# Suggested method for deformability determination a stiff dilatometer

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## SUGGESTED METHOD FOR DEFORMABILITY DETERMINATION USING A STIFF DILATOMETER

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## INTRODUCTION

Over the past three decades, borehole dilatometers have come into common use for evaluating load–deformation properties of rock masses *in situ* [1–7]. Borehole dilatometer testing augments other *in situ* deformability measurement methods, such as the plate loading and radial jacking tests. The ISRM Commission on Testing methods has sponsored two suggested methods that are aimed to help achieve some measure of standardization of use without inhibiting the development and improvement of techniques. The first of the two suggested methods, addressing borehole tests with flexible dilatometers, has already been published [8]. This document, the second of the two suggested methods, covers applications of relatively stiff dilatometers that are commercially available and in common use.

## ACKNOWLEDGEMENTS

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# Suggested Method for Deformability Determination Using a Stiff Dilatometer

## SCOPE

1. (a) This suggested method describes a procedure for measuring rock mass deformability by using a borehole dilatometer with stiff loading platens. A separate suggested method describes the determination of rock mass deformability using dilatometers that have flexible loading membranes [8]. The procedure described here involves expanding the loading platens of a dilatometer against opposite walls of a borehole, and measuring the change in borehole diameter resulting from successive increments of loading and unloading. With exceptions explained below, an elastic deformability of the rock mass may be calculated from data recorded during this test. Since only one diameter of the borehole is loaded in each test, the dilatometer orientation in the borehole may be changed between tests to detect anisotropy in the deformability of the rock mass. In some cases the dilatometer can also provide useful qualitative information about nonelastic behavior indicated by creep and deformation recovery upon unloading.

(b) A borehole dilatometer known as an NX Borehole Jack was developed nearly 30 years ago, and is still in common use. Significant advances in technical understanding of the applications and limitations of stiff dilatometers have come from experience with thin particular device. This suggested method will, therefore, focus on the use of the NX Borehole Jack, although the general principles described may be usefully applied with other stiff dilatometers that are designed to test borehole deformation along a single diametric axis of loading.

(c) Deformability values determined with a borehole dilatometer might be used as a design parameter (Young's modulus) or as an index property to log and compare the stiffnesses of different parts of a rock mass. Dilatometer tests may also be used to initially identify time-dependent deformational behavior, which can be a considerable portion of total deformation in some rocks. Other aspects of nonelastic behavior, such as irrecoverable deformation, may be important in some applications. Although the dilatometer may not be able to provide quantitative characterization of these deformation phenomena, it can indicate their presence early in a site characterization program so as to establish the need for other testing.

(d) Determination of rock mass deformability with a dilatometer may be limited in several ways. If the rock is weak, the walls of the borehole may fail at low loads before complete test data can be obtained. It may not be possible to complete a test if the rock is highly fractured or if the borehole is not stable, even though highly deformable zones of rock may be of particular interest for engineering purposes. Further, tests may not be possible in boreholes that are uneven in profile or are seriously undersized or oversized in diameter compared to the curvature of the dilatometer loading platens.

(e) The volume of rock stressed to a given level by the dilatometer is generally much smaller than the volume of rock stressed in a plate loading test or a radial jacking test, but it is larger than the volume of rock tested in most laboratory procedures. The rock mass volume tested by the dilatometer may not include enough joints or other types of discontinuities to be representative of the rock mass at larger scales.

(f) Stiff dilatometers are commercially available for use in boreholes that are nominally 76.2 mm (3.000 in) in diameter (NX boreholes). One available model is used for relatively strong and stiff rocks, while another is designed for softer, weaker rocks. A typical stiff dilatometer, known commercially as the NX Borehole Jack (manufactured under patent and marketed as a "Goodman Jack") is shown in Fig. 1, courtesy of Slope Indicator. Measurement of rock mass modulus with expedient borehole tests is an area of continuing research and development [7,9,10], but this suggested method will focus on the NX Borehole Jack because of its commercial availability and more common use in site characterization and rock mass engineering.

