Borehole Deformability Testing

Borehole deformability tests are used for in-situ modulus measurements in boreholes. Instrument setups can be broken down into two groups according to the area of application: Low pressures and long displacements are required in soils, high pressures and relatively short displacements in rock. The following methods exist to meet the particular requirements:

1. Hydraulic cylinders combined with clamshell-type loading plates and electric displacement transducers (borehole jack devices)
2. Hose packers with volumetric determination of borehole deformability (MÉNARD pressuremeter)
3. Hose packers combined with electric displacement transducers (flexible dilatometer)

The advantage of solution 1 is the high pressures that can be applied by way of the cylinders. Its disadvantage, particularly in rock, are the clamshell-type loading plates, which have to be adapted exactly to the borehole diameter because otherwise the hydraulic pressure will only be transferred to the borehole wall as a linear load. SWOLFS and KIBLER (1982) as well as SHURI (1981) drew attention to this problem, after which the use of this type of probe in rock declined notably (see Fig. 1).

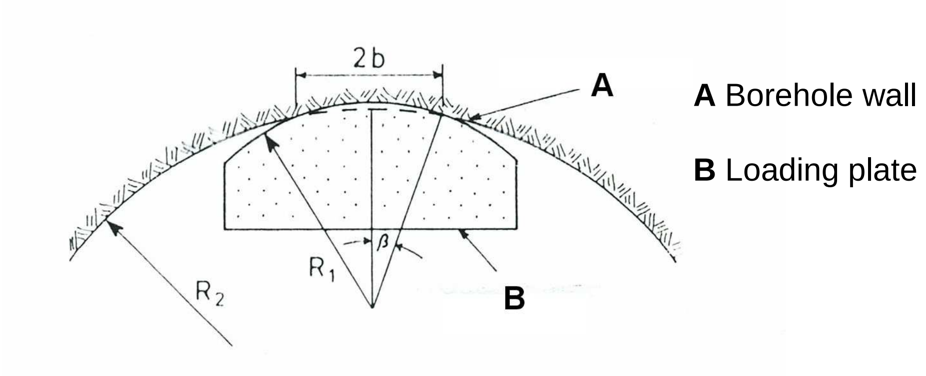

Fig. 1 Incomplete contact between loading plate and borehole wall in a borehole with a radius bigger than the radius of the loading plate camber (from BECKER, 1985)

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In soil and soft rock, on the other hand, the loading plates can press themselves into the foundation, ensuring complete contact with the surroundings.

This type of probe is available in three different diameters:

- GOODMAN probe (borehole diameter 76 mm)
- Ettlinger borehole jack device 101 (borehole diameter 101 mm)
- Ettlinger borehole jack device I-II/146 (borehole diameter 146 mm)

The GOODMAN probe is built for a borehole diameter normally used for exploration drillings particularly in the Anglo-Saxon area. The probe's great advantage of being able to apply high pressures to the borehole wall is offset by the disadvantage of a measuring path of just 5 mm with a reading accuracy of 0.01 mm. It is a contradiction of design that the probe should have enough force to test rock with high and extremely high spring constants yet its displacement measuring system has a reading accuracy (as opposed to measuring accuracy) of just 0.01 mm. On the other hand, if this probe is used in less hard rock, its measuring path of 5 mm will be completely insufficient for applying higher probe pressures and hence exploiting the probe's advantages. If you add this drawback to the above mentioned effect of the contact between loading plate and borehole wall being incomplete, and if you also consider the small borehole diameter to be a disadvantage, then you have to conclude that the GOODMAN probe is now obsolete in terms of engineering and rock mechanics.

Our response to these contradictions and shortcomings was the development of two borehole jack devices for a borehole diameter of 101 mm and one for 146 mm. They cover a measuring path of 40 and 50 mm with a reading accuracy of 0.001 mm. The probe forces are designed for use in less hard rock and soil. The probe diameter of 101 mm was chosen in particular for those geological situations where the vicissitude of the rock calls for a quick decision after completing the preliminary borehole as to whether to conduct a borehole jack test or a flexible dilatometer test. Formerly this option was not available.

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The second variation of the borehole deformability test was introduced to soil mechanics as the pressiometric method according to MÉNARD. The borehole wall is subjected to radial-symmetric loading, which represents a more positive mechanical loading of the soil than the clamshell-type loading of variant 1. With large deformations (i.e. in soils), measurement of the change of diameter is fairly reliable and very economical. With small changes of diameter in solid rock, on the other hand, the method produces unsatisfactory results because its measurement of deformations is too imprecise.

The third variation listed above has scored good marks, particularly when combined with exploration boreholes of diameter 146 mm (SK6L). With this type of test, the borehole wall is again subjected to radial-symmetric loading. A probe diameter of 95 mm is an advantage because this enables its use in combination with the wire line core barrel SK6L and a preliminary borehole diameter of 101 mm. A smaller probe diameter is undesirable for reasons of rock mechanics.

This type of probe, also known as a flexible dilatometer, is ideal for tests in rock with uniaxial strengths ≥ 25 MPa because the hose packer adapts to the actual borehole diameter and complete contact between the probe and borehole wall is assured even with irregular wall surfaces. The two other test variants, on the other hand, are mainly used in soils (uniaxial compressive strength ≤ 1 MPa) and rock of very low strength (with a uniaxial compressive strength between 1 and 25 MPa) where full contact between probe and borehole wall is assured after a short nestling phase, which is usually well reflected in the test diagram.

