Designation: D4729 − 19

Standard Test Method for In Situ Stress and Modulus of Deformation Using the Flat Jack Method[1]

This standard is issued under the fixed designation D4729; 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 The flat jack test measures the natural or altered in situ stress at a rock surface either for a surface outcrop or an underground excavation surface. The modulus of deformation and the long-term deformational properties (creep) may also be evaluated for the applied stress range, however long-term creep is not covered by this method.

1.2 This method covers square flat jacks that are placed in a rock slot and if required encapsulated in the slot.

1.3 Deformation readings are taken at the surface, but this standard does not exclude deformation readings being taken below the surface, such as using a flat jack which is set up to obtain displacement data internally.

1.4 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.4.1 The procedures used to specify how data are collected/recorded or calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.5 *Limitation*—The flat jack test measures the average stress normal to the surface of the test chamber, underground excavation, or outcrop. In situ stress levels must be determined by theoretical interpretations of these data.

1.6 *Assumptions and Factors Influencing the Data:*

1.6.1 The stress relief is assumed to be an elastic, reversible process. In nonhomogeneous or highly fractured materials, this may not be completely true.

1.6.2 The equations assume that the rock mass is isotropic and homogeneous. Anisotropic effects may be estimated by testing in different orientations.

1.6.3 The flat jack is assumed to be 100 % efficient. The design and size requirements of 7.1 were determined to satisfy this requirement to within a few percent.

1.6.4 The jack is assumed to be aligned with the principal stresses on the surface being measured. Shear stresses are not canceled by jack pressure. Orientating the tests in three directions in each plane tested prevents the misalignment from being excessive for at least one of the tests.

1.7 *Units*—The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard. Add if appropriate, "Reporting of test results in units other than inch-pounds shall not be regarded as nonconformance with this standard."

1.7.1 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs. The slug unit is not given unless dynamic (F=ma) calculations are involved. For standards involving the determination of mass or the use of density and unit weight, include the following numbered paragraph.

1.7.2 The slug unit of mass is typically not used in commercial practice; that is, density, balances, and so on. Therefore, the standard unit for mass in this standard is either kilogram (kg) or gram (g) or both. Also, the equivalent inch-pound unit (slug) is not given/presented in parentheses.

1.7.3 It is common practice in the engineering/construction profession to concurrently use pounds to represent both a unit of mass (lbm) and of force (lbf). This practice implicitly combines two separate systems of units; the absolute and the gravitational systems. It is scientifically undesirable to combine the use of two separate sets of inch-pound units within a single standard. As stated, this standard includes the gravitational system of inch-pound units and does not use/present the slug unit for mass. However, the use of balances or scales recording pounds of mass (lbm) or recording density in lbm/ft^3 shall not be regarded as nonconformance with this standard.

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

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***A Summary of Changes section appears at the end of this standard**

1.8 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C476 Specification for Grout for Masonry

C1196 Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flatjack Measurements

C1197 Test Method for In Situ Measurement of Masonry Deformability Properties Using the Flatjack Method

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Exploration

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D5720 Practice for Static Calibration of Electronic Transducer-Based Pressure Measurement Systems for Geotechnical Purposes (Withdrawn 2018)[3]

D6026 Practice for Using Significant Digits in Geotechnical Data

D6027/D6027M Practice for Calibrating Linear Displacement Transducers for Geotechnical Purposes

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *cancellation pressure, n*—the pressure in the flat jack required to return the rock to its initial position before the slot was cut.

3.2.2 *coefficient for test geometry, n*—a constant dependent upon the point at which pressure is measured, size of the flat jack, and its relationship with the slot dimension and nearness of surface.[4]

3.2.3 *demountable mechanical (DEMEC) strain gauges, n*—mechanical gauges using 'contact' measuring principles to make transfer-length strain measurements.

3.2.4 *skin stress, n*—the tangential stress at the surface of an opening.

3.2.5 *in situ stress, n*—the stress field existing in a rock mass at the surface or below the surface prior to or after excavation of an opening.

4. Summary of Test Method

4.1 The in situ stress in the rock mass is relieved by cutting a slot into the rock perpendicular to the surface of the underground excavation or rock outcrop using a diamond saw or overlapping drill holes. The deformation caused by this stress relief is measured.