## APPARATUS

*List of equipment and supplies*

2. The borehole dilatometer shown in Figs 1 and 2 has 12 hydraulic pistons that force the loading platens against the walls of the borehole. These pistons can also be retracted to allow the dilatometer to be moved or relocated after each test. Two LVDTs (linearly variable differential transformers) in the dilatometer monitor borehole diameter changes caused by the loading cycle. The following equipment and supplies are needed to conduct the tests:

NX Borehole Jack (borehole dilatometer).

Hydraulic pump to pressurize the dilatometer pistons.

Pressure gauge or electronic pressure transducer to measure the hydraulic line pressure.

LVDT readout or recording device.

Hydraulic hose to connect the hydraulic pump to the dilatometer.

Electrical cables to connect the dilatometer LVDTs to the readout box.

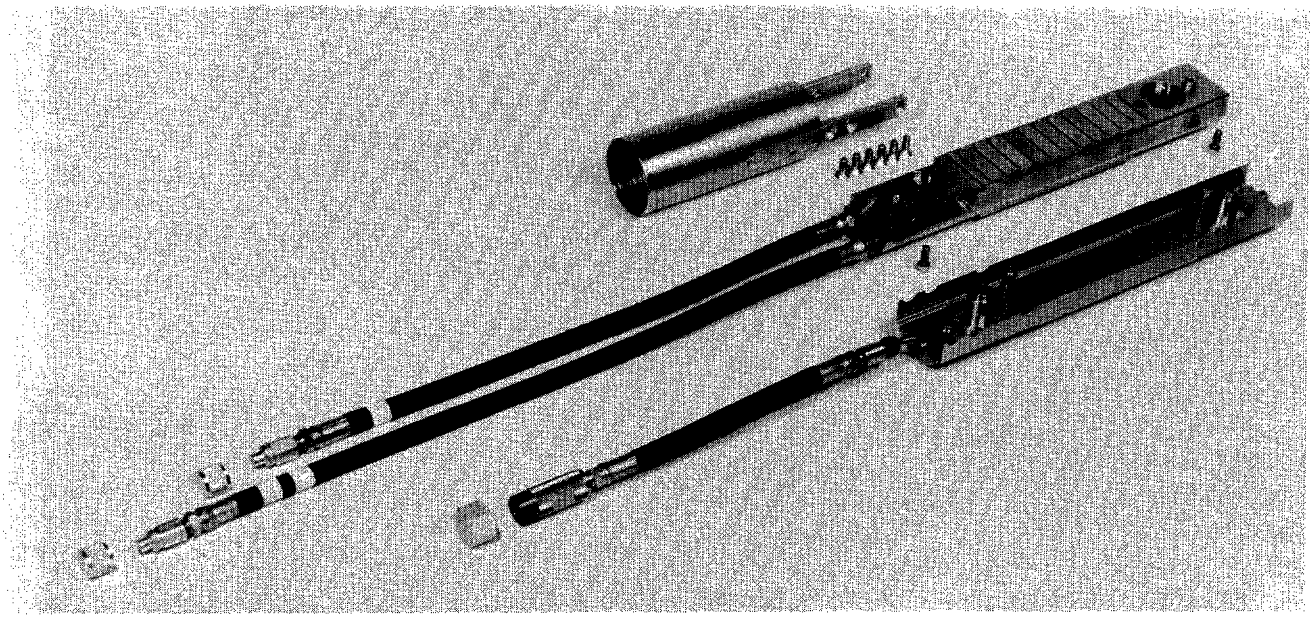

Fig. 1. The NX Borehole Jack (disassembled). This is a proprietary, commercially available stiff dilatometer for use in relatively hard rocks (courtesy of Slope Indicator).

Two micrometer or vernier calipers able to measure from 69.9 mm (2.75 in) to 82.6 mm (3.25 in).

Thick-walled steel ring bored out to a 76.2 mm (3.000 in) inside diameter.

BX (73.0 mm or 2.875 in) casing to position the dilatometer in the borehole.

Steel tape measure to determine depth of the dilatometer in the borehole.

Plumb line, compass or other device to orient the dilatometer in the borehole.

Stopwatch or clock for tests where loading is to be held constant for a specified duration.

Data sheets and pens for recording data from each test.