If we also assume that the general structural loads of our structures lie between 0 and 4 MPa, there will be an obvious interest in using probes that are also able to determine the in-situ modulus in this load range.

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The Ettlinger borehole jack (ESDS) is a borehole probe that uses two cylindrical loading plates to subject the in-situ rock to a uniaxial load in perpendicular direction to the borehole axis. There are two versions of the borehole jack device for use in boreholes with a minimum diameter of 146 mm or 101 mm. The Ettlinger pressure device ESDS l/146 is a further development of the Stuttgarter borehole jack, the only unchanged feature, however, is the geometry of the cylindrical loading plates.

The ESDS I/146 probe consists of two cylindrical shell segments (Fig. 1) with a projection width of 126 mm and length of 195 mm, i. e. each has a projected load surface of 0.02457 m². The loading shells have articulated bearings and can be pressed hydraulically up to 50 mm apart by means of two pressure cylinders.

Fig. 1 Ettlinger borehole jack ESDS I/146:
Loading shells, cylinders and displacement transducers

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Probe ESDS I/146 can exert a pressure of over 6 MN/m², which is more than enough to test the modulus of deformation of soils and low-strength rock. An electric transducer measures the displacement of the loading plates at their centre axis as the overall relative displacement of the two plates. The connections for the electronic and hydraulic lines are accommodated above the probe head in a tube 540 mm long. This tube is connected in upwards direction to a 1200 mm long sump tube, which accommodates a fixture for an orientation rod and an eye for attaching a steel rope (Fig. 2).

Fig. 2 Ettlinger borehole jack ESDS I/146 with sump tube

The borehole jack, which has a diameter of max. 144 mm when retracted, is inserted with a winch into the borehole of 146 mm diameter and, if required, is positioned in depth and operating direction using an orientation rod attached to the probe.

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The length of the Ettlinger borehole jack ESDS I/146 is deliberately kept to just 195 mm in order to be able to investigate the often thin layer elements to be found in soils and soft rocks (SMOLTCZYK and SEEGER, 1980). In monotonous rock series, on the other hand, there is an advantage in using pressure plates which theoretically are best if they are of an infinite height. So as not to forgo this advantage, we can also supply the Ettlinger borehole jack with plate lengths of 490 mm (ESDS II/146) (see Fig. 3). This variation is made possible by having the load on the pressure plates generated by cylinder modules, which are attached to the 195 mm high probe, and by replacing just the pressure plate with one of the required length.

The projected loading area of the device ESDS II/146 with a plate length of 490 mm amounts to 0.06174 m².

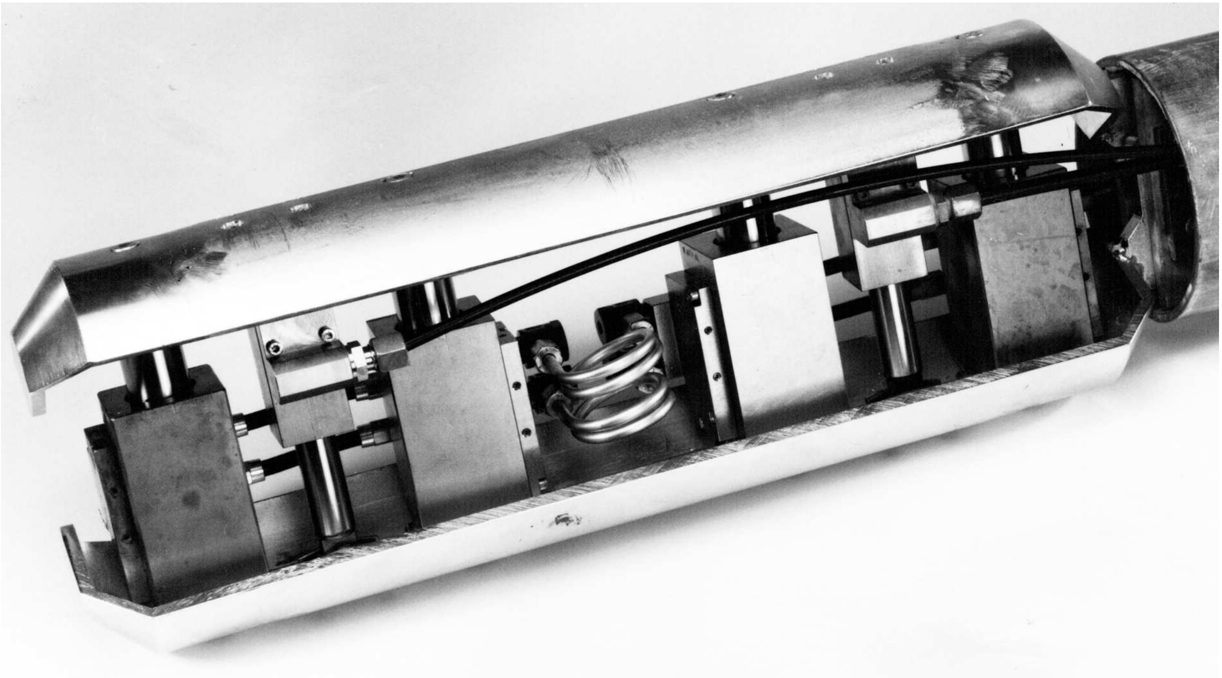

Fig. 3 Ettlinger borehole jack ESDS II/146:
Loading shells, cylinders and displacement transducers

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We can also supply a borehole jack for boreholes with a nominal diameter of 101 mm. Like all other Ettlinger borehole jacks its cylindrical shell segments have an opening angle of 120 °. With a projection width of 87.5 mm and length of 490 mm, this particular probe ESDS 101 has a projected loading area of 0.04287 m². The loading shells can be pressed apart hydraulically from 96 mm to 136 mm by means of four pressure cylinders. A maximum pressure of more than 5 MN/m² can be exerted on the surroundings.

