Suggested Method for Deformability Determination Using a Large Flat Jack Technique

SCOPE

1. (a) This test method is intended for the assessment of the *in situ* deformability modulus of rock masses using flat jacks in slots which are cut in the rock mass with a disc saw or by line drilling a series of boreholes. Creep tests can also be performed.

(b) Simultaneous tests are usually carried out in up to four co-planar, contiguous slots which accommodate flat jacks connected "in parallel" to the same pressurizing unit.

(c) Normally, the tests form part of the exploratory investigation for dams, tunnels, caverns, etc. The results provide design data for such structures.

ADVANTAGES AND DISADVANTAGES OF THE LARGE FLAT JACK (LFJ) TEST

Advantages

2. (a)—For LFJ tests, the volume of rock subjected to load is greater than for plate loading* tests but smaller than for radial jacking* tests in tunnels.

—The applied pressure can be up to 20 MPa.
—The set up of the equipment and the test performance is easier than for the other two methods mentioned above.
—The LFJ test is performed inside a relatively undisturbed zone of the rock mass.
—The displacements of the slot walls are measured at several points within the slots, and an idea of the heterogeneity of the rock is obtained.

Disadvantages

(b)— The LFJ test requires a special heavy diamond saw or accurate line drilling equipment to prepare the slots. Skilled staff are also required.
—Generally the measuring range is less than 10 mm.
—When a high initial state of stress occurs together with unfavourable geologic structures, the cutting of the slots may be difficult.
—Generally the flat jacks cannot be recovered after the tests.

* See—ISRM Suggested methods for determining *in situ* deformability of rock. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* **16**, 195–214 (1979).

† Superscript numbers refer to Notes at the end of the text.

APPARATUS

3. (a) Equipment for cutting the slots including a cutting machine such as a diamond disc saw to produce a test slot of suitable dimensions (see 6f) with a drill to provide a hole that will receive the disc-holding tube of the machine (see Fig. 1). Alternatively, a drilling machine and a suitable frame for creating a slot of line drilling.

(b) Equipment for grouting the slot if required (e.g. if the slot was made by line drilling).

Test equipment

4. The test equipment (see Fig. 2) should consist essentially of:

(a) One or more flat jacks, consisting of two steel sheets less than 1 mm thick, welded around the edges and inflated with oil or another hydraulic fluid so as to adjust to the surface of the slots and apply a uniform pressure, with one pipe to inject oil, one to bleed off air and outlets for the electric cables of the displacement measuring system (Fig. 3).[1]†

(b) A system for measuring the displacements of the rock perpendicular to the slot and in the direction of pressure application at several points on the tested surface. Generally, four deformeters are used, each deformeter being basically formed by two flat steel springs fixed to one of the flat jack walls and kept in contact with the other due to their own spring action, and instrumented with four electric strain gauges forming a full bridge, thus providing automatic temperature compensation.[2] The measuring range should be at least 4 mm with an accuracy of ± 0.005 mm.

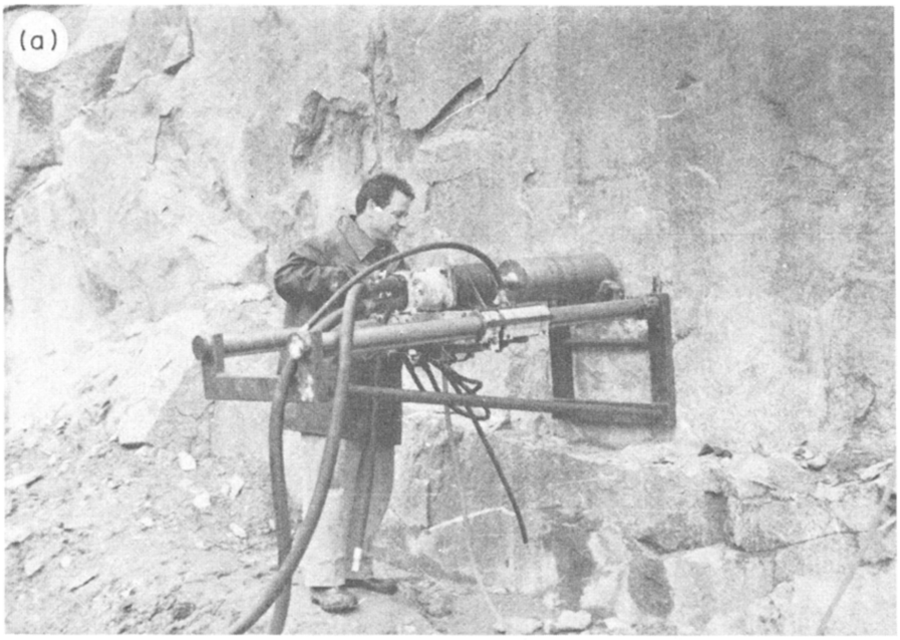
(c) A hydraulic pressure generator, such as a hand pump, to which an oil/nitrogen pressure accumulator may be connected to hold the pressure constant during creep tests.