*Equipment tolerances and specifications*

3. (a) The NX Borehole Jack (dilatometer) and auxiliary equipment should meet the following tolerances and specifications:

Radius of curvature of loading platen: 38.1 mm (1.500 in).

Length of loading platen contact surface: 203.2 mm (8.00 in).

Range of platen travel: 12.7 mm (0.50 in) from a closed minimum of 69.9 mm (2.75 in) to an open maximum of 82.6 mm (3.25 in).

Displacement measurement range: 72.4–80.0 mm (2.850–3.150 in).

Displacement measurement resolution: at least 0.025 mm (0.001 in).

Maximum bearing pressure achievable on borehole wall by dilatometer: 64 MPa (9300 psi).

Pressure measurement range: 0–69 MPa (0–10000 psi).

Pressure measurement resolution: at least 0.34 MPa (50 psi).

(b) In addition, the tape and orientation measurement equipment should be able to provide measurements of

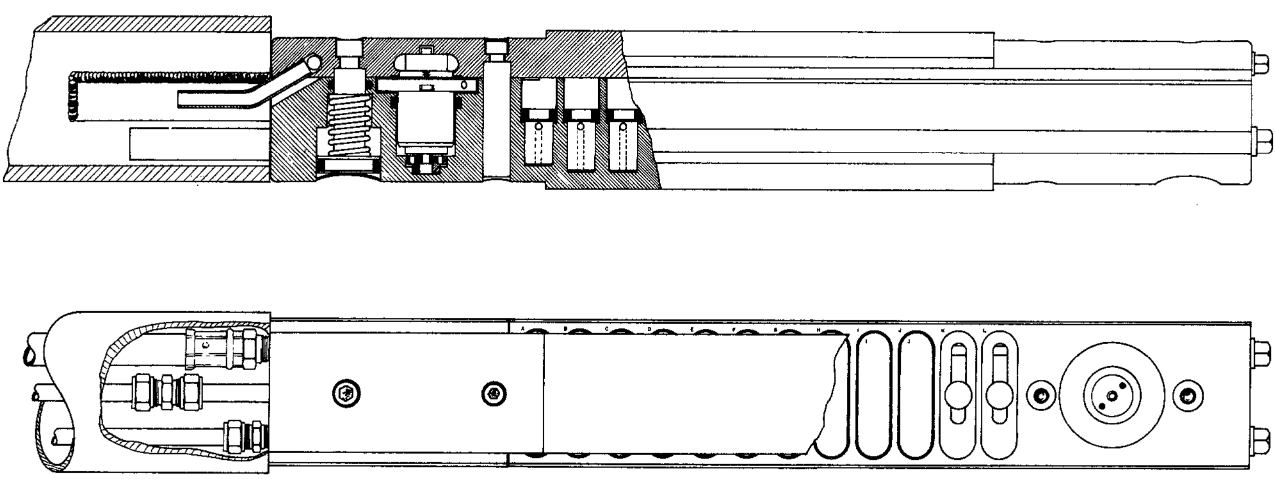

Fig. 2. Detailed line drawing showing the NX Borehole Jack for use in hard rock (courtesy of Slope Indicator). The version of the NX Borehole Jack for softer rocks is designed with three rather than 12 hydraulic pistons for applying pressure to the loading platens.

the depth of the dilatometer in the borehole to the nearest 1.0 mm, 0.1 in or such other accuracy as required by the intended use of the data. The orientation of the dilatometer should be measurable to the nearest 1 degree of arc, or such other accuracy as required by the intended use of the data.

## PROCEDURE

*Qualification of personnel*

4. Personnel who plan, conduct or interpret borehole dilatometer tests should be qualified in accordance with the quality assurance and other needs of the testing program.

