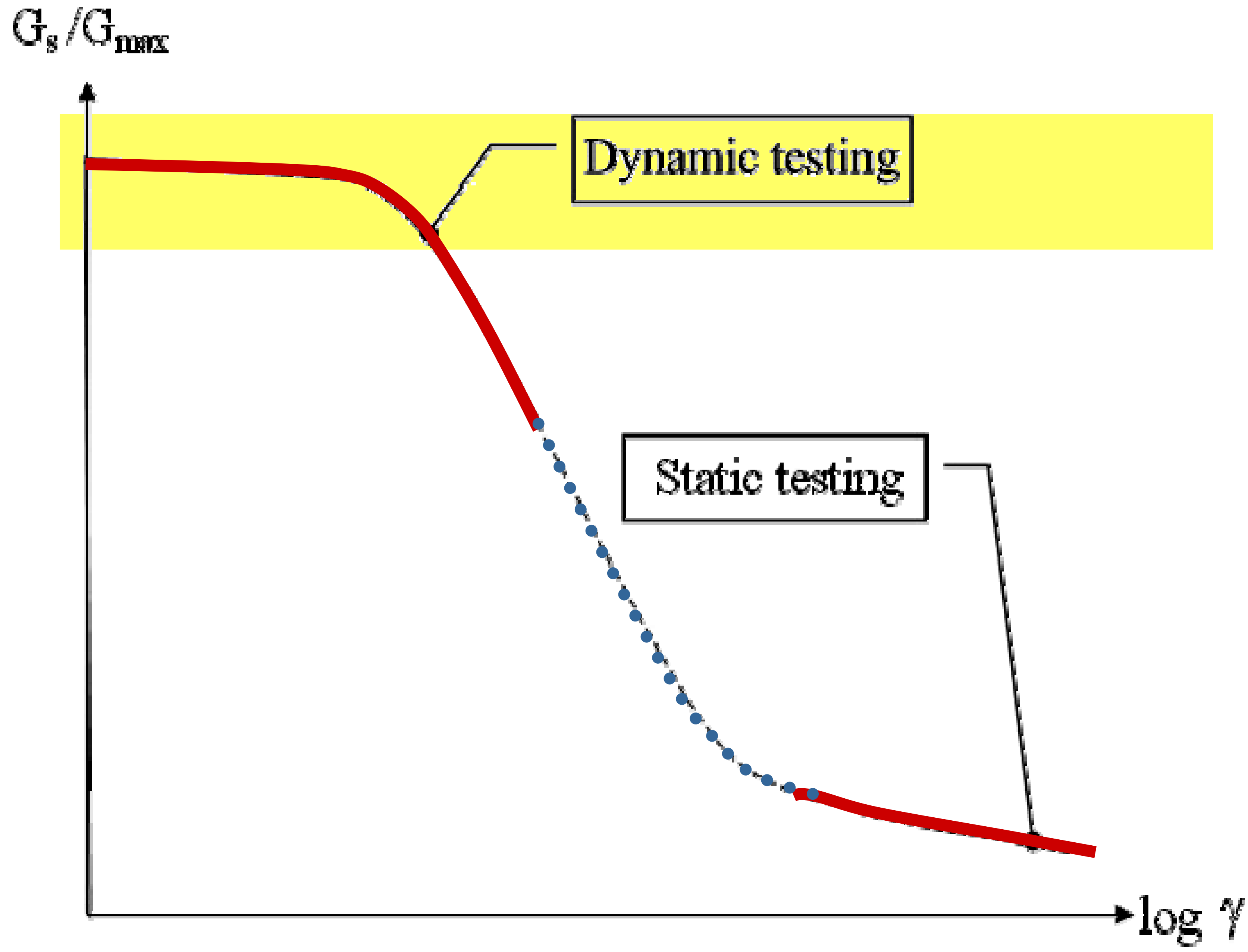


$$\frac{G_s}{G_{max}} = \frac{1}{\left[1 + a\,\gamma\left(1 + 10^{-\beta\gamma}\right)\right]}$$