(d) A unit for reading the applied pressures, such as a Bourdon-type presure gauge or pressure cell, with a suitable pressure range for the maximum applied pressure and an accuracy of $\pm 1.0\%$ of the maximum range throughout the test.

PROCEDURE

Selection of test locations

5. (a) Tests should be performed at representative locations in the rock mass, preferably directly in the zones which will influence the behaviour of the future works.



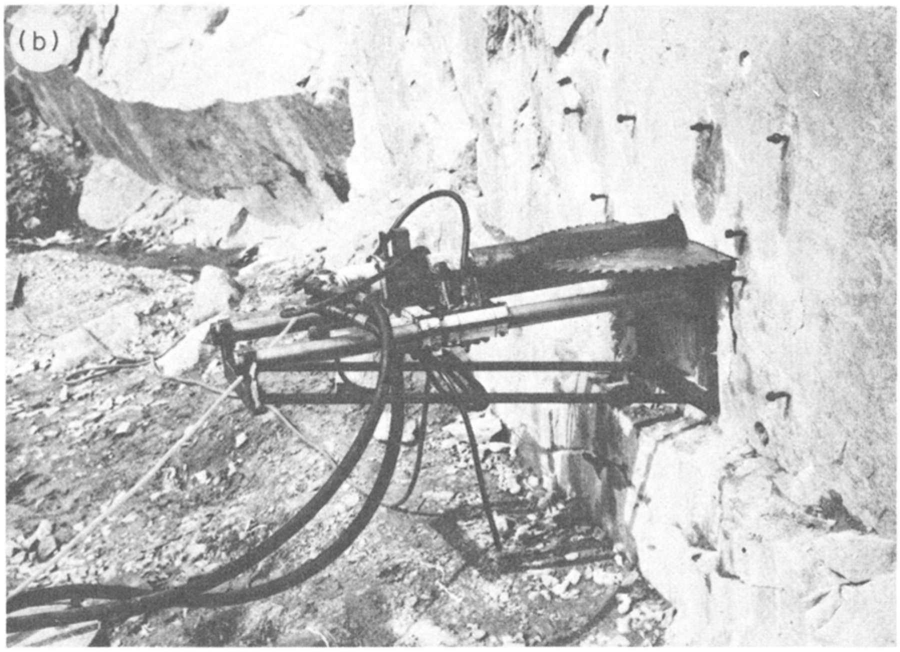


Fig. 1. Cutting machine. (a) Preparation drilling. (b) Preparation for cutting the slot.

(b) The number of co-planar, contiguous slots should be at least two in order to allow a suitable analysis of the results, see 11b, (Fig. 4).

(c) Each zone should be tested at least in the direction of the anticipated maximum compressive stress, but preferably in several directions to allow for the study of the rock mass anisotropy.

Slot cutting and preparation

6. (a) When testing underground, the adit or test chamber must have a cross-section large enough to allow the mounting of the cutting machine or drilling equipment. Zones must be prepared in order to obtain a flat surface perpendicular to the chosen jack position (Fig. 5). Near surface rock which has been disturbed by excavation of the adit, e.g. by blasting, should be removed if possible by pneumatic tools to produce a sound flat surface.

(b) The above-mentioned flat surface may be lined with a smooth layer of mortar no more than 5 cm thick, in order to make installation of the cutting machine possible (Fig. 5).

(c) The cutting machine is usually held by means of anchor bolts in order to avoid deviations of the borehole and of the slot. The anchor bolts must not disturb the rock mass volume to be tested.[3]

(d) If necessary, a borehole with a size suitable for the disc-holding tube to pass is drilled.

(e) Thereafter, the slot is cut by means of a diamond-disc saw or line drilling equipment.