*Equipment calibration*

5. (a) The dilatometer displacement readout should be calibrated prior to use. Additional displacement calibrations should be performed at regular intervals during use, when instrument damage is suspected, or when divergent LVDT readings indicate a possible problem with dilatometer performance. Displacement calibration is best performed in a location where the dilatometer and calibration equipment can be protected from adverse effects of temperature, precipitation, dust, mud, mechanical impact, vibration or other detrimental factors. Calibration should follow the manufacturer's instructions, which are summarized below:

(b) Connect the hydraulic and electronic systems to the dilatometer and expand the dilatometer to a diameter of approximately 76.2 mm (3.000 in). Place the calipers at each end of the loading platens, taking care that they are located at the same distance from the respective ends of the platens for each diameter measurement. Record the reading for each LVDT and caliper. Compare the LVDT readings with the caliper readings and then adjust the LVDTs so as to obtain zero values at a 76.2 mm (3.000 in) dilatometer diameter. Retract the dilatometer, and repeat the measurement and LVDT adjustment process for two or three diameters on each side of the zero (null) position of 76.2 mm (3.000 in). After the zero reading is adjusted satisfactorily, expand the dilatometer platens to a diameter of about 78.7 mm (3.100 in) and adjust the scale factor for each LVDT to bring it into agreement with the caliper values. After the scale factor is adjusted, retract the platens until the dilatometer is closed. Then cycle the platens through the entire displacement range of the dilatometer in at least 20 approximately equal increments, stopping at each increment to note both LVDT readings and the corresponding caliper readings. These sets of values should then be plotted into a calibrations curve for each LVDT (Fig. 3).

*Borehole preparation*

6. (a) Actual selection of locations, orientations and depths of boreholes to be tested with a dilatometer will be based upon the needs of the engineering project that requires the rock mass deformability data.

(b) Boreholes to be tested by the dilatometer should be core drilled with a diamond bit to within 0.25 mm (0.010 in) of 76.2 mm (3.000 in) in diameter. This is to minimize mismatch of the loading platen radius with the radius of the borehole. Note that the nominal diameter of an NX or NWG borehole is 75.7 mm (2.980 in). Further, actual borehole diameter will vary with the rock type or structure, type of bit, bit wear, drilling pressure, drill rotational speed and skill of the driller. Therefore, the actual borehole diameter should be measured and a reaming bit used to enlarge the borehole to the proper

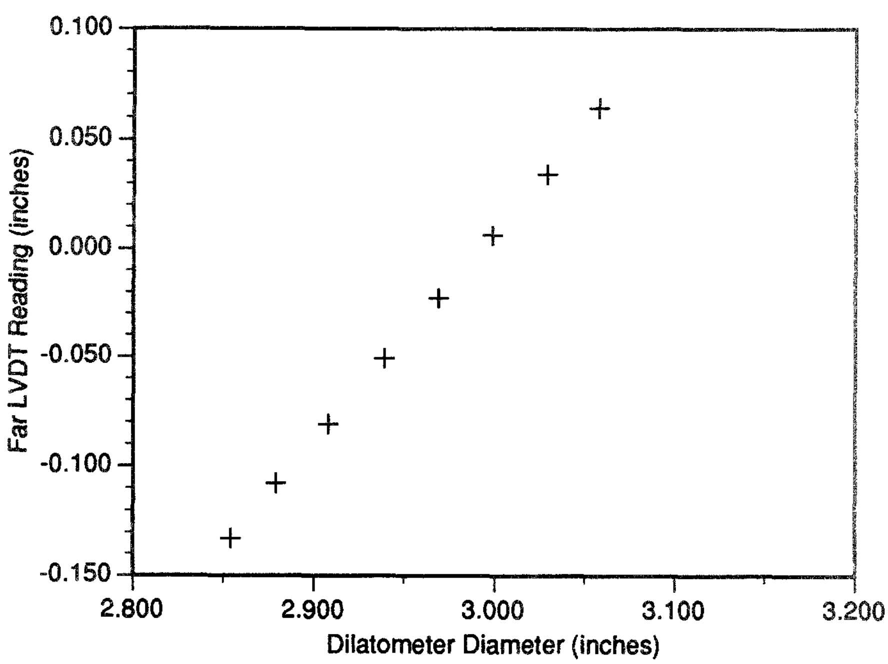


Fig. 3. Typical calibration curve developed for one of the two LVDTs (linearly variable differential transformers) in the NX Borehole Jack.

diameter if the borehole is originally undersized. A reaming bit or shell may also be used to generally smooth or condition the borehole for testing. Boreholes should be clean prior to testing; they may be flushed with water to remove drill cuttings and dirt. Air flushing or dry swabbing may be required if the rock quality or other rock mass parameters of interest would be degraded by water.

