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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Test Method for Determining the In Situ Modulus of Deformation of Rock Mass Using a Radial Jacking Test[1]

This standard is issued under the fixed designation D 4506; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method is used to determine the in situ modulus of deformation of rock mass by subjecting a test chamber of circular cross section to uniformly distributed radial loading; the consequent rock displacements are measured, from which elastic or deformation moduli may be calculated. The anisotropic deformability of the rock can also be measured and information on time-dependent deformation may be obtained.

1.2 This test method is based upon the procedures developed by the U.S. Bureau of Reclamation featuring long extensometers **(1)**[2]. An alternative procedure is also available and is based on a reference bar **(2)**.

1.3 Application of the test results is beyond the scope of this test method, but may be an integral part of some testing programs.

1.4 The values stated in inch-pound units are to be regarded as the standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 4403 Practice for Extensometers Used in Rock[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *deformation*—change in shape or size (from Terminology D 653) (see 3.2.1).

3.1.2 *modulus of deformation*—the ratio of stress to strain for a material under given loading conditions; numerically equal to the slope of the tangent or the secant of a stress-strain curve. The use of the term *modulus of elasticity* is recommended for materials that deform in accordance with Hooke's law; the term *modulus of deformation* for materials that deform otherwise (from Terminology D 653).

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *deformation*—the change in the diameter of the excavation in rock (test chamber).

4. Summary of Test Method

4.1 A circular test chamber is excavated and a uniformly distributed pressure is applied to the chamber surfaces by means of flat jacks positioned on a reaction frame. Rock deformation is measured by extensometers placed in boreholes perpendicular to the chamber surfaces. Pressure is measured with a standard hydraulic transducer. During the test, the pressure is cycled incrementally and deformation is read at each increment. The modulus is then calculated. To determine time-dependent behavior, the pressure is held constant and deformation is observed over time.

5. Significance and Use

5.1 Using this test method, a volume of rock large enough to take into account the influence of discontinuities on the properties of the rock mass is loaded. The test should be used when values are required which represent the true rock mass properties more closely than can be obtained through less expensive uniaxial jacking tests or other procedures.

6. Apparatus

6.1 *Chamber Excavation Equipment*—This includes drilling and "smooth wall" blasting equipment or mechanical excavation equipment capable of producing typically a 9-ft (3-m) diameter tunnel with a length about three times that dimension.

6.2 *Concreting Equipment*—Concreting materials and equipment for lining the tunnel, together with strips of weak jointing materials for segmenting the lining.

6.3 *Reaction Frame*—The reaction frame shall be comprised of steel rings of sufficient strength and rigidity to resist the force applied by flat jacks, as depicted in Fig. 1. For load application by flat jacks, the frame must be provided with smooth surfaces; hardwood planks are usually inserted between the flat jacks and the metal rings.

6.4 *Loading Equipment*, to apply a uniformly distributed

[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

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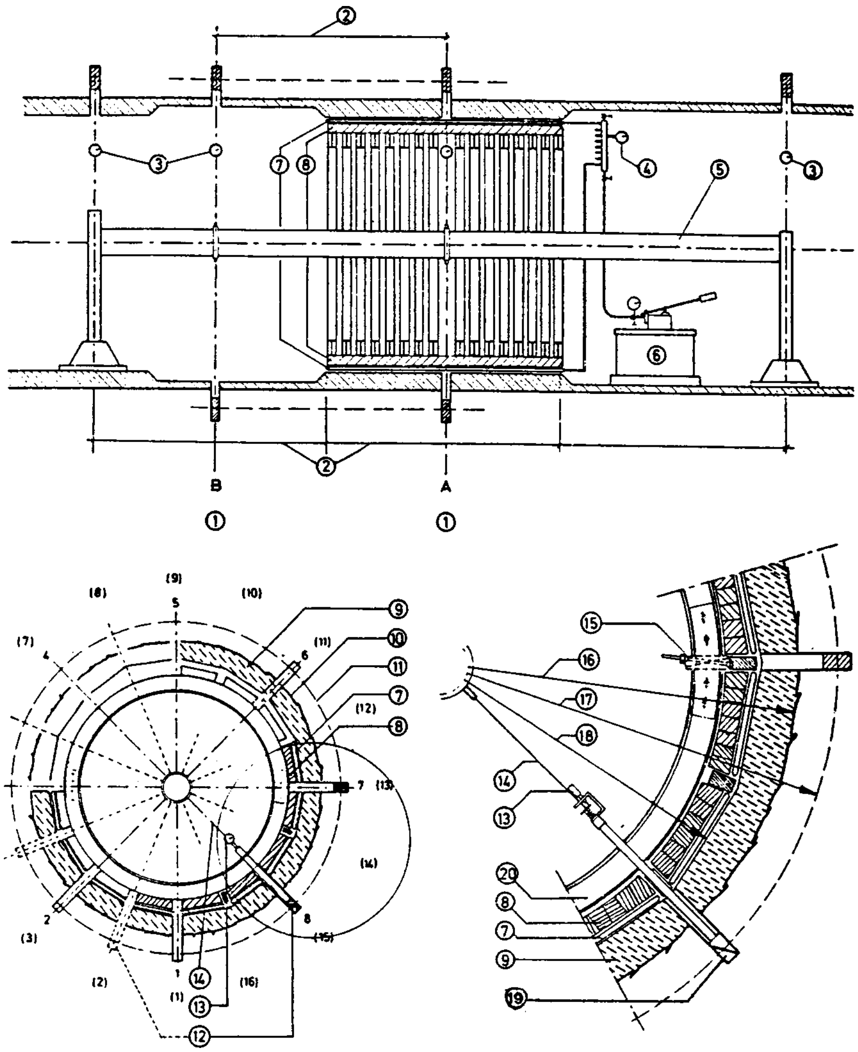
[2] The **boldface** numbers in parentheses refer to the list of references appended to this standard.