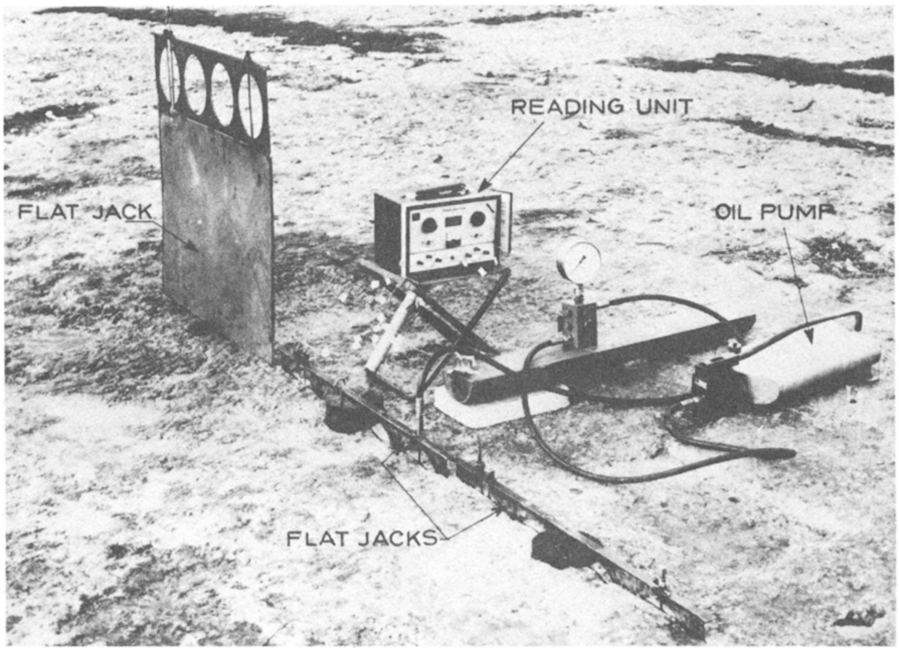


Fig. 2. Test equipment.

(f) The slot should have a width of between 5 and 10 mm larger than the flat jack, an aperture of approximately 1 mm larger than the flat jack thickness and a depth which allows the pressure to be applied to an undisturbed rock mass zone (a depth at least 0.25 m greater than the length of the active part of the jack should be used).

(g) The slots should be cut in such a way that the slot walls remain smooth and straight to ± 0.5 mm.[4]

(h) No slot imperfections of greater amplitude, such as cavities, ripples or grooves, should be tolerated near the measuring zone.

(i) In the case of two or more in-line slots, interpenetration must be avoided. The separation distance of intact rock between two in-line slots should be ± 10 mm. The interceptions of in-line slots with the surface of the adit should be co-linear with a tolerance of ± 5 mm. Angular deviations between the slots should not exceed 2°.

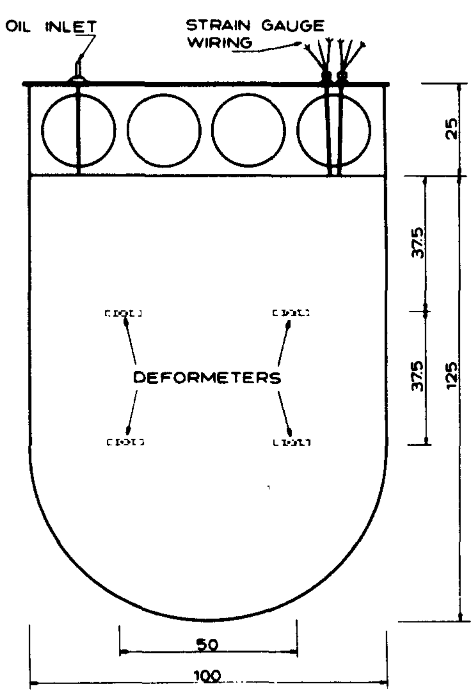


Fig. 3. Recommended flat jack dimensions.

(j) A large flat jack with a suitable form is inserted into each slot. If the slot was formed by line drilling, the semi-circular gaps between the flat jack and the rock surface should be filled with mortar.

(k) The flat jack, or jacks as the case may be, is filled with oil through the lower pipe, the upper one being opened in order to bleed the air. When no more air is expelled from the flat jack, the air bleed pipe is closed and an additional $\pm 100\ \text{cm}^3$ of oil introduced into the flat jack.[5]

(l) If a hole for the disc-holding tube has been drilled, it must be filled with mortar or other suitable material.[6]

Calibration of the equipment

7. (a) The deformeters of the flat jack should be calibrated before each test series.