(c) Once the borehole is drilled, the core should be logged to assist in selecting borehole intervals for testing. In some cases it may also be useful to inspect the borehole walls with a borescope or borehole television camera to detect irregularities and help choose test intervals. Fractures, joints and other types of discontinuities encountered by the borehole should be described because of their potential influence on rock mass deformability.

*Equipment setup*

7. The dilatometer apparatus is set up by attaching the dilatometer to BX casing, and marking or scribing the casing segments so that the depth and loading direction of the dilatometer can be related to a reference at the borehole collar while the dilatometer is in the borehole. Hydraulic lines and electrical cables from the dilatometer to the hydraulic pump and LVDT readout are threaded through the BX casing as each segment of casing is attached. Care should be taken to avoid damaging the lines and cables on the edges of the casing segments, and to avoid systematic or cumulative errors in orientation as the casing string is assembled and placed in the borehole. The dilatometer and casing string are inserted into the borehole until the deepest test location is reached. Segments of BX casing are taken off of the casing string as the dilatometer is retracted for successive tests. As described below, testing should start with the deepest planned locations in the borehole and proceed towards the hole collar in order to reduce the possibility that any rock failure that might be induced during a test could interfere with subsequent testing or relocation of the dilatometer.

*Testing*

8. (a) Once the dilatometer is at the desired depth and orientation, start the test by raising the hydraulic line pressure 0.35 MPa (50 psi) to seat the loading platens against the borehole walls. This is considered to be the nominal zero pressure for the remainder of the test. Both LVDT readings should be recorded to indicate the initial borehole diameter. Note that the quality of this initial diameter measurement depends on the calibration described above.

(b) The test should be continued by raising the hydraulic line pressure of the dilatometer system to its maximum in 10 or more equal increments, and recording the gage pressure and both LVDT readings for each increment. The borehole wall should not be failed deliberately, though, as might be indicated by a sudden increase in the LVDT readings without a corresponding increase in line pressure. The range of displacement of the dilatometer should also not be exceeded. Therefore, the maximum test pressure may be selected at some value lower than the maximum attainable with the dilatometer.

(c) Once the maximum increment of loading is reached and recorded, reduce the pressure to the nominal zero pressure in decrements, and note the gage pressure and LVDT readings for each decrement. To the extent possible, the pressure decrements during this unloading part of the test should correspond to the increments of the loading portion of the test. If desired, the cycle of loading and unloading can be repeated to examine the effects of loading cycles on the deformability of the rock mass. Once the nominal zero pressure is reached and recorded, and testing is complete for that borehole location and orientation, the dilatometer pistons are retracted to allow the dilatometer to be moved.

(d) If deformability tests are desired at different locations in the borehole, the dilatometer should be moved at least 30.5 cm (12 in) from the previous test location in order to test an undisturbed portion of the borehole. The first test in a borehole should be conducted at the deepest selected location in the deepest rock unit being investigated so that any borehole damage resulting from a test does not interfere with moving the dilatometer or with subsequent tests. Tests of differing orientations should also be separated within the borehole unless rock conditions are such that borehole damage is extremely unlikely.

(e) Time dependent behavior of the rock mass can be detected during a dilatometer test by maintaining the hydraulic line pressure at its maximum for an extended time period. Gage pressure and LVDT readings should be recorded at regular intervals during this time period. It is suggested that at least three tests in each rock type under investigation include two 15 min periods of monitoring at constant load to check for time dependency of the rock mass deformation. The first monitoring period should be conducted at maximum pressure at the peak of the loading cycle, and the second should be conducted at the end of the first loading cycle to check for rebound.