[3] *Annual Book of ASTM Standards*, Vol 04.08.



1. Measuring profile. 2. Distance equal to the length of active loading. 3. Control extensometer. 4. Pressure gage. 5. Reference beam. 6. Hydraulic pump. 7. Flat jack. 8. Hardwood lagging. 9. Shotcrete. 10. Excavation diameter. 11. Measuring diameter. 12. Extensometer drillholes. 13. Dial gage extensometer. 14. Steel rod. 15. Expansion wedges. 16. Excavation radius. 18. Inscribed Circle. 19. Rockbolt anchor. 20. Steel ring.

FIG. 1 Radial Jacking Test

radial pressure to the inner face of the concrete lining, including:

6.4.1 *Hydraulic Pump*, with all necessary hoses, connectors, and fluid, capable of applying the required pressure and of holding this pressure constant to within 5 % over a period of at least 24 h.

6.4.2 *Flat Jacks*, used for load application (Fig. 1), of a practicable width and of a length equal at least to the diameter of the tunnel (9 ft (3m)). The jacks should be designed to load the maximum of the full circumference of the lining with sufficient separation to allow displacement measurements, and should have a bursting pressure and travel consistent with the anticipated loads and displacements. Stainless steel flat jacks in effective contact with 90 % of the area are recommended, with the maximum pressure capacity twice the design pressure.

6.5 *Load Measuring Equipment*—Load measuring equipment shall consist of one or more hydraulic pressure gages or transducers of suitable range, capable of measuring the applied pressure with an accuracy better than ±2 %. Measurements are usually made by means of mechanical gages. Particular care is required to guarantee the reliability of electric transducers and recording equipment, when used.

6.6 *Displacement Measuring Equipment*—Displacement measuring equipment to monitor rock movements radial to the tunnel must have a precision better than 0.01 mm. Multiple-position (six anchor points) extensometers in accordance with Practice D 4403 should be used. The directions of measurement should be normal to the axis of the tunnel. Measurements of movement should be related to reference anchors rigidly secured in rock, well away from the influence of the loaded zone. The multiple-position extensometers should have the deepest anchor as a reference situated at least 3 test-chamber diameters from the chamber lining.

7. Personnel Qualification and Equipment Calibration

7.1 All personnel involved in performing the test, including the technicians and test supervisor, shall be formally prequalified under the quality assurance procedures established as part of the overall testing program.

7.2 The compliance of all equipment and apparatus with the performance specifications in Section 6 shall be verified. Performance verification is generally done by calibrating the equipment and measurement systems. Calibration and documentation shall be accomplished in accordance with standard quality assurance procedures.

8. Procedure

8.1 *Test Chamber*:

8.1.1 Select the test chamber location taking into consideration the rock conditions, particularly the orientation of the rock mass elements such as joints, bedding, and foliation in relation to the orientation of the proposed tunnel or opening for which results are required.

8.1.2 Excavate the test chamber by smooth (presplit) blasting to the required diameter of 9 ft (3 m), with a length equal to at least three diameters.

8.1.3 Record the geology of the chamber and specimens taken for index testing, as required. Core and log all instrumentation holes as follows:

8.1.3.1 *Cored Boreholes*—Drill the boreholes using diamond core techniques. Continuous core shall be obtained.