With all Ettlinger borehole jacks, the lateral pressure is specified by the test engineer and checked by electric pressure transducers. Contact pressure at commencement of the test usually equals 50 kN/m². The load is applied in stages. As a rule it is sufficient to hold each loading stage for two minutes and then read off the shell displacement. Additional interim readings are taken to establish time-related deformation behaviour.

Using the theory of elasticity, the modulus of sub grade reaction K_{SS} is derived from the test as a device-specific parameter, which can be used in turn to derive a modulus of elasticity or deformation. The probe's range of application covers soil, rocks of alternating strength, and low-strength rock.

The test is normally conducted with three loading and stress-relief cycles, the maximum pressure of the first and repeat loading cycles being duly co-ordinated with the rock burden or requirements of the planned structure. The maximum load is reached when the probe's capacity is exhausted or when there are signs of soil failure in the development of the stress-deformation diagram.

According to the used device, the diameter of the test borehole must be at least 146 or 101 mm throughout. In the test zone the borehole diameter must not exceed 156 or 111 mm. If the upper section of the borehole is secured with casing, the internal diameter of the casing must likewise equal at least 146 or 101 mm throughout.

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The borehole must be stable. If it is inclined to cave in, the borehole wall must be secured, e. g. by introducing a thixotropic stabilising liquid. The length of the uncased test zone must be at least 1 m. The borehole wall in the area of the testing point should be disturbed as little as possible. After the test is completed, the borehole is sunk to below the next test point and the casing is extended accordingly.

If there is water in the borehole, the borehole deformability test cannot be started until sedimentation of the wet drillings is more or less completed.

It takes between two and four hours to conduct a standard test, including installation and removal of the probe, depending on the depth of the test.

The measured data logged during the borehole jack test are evaluated by a data processing system, and the test results are presented in two forms:

- Graphic presentation of stress-deformation diagrams
- Tabular overview of the measured data plus the characteristic values calculated from this data

The stress-deformation diagrams (Fig. 4) show a more or less pronounced bend under low lateral pressures, depending on the consistency of the borehole wall and rock. In range I, contact between the loading plates and the soil is still incomplete. In range III there are signs of the borehole failing in the loaded area. Range II represents the linear-elastic range of the stress-deformation diagram; only this range complies with the test evaluation principles.

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The stress-strain state induced in the rock by the loading was investigated by SEEGER (1980) on the basis of the theory of elasticity and, with the help of a spatial finite element study (BUCHMAIER and SCHAD, 1982; REIK and XING, 1993), was calculated numerically.

The following relationships apply:

Probe-specific modulus of sub grade reaction $K_{SS} = 2\,\frac{\Delta\sigma}{\Delta v}$

Modulus of deformation $E_B = f \cdot \frac{d}{\Delta d} \cdot \Delta p$

where:
- d = Initial diameter of test borehole
- f = Instrument-specific factor according to FE calculation
- Δd = Borehole expansion in the load interval
- Δp = Lateral pressure in the load interval

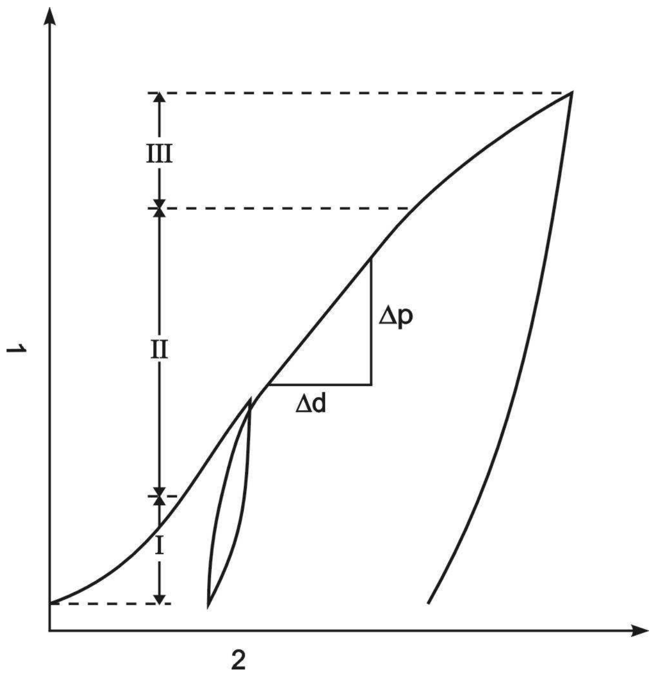

Fig. 4 Typical stress-deformation diagram of a borehole jack test

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The following instrument-specific factors f apply for the borehole jack ESDS I/146 with the above mentioned dimensions, according to the Poisson's ratio of the rock:

For $\nu = 0.25$: $f = 0.792$
For $\nu = 0.30$: $f = 0.785$
For $\nu = 0.40$: $f = 0.749$

In our evaluation (see attachment), the loading and stress-relief module is calculated for each load cycle. In the loading branches the first loading modules and the repeat loading modules are distinguished. Where "XXXXXX" is printed in the tabular overview instead of a numerical value, the calculation produced an infinitely large modulus of deformation. This is the case when the change of displacement of a load interval is $v = 0.000$ mm. A deformation modulus of $E_B = 0$ results, on the other hand, when the stress-deformation diagram runs horizontally, i. e. when continuation of the displacement as a function of time was measured under the same lateral pressure.

The older test-setups for borehole deformability tests were also evaluated with the theory of linear elasticity. KÖGLER simplified the mechanical state further still into a uniaxial state of stress, to which he applied HOOKE'S law. MÉNARD uses the solution derived from the theory of elasticity for a thick-walled cylinder, whose outer radius approaches infinity, i. e. a uniform state of deformation. There is a certain illogic in this, however, because

– either the state of deformation really does extend over a large range, in which case the assumption of a uniform state is unjustified,
– or the displacements are restricted to a sufficiently small range, in which case you cannot apply the solution for an infinitely thick cylinder.

The fact that a range III is clearly measured during borehole jack tests indicates that the former assumption is the more correct of the two.

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When designing the Stuttgarter borehole jack, SEEGER (1980) dispensed from the outset with creating a pseudo-uniform state. Instead the three-dimensional state of a pair of forces acting symmetrically outwards in a cylindrical opening was calculated for the drained, linear-elastic state of the soil. If the opening was disregarded, it was also possible to draw on the analytical solution, i. e. the integrated MINDLIN solution over a vertical rectangular plate. If, on the other hand, the opening was taken into consideration, preference was given to the finite element method, which is very reliable for linear-elastic problems.

Depending on the coefficient of lateral contraction, the FE calculations in the linear-elastic infinite mass (connection with tensile strength in the vertical plane of symmetry) or semi-infinite mass (plane of symmetry without tensile strength) produced a required load of between 15.8 kN and 29.4 kN to achieve a displacement of 1 cm. The modulus of elasticity of the continuum equalled 5000 kN/m². When the ruling probe dimensions are applied, we obtain the instrument-specific factors f, as we called them above.

The following instrument-specific factors f apply for the borehole jack II/146:

For $\nu = 0.25$: $f = 0.960$
For $\nu = 0.30$: $f = 0.949$
For $\nu = 0.40$: $f = 0.898$

The weak dependence of the function $P(\nu)$ on the Poisson's ratio previously noted by GOODMAN et al. (1968) was confirmed by SEEGER: P increased with ν in accordance with the increasing constancy of volume, the greatest increase taking place with the infinite mass solution, i. e. 14 % in the transition from $\nu = 0.30$ to 0.40.

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GOODMAN et al. give the following formula for the evaluation of their borehole jack tests:

$$V, E = \frac{0.8 \cdot d \cdot \Delta p}{\Delta d} \cdot K$$

where

d = Initial diameter of the test borehole
K = Stress factor as a function of the central angle ß of the load and of the Poisson's ratio ν

The stress factor K can be taken from the following table:

β	$\nu = 0.30$	$\nu = 0.40$
60	1.152	1.080
70	1.200	1.129
80	1.225	1.159
90	1.232	1.170
100	1.224	1.169
110	1.204	1.156
120	1.155	1.088

It is known that an evaluation based on GOODMAN et al. (1968) fails to produce satisfactory results for moduli of over 3000 MPa. In such cases the moduli need to be corrected by the function published by HEUZE and SALEM (1977). The use of borehole jack devices in hard rock is generally problematic, as BECKER (1985) has pointed out.

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Sales Information

Item	Description
16.1.1	Ettlinger borehole jack ESDS I/146 with loading plates 195 mm for hydraulic operation in boreholes of 146 mm ∅, for max. lateral pressure of > 4 MPa with one potentiometer transducer, measuring range 50 mm, complete with connections for supply lines and mud casing with possible connection for setting rods.
16.1.2	as before, but ESDS II/146 with loading plates of 490 mm and two potentiometer transducers.
16.1.3	as item 16.1.2, but ESDS 101 for boreholes of 101 mm ∅, measuring range 40 mm.
16.1.4	Automatic data recording by laptop, online representation of all measuring values and graph of selected measuring values. Readout of the data on hard disc. 12 V connection and 12 V voltage output for laptop. With laptop, with air quantity regulator with precision measuring manometer 0 – 100 bar, class 0.6.
16.1.5.1	Electric cable with pressurised water resistant plug (on probe side) and plug for display unit. Length 50 m.
16.1.5.2	Length 100 m.
16.1.6.1	High pressure hose (double line) for hydraulic operation, NW 4, 500 bar, on both sides with couplings. Length 50 m.
16.1.6.2	Length 100 m.
16.1.7	Hose and cable reel for max. 100 m line, portable, robust construction.
16.1.8	Two-step piston pump for manual operation 0 - 600 bar, with 5 l oil tank as well as switchable terminal strip.