*Sources of problems*

9. (a) Problems can develop during a dilatometer test if the test apparatus malfunctions during the test, if the rock wall of the borehole fails, if the loading platens travel beyond their allowable range, or if the LVDT readings differ by more than about 0.5 mm (0.020 in). Test apparatus malfunctions may or may not require that testing be stopped, depending on the nature of the malfunction. Failure of the borehole wall may be recognized from suddenly increased borehole deformation without corresponding increases in loading increments, or from an excessively large magnitude of deformation for a given pressure increment. Tests which encounter this problem could result in wedging of the dilatometer in the damaged borehole. A dilatometer test must also be stopped to prevent damage to the

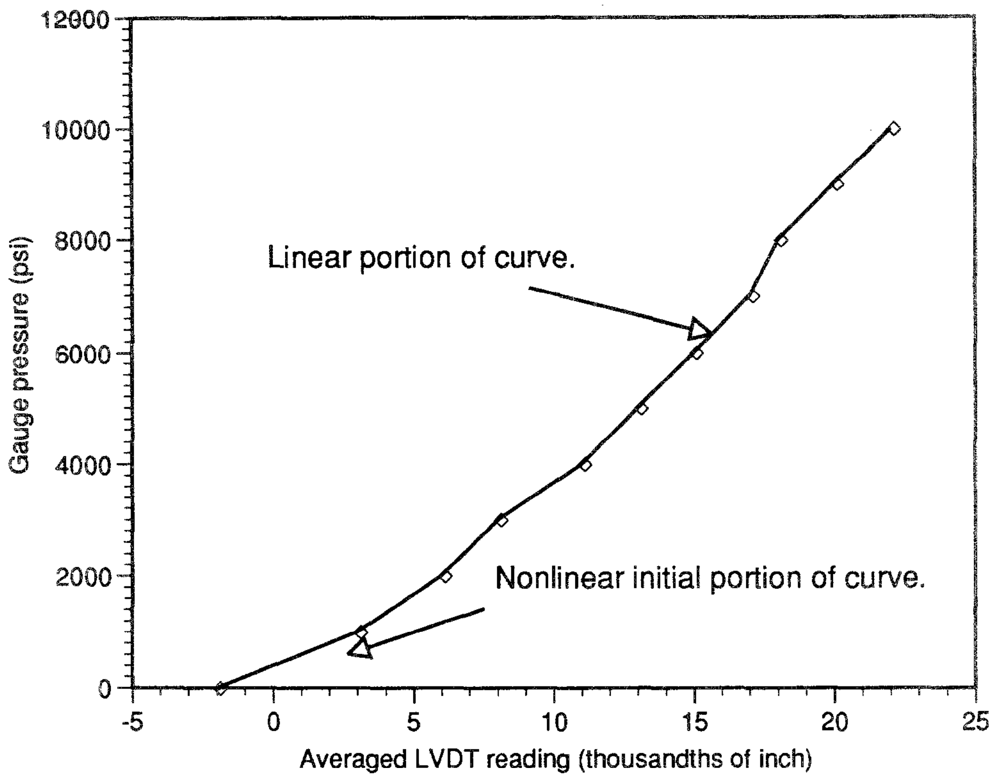


Fig. 4. Example data from a test using a stiff dilatometer (in this case an NX Borehole Jack) in a borehole. Abscissa values represent borehole diameter deviations from 76.2 mm (3.000 in) in thousandths of an inch, while ordinate values show hydraulic line pressure during the test. Note that the NX Borehole Jack LVDT readout and pressure gage provide data in units of inches and pounds per square inch, respectively. Zero deviation on the abscissa represent a borehole diameter of 76.2 mm (3.000 in).

dilatometer if the platens travel beyond the range of travel specified above. The test location should then be shifted by a small distance in the borehole before another test is attempted.

(b) Problems such as those outlined above must be considered on an individual basis, and require that field personnel be qualified to recognize problems as they arise. Nonlinear deformation of the rock may mask the effects of borehole failure or other difficulties, but these ambiguities are not easily resolved with the current state of knowledge.

*Equipment disassembly and storage*

10. Special attention should also be given to keeping the hydraulic and electrical connections clean and dry during assembly, disassembly and storage. After completion of testing, the apparatus should be disconnected into its separate components. Any parts of the equipment that are dirty (particularly the dilatometer, hydraulic lines and electrical cables that go into the borehole) should be cleaned before storage. The apparatus should then be placed in padded boxes so as to avoid damage during transportation and storage.