4.2 A hydraulic flat jack (Fig. 1) is placed into the slot and grouted if the slot is too wide or the surface was left uneven and could puncture the flat jack. The flat jack is then pressurized until the above-measured (stress relief) displacement is canceled or recovered. This reapplied stress is approximately equal to the stress in the rock mass at the test location in a direction perpendicular to the plane of the jack. The deformational characteristics of the rock mass are evaluated by incrementally loading or unloading the flat jack and measuring the corresponding deformation.

5. Significance and Use

5.1 Flat jack tests are useful to assess rock mass deformability and stresses in the design stages of projects as well as for issues with existing projects; for example, stresses around an underground opening. The in situ stress values can be used as an important parameter for interpretation and validation of test results and analytical models.

5.2 This test method has been successfully used for other applications such as concrete dams and masonry structures. This test method is similar to the techniques and equipment used in C1196 and C1197. However, this standard is written more for rock and where irregular surfaces may be involved and both in situ stress and deformability are obtained in one test.

NOTE 1—Notwithstanding the statements on precision and bias contained in this test method; the precision of this test method is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing. Users of this test method are cautioned that compliance with Practice D3740 does not in itself assure reliable testing. Reliable testing depends on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Interferences

6.1 *Local Geologic Features*—Local features, particularly faults, shear zones, and alike, can influence the local stress field. Large inclusions in the rock can affect both the stress and deformational properties. Test locations should be carefully selected so that the effects of such features are reduced or, if they are the features of interest, accounted for fully.

6.2 *Influence of Excavations*—Other excavations intersecting the test site will cause complex stress concentration effects

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Lama, R.D., and Vutukuri, V.S., *Handbook on Mechanical Properties of Rocks; Testing Techniques and Results, Volume III*, Department of Mining Engineering, Broken Hill Division, Australia, 1978.

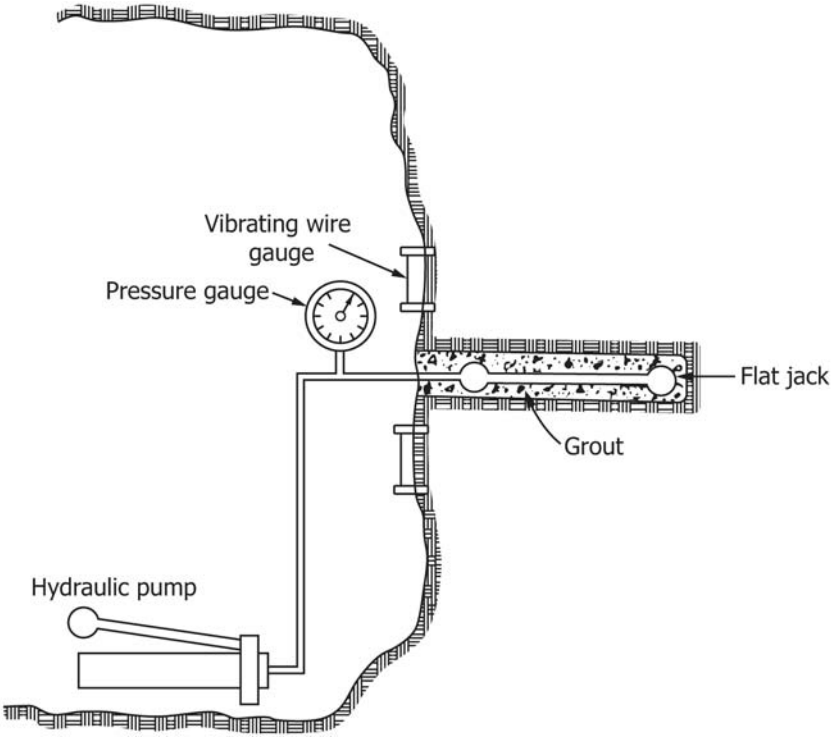

FIG. 1 General Diagram of Flat Jack Test Apparatus with Flat Jack Installed in the Tunnel Wall and Vibrating Wire Displacement Gauges

by superposition. Flat jack tests should be located at least three diameters of the intersecting feature away from that feature. If the underground excavation is excavated by conventional methods, then the surfaces for testing should be further excavated by non-blasting techniques to remove loose material resulting from stress relief or blasting.