8.1.3.2 *Core Logged*—Completely log the recovered core, with emphasis on fractures and other mechanical nonhomogeneities.

8.1.4 Accurately mark out and drill the extensometer holes, ensuring no interference between loading and measuring systems. Install six-point extensometers and check the equipment. Place two anchors deep beyond the tunnel influence, appropriately spacing the other four anchors as close to the surface of the tunnel as possible.

8.1.5 Assemble the reaction frame and loading equipment.

8.1.6 Line the chamber with concrete to fill the space between the frame and the rock.

8.2 *Loading*:

8.2.1 Perform the test with at least three loading and unloading cycles, a higher maximum pressure being applied at each cycle. Typically, the maximum pressure applied is 1000 psi (7 MPa), depending on expected loads.

8.2.2 For each cycle, increase the pressure at an average rate of 100 psi/min (0.7 MPa/min) to the maximum for the cycle, taking not less than 10 intermediate sets of load-displacement readings in order to define a set of pressure-displacement curves (see Fig. 2). The automation of data recording is recommended.

8.2.3 On reaching the maximum pressure for the cycle, hold the pressure constant for 10 min. Complete each cycle by reducing the pressure to near zero at the same average rate, taking a further three sets of pressure-displacement readings.

8.2.4 For the final cycle, hold the maximum pressure constant for 24 h to evaluate creep. Complete the cycle by unloading in stages, taking readings of pressure and corresponding displacements similar to the loading cycle.

9. Calculation

9.1 Correct the applied load values to give an equivalent distributed pressure, p_1, on the test chamber lining, as follows:

$$p_1 = \frac{\Sigma b}{2 \cdot \pi \cdot r_1} \cdot p_m \qquad (1)$$

where:

p_1 = distributed pressure on the lining at r_1, psi (MPa),
r_1 = radius, ft (m),
p_m = pressure in the flat jacks, psi (MPa), and
b = flat jack width (see Fig. 3), ft (m).

9.1.1 Calculate the equivalent pressure p_2 at a "measuring radius" r_2 just beneath the lining; this radius being outside the zone of irregular stresses beneath the flat jacks and the lining and loose rock (see Fig. 3).

$$P_2 = \frac{r_1}{r_2} \cdot P_1 = \frac{\Sigma b}{2 \cdot \pi \cdot r_2} \cdot P_m \qquad (2)$$

$$P_m \Sigma b = P_1 \cdot 2 \cdot r_1 \cdot \pi$$

$$P_1 = \frac{P_m \Sigma b}{2 \cdot \pi \cdot r_1}$$

$$P_2 = P_1 \frac{r_1}{r_2}$$

9.2 Superposition is only strictly valid for elastic deformations but also gives a good approximation if the rock is

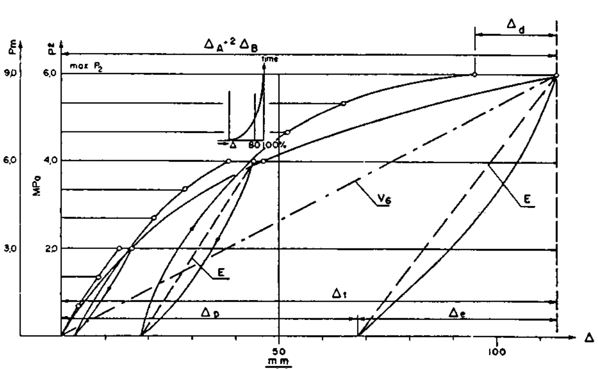


FIG. 2 Typical Graph of Applied Pressure Versus Displacement

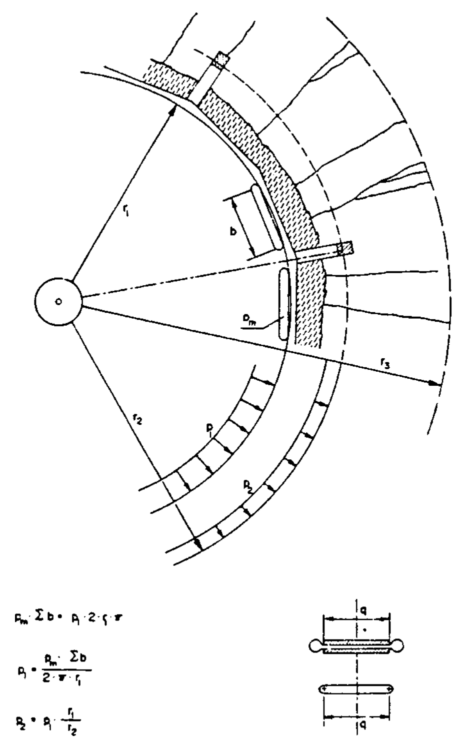


FIG. 3 Scheme of Loading Showing Symbols Used in the Calculations

moderately plastic in its behavior. Superposition of displacements for two fictitious loaded lengths is used to give the equivalent displacements for an "infinitely long test chamber." This superposition is made necessary by the comparatively short length of the test chamber in relation to its diameter.