## CALCULATIONS

*Preparation of data for analysis*

11. Data from each test should be plotted on a separate graph for inspection. Normally the average of the two corresponding LVDT readings is plotted as the abscissa to represent deviation in borehole diameter and the hydraulic line pressure is plotted as the ordinate. Each resulting graph is examined for linear and nonlinear trends, and for hysteresis. A typical data plot is shown in Fig. 4.

*Recognition of problems in data*

12. (a) Hysteresis between loading and unloading parts of the test or between test loading cycles conducted at the same orientation and borehole location may indicate damage to the borehole wall or some type of inelastic rock behavior. This complication is usually avoided in the calculation of rock mass deformability by using the initial loading curve for analysis. However, it may be more appropriate to use the unloading data curve in certain applications.

(b) In cases where the borehole diameter is significantly different from 76.2 mm (3.000 in), an initial nonlinear portion of the dilatometer loading curve is thought to represent a combination of seating of the platens in the borehole and genuine rock behavior. It is usually not possible to assess the relative contribution of these effects by inspecting the data. However, if the initial borehole diameter is within about $\pm 0.5$ mm ($\pm 0.020$ in) of 76.2 mm (3.000 in), a nonlinear deformation curve probably reflects a nonlinear rock mass response [7].

*Computation of field value for deformability*

13. (a) The equations and coefficients used to calculate field values of deformability assume full contact between the loading platens and the borehole wall. The initial

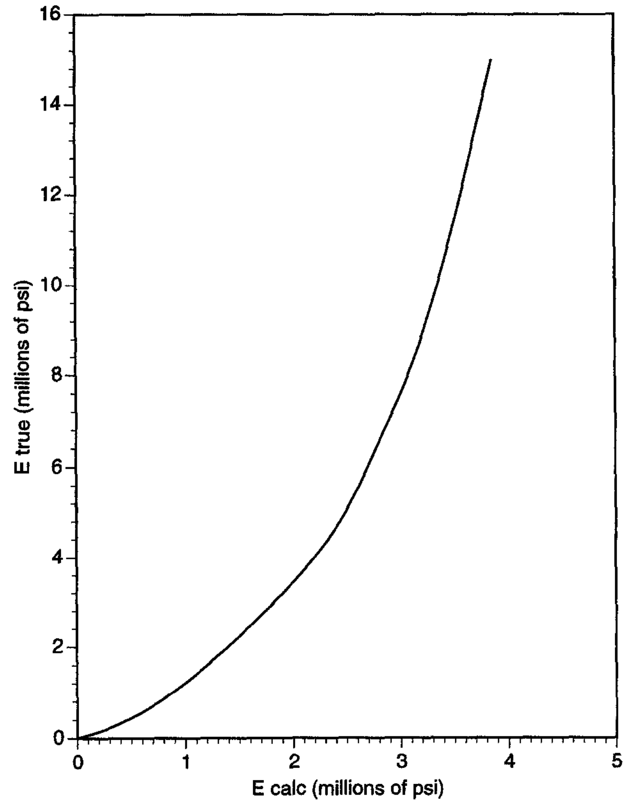


Fig. 5. Modulus correction for longitudinal platen bending during tests with the NX Borehole Jack, assuming full contact between platens and borehole wall, and with rock Poisson's ratio = 0.33 [11].

borehole diameter is the most expedient indicator of how well this criterion is met in each test, although borehole caliper logs (if available) can provide a valuable supplement to this assessment. The linear portion of the plot may also be used to indicate full contact, but this is a less reliable alternative. The dilatometer platens are known to bend longitudinally during the test; correction for this effect is discussed below.

(b) The following equation [11] is used to compute a field value for the modulus of deformation from the test data:

$$E_{\text{calc}} = 0.86 * 0.93 * \Delta Q_h * (D/\Delta D) * T^* \tag{1}$$

0.86 = coefficient for three-dimensional effects
0.93 = hydraulic efficiency of dilatometer
$D$ = borehole diameter
$\Delta D$ = change in borehole diameter
$\Delta Q_h$ = gauge pressure increment
$T^*$ = coefficient that depends on Poisson's ratio.

(c) $\Delta Q_h/\Delta D$ is the slope of the linear portion of the loading curve described above. Values of $T^*$ are shown in Table 1. Note also that although the equation above is valid for either SI or English systems, the pressure gage and LVDT readout of the commercially available NX Borehole Jack provide English units of pounds per square inch hydraulic line pressure and inches of displacement, respectively.