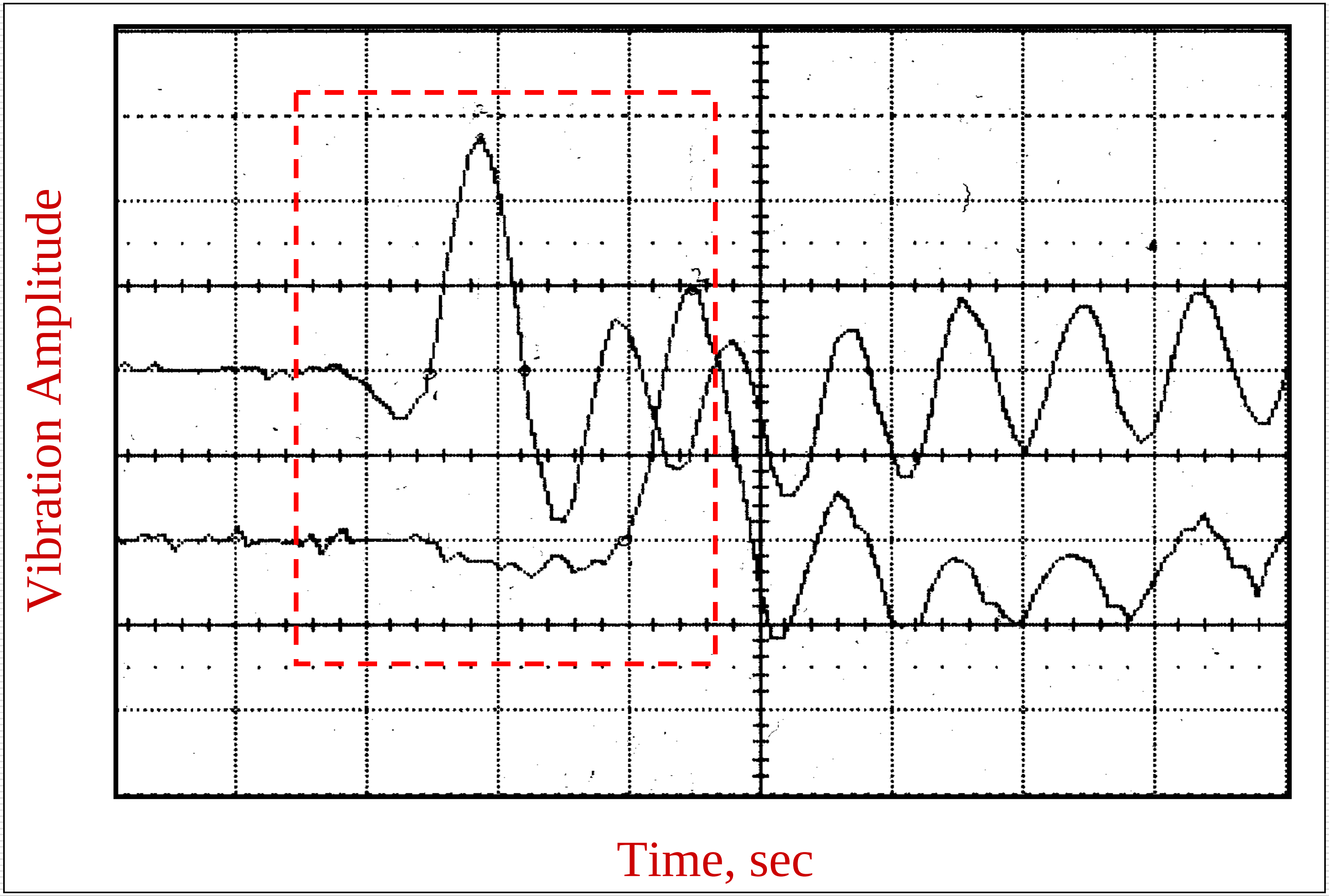


Modulus Reduction with Shear Strain





G_s / G_{max}
Dynamic testing
Static testing
log γ

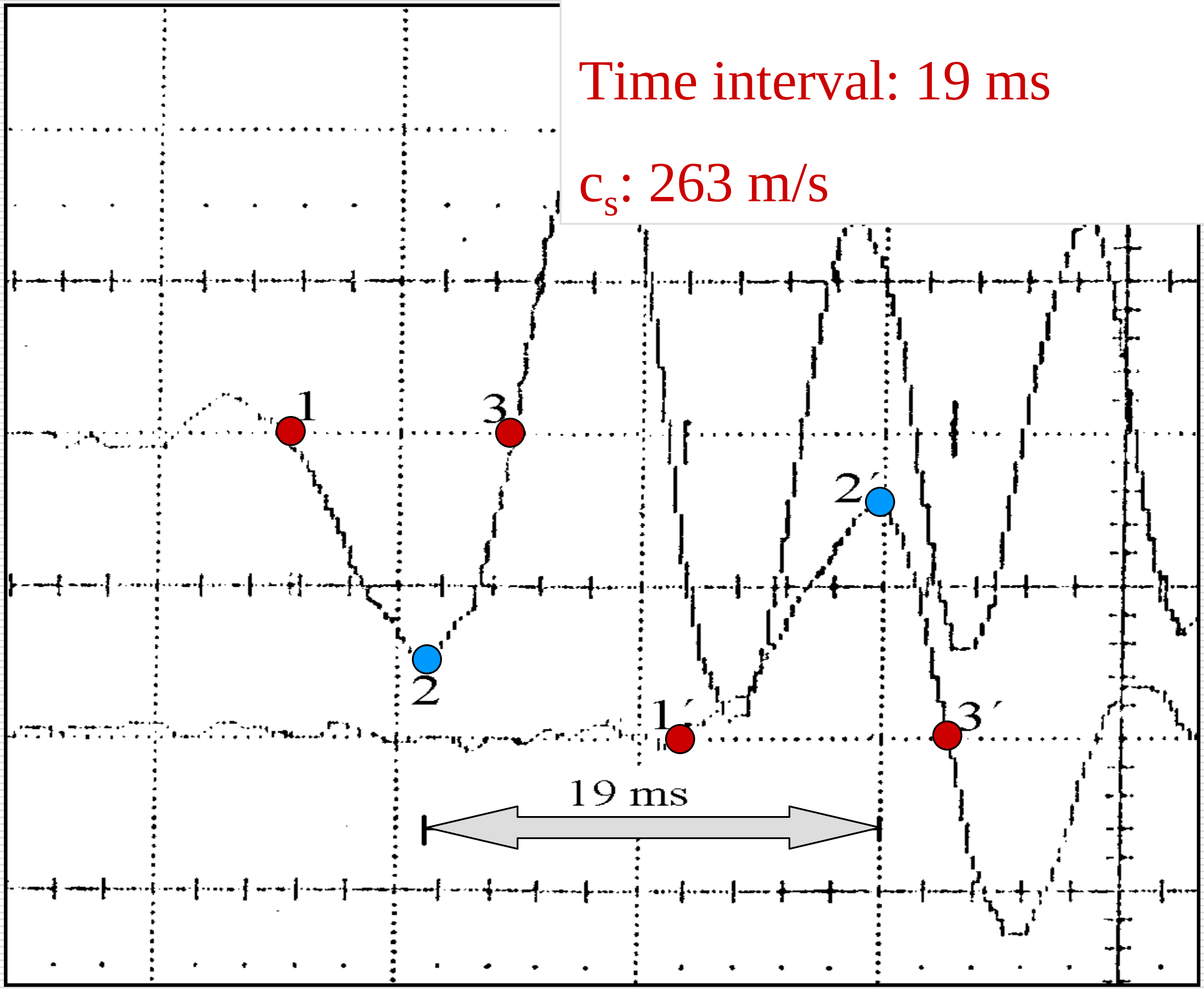

Vibration Amplitude
Time, sec

Determination of first arrival time and time intervals

Distance between sensors: 5 m

Time interval: 19 ms

c_s: 263 m/s



Seismic Field Tests

CLAY

τ_{fu} = 15 kPa
w = 80 %

c_s = 40 m/s

G_{max} = 2.9 MPa

DM COLUMN

50% Lime-cement
LC-content 22 – 44 kg/m