(b) The deformeters must be calibrated, either separately before being introduced in the flat jack, or all together after the welding of the jack. In the first case, known displacements d are applied to the deformeter and the corresponding readings r taken. In the second case, the flat jack is introduced into a structure and oil under pressure injected into it: the displacements of the structure are measured and the corresponding readings of the deformeters made.

(c) The calibration curves should be linear[7] from zero to the maximum deformation expected for the deformation measuring system. The correlation factor should be 0.98 or greater (Fig. 6).

(d) The calibration factor d/r for each deformeter should be printed on a metal tag fixed to the flat jack.

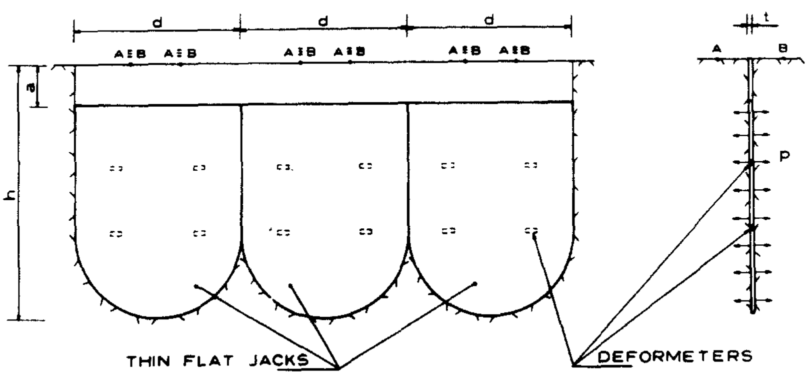


Fig. 4. Combination of three, co-planar flat jacks.

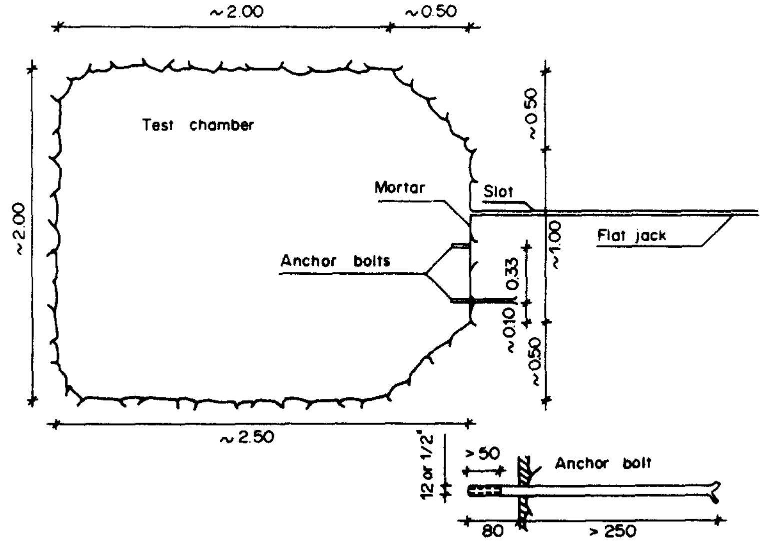


Fig. 5. Cross section of a horizontal test chamber.

The gauge factor for the strain gauges in the deformeter as well as the jack number should also be provided.

Testing

8. (a) The test should be conducted using at least three loading–unloading cycles, until the variation in total deformation at the maximum and at the minimum load in the two last cycles does not exceed 5% of the overall deformation.

(b) The test pressure should not fall below 0.2 MPa during the test to ensure permanent contact of the flat jack surface with the slot walls. Maximum test pressure should in general be selected as 120–150% of the maximum stress expected due to loading by the proposed structure.

(c) The cycles should consist of a sufficient number of loading and unloading increments to allow the pressure–deformation curve to be plotted accurately. The time interval between increments should be constant during both loading and unloading.