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Item	Description
16.1.9	Setting rods in square steel profile 3 m length each, plug connection. Per shot
16.1.10.1	Mud casing lengthening, length 2.1 m for ESDS 146.
16.1.10.2	Mud casing lengthening, length 2.1 m for ESDS 101.
16.1.11	Data evaluation software - base Excel - on PC. Readout of load and unload modulus as well as measuring values and graphics on printer. Data take over from the data recording unit.

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The pressuremeter set developed by MÉNARD is based on the idea of a lateral pressure device according to KÖGLER (1933) and consists on the one hand of a cylindrical probe, which can be extended laterally and is lowered into a borehole down to testing depth, and on the other hand of a measuring apparatus that remains on the surface. The probe, which consists of three cells, exerts a calculable uniform pressure on the borehole wall in the area of the central measuring cell. The displacement of the borehole wall caused by the loading is read off and recorded for each pressure stage as a function of time (Fig. 1).

The pressure and control mechanisms are based on pneumatic principles. Data concerning the deformation of the soil is transmitted hydraulically and appears on a high-precision volumeter. The sets can be equipped with a series of probes in diameters to match the most common boreholes and named according to their nominal diameter:

<table>
<tr><th rowspan="2">Code
DCDMA</th><th rowspan="2">Probe
diameter
mm</th><th colspan="2">Borehole diameter
mm</th></tr>
<tr><th>min.</th><th>max.</th></tr>
<tr><td>EX</td><td>32</td><td>34</td><td>38</td></tr>
<tr><td>AX</td><td>44</td><td>46</td><td>52</td></tr>
<tr><td>BX</td><td>58</td><td>60</td><td>66</td></tr>
<tr><td>NX</td><td>(72) 74</td><td>(74) 76</td><td>80</td></tr>
</table>

The sets in current use belong to type G. They are characterised by two concentric connection lines for water and air (coaxial hose), which prevent parasitic extensions. Their use even in hard rock (modulus of elasticity ≥ 20.000 MPa) thus appears to be possible.

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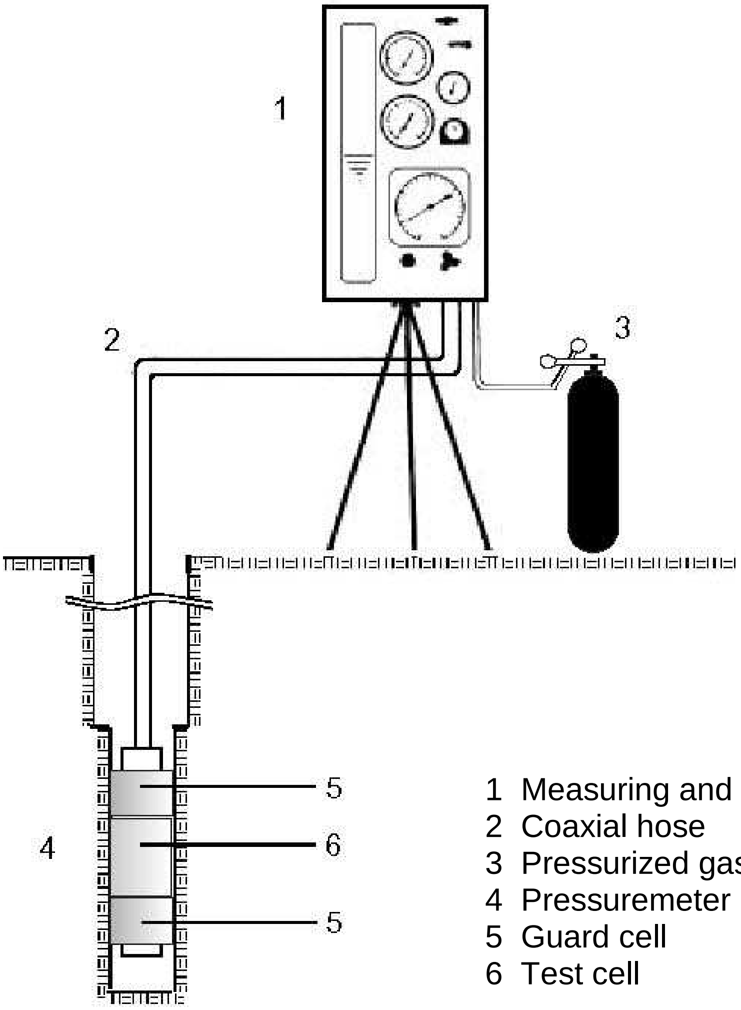
In very soft soil characterised by a boundary pressure of less than 1.5 bar, it is advisable to use a membrane and protective sleeve made of very soft material (latex) with an intrinsic rigidity of less than 0.6 bar. This is the case with sludge and peat.



1 Measuring and control unit
2 Coaxial hose
3 Pressurized gas
4 Pressuremeter
5 Guard cell
6 Test cell

Fig. 1 Schematic test setup for the pressuremeter test according to MÉNARD

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For very high moduli (above 2.000 MPa), on the other hand, you must use highly resistant membranes and protective sleeves, which are calibrated in advance. These membranes are characterised by poorer but more uniform compression. If the change of volume caused by a 1 bar change in pressure turns out to be less than 0.5 cm³ (modulus higher than 400 MPa), you should use the changeover device on the volumeter, which increases the sensitivity of the readings a hundred-fold.