c_s = 250 - 350 m/s

G_{max} = 165 MPa

$$G_{max} = C_s^2 \ \rho$$

$$G = R_G G_{max}$$

R_G = 0,35 at 0.5 % shear strain

G_{max} = 1.0 MPa

R_G = 0.35 at 0.5 % shear strain

G_{max} = 58 MPa

Seismic Field Tests

Soft Clay

τ_{fu} = 15 kPa

w = 80 %

c_s = 40 m/s

G_{max} = 2.9 MPa

2%

R_G = 0,35 at 0.5 % shear strain

G_{max} = 1.0 MPa

$$G_{max} = C_s^2 \rho$$

$$G = R_G G_{max}$$

Dry Mixed-in-Place Columns

50% Lime/cement

LC-content 22 – 44 kg/m

c_s = 250 - 350 m/s

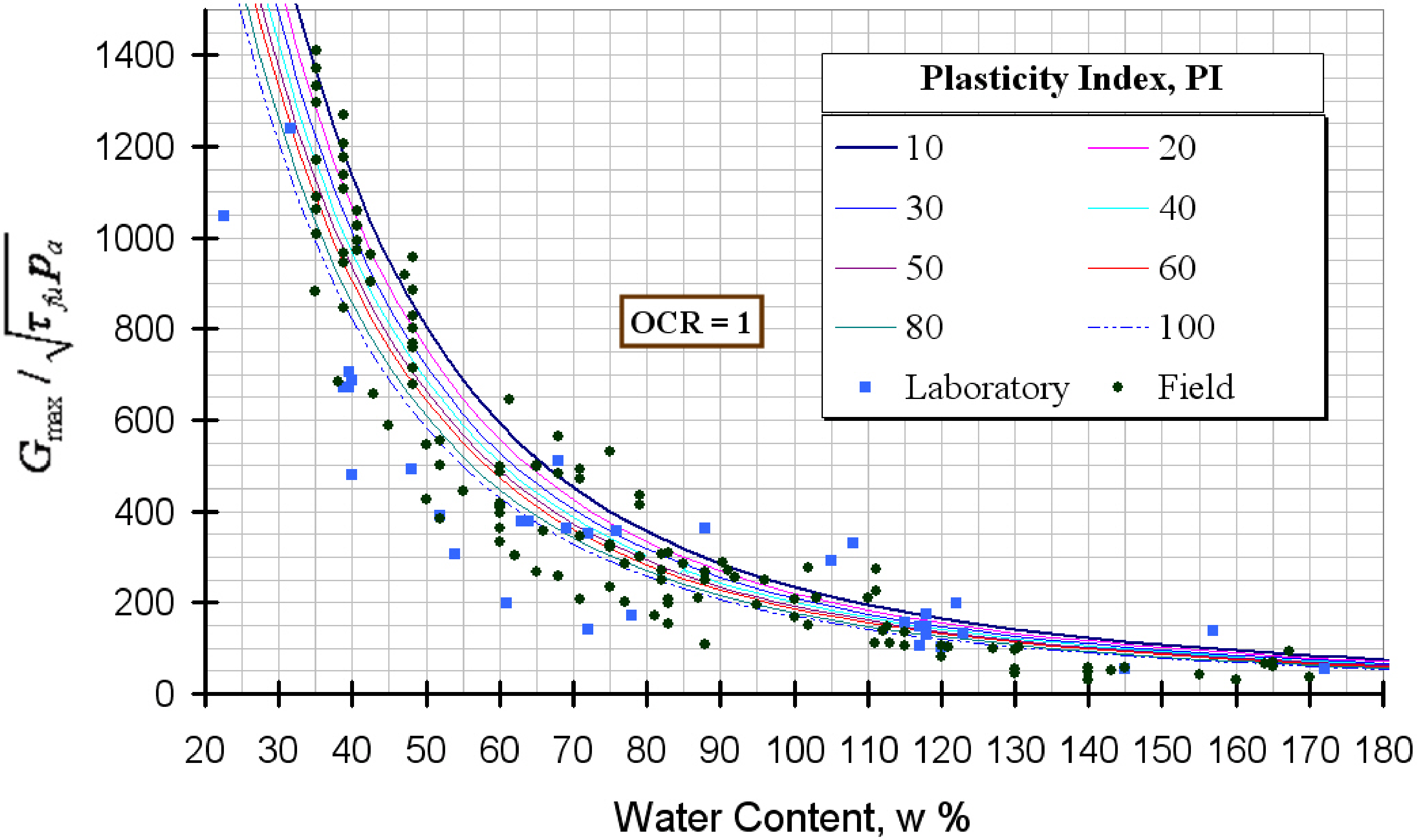
G_{max} = 165 MPa

58 times higher

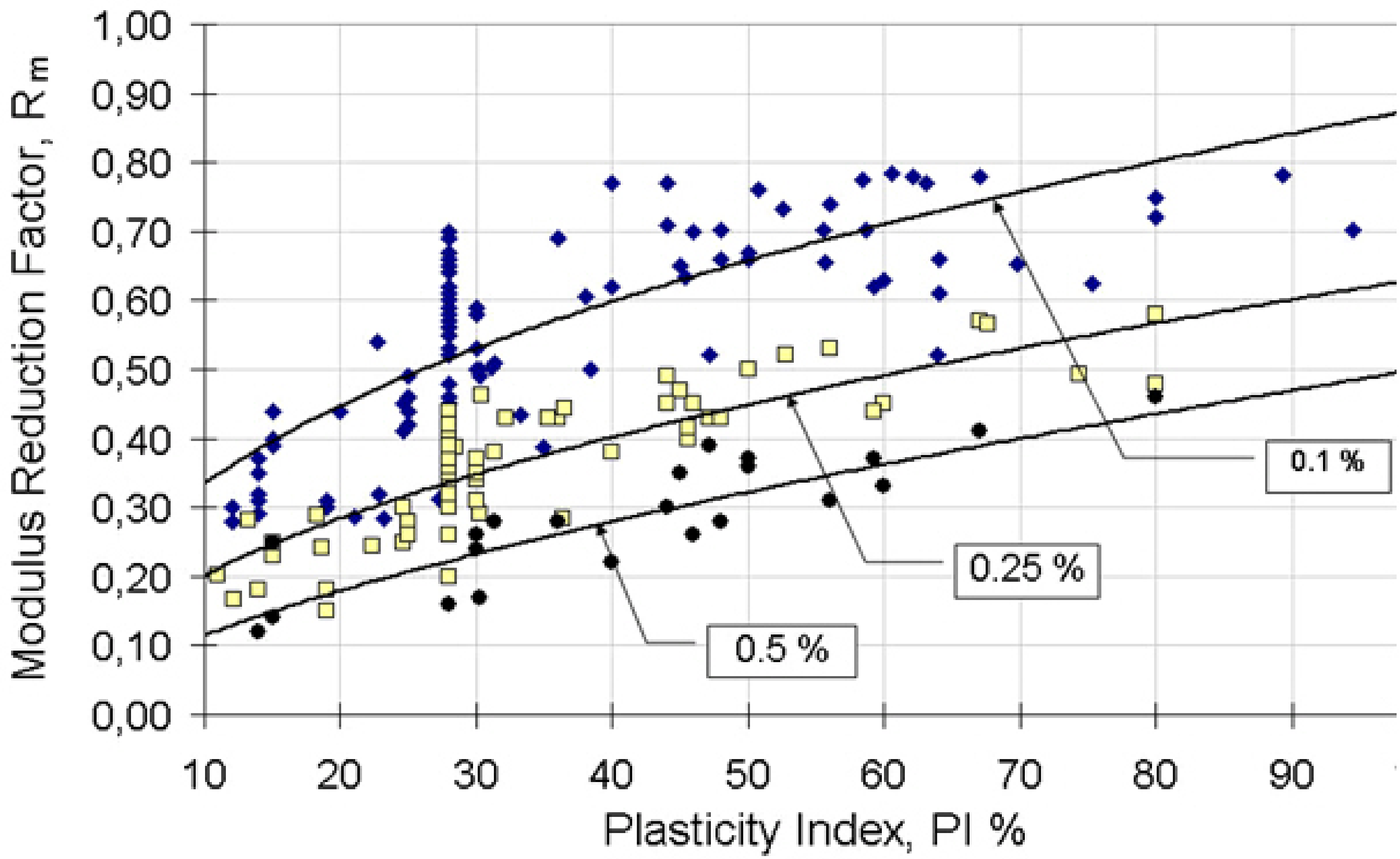
R_G = 0.35 at 0.5 % shear strain

G_{max} = 58 MPa

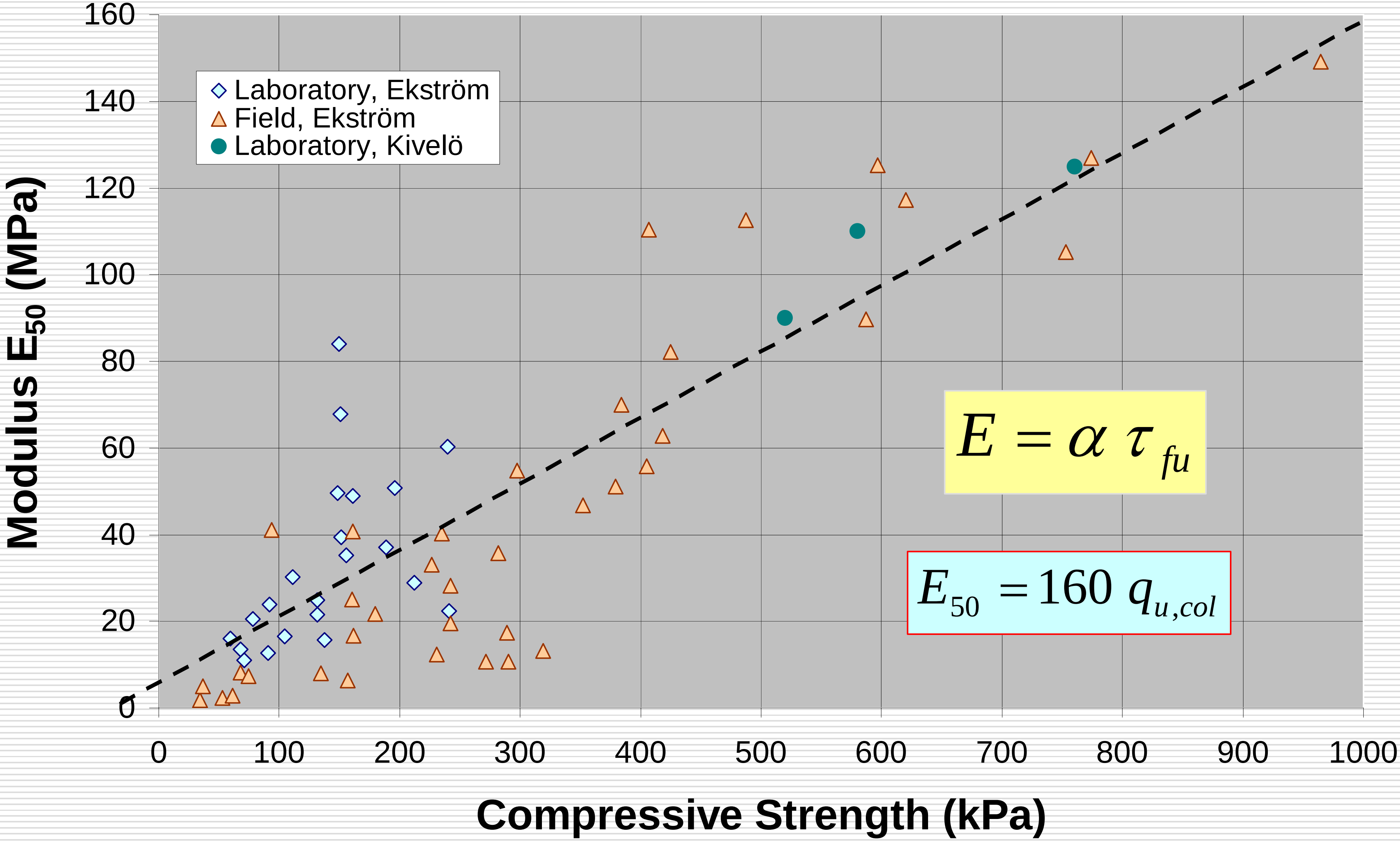
Relationship between the normalized shear modulus at small strains, *Gmax* and the water content



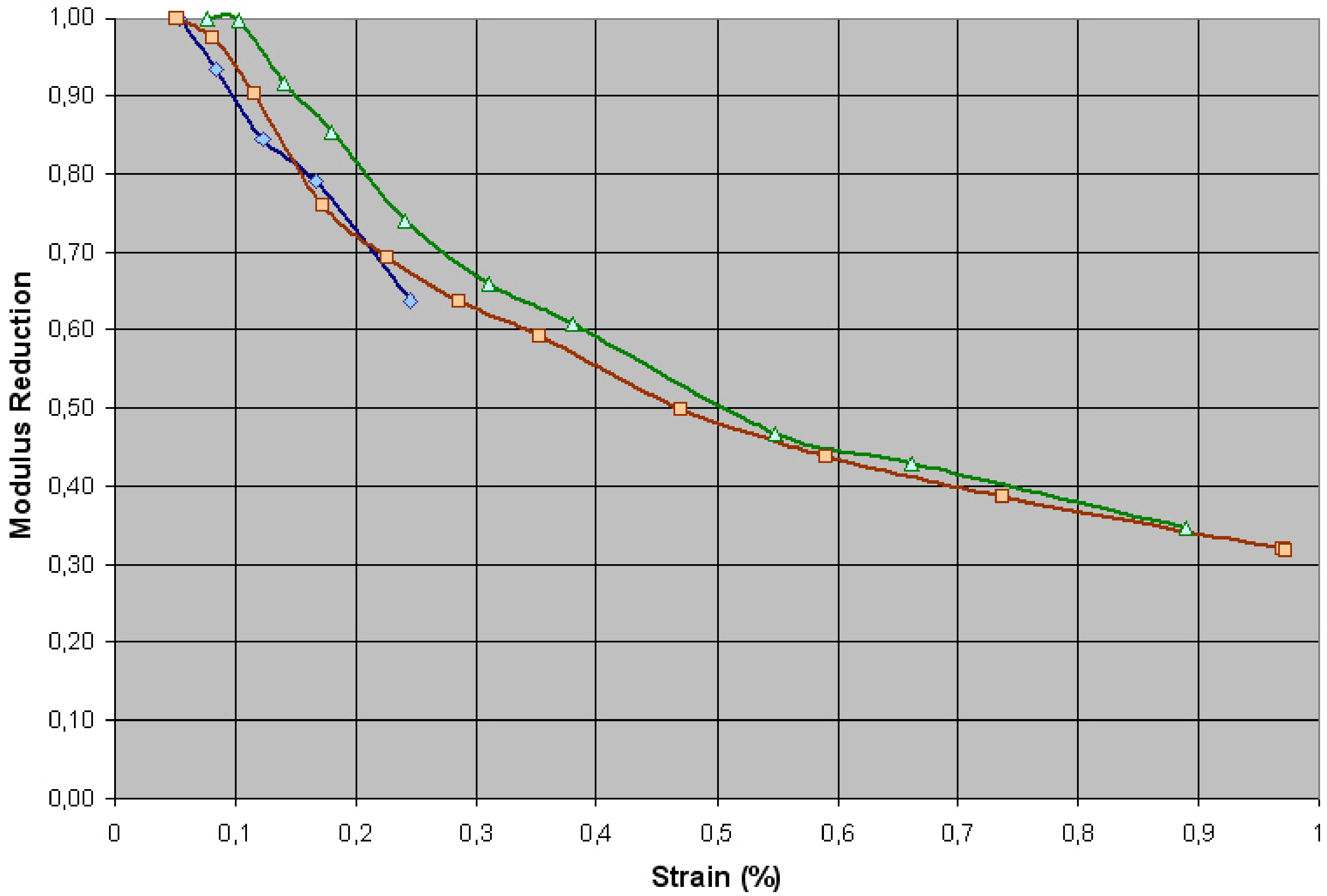
Modulus reduction factor, R_m as function of the plasticity index, *PI* at three strain levels