(d) If creep tests are to be undertaken, usually at the maximum test pressure, an additional creep test under

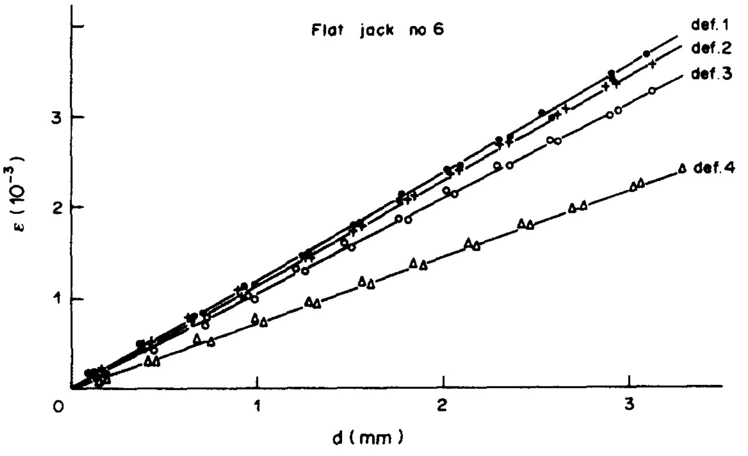


Fig. 6. Calibration curves of a flat jack.

minimum test load and of the same duration as the test under maximum load should also be carried out in order to assess the recovery of the rock mass.

(e) The time intervals between readings during creep tests should be such as to allow the accurate plotting of the deformation–time curves.

(f) During a creep test, the applied pressure should not vary more than $\pm 2\%$ in order to obtain meaningful results. A system to maintain pressure constant within thse limits should therefore be used.

Recording of the results

9. (a) Before conducting a test the date, location, slot orientation, number of slots under pressure,[8] calibration factors of all deformeters in the jacks used, and deformeter locations should be recorded.

(b) During cyclic loading–unloading, the applied pressure and all deformeter readings should be recorded for each pressure increment.

(c) During creep tests the applied pressure, time and all deformeter readings should be recorded.

CALCULATIONS

10. In order to obtain the deformability modulus, the following calculations must be performed:

(a) Change in slot opening at each deformeter (measuring point) are obtained by multiplying the readings by the corresponding calibration factor.

(b) Modulus of deformability of the rock mass for different crack depths is calculated from the formula:

$$E_i = k_i(1 - \nu^2)\frac{p}{d_i}, \tag{1}$$

where:

E_i—modulus of deformability at measuring point i,
p—increment of the applied pressure, generally $p = p_M - p_m$,
p_M—maximum test pressure,
p_m—minimum test pressure,
d_i—increment of the slot opening at measuring point i corresponding to the variation of the applied pressure p,
ν—Poisson's ratio of the rock mass, generally assumed as 0.2 if unknown,
k_i—coefficient depending on the stiffness, shape, arrangement and number of flat jacks, on the location of the measuring point i, on the shape of the test chamber and on the depth of the crack formed in the rock by the application of pressure in the slots [2,3].

Values of k_i for several flat jack combinations are presented in Table 1. These values are valid for the flat jack configurations shown in Fig. 3 and for test chambers 3.5 m long and 2.5 m wide. For other flat jack and test chamber shapes, values of k_i can be determined as discussed in reference [3] or by using a numerical or other suitable model.

Most probable modulus of deformability

11. The state of stress induced by the test near the border of the slots is always a tension which often leads to the opening of a crack in the slot plane. The interpretation of the test results is uncertain due to the lack of knowledge of the crack depth which is difficult to evaluate even when the crack is visible at the surface of the test chamber.

In order to interpret the results, the influences of the initial stress and the tensile strength of the rock mass must be quantified, as well as their variation with the crack depth. The crack propagates to a depth h, for which, [2,3]:

$$p_M = f_1\sigma_i + f_2\sigma_t, \tag{2}$$

where:

σ_i—initial stress in the rock mass,
σ_t—tensile strength of the rock mass,
h—crack depth,
f_1 and f_2—coefficients depending on the shape of the test chamber, on the number of jacks and on the crack depth h, whose values have been determined by computer analysis.

(a) If the values of σ_i and σ_t are known, ratios p_M/σ_i and σ_t/σ_i can be determined, and from one of the graphs in Figs 7–9, the corresponding crack depth h. The value of the most probable modulus of deformability E of the rock mass is then found from:

$$E = (1 - \nu^2)p\frac{\sum_i k_i}{\sum_i k_i d_i}, \tag{3}$$

where the values of k_i are obtained from Table 1 for the correct depth.