6.3 *Temperature*—Temperature can have a significant effect on surface stress measurements, especially for rock outcrops. Therefore, temperature must be considered in the scope and purpose of the testing program.

6.4 *Tests in Orthogonal Directions*—The flat jack most accurately determines the stress parallel to the long axis of the underground excavation because this stress is the least affected by the presence of the opening. (The other tangential stress is highly concentrated.) In addition, if the underground excavation is in a stress field where one of the stresses is significantly larger than the others (3 or 4 times), certain locations in the underground excavation may be in very low compressive or even tensile stress. Flat jack tests in these locations can give what appears to be anomalous and misleading results unless the user is aware that testing can occur in zones with concentrations or reduction of stress.

7. Apparatus (See Figs. 1 and 2)

7.1 *Flat jacks*—Flat jacks shall be designed to operate at pressures of several thousand pounds per square inch when properly installed (Figs. 1, 2, 3, and 4). The jacks shall be constructed so that the two main plates move apart in essentially a parallel manner over the range of the jack. The range shall be at least 0.25 in. (6 mm). The jacks covered by this standard are square and the area of the jack shall be no less than 2 ft (0.6 m) wide. Any calibration factors for pressure for the flat jacks should be provided by the manufacture or obtained by calibrations by the user.

NOTE 2—Other flat jack shapes are available that may be better suited for specific applications. This standard only covers the basic square flat jack, however the basic principles discussed here will still apply.

7.2 *Instrumentation:*

7.2.1 *Pressure*—Electronic transducers or hydraulic gauges may be used to monitor flat jack pressure. The pressure transducer shall have an accuracy of at least ±20 lbf/in.^{2} (±0.14 MPa), including errors introduced by the readout system and a sensitivity of at least 10 lbf/in.^{2} (0.069 MPa).

7.2.2 *Deformation*—Deformation measurement devices including mechanical dial gauges, and electronic transducers such as LVDTs, vibrating wire or linear potentiometers. The devices can be either stationary, or portable, such as demountable mechanical (DEMEC) strain gauges, depending on the site requirements. The deformation device shall have an accuracy of at least ±0.0001 in. (±0.0025 mm) and a sensitivity of at least 0.00005 in. (0.0013 mm).

7.2.3 *Internal Gauges*—Strain gauges inside the flat jack shall be calibrated prior to installation of the jack. The effects of the hydraulic oil and ambient pressure increase on the gauges shall be determined prior to testing.

7.3 *Grout, Mortar, or Other Suitable Encapsulation Compound*—Any suitable encapsulation compound may be used that meets the requirements of the rock and other test criteria discussed in this standard. The encapsulating material used to secure or minimize expansion of the flat jack in the slot or to protect the flat jack from any irregularities on the wall of the slot that could puncture the flat jack. The encapsulation