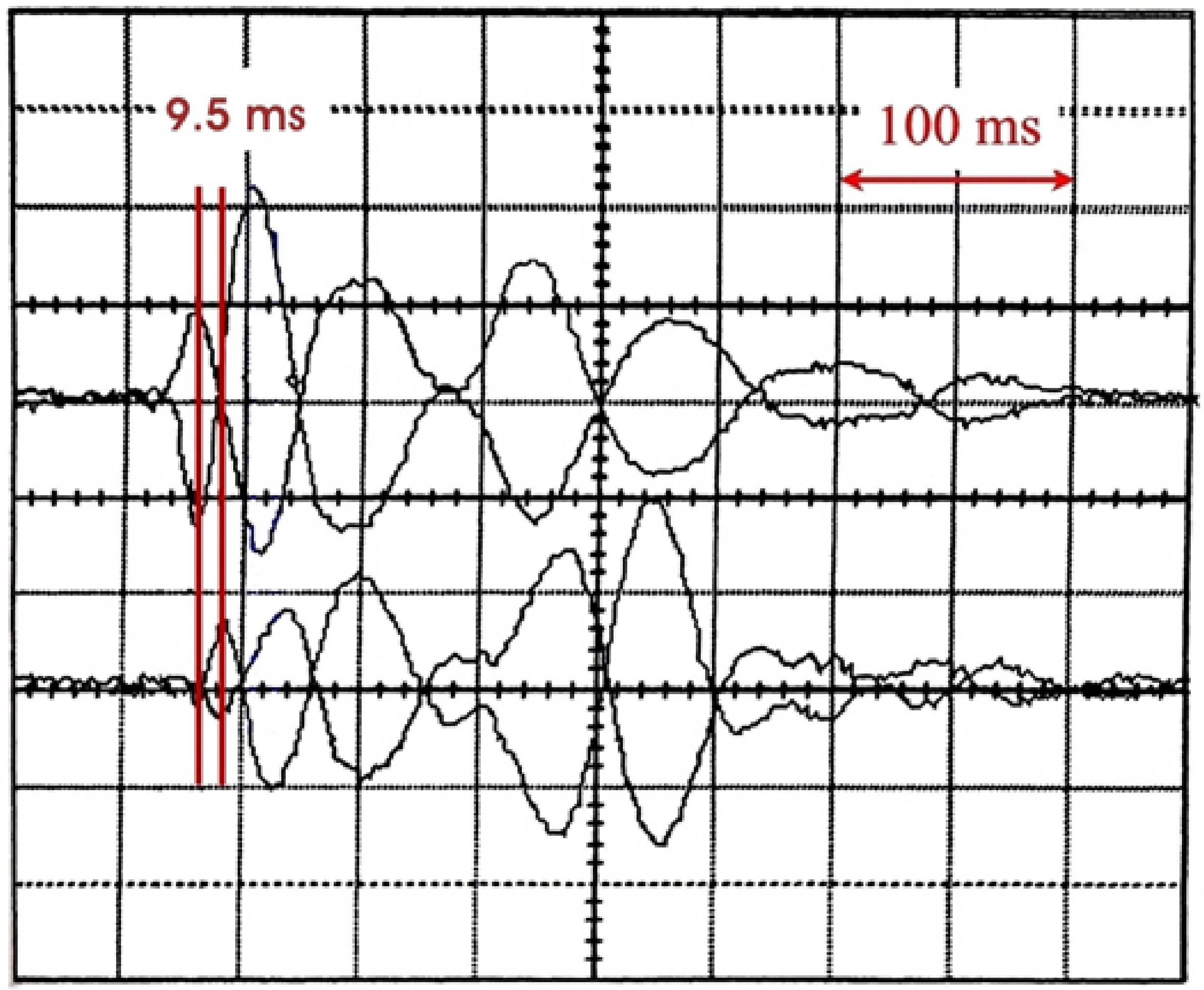
Relationship between Unconfined Compressive Strength, $q_{u,col}$ and Modulus of Elasticity, E_{50}.



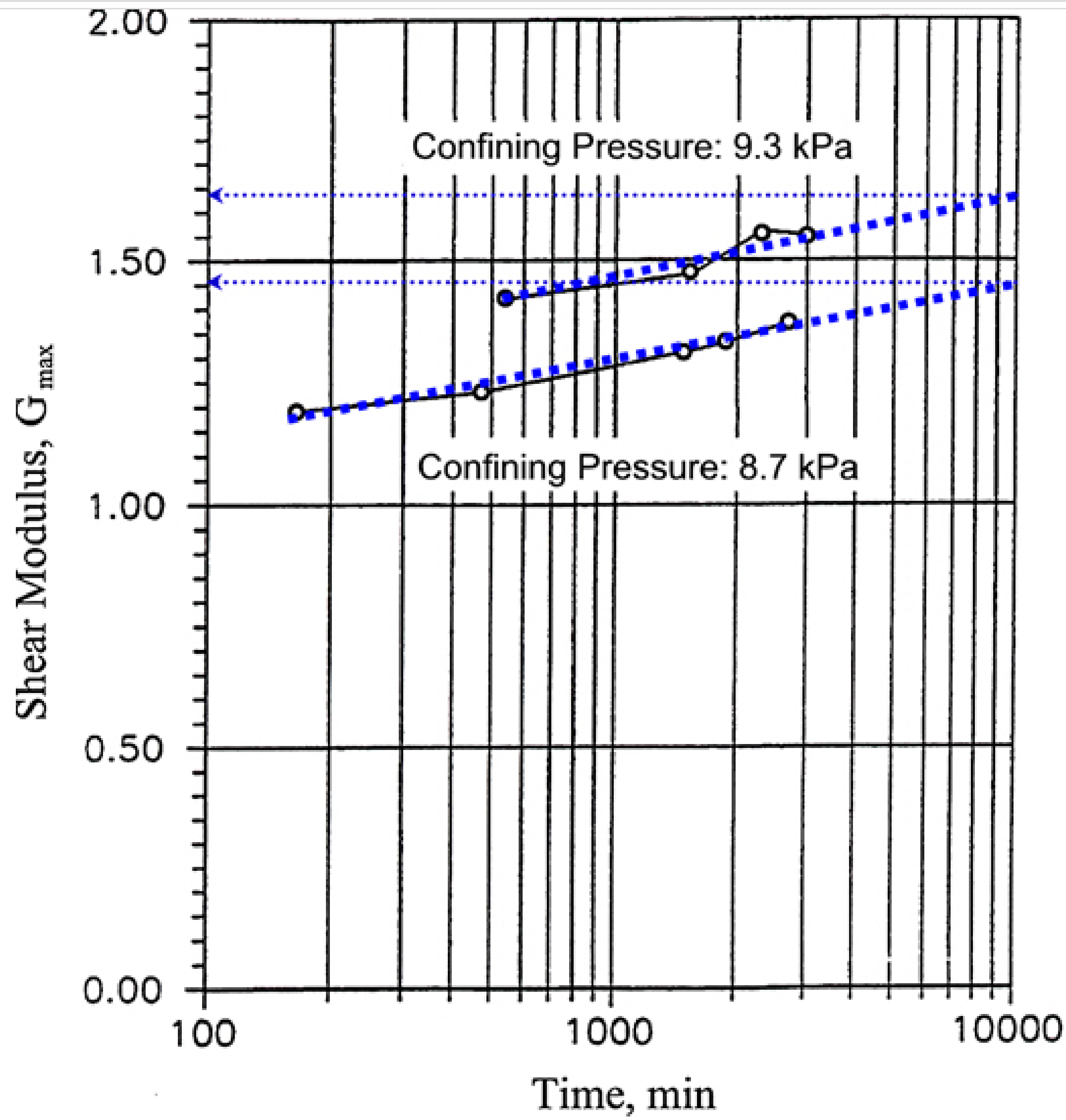
Reduction of compression modulus from field load tests on LC columns