(b) If the values of σ_i and σ_t are not known, the least square method should be used, and for each arrange-

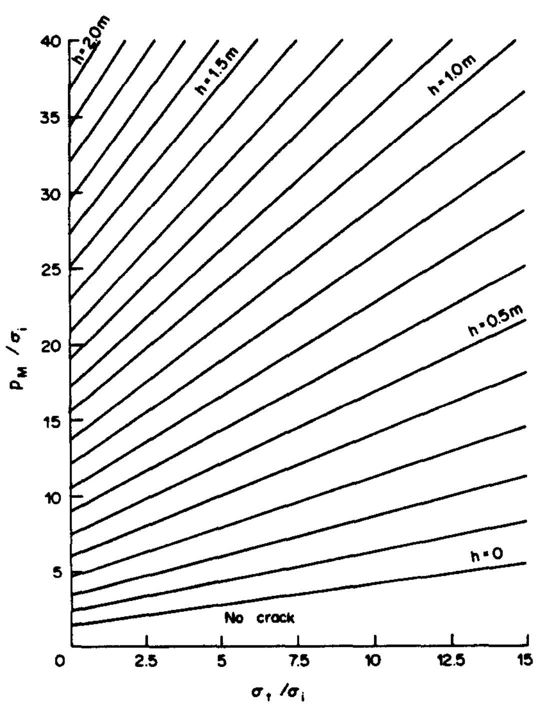


Fig. 7. Variation of the crack depth h (m) with the initial stress σ_i, the tensile strength σ_t of the rock mass and the maximum applied pressure p_M, for one slot.[10]

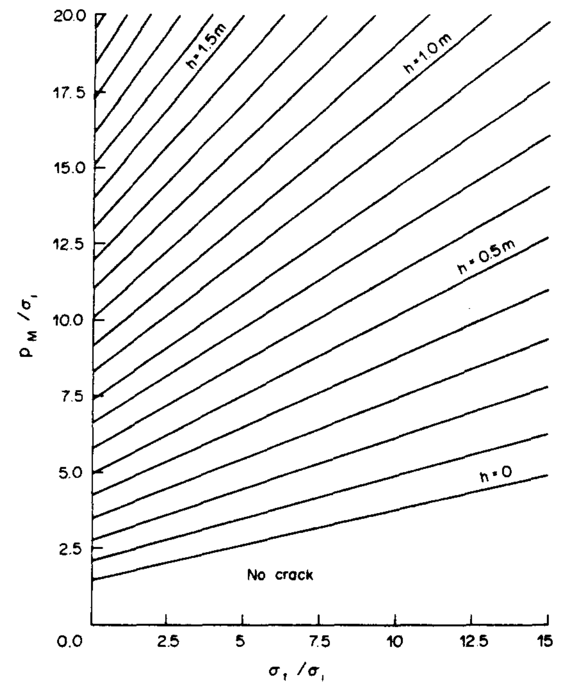


Fig. 8. Variation of the crack depth h (m) with the initial stress σ_i, the tensile strength σ_t of the rock mass and the maximum applied pressure p_M, for two contiguous slots.[10]

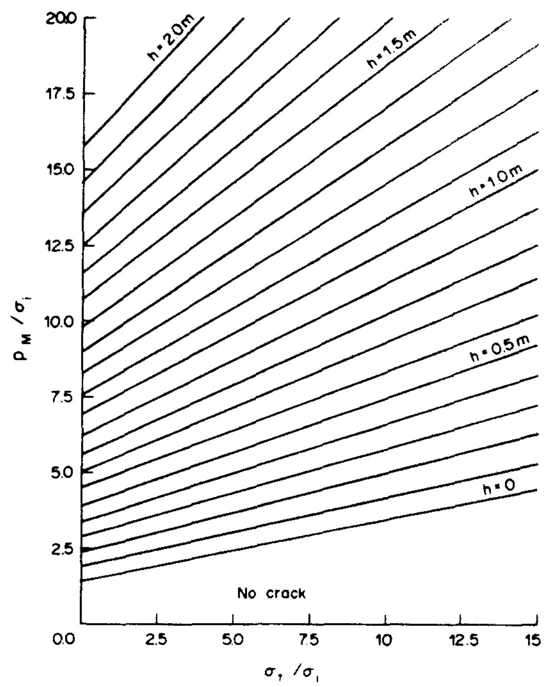


Fig. 9. Variation of the crack depth h (m) with the initial stress σ_1, the tensile strength σ_t of the rock mass and the maximum applied pressure p_M, for three contiguous slots.[10]

Table 1. Coefficients k_i (cm) for different combinations of large flat jacks[9]