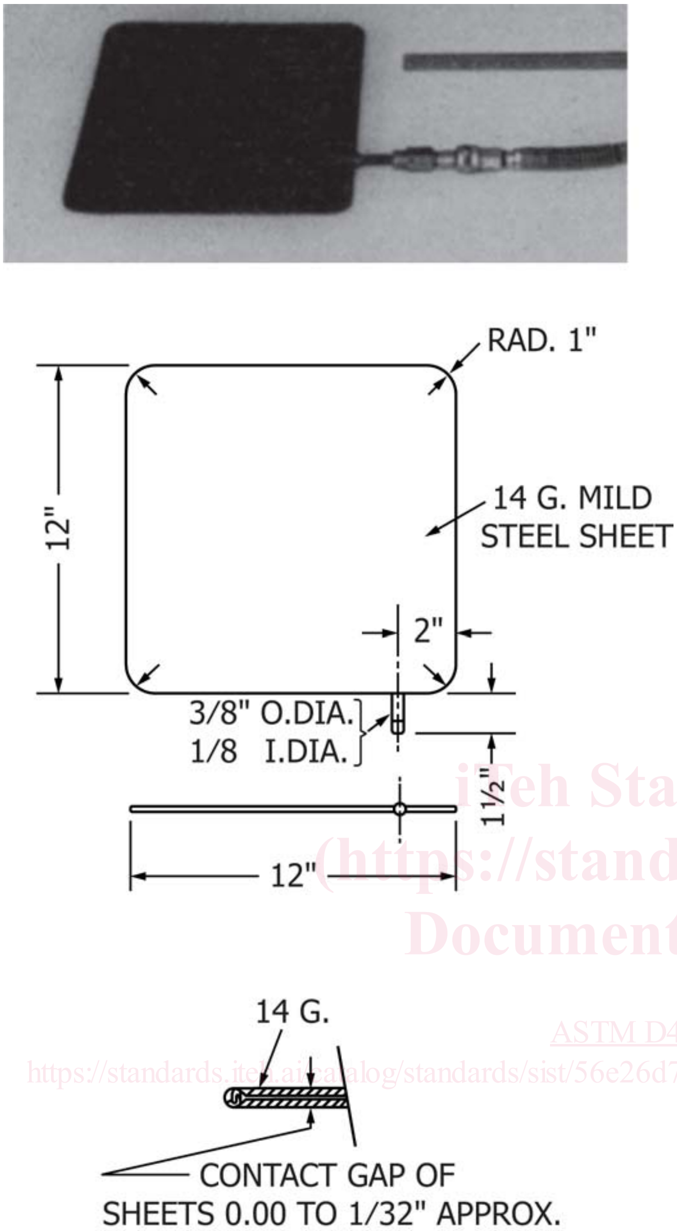

FIG. 2 Example of Square Flat Jack with One Pressure Port

material should be a high-early strength, non-shrink material. Mortar may include up to 50 % clean sand by weight, with grain size between 20- and 60-mesh. Clean, potable water shall be used. The cured encapsulation material shall have a strength greater than the stress applied by the flat jack. The modulus of the encapsulation material must be removed from the determinations of rock modulus.

NOTE 3—The main difference between mortar and grout is the amount of water in the mix. Grout must be made with enough water to make it pourable or pump able but not with so much water that the grout components segregate. Grout slump generally should be between 10 ½ and 11 inches (27 and 28 cm). Mortar, on the other hand, should contain only enough water to produce a smooth, plastic, "buttery" consistency that sticks to the trowel and is easy to spread. Mortar and grout also contain different ingredients. Mortar often contains hydrated lime; grout usually contains little if any hydrated lime (ASTM C476, allows up to 1/10-part lime to 1-part cement). In addition, coarse grout contains larger aggregates than mortar or fine grout. Mortar should not be substituted for grout unless the substitution is allowed by the specifications. Mortar often is too stiff to flow around steel into small cavities or cores without leaving voids. These voids not only reduce strength but also can lead to water leakage problems. Mortar often is used to slush collar joints instead of filling collar joints with grout. This practice is convenient for masons but has disadvantages. First, slushing joints with mortar provides much lower strengths. Steel protection plates can also be used in conjunction with the mortar to protect the flat jack as with the mortar the modulus of the steel is removed from the determination of rock modulus.

7.4 *Slot Cutting Equipment:*

7.4.1 *Diamond Saw*—Any diamond saw that cuts rock and to the depth and specifications (perpendicular to test surface, suitable for square flat jack, and the like.) required for this test. Equipment used to saw a slot in the rock should be of a type where large center or end holes are not required. These large holes can cause serious changes in the stress field to be measured.

7.4.2 *Rock Drill*—Either a core or percussion drill is allowed as long as the holes can be drilled with enough control to produce the slots per the requirements of this standard and can ream or remove any aspects of the rock webs between the overlapping drill holes on the slot geometry or side walls.

7.5 *Measurement Points*—Specifications for measurement points will vary depending on the type of distance measurement device to be used. For example, if a demountable mechanical (DEMEC) strain gauge is used steel pins are inserted in the rock that are specific to the gage points on each end of the gauge. Regardless of the type of distance measurement device used the points must be placed or protected so they are not damaged from cutting the flat jack slot or any other work activities prior to or during the testing.

8. Procedure

8.1 *Personnel Prequalification and Equipment Performance Verification*—See Annex.

8.2 *Groups at Each Test Station*—At least one group of flat jacks should be tested in each test section. Each group should have three flat jacks installed horizontally inclined 45° and vertically. The flat jacks in each group should all be placed in one part of the test section within 20 ft (6.1 m) of each other along the length of the test section.