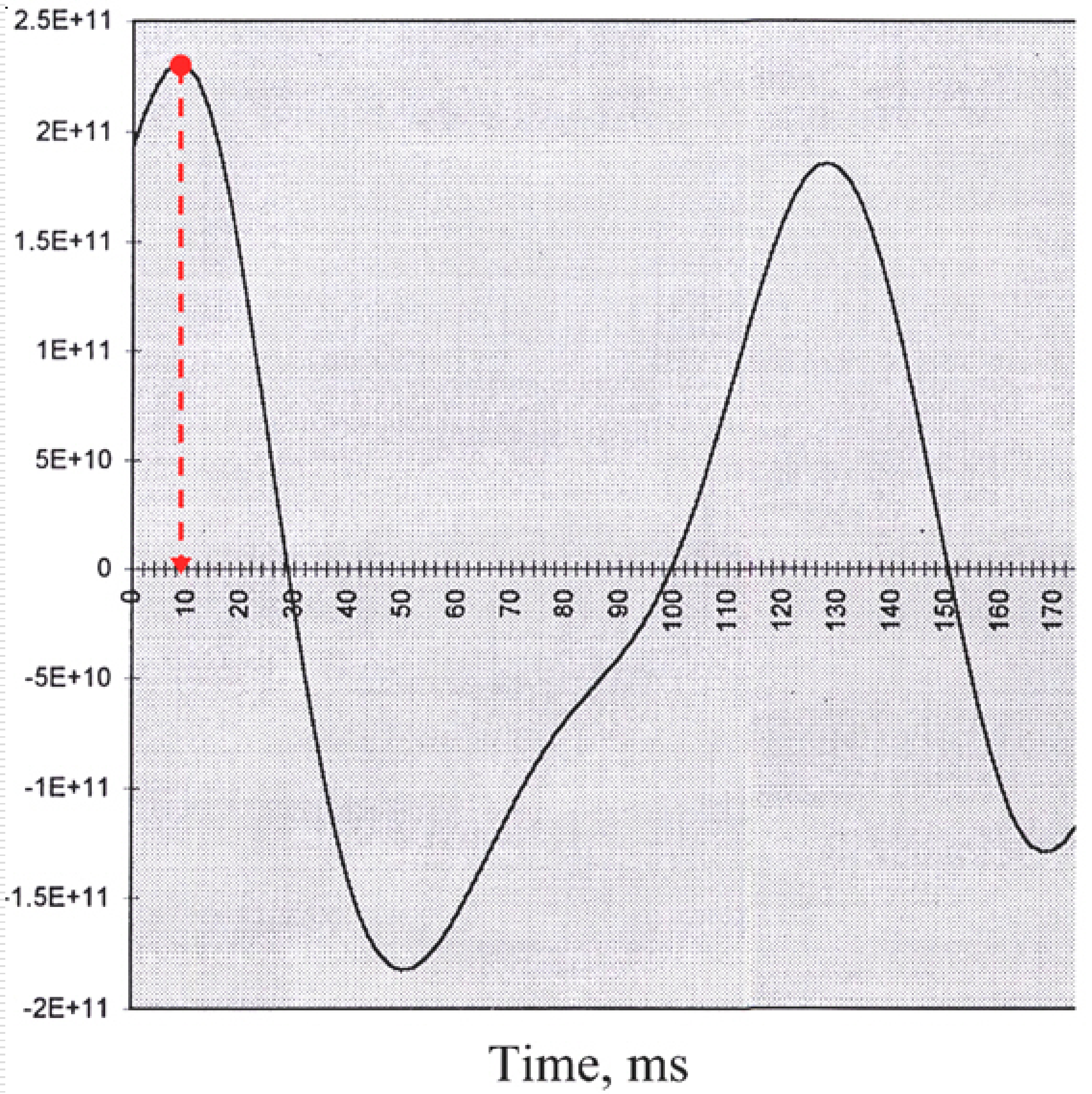
Signal from reverse impact test (depth interval 2.5 to 5.5 m) in column (156 kg/m3), 41 days after installation