9.3 Plot the result of the long duration test, Δ_d under maximum pressure, max P_2, on the displacement graph (Fig. 4). Proportionally correct test data for each cycle to give the complete long-term pressure-displacement curve. The elastic component, Δ_e, and the plastic component, Δ_p, of the total deformation, Δ_t, are obtained from the deformation at the final unloading:

$$\Delta_t = \Delta_p + \Delta_e \text{ (see Fig. 4)} \tag{3}$$

9.4 The elastic modulus, *E*, and the deformation modulus, *D*, are obtained from the pressure-displacement graph (Fig. 2) using the following formulae based on the theory of elasticity:

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \frac{(1 + \nu)}{\nu} \tag{4}$$

$$D = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \frac{(1 + \nu)}{\nu}$$

where:
p_2 = maximum test pressure, and
ν = estimated value for Poisson's Ratio.

9.4.1 As an alternative to 9.4, the moduli of undisturbed rock may be obtained, taking into account the effect of a fissured and loosened region, by using the following formulae:

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \left(\frac{\nu + 1}{\nu} + ln \frac{r_3}{r_2}\right) \tag{5}$$

$$D = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \left(\frac{\nu + 1}{\nu} + ln \frac{r_3}{r_2}\right)$$

where:
r_3 = radius to the limit of the assumed fissured and loosened zone, ft (m), and
ln = natural logarithm.

9.4.2 *Assumptions*—This solution is given for the case of a single measuring circle with extensometer anchors immediately behind the lining. The solution assumes linear-elastic behavior for the rock and is usually adequate in practice, although it is possible to analyze more complex test configurations (using, for example, a finite element analysis).

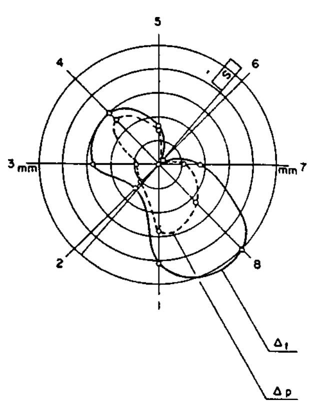


FIG. 4 Typical Graph Showing Total and Plastic Displacements as a Function of Direction Perpendicular to the Test Chamber Axis

10. Report

10.1 The purpose of this section is to establish the minimum requirements for a complete and usable report. Further details may be added as appropriate, and the order of items may be changed. If application of the test results is part of the testing program, an application section compatible with the format described below should be included. The report shall include the following:

10.1.1 *Introductory Section*—The introductory section is intended to present the scope and purpose of the testing program and the characteristics of the material tested, as follows:

10.1.1.1 *Scope*—This shall include (*1*) the location and orientation of the test boreholes (a graphic presentation is recommended), (*2*) the reasons for selecting the test locations, and (*3*) in general terms, a discussion of the limitations of the testing program, that is, the areas of interest not covered by the testing program and the limitations of the data within the areas of application.

10.1.2 *Brief Description of the Test Site Geology*—Describe the rock type macroscopically from both field inspection and from the core logs of the test boreholes. Discuss structural features affecting the testing, as appropriate. Include a listing of the types of data available on properties of the rock cores containing such property data as may aid interpretation of the test data (for example, rock quality designation (RQD), laboratory tests of strength and deformation).

10.1.3 *Test Method Section*:

10.1.3.1 *Equipment and Apparatus*—Include a detailed listing of the equipment actually used for the test. The name, model number, and basic specifications of each major piece shall be presented in the report.

10.1.3.2 *Procedure*—List in detailed steps the procedure actually used for the test.

10.1.3.3 *Variations*—If the actual equipment or procedure has varied from the requirements contained in this test method, note each variation and the reasons for such variation. Discuss the effect of the variation upon the test results.

10.1.4 *Analytical Background*:

10.1.4.1 *Data Reduction Equations*—All equations used to reduce the data shall be clearly presented and fully defined. Note any assumptions inherent in the equations or limitations in their applications and the effect on the results discussed.

10.1.4.2 *Site-Specific Influences*—Include a discussion of the degree to which the actual test site conditions conform to the assumptions contained in the data reduction equations and fully explain any factors or methods applied to the data to correct for a non-ideal situation.