8.3 *Tests in Orthogonal Directions*—As discussed in section 6.4, the test underground excavation should have at least two, and preferably three, long (at least 4 to 5 times the diameter), straight sections at about 90° to each other. Testing should be distributed evenly in all three sections to provide redundant data and, if results in one section are anomalous, to allow the program to produce sufficient usable data.

8.3.1 *Rock Quality*—The flat jack and deformation instrumentation should not be installed in loose, broken, or drummy material. Loose, broken, or drummy material may be detected by a dull, hollow sound when struck with a hammer; such material should be removed, or a new test site selected.

8.4 *Surface Measurement Area Preparation:*

8.4.1 *Dimensions*—The prepared surface for each flat jack shall extend at least 1 ft (0.30 m) past either end of the flat jack slot and at least 1 ft (0.30 m) past the furthest measuring points.

The transducers or flat jack shall be 1 ft (0.30 m) inside the prepared surface at any point (see Fig. 3).

8.4.2 *Method*—Drilling to a uniform depth may be required to prepare the rock face. Residual rock between the drill holes may be removed by moving the drill bit or special reaming or flattening bit back and forth until a smooth surface is achieved. In softer material, coarse grinding, chipping, or cutting devices that are not as aggressive may be required or utilized.

8.4.3 *Smoothness*—Ideally, the prepared surface should be a plane. The difference between the highest and lowest points on the prepared surface shall be not greater than 2 in. (50 mm).

8.5 *Transducer and Measurement Points Installation*—Transducers, other than any inside the flat jack, and measurement points shall be installed on the centerline normal to where the flat jack slot will be cut, either at the surface or at depth as shown in Fig. 3. Transducers for stress determination shall be installed within *L*/2 of the flat jack slot, where *L* is the width of the flat jack.

8.6 *Transducer and Measurement Points Initial Readings*—Take initial readings of all transducers or between measurement points as shown in Fig. 3 and record on data sheet.

8.7 *Slot Cutting*—The slot can be formed by saw cutting or by drilling overlapping holes. In weak or highly fractured material, any vibrations should be reduced to help assure a slot with walls that are still intact. The slot shall be no more than 3 in. (74 mm) wide if by drill holes and extend no more than 3 in. (75 mm) past the edges of the flat jack. It shall be deep enough that the flat jack may be inserted 3 in. (75 mm) beyond the lowest point on the rock face adjacent to the slot. If drilled, care shall be taken that the holes are straight and parallel to keep the bottom of the slot open to receive the jack. The slot shall be washed clean of all dirt and cuttings, using clean water.

8.8 *Relaxation Measurements*—Deformation between all measurement points shall be measured and recorded immediately upon completion of slot cutting and again immediately prior to testing. The number of significant digits to be read will depend on the stiffness of the rock and the type of readout being used. The number of significant digits should be such that the readout can obtain a reading, differing by at least two units, for each increment and decrement. If the rock undergoes strain under constant load over a period of time, several intermediate readings shall be taken to evaluate this effect.

8.9 *Flat Jack Installation*—Flat jacks shall be centered in the slot and recessed 3 in. (75 mm) from the face of the excavation to minimize the possibility of rupture during pressurization. The encapsulation material, if used, should surround the jack to protect it from being punctured or have excessive expansion and shall be free from voids. The jack shall be installed and allowed enough time for any encapsulation material to attain compressive strength greater than maximum anticipated jack stress.

NOTE 4—If the slot is prepared such that the dimensions, planarity, and smoothness of the slot will support the type of flat jack inserted such that the desired pressure and deformations can be obtained without damage to the flat jack, then encapsulation of the space between the rock and flat jack may not be needed. The advantage of not grouting the flat jack in the slot is that they maybe be able to be reused and reduce costs.

8.10 *Flat Jack Testing:*

8.10.1 The flat jack pressure shall be raised in 100 lbf/in.^{2} (0.7 MPa) increments until cancellation of all measuring points has been achieved. Deformation shall be read after each pressure increment and when the cancellation pressure is reached. The cancellation pressure shall be maintained for 15 min to check for time-dependent deformation; deformation readings shall be taken every 5 min.