The standard test must be conducted within 24 hours of making the borehole; this does not apply to cast-in-situ probes, for which there is no fear of the soil being disturbed by the risk of water ingress in the borehole. If need be, intervals of several days may be allowed for boreholes without water flushing (hand auger, pneumatic drilling with pneumatic conveyance of the rock cuttings) above the ground water level.

The test itself is standardised and must be conducted using 10 identical pressure stages (6 to 14 pressure stages are permitted) until the failure limit is reached. Readings of the borehole deformation (volume increase) as a function of time are taken for each pressure after 15, 30 and 60 seconds of reaching the pressure (Fig. 2).

To obtain as exact a load curve as possible, the measured volume must equal 700 cm³ when $p_l < 8$ bar and 600 cm³ when 8 bar $< p_l <$ 15 bar. In the remaining cases the test must be continued at up to 20 - 25 bar pressure in soils and 50 - 70 bar in rock.

The chief mechanical properties of the soil, i. e. the deformation modulus (MÉNARD modulus E_M) and the limit pressure (failure limit p_l), are calculated from the load/volume diagrams (material stress-deformation diagram) for each depth level. The pressiometric modulus E_M is a shear modulus of the soil measured in a deviatoric field of stress. It characterises the pseudo-elastic phase of the test.

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By definition, the limit pressure p_l corresponds to the limit failure state of the soil when it is exposed to a uniformly increasing load acting on the wall of a cylindrical cavity.

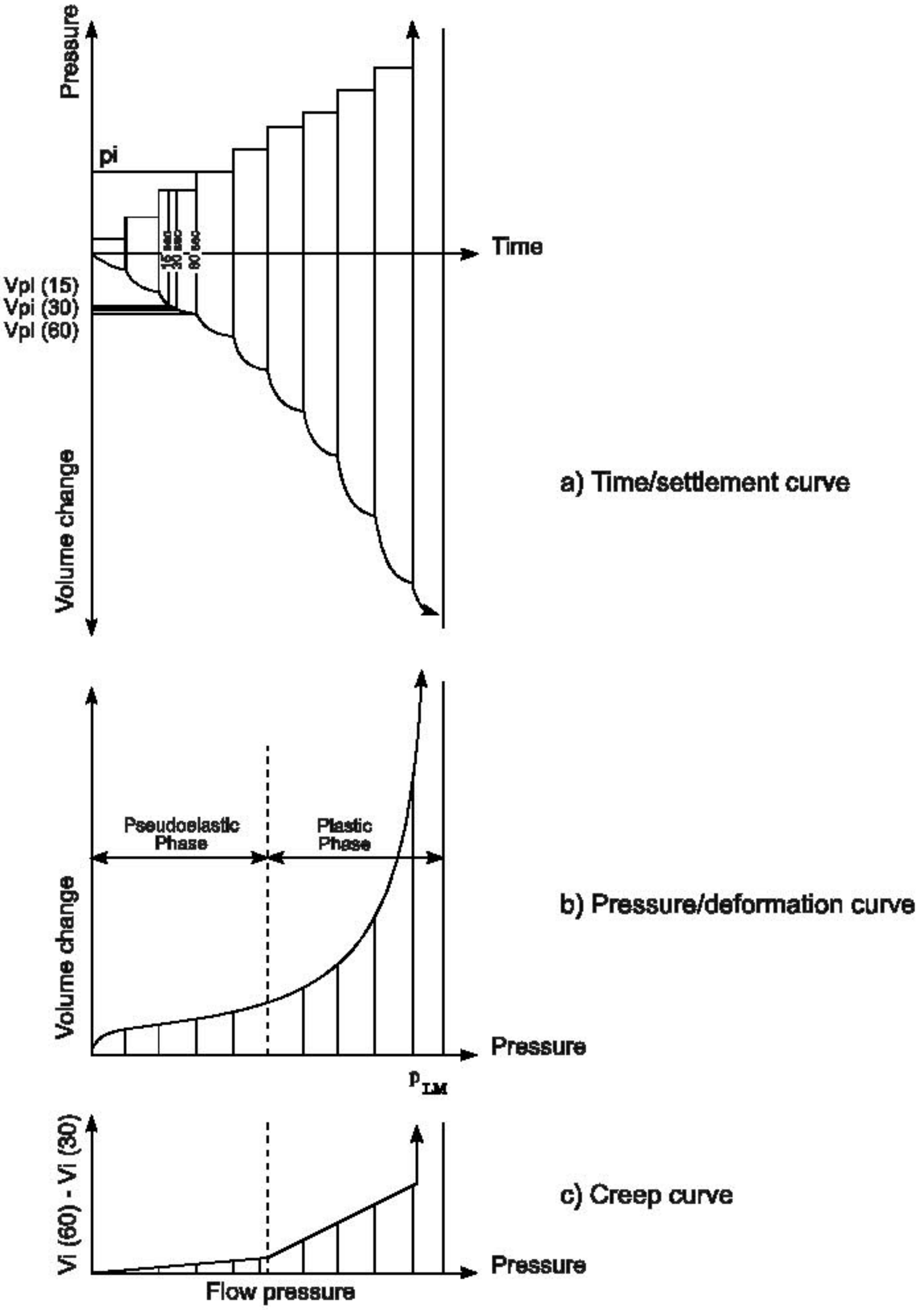

Fig. 2 Schematic test recording of a MÉNARD test

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To calculate the pressiometer modulus (E_M) you proceed from the basic formula according to LAMÉ for the expansion Δr of a cylindrical cavity with radius r and the effect of an increasing pressure Δp:

$$\frac{\Delta r}{r} = \frac{1+\nu}{E}\,\Delta p \qquad \text{or} \qquad E = (1+\nu)\,\frac{r}{\Delta r}\,\Delta p$$

where ν is Poisson's ratio. If the volume change Δv is used instead of the radius change Δr, the formula is:

$$E = 2\,(1+\nu)\,v\,\frac{\Delta p}{\Delta v}$$

The pressiometer modulus E_M is:

$$E_M = K\,\frac{\Delta p}{\Delta v}$$

where K is a geometric constant of the pressiometer probe. Δp and Δv are the related changes of pressure and volume in the pseudo-elastic phase of the test (Fig. 2b). The lower limit of the range of fluctuation Δp should always be higher than the horizontal earth pressure at rest p_h.

It can be shown that:

$$K = 2.66\,(v_o + v_m)$$

where

v_o	is the volume of the measuring cell at rest
v_m	is the volume of liquid which is filled into the measuring cell on account of the applied mean pressure p_m

Poisson's ratio *v* is normally taken as 0.33.

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The limit pressure p_l is derived from the position of the asymtote on the pressiometric curve and can be read off the absciss directly in the diagram.

The following typical values are listed to provide an idea of the magnitude of E_M and p_l:

Soil type	E_M [MPa]		p_l [bar]	
Sludge and peat	0.2 to	1.5	0.2 to	1.5
Soft clays	0.5 to	3.0	0.5 to	3.0
Plastic clays	3.0 to	8.0	3.0 to	8.8
Stiff clays	8.0 to	40.0	6.0 to	20.0
Marl	5.0 to	60.0	6.0 to	40.0
Silty fine sands	0.5 to	2.0	1.0 to	5.0
Silts	2.0 to	10.0	1.0 to	15.0
Gravelly sands	8.0 to	40.0	12.0 to	50.0
Fine sands	7.5 to	40.0	10.0 to	50.0
Calcareous rock	80.0 to	20,000	30.0 to	above 100
New fills	0.5 to	5.0	0.5 to	3.0
Old fills	4.0 to	15.0	4.0 to	10.0

Due to the fact that the LAMÉ equation disregards the absence of the tensile strength of the examined soil, a modulus two or three times smaller than the modulus determined by other customary methods is determined with the MÉNARD test. That's why the result of the pressuremeter test is also named MÉNARD modulus E_M. This modulus is only used in a specific proceeding to dimension a foundation or piles.

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The flexible dilatometer is generally used for conducting static load tests on in-situ rock in order to determine its stress/strain characteristics. The tests are carried out with the help of a cylindrical, radially expandable probe at freely selectable points inside a borehole (∅ 101 mm). The probe's diameter equals 95 mm.

The advantages of an in situ method of this type lie in being able to determine a foundation's characteristics in the practically undisturbed state, whereas laboratory tests usually measure only the maximum values of select specimens.

The measuring system (see Fig. 1) consists of the actual probe with three displacement transducers each set at an angle of 120 ° to the others, a cable reel for holding the combined measuring and pressure line, a pressure generator and the measurement electronics.