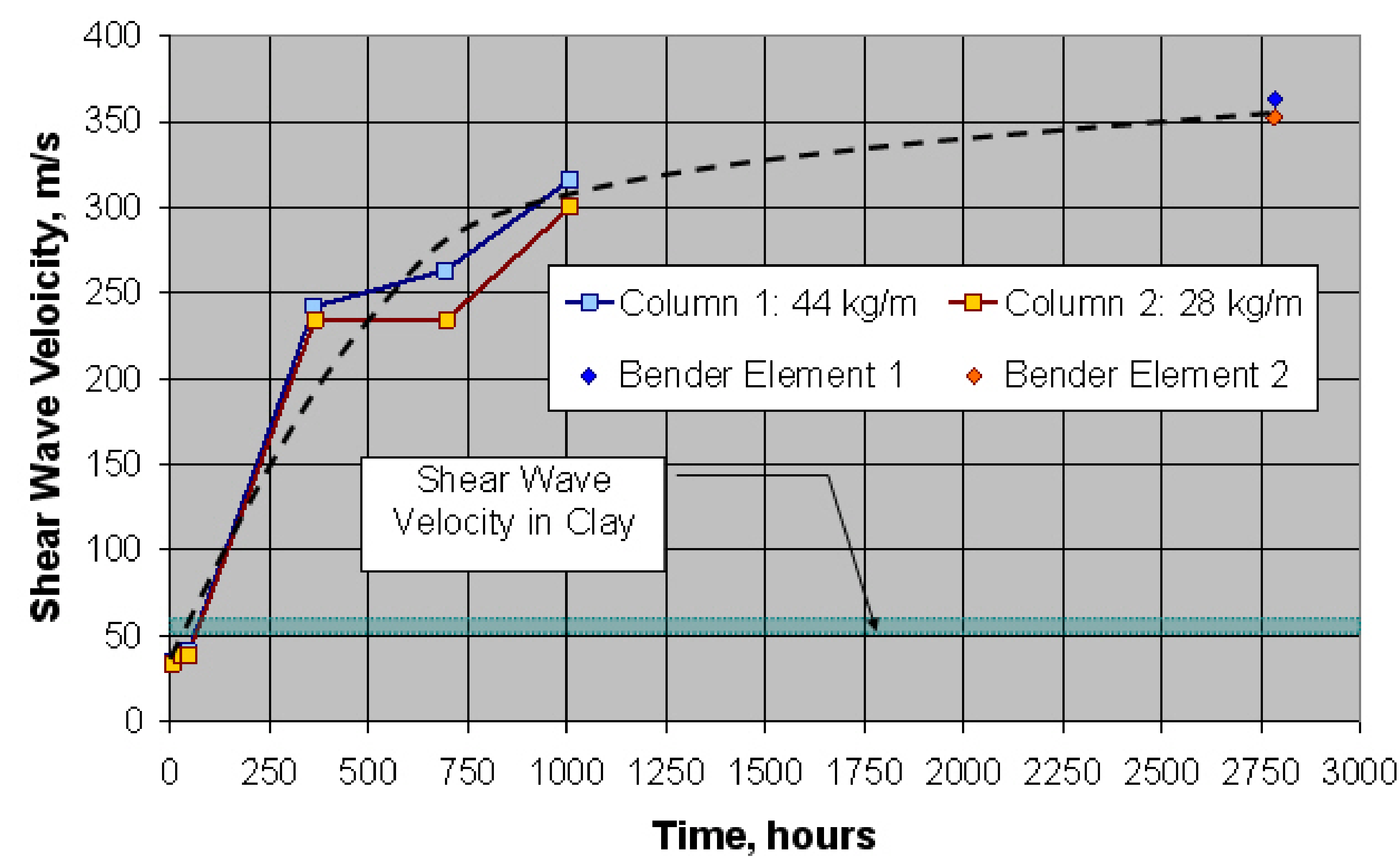
Shear modulus determined on clay sample at two different confining stresses.



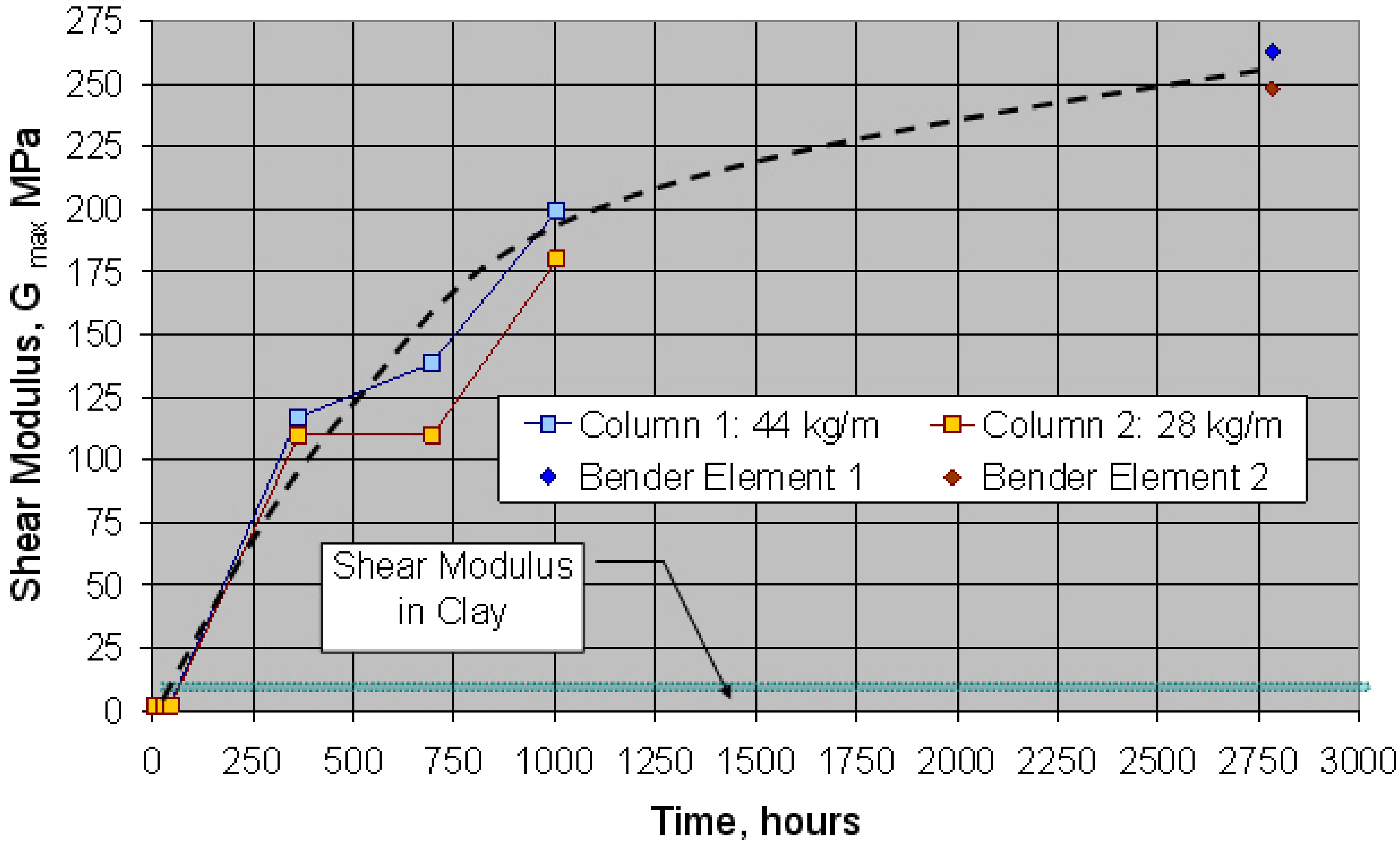
Determination of the shear wave velocity by cross-correlation of the signal