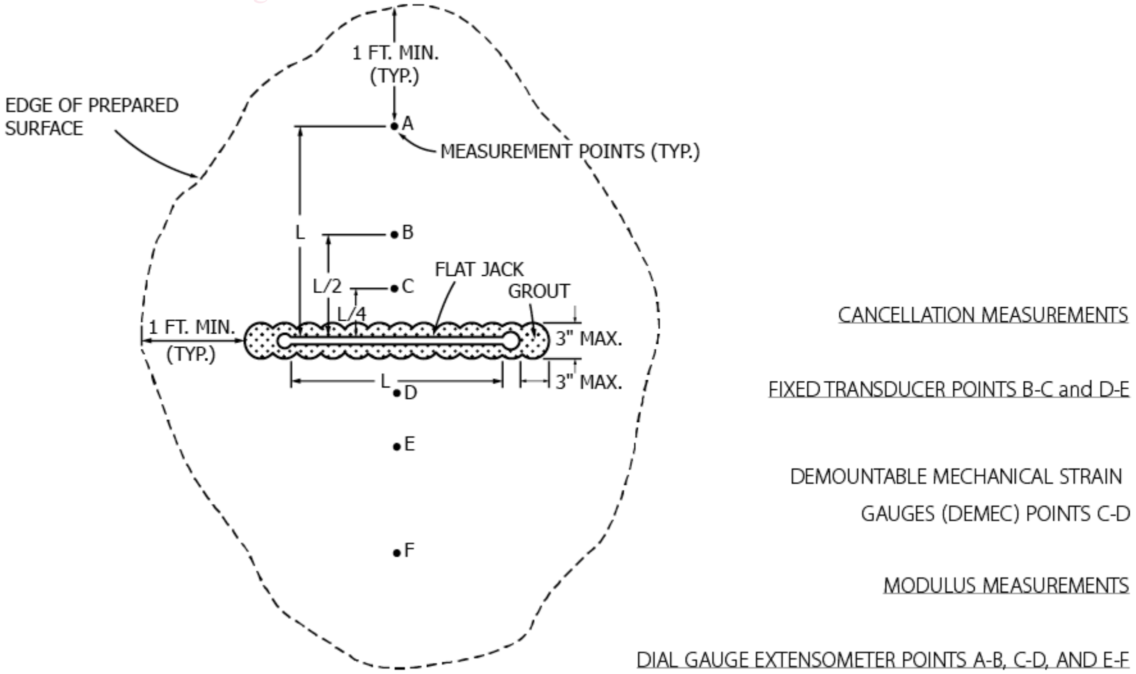

FIG. 3 Recommended Flat Jack Test Setup Showing the Prepared Rock Face Array of Surface Measurement Points

8.10.2 The pressure shall be reduced in 100 lbf/in.^{2} (0.7 MPa) decrements to zero, with deformation read after every decrement. Zero pressure shall be maintained for 15 min to check for time-dependent deformation; deformation readings shall be taken every 5 min.

8.10.3 Subsections 8.10.1 to 8.10.3 of this procedure shall be repeated at least two more times using equal pressure increments and decrements. The peak jack stress of these cycles should be as high as possible and be determined by the test engineer in the field depending on the jack and rock strength and the cancellation pressure.

8.11 *Data Recording Requirements*—Examples of test data sheets and the type of data to record are shown in the Appendix. However, the data requirements may be site specific and shall be developed using the minimum requirements specified in Section 10, Reports.

9. Calculation

9.1 *General:*

9.1.1 The calculation of stress and modulus of deformation from flat jack data is influenced by the complex loading geometry of the test. In addition, the load applied by the flat jack is not the same as the load originally acting on the rock. The jack expands in one direction only, so lateral and shear components are not restored. This is particularly significant when the jack is not aligned with a principal stress. Several elastic models and assumptions have been used to compensate for these factors, leading to varied and sometimes contradictory methods of data reduction.

9.1.2 The equations presented here are among those more widely accepted and have been found to produce results comparable with those of other in situ methods. The analysis of data, however, is dependent on site-specific factors such as geology and the existing stress field.

9.1.3 In the future, individualized analysis of each test by numerical techniques such as finite element methods may prove to be the most effective approach.