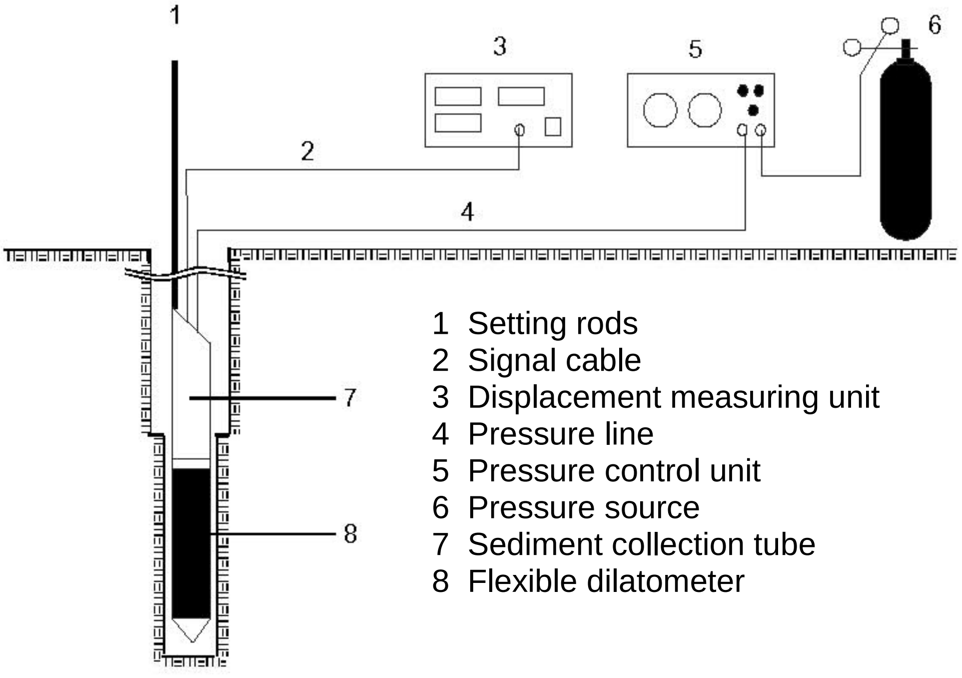

Fig. 1 Schematic representation of the flexible dilatometer setup

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Using this test setup it is possible to exert a pressure of 100 bar and more on the borehole wall by pneumatic means. The pressure in the probe is checked with either a high-precision gauge class 0.6 or an electric pressure sensor. The deformation values measured by the displacement sensors are transmitted electrically to a measuring bridge. Thanks to its relatively large measuring range of 25 mm (reading accuracy ± 0.001 mm), the probe can be used in stiff soil as well as in rock. For special applications a rod can be used to insert the probe in the borehole properly orientated.

The measuring setup consists of the following individual components:

- Flexible dilatometer probe (dia. 95 mm)
- Calibrating tube made of aluminium (internal dia. 100 mm; length 1500 mm)
- Sediment collection tube, short (length 1000 mm)
- Sediment collection tube, long (length 2100 mm)
- Peg for coupling the steel rope to the sump tube
- Aluminium rod (in lengths of 3 m)
- Pressure line
- Signal cable
- Cable trolley for winding up the bundled measuring lines
- 10 m of connecting line (pressure reducer / pressure measuring unit)
- Displacement measuring unit
- Pressure control unit
- 50 l pressure bottle of nitrogen
- Pressure reducer (p_v max. 300 bar; p_h max. 150 bar; Q_n 150 m^3/h)
- Automatic data acquisition

The borehole is loaded during the test in several load cycles; readings are taken of the borehole deformations at each loading stage and the deformations are tracked in each final stage of the loading cycle until they subside. The pressure is then relieved, likewise in stages, with simultaneous measurements taken off the reverse deformation until it stops. The same procedure is followed for the next higher and further load cycles.

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The measurement results thus obtained are presented in the form of a diagram that allows for a first assessment of the deformation characteristic.

As a rule the formula for thick-walled tubes according to LAMÉ is used to calculate the moduli of loading and stress-relief:

Loading and stress-relief modulus $E = (1+\nu)\,\frac{d}{\Delta d}\,\Delta p \quad [\mathrm{MPa}]$

ν = Poisson's ratio
d = Initial diameter of the borehole [mm]
Δp = Pressure differential [MPa]
Δd = Deformation [mm]

The Poisson's ratio used in this formula can be determined by laboratory tests or be taken from suitable tables.

All moduli are calculated as a secant module, i.e. as the difference between two co-ordinate pairs in the stress-deformation diagram. The loading modulus thus corresponds to the gradient of the rising section of the stress-deformation diagram and from the 2nd test cycle on it can still be divided into a first and a repeat loading modulus. The modulus of stress-relief corresponds to the gradient of the falling section of the stress-deformation diagram between the points with maximum load and minimum load of the respective stress-relief cycle.

The loading moduli and stress-relief moduli for pressures between 0.5 MPa and 10 MPa can be derived from the measurement results. Since each test is conducted with three displacement sensors concurrently, just a small number of tests are needed to carry out an adequate statistical evaluation or to assess the anisotropy of the rock body in terms of its moduli.

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Sales Information

Item	Description
16.3.1	Ettlinger flexible dilatometer EDI 95 for pneumatic operation in boreholes of 101 mm ∅, for max. pressure up to 10 MPa with 3 potentiometer transducers, measuring range 20 mm, for simultaneous measurement of rock deformation in 3 directions, complete with rubber sleeve as well as connections for supply lines and mud casing with possible connection for setting rods.
16.3.2	Automatic data recording by laptop, online representation of all measuring values and graph of selected measuring values. Readout of the data on hard disc. 12 V connection and 12 V voltage output for laptop. With laptop, with air quantity regulator with precision measuring manometer 0 – 100 bar, class 0.6.
16.3.3.1	Electric cable with pressurised water resistant plug (on probe side) and plug for display unit, Length 50 m.
16.3.3.2	Length 100 m.
16.3.4.1	High pressure hose for pneumatic operation, NW 8, 180 bar, on both sides with couplings, Length 50 m.
16.3.4.2	Length 100 m.
16.3.5	Hose and cable reel for max. 100 m line, portable, robust construction.
16.3.6	Set of electric and pneumatic connection line and connection line (HD-hose) between regulator and nitrogen bottle.
16.3.7	Pressure reducing valve for nitrogen bottle.
16.3.8	Aluminium calibration tube for functional test of the borehole probe, i. d. 100 mm and o. d. 120 mm.
16.3.9	Protective and transportation box for storage and transportation of probe and test tube.

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Item	Description
16.3.10	Mud casing lengthening, length 2.1 m.
16.3.11	Setting rods in square steel profile 3 m length each, plug connection. Per shot
16.3.12	Spare rubber sleeve.
16.3.13	Data evaluation software for MS-DOS systems. Readout of load and unload modulus as well as measuring values and graphics on printer. Data input by keyboard or taking over from the data recording unit.
16.3.14	On-the-job training by our staff.

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