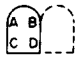
Case		Depth h (m) of the crack								
		0.0	0.2	0.5	1.0	1.5	1.7	2.0	3.0	∞
	AB	131.4	163.0	183.9	196.7			205.8		222.4
	CD	136.8	166.0	184.4	196.7			205.0		221.5
	AF	150.3	193.0	214.2	232.1	240.7		246.9		280.8
	BE	191.0	239.0	257.0	273.0	281.1		286.6		320.3
	CI	160.7	198.2	217.1	232.6	240.5		246.2		279.8
	DG	215.3	245.4	260.6	274.1	281.3		286.6		319.7
	A	137.4	167.8	185.7	196.7			205.8		222.4
	B	151.5	175.2	187.3	196.7			205.8		222.4
	C	144.7	171.3	186.6	196.7			205.0		221.5
	D	164.8	179.4	188.8	196.7			205.0		221.5
	AL	155.7	199.3	224.9	242.4	257.3		267.3		313.2
	BJ	202.8	255.5	277.8	294.2	307.6		316.8		361.9
	CN	167.7	206.2	228.4	243.5	257.5		266.9		312.2
	DM	231.7	264.9	282.6	296.0	308.2		316.8		361.3
	EF	216.9	273.9	296.0	312.2	325.0		333.8		378.6
	GI	249.7	284.4	301.2	314.2	325.6		333.9		378.0
	AL	141.1	178.7	198.2	213.4			224.0		254.9
	BJ	159.7	192.8	209.7	223.8			233.9		264.1
	CN	149.5	183.3	200.3	213.7			223.5		253.8
	DM	176.0	198.7	212.2	224.2			234.3		263.1
	EF	159.8	182.9	190.4	196.7			205.8		222.4
	GI	176.1	187.8	192.3	196.7			205.0		221.5
	A	137.9	171.3	187.2	199.0			205.8		222.4
	B	152.2	177.9	190.1	199.1			205.8		222.4
	C	145.1	175.3	188.6	199.3			205.0		221.5
	D	165.7	182.5	191.7	199.5			205.0		221.5
	A	152.2	197.1	213.5	232.1	240.7		246.9		280.8
	B	195.3	234.5	256.8	273.0	281.1		286.6		320.3
	C	163.3	203.4	217.0	232.6	240.5		246.2		279.8
	D	221.4	251.4	261.1	274.1	281.2		286.6		319.7
	E	200.7	247.0	258.7	273.0	281.1		286.6		320.3
	F	175.7	210.6	220.0	232.1	240.7		246.9		280.8
	G	228.6	255.3	263.2	274.1	281.2		286.6		319.7
	I	197.2	218.1	224.1	232.6	240.5		246.2		279.8
	AP	157.5	199.4	225.5	250.0		268.9		288.1	335.7
	BO	206.2	258.6	284.3	306.4		323.6		341.5	388.5
	CR	170.5	209.1	231.1	252.6		269.3		287.2	334.6
	DQ	237.5	271.6	291.1	309.6		324.4		340.9	387.8
	EL	223.4	282.4	309.3	331.0		347.4		364.4	411.1
	FJ	228.8	291.6	319.4	341.1		357.2		373.8	420.3
	GN	259.9	296.8	316.6	334.1		348.2		363.8	410.4
	IM	267.9	306.8	326.9	344.3		358.0		373.3	419.7

Table 2

						TEST WITH LARGE FLAT JACKS						SHEET No.		
						SITE								
ADIT			CHAMBER			SKETCH								
ROCK TYPE														
SLOT			PRES. IN											
DATE / /			JACK No.											
NOTES:														
p	TIME		DEF. 1 a=			DEF. 2 a=			DEF. 3 a=			DEF. 4 a=		
(MPa)	T	$T-T_0$	R	$R-R_0$	$d(\mu m)$	R	$R-R_0$	$d(\mu m)$	R	$R-R_0$	$d(\mu m)$	R	$R-R_0$	$d(\mu m)$

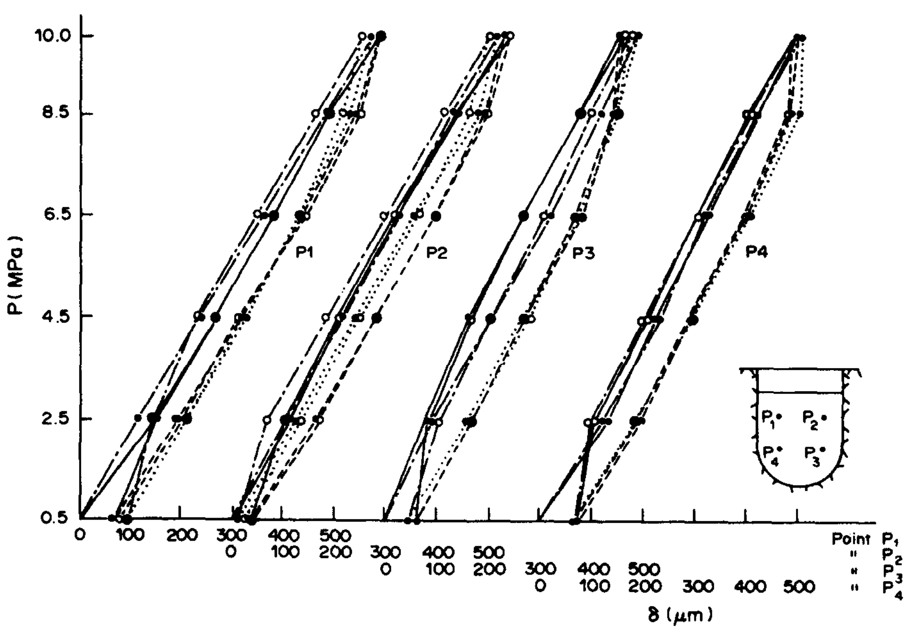


Fig. 10. Pressure–displacement curves.

ment of large flat jacks and each crack depth presented in the table, the value of E should be calculated from expression (3). This value allows the calculation of the sum of the squares:

$$\Delta = \sum_i (d_i - \frac{1 - \nu^2}{E} pk_i)^2. \quad (4)$$

As these sums reflect the deviation of the real deformation from the theoretical deformation, the most probable crack depth is the one which leads to the least value of Δ, and the most probable deformability modulus the one which is obtained from expression (3) for that crack depth.

This calculation procedure requires a reasonable number of measuring points in each test in order to give accurate results and a minimum of six measuring points is recommended, see 5b.

REPORTING OF THE RESULTS

12. The report should include the following information:

(a) Site location, with plans and sections showing test locations, directions, depths, dates of testing, etc.

(b) Information on the type and quality of rock at each test location, and on the adequacy or otherwise of the slots.

(c) Details of the test equipment used.

(d) For each test, a table of results (as illustrated in Table 2), giving applied pressure, time after starting of the test, and all measured values of displacements d_i and incremental displacements.

(e) Pressure–displacement graphs (Fig. 10) showing the measuring points and the range of pressure displacement over which modulus values have been calculated.

(f) If applicable, displacement time graphs showing creep characteristics at the measuring points.

(g) Calculated modulus/creep parameters, also the formulae used in their calculation and a list of assumptions made (e.g. values for Poisson's ratio).

NOTES

1. The dimensions presented correspond to the LFJs used by the Laboratório Nacional de Engenharia Civil in Portugal (LNEC), in normal cases, but others with 2.25 m length of the active part (an active area of 2.14 m^2 and 8 deformeters) are also used. Other shapes such as rectangular flat jacks can also be used in slots created by line drilling.

2. The deformeters described are those used in the LFJs developed by the LNEC, but other displacement measuring systems with the required accuracy may be used.

3. For horizontal or inclined slots, it is convenient to support the cutting machine with timber, especially in cases of weak rocks.

4. Paragraphs (g), (h) and (i) are only applicable to slots cut by means of a diamond-disc saw.

5. When initial oil pressure is applied, the jack fills the slot completely, thus preventing mortar entering the slot when the central hole is filled. Prior to filling of the central hole, high pressure may not be applied since the jack steel sheets are not strong enough to withstand high oil pressure without support.

6. The central hole may also be filled in with half cylinders of hard wood.

7. If the calibration curves are not linear, they must be supplied together with the flat jack. Deformeters which show hysteresis should not be used.

8. If several, co-planar, contiguous slots have been cut, pressure may be applied only in some of the corresponding flat jacks. It should therefore be stated which flat jacks have been subjected to the pressure.

9. The constants of Table 1 refer to flat jacks with dimensions shown in Fig. 3. For other configurations these should be calculated using a numerical technique such as the boundary element method.

10. The graphs of Figs 7–9 refer to flat jacks with dimensions shown in Fig. 3. For other configurations these should be calculated using a numerical technique such as the boundary element method.

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