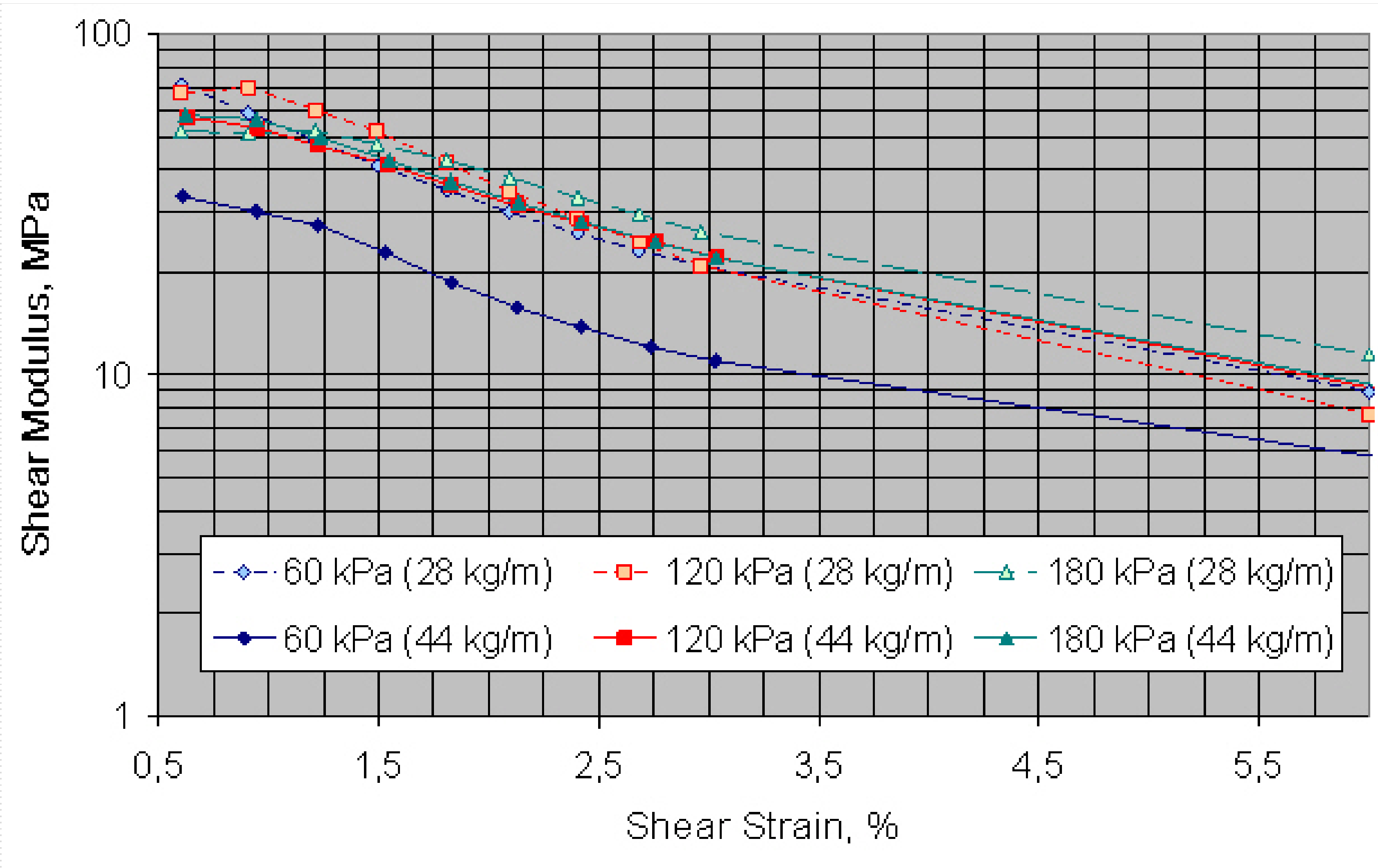
Variation of shear wave velocity with time, determined in-situ by down-hole tests and in the laboratory by bender element tests



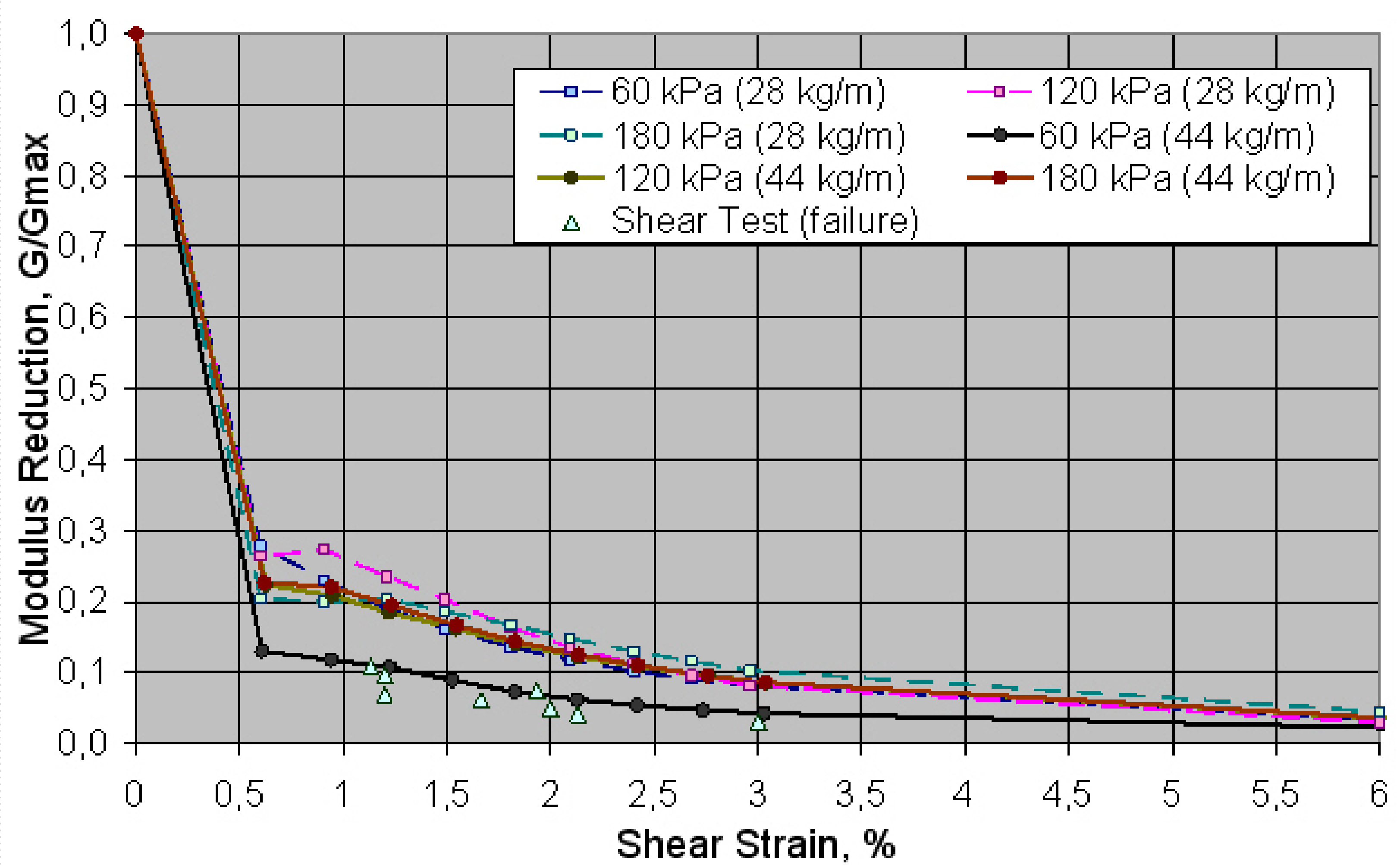
Variation of shear modulus Gmax with time after installation of LC columns



Shear modulus determined from triaxial tests within shear strain range of 0.5 to 6 %



Decrease of shear modulus with shear strain for triaxial and direct shear tests



Shear strength of samples from LC columns determined by triaxial and direct shear tests