9.2 *Cancellation Pressure*—The cancellation pressure is not necessarily equal to the skin stress because of the factors discussed in 9.1. Skin stress calculations fall into two major categories: one in which deformations are measured on one side of the flatjack slot, and one in which deformations are measured across the slot.

9.2.1 When deformation is measured between points on one side of the flat jack slot, the skin stress is calculated using elastic theory and strain. Tincelin[5] found that the strain caused by cutting the slot was similar to the strain produced by a long elliptical opening in an elastic plate, and the strain produced by the flat jack was similar to that caused by uniformly loading the edge of a semi-infinite plate. The ratio of actual stress to cancellation pressure is shown in Table 1 for cancellation measured at various distances from the slot, and from several Poisson's ratios. These factors were derived by Tincelin for a 1.09-yd square (1-m square) flat jack, but are not substantially different from jacks nearly this size. Field experience indicates that this table cannot be used to correct cancellation pressures directly, but only as an indication of where to locate the cancellation measuring points to minimize error. In practice, skin stress measurements are made close enough to the slot that they may be assumed to equal the cancellation pressure within an acceptable error.

TABLE 1 Ratio of Skin Stress to Cancellation Pressure for 1.09-yd Square (1-m Square) Flat Jack

Distance from Slot	Poisson's Ratio of Rock			
	0.10	0.20	0.33	0.50
0	0.99	0.99	0.98	0.92
0.1 *L*[A]	0.98	0.98	0.94	0.89
0.2 *L*	1.00	0.98	0.93	0.88
0.3 *L*	1.04	1.01	0.98	0.93
0.4 *L*	1.10	1.08	1.02	1.01
0.5 *L*	1.20	1.17	1.11	1.08
0.6 *L*	1.31	1.27	1.24	1.18
0.7 *L*	1.44	1.39	1.37	1.30
0.8 *L*	1.58	1.52	1.48	1.38
0.9 *L*	1.71	1.69	1.61	1.46
1.0 *L*	1.87	1.83	1.73	1.53

[A] *L* = width of flat jack.

9.2.2 When deformation is measured between points on opposite sides of the flat jack slot, elastic theory and deformation are used to calculate skin stress. Alexander[6] assumed that the deformations due to cutting the slot were similar to the deformations caused by a finite elliptical opening in a uniformly loaded elastic plate, and the deformations caused by the jack were similar to those caused by an infinitely thin elliptical opening the length of the jack. The deformation on one side of the jack, due to cutting the slot, *W*, is given by the following equations:

$$W_o = \frac{SC}{E}\left\{(1-\nu)\left[\left(1+\frac{Y^2}{C^2}\right)^{\frac{1}{2}}-\frac{Y}{C}\right]+\left[(1+\nu)/\left(1+\frac{Y^2}{C^2}\right)^{\frac{1}{2}}\right]\right\} \quad (1)$$

$$W_1 = \frac{SY_o}{E}\left\{(-2\nu)\left[\left(1+\frac{Y^2}{C^2}\right)^{\frac{1}{2}}-\frac{Y}{C}\right]+\left[(1+\nu)/\left(1+\frac{Y^2}{C^2}\right)^{\frac{1}{2}}\right]\right\} \quad (2)$$

$$W_2 = W_1\frac{Q}{S} \quad (3)$$

$$W = W_o + W_1 + W_2 \quad (4)$$

where:

W_o = displacement on one side of the slot during cutting of an infinitely thin slot, in. (mm),

W_1 = displacement on one side of the slot due to finite slot width, in. (mm),

W_2 = displacement on one side of the slot due to biaxial stress, in. (mm),

S = rock stress normal to the jack, lbf/in.^{2} (MPa),

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[5] Tincelin, M. E., "Mesure des pressions de terrains dans les mines de fer de l'Est: Annales de l'Institut Technique de Batiment et des Travaux Publics," serie: *Sols et Foundations*, No. 58, pp. 972–990. Translated by S. H. Britt, U.S. Geological Survey open file report No. 28927, Washington, DC, 1953.

[6] Alexander, L. G., "Field and Laboratory Tests in Rock Mechanics," *Third Australia—New Zealand Conference on Soil Mechanics and Foundation Engineering*, Sydney, Australia, 1960.