Table 1. $T^*$ for full platen contact [11]

| Poisson's ratio | 0.1 | 0.2 | 0.25 | 0.3 | 0.33 | 0.4 | 0.5 |
|---|---|---|---|---|---|---|---|
| Value of $T^*$ | 1.519 | 1.474 | 1.438 | 1.397 | 1.366 | 1.289 | 1.151 |

*Correction for platen bending*

14. Values of rock mass deformability computed with equation 1 must be adjusted for longitudinal platen bending during the test. This is done by entering Fig. 5 with the computed field value for deformability on the abscissa and finding the corresponding ordinate value for deformability as defined by the curve. Figure 5 is based on finite element analyses with limited verification from actual deformability tests, and the analyses used to develop the curve assumed full contact between the platens and rock. Figure 5 has an upper limit of about 100 GPa ($15 \times 10^6$ psi); no correction is needed for values below about 6.9 GPa ($1 \times 10^6$ psi). The validity of deformability values developed through these corrected calculations should be checked against laboratory-determined modulus or deformability values if such data are available. Rock mass deformability determined in field measurements will normally be somewhat lower than values determined in laboratory tests because of the effects of test scale and *in situ* discontinuities.

## REPORTING RESULTS

15. All reports of test results should contain the following information:

*Field setting of test*

16. Reports of field determinations of rock mass deformability should include a description of the field setting of the tests with a brief description of (a) the site geology, (b) the locations, depths and orientations of the boreholes in which tests were conducted, and (c) a description of the character of the rock encountered in the boreholes. Discontinuities encountered by the borehole should be described, although the fractures that most heavily influence measurements by dilatometer tests (fractures perpendicular to the loading direction) are the least likely to be intersected by the borehole. The drilling of the boreholes should be summarized with respect to the types of drills and drill bits used. Unusual drilling or borehole conditions should be noted. Sketches and diagrams of field conditions are especially valuable in this section of the report.

*Description of test method*

17. This part of the report should review the dilatometer testing methods that were used. The apparatus should be listed, and the instrument components should be mentioned by type, manufacturer, model and serial number. The condition of the equipment should be noted, and instrument calibration records should be described or included as appendices to the report. The suggested method used should be referenced with its publication date and revision status, and deviations from the suggested method should be described and explained.

*Test data*

18. Each dilatometer test should be described in the report with respect to test location and orientation. Raw data from each test should be included either as listings of times and pressure and dilation values, or (preferably) as plots of borehole dilation vs pressure. Test descriptions should contain enough detail to allow the test records to be understood, and descriptions of tests that were not completed should include an explanation of any problems that were encountered.

*Summary of data reduction and analysis*

19. (a) Deformability values that result from the reduction and analysis of test data should be presented in tables, and the analytic methods should be described in enough detail to allow checking and review of the results. The results may be plotted with respect to test location and orientation to aid in interpretation.

(b) Interpretation and application of test results are beyond the scope of this suggested method, except for judgments about the validity of test results. As mentioned above, seating of the dilatometer in the borehole can be a source of error that can invalidate a data set from a test. The equations and coefficients used to calculate dilatometer test results all assume complete seating of the loading platens in the borehole. Therefore, the importance of conducting dilatometer tests in boreholes with diameters that are within tolerance (see the section on borehole preparation, above) must be strongly emphasized. Other problems can arise during the conduct of a test as described in Section 3.6.

(c) The effects of borehole diameter deviations and consequent incomplete seating of dilatometer loading platens in the borehole were the focus of several investigations. Shuri [12] provided an initial examination of the effects of unmatched borehole and platen radii (which control platen seating) on dilatometer test results. Heuze and Amadei [11] extended this approach to suggest criteria with which dilatometer tests could be screened for inadequate platen seating. These screening criteria are based on the borehole diameter and modulus of the rock, but can under certain circumstances have a deleterious effect by leading to mistaken rejection of some data sets or mistaken acceptance of other sets [13]. Description of data and test results should, therefore, include a discussion of any selection or screening process used in the analyses.

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