10.1.5 *Results*:

10.1.5.1 *Summary Table*—Present a summary table including the rock materials, the pressure range over which the modulus values were calculated, the average modulus values, ranges, and uncertainties.

10.1.5.2 *Table of Individual Results*—Present a table listing extensometer number, rock material/structure, and average modulus values for each location.

10.1.5.3 *Graphic Presentation*—Present a typical pressure versus deformation curve for each rock material.

10.1.5.4 *Other*—The following types of analyses and presentations may be included as appropriate: relationship between modulus and applied stress; discussions of modulus dependence on geology; comparison with laboratory modulus values or the results of other in situ modulus tests; and comparison of results to other rock types or previous studies.

10.1.6 *Appended Data*:

10.1.6.1 *Pressure versus Deformation Curves*—Include a pressure versus deformation curve from each test in an appendix to the report.

10.1.6.2 *Test Form*—Include a completed test data sheet, such as Fig. X1.1, for each test in an appendix to the report.

10.1.6.3 *Drawings*—Drawings to the report shall include the following:

10.1.6.3.1 A diagram giving all dimensions of the test equipment and instrumentation. Photographs of the experimental test set-up should also be included.

10.1.6.3.2 Geological plans and sections of the test chamber showing the relative orientations of bedding, jointing, faulting, and any other features that may affect the test results, preferably with index test data to give further information on the mechanical characteristics of the rock tested.

10.1.6.3.3 Logs of geological and geotechnical data from the extensometer holes, including RQD, fracture spacing, and water pressure.

10.1.6.3.4 Transverse section of the test chamber showing the deformation resulting from the maximum pressure, as a function of the variation of extensometers (see Fig. 4). The orientations of significant geological fabrics should be shown on this figure for comparison with any anisotropy of test results.

10.1.6.3.5 The graphs showing deformation as a function of applied pressure (see Fig. 2) should be annotated to show the corresponding elastic and deformation moduli and data from which these were derived.

10.1.6.3.6 Any other results and data from other relevant deformability tests, both in situ and laboratory.

11. Precision and Bias

11.1 *Precision*—Due to the nature of rock materials tested by this test method, it is, at this time, either not feasible or too costly to produce multiple specimens that have uniform physical properties. Therefore, since specimens that would yield the same test results cannot be tested, Subcommittee D18.12 cannot determine the variation between tests since any variation observed is just as likely to be due to specimen variation as to operator or laboratory testing variation. Subcommittee D18.12 welcomes proposals to resolve this problem that would allow for development of a valid precision statement.

11.2 *Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined.

12. Keywords

12.1 discontinuities; in situ stress; loading tests; radial jacking test

APPENDIX

(Nonmandatory Information)

X1. Test Form Example

1	2	3	4	5	4 + 5	6	7	4 + 5 + 7	8	9
NR	time	p_2	Δ_A	Δ_B	$\Delta_A + \Delta_B$	Δ_d	Δ_d corr.	Δ_t	Δ_e	Δ_p
1						—	—			
2						—	—			
3a							—			
3b							—			
3c										
4										
5										
6a							—			
6b							—			
6c										
7										
8										
9a										
9^{∞}							—			

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \frac{\nu + 1}{\nu} = \underline{\hspace{4cm}}$$

$$V = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \frac{\nu + 1}{\nu} = \underline{\hspace{4cm}}$$

FIG. X1.1 Suggested Layout for Test Data Sheet

REFERENCES

(**1**) Wallace, G. B., Slebir, E. J., and Anderson, F. A., "In Situ Methods for Determining Deformation Modulus Used by the Bureau of Reclamation," *ASTM STP 477*, ASTM, 1969, pp. 3–26.

(**2**) Lauffer, H., and Seeber, G.," Design and Control of Linings of Pressure Tunnels and Shafts Based on Measurements of the Deformability of the Rock," *Proceedings, 7th International Congress on Large Dams*, Rome, 1961, 91, Question No. 25, pp. 679–709.

(**3**) Wohnlich, M., and Schade, D., "Analysis and Interpretation of Rock Parameters From a Radial Jack Test," *Rock Mechanics*, Vol 11, 1979, pp. 191–216.

(**4**) "Suggested Methods for Measuring Rock Mass Deformability Using a Radial Jacking Test," *International Journal of Rock Mechanics Min. Sci.*, Vol 16, No. 3, pp. 195–214.

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(**8**) Lauffer, H., and Seeber, G.," Measurement of Rock Deformability with the Aid of the Radial Jack," *Proceedings, 1st International Congress on Rock Mechanics*, ISRM, Lisbon, 1966, Vol 2, pp. 347–356.