The storage coefficient of fractured rock determined from deformation tests

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The elastic storage coefficient is often essential for the evaluation of hydraulic tests in boreholes. This is the case for single-hole measurements, where the skin effect carries great weight for the pressure transience. One way to obtain the storage coefficient is to use data from deformation tests, but these are made mostly on unfractured drill cores. To obtain the actual deformation properties of the fractured rock mass, it is necessary to make large-scale, in-situ tests. This paper gives some results of such tests, together with a brief description of the testing technique and the equipment. The test results are evaluated in a way which is compatible with the actual load during a hydraulic test. In the tests performed, it was found that the modulus of deformation for the storage coefficient may be less than one per cent of the modulus of elasticity obtained from drill cores. The rock masses tested have storage coefficients in the range 10^{-6}—10^{-4}.

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Introduction

It is often essential to obtain an accurate approximation of the elastic storage coefficient for the evaluation of hydraulic tests. This is especially pronounced in single-hole tests under transient conditions, where the calculated value of the storage coefficient is usually influenced by skin effects, i.e. different hydraulic properties in an infinitesimal zone around the borehole compared with the properties of the formation as a whole. The modulus of elasticity or the compressibility must be known, to determine the storage coefficient. The modulus of elasticity is usually determined in a small scale, i.e. on drill cores. The values obtained are therefore not representative of the rock mass, where the fractures and other structural discontinuities influence the deformation properties. From an empirical point of view, it has been shown that modulus of deformation of the fractured rock mass is about 0,3—0,5 of the modulus of elasticity of the rock (Hiltscher 1965). However, this relationship must be regarded as very rough and inaccurate. To obtain a more accurate value of the modulus of deformation of the fractured rock, it is necessary to make direct measurements in the rock mass, to take into account the existing discontinuities.

The aim of this paper is to present some results from a number of large-scale, in-situ deformation tests and to give a brief description of the method used to make the measurements.

The storage coefficient

The storage coefficient is defined as the volume of water which is removed over a unit area, for a drawdown of one unit. It is a function, which depends both on the material in the water-bearing formation and on the properties of the water, as shown by the following equation:

$$S = \varrho_w g m (c_f + \Phi c_w) \qquad (1)$$

or

$$S_s = S/m = \varrho_w g (c_f + \Phi c_w) \qquad (2)$$

where S = storage coefficient
S_s = specific storage coefficient
ϱ_w = density of the water
g = acceleration due to gravity
m = thickness of the formation
Φ = porosity of the formation
c_f = compressibility of the formation
c_w = compressibility of the water.

In a formation with low porosity, such as crystalline rocks, the term Φc_w will become small compared with c_f, which indicates that the storage coefficient depends almost exclusively on the elastic properties of the formation. The compressibility is

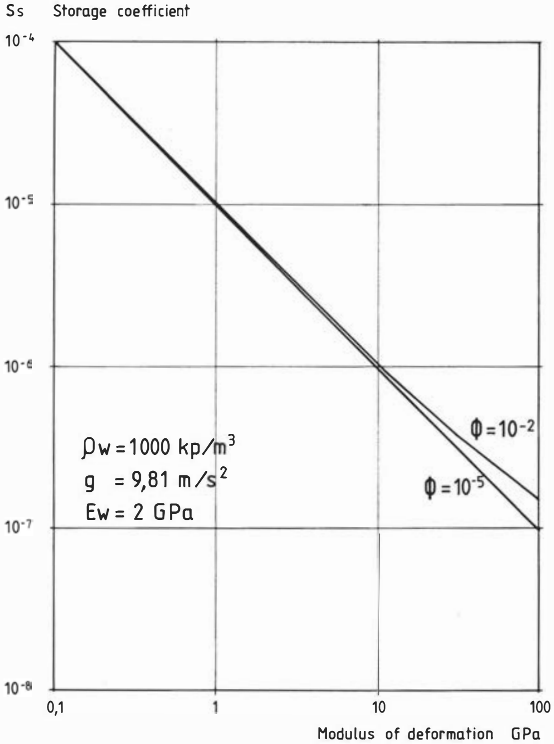

Fig. 1. The storage coefficient versus the modulus of deformation for different values of the porosity.

defined as the inverse of the modulus of deformation or elasticity. Thus

$$S_s = \varrho_w g \left(\frac{1}{D_r} + \frac{\Phi}{E_w} \right), \tag{3}$$

where D_r = modulus of deformation of the formation
E_w = modulus of elasticity of the water.

The relationship is shown graphically in Figure 1. The water is of minor importance and contributes to the coefficient of storage only when the porosity is high, i.e. more than one per cent.

Determination of the modulus of deformation

For the present work, results from large-scale, in-situ deformation tests have been used. The tests were originally performed with the aim of investigating the properties of rock for turbine foundations in nuclear power plants. However, it is also possible to use the test results for the present purpose, by recalculating with the load conditions which may be assumed to exist during the hydraulic test. A modulus of deformation has therefore been calculated for the very small loads which are created during a hydraulic test.

The test is based on an evenly distributed load which acts on a rock surface levelled with a thin

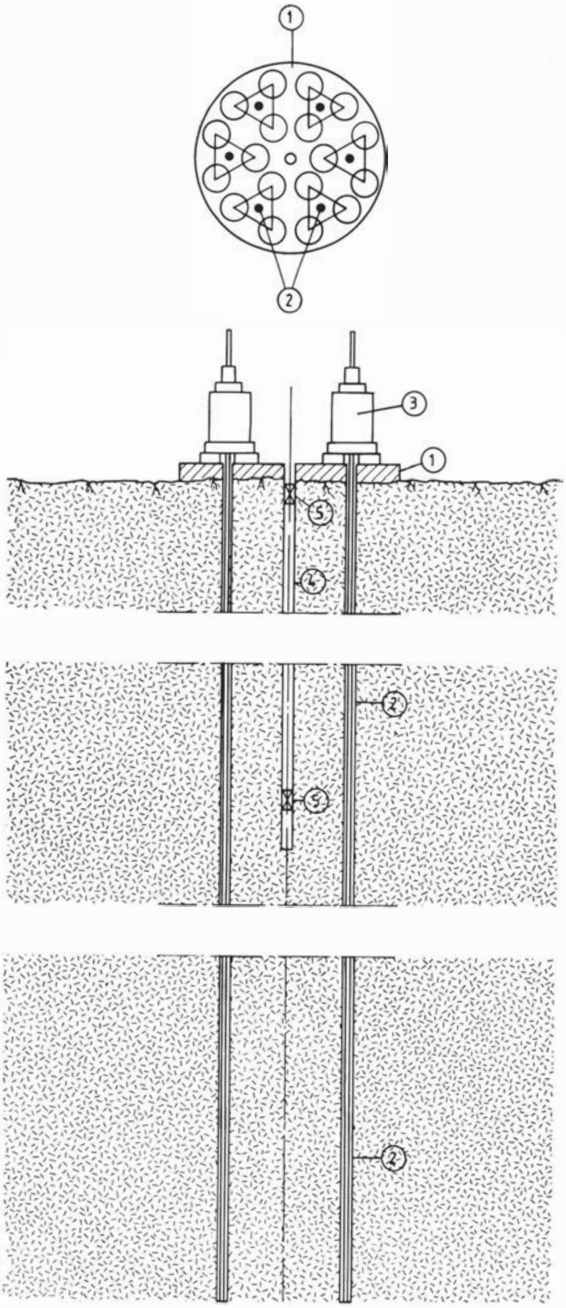

Fig. 2. Schematic layout of the testing device. 1. Concrete slab. 2. Steel bars anchored below the 6 m-level. 3. Hydraulic jacks. 4. Measuring hole. 5. Bench marks clamped into the borehole.

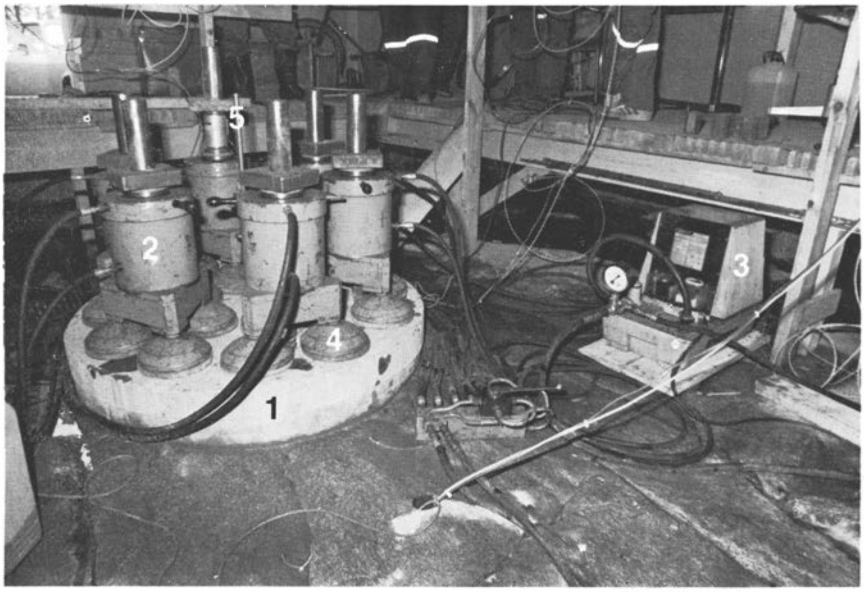

Fig. 3. A deformation test. 1. Concrete slab. 2. Hydraulic jacks. 3. Motorized pump for the jacks. 4. Plates for load distribution. 5. Measuring rod. Photograph by A. Carlsson.

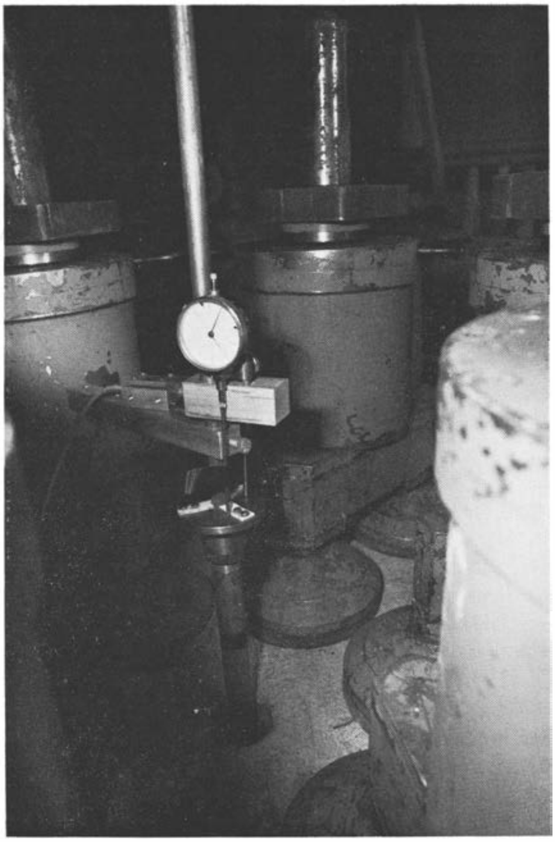

Fig. 4. Close-up of the measuring rod, with strain gauge and a dial gauge. Photograph by A. Carlsson.

layer of concrete, 1 m^2 in area. Figure 2 shows the layout of the test schematically. The load is supplied by six hydraulic jacks acting in parallel, through steel bars anchored six metres deep in the rock. A system of levers distributes the load from each jack to the plate of concrete, to produce a stress field that is fairly evenly distributed over the test area. In all, the load from the jacks is distributed as 18 point loads over the surface of the concrete.

With this equipment, a maximum pressure of up to 3,6 MPa (360 tonnes/m^2) may be exerted. The surface part of the testing device is shown in Figure 3.

The deformation measurement is made in a particular borehole in the centre of the test area, in which a system of bars is placed. For the measurement, the rod is equipped with a spring and a strain gauge connected to a recording device (cf. Figure 4). The system of bars is connected to two movable bench marks which are clamped into the borehole at certain levels. Hiltscher et al. (1982) present a detailed description of the measuring technique, while in this paper it is described very briefly.

The deformation due to the load is obtained and is, according to Boussinesq:

$$\delta_0 = \frac{\sigma d}{E}(1-\nu^2), \tag{4}$$

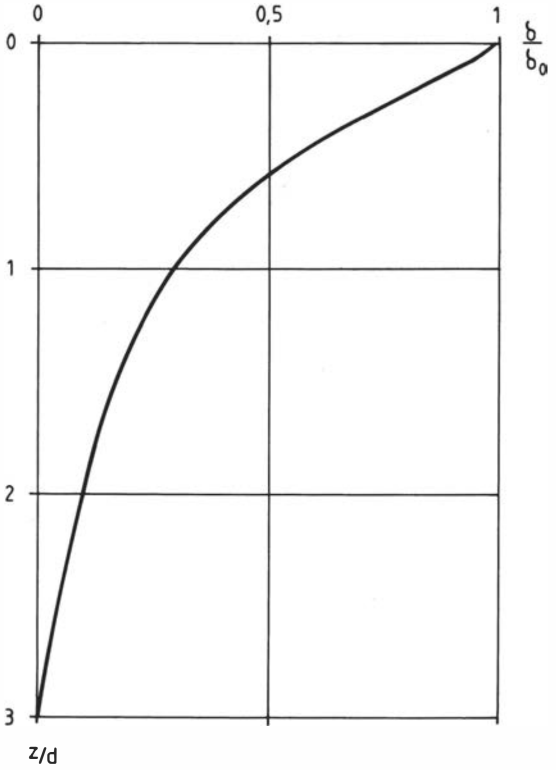

Fig. 5. Reduction factor versus the relative depth.

where δ_0 = the deformation of the rocks surface
σ = the load
d = diameter of the test area
E = modulus of elasticity or deformation
ν = Poisson's ratio.

The term $(1-\nu^2)$ is approximately equal to 1 in a fractured rock mass with a Poisson's ratio of about 0,2. The modulus of deformation is defined as the integrated modulus of elasticity over the rock mass, including rock matrix and discontunuities. The modulus may be calculated as:

$$D = \frac{\sigma d}{\delta_0}, \qquad (5)$$

where D = the modulus of deformation.

In order to avoid difficulties arising from measurement in relation to a bench mark outside the test area, the method is based on the measurement of the difference in deformation between two measuring points located in the borehole (cf. Figure 2). Figure 5 shows a theoretical curve for the relative deformation at different depths. The deformation decreases with increasing depth and is a maximum at the rock surface, where the deformation is δ_0. At the midpoint between the rock surface and the depth at which the steel rods are anchored, the relative deformation is 0. In order to use the relative deformation, it is thus necessary to consider the difference in depth between the bench marks in the borehole. For this purpose, a reduction factor based on the relative deformations has been used (cf. Figure 5). The value of this factor depends on the depths at which the measuring points are located. The equation which describes the modulus of deformation from the tests may be written:

$$D = d\sigma \frac{c_1 - c_2}{\delta_1 - \delta_2} = \frac{d\sigma\Delta c}{\Delta\delta}, \qquad (6)$$

where c_2 and c_1 = the δ/δ_0 values from Figure 5 for the respective depths of the bench marks
δ_1 and δ_2 = the absolute deformation at the respective depths
$\Delta\delta$ = the measured difference in deformation.

The measurements were made with repeated loading cycles and the deformation versus load was recorded for each cycle, as shown in Figure 6. Figure 7 shows a typical load/deformation graph. From these graphs, it is then possible to calculate any desired modulus of deformation. For the present purpose, a secant modulus to the 0,5 MPa load was determined, as indicated .in Figure 7.

Results

The measurements have been carried out at the Forsmark area in southern, central Sweden, in a total of 24 tests (Hiltscher & Strindell 1976a and 1976b). In addition to the main tests, another set of 21 measurements is included, these tests being taken from Seitevaare in northern Sweden (Hiltscher 1965). However, a different measuring technique was used at Seitevaare, i.e. a plate load test in boreholes where a much smaller volume of rock was tested. Nevertheless, because of a shortage of information of the deformation properties, it has been found suitable to include the resuls from the Seitevaare tests, since they represent a different kind of rock from that in Forsmark.

The results, as deformation moduli for the initial load of the fractured rock mass are presented in Table 1, where each rock type is represented. Figure 8 shows the compiled results related to the different rock types. The corresponding values of the storage coefficients are also included in the figure, together with the results

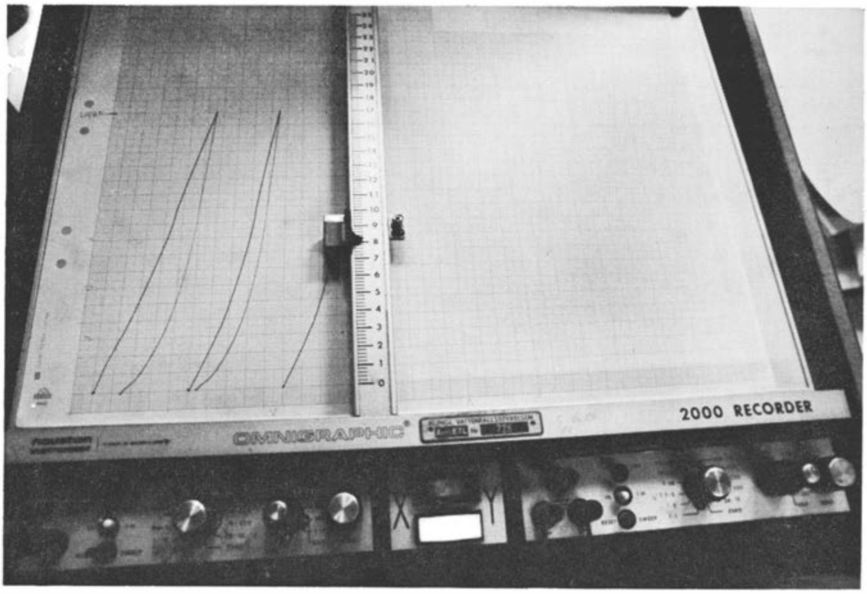

Fig. 6. Recording the load/deformation graph. Photograph by A. Carlsson.

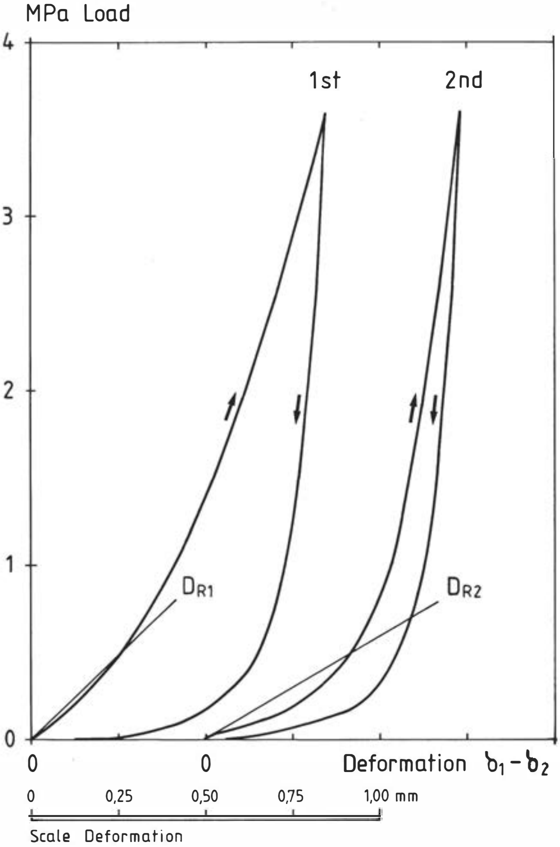

Fig. 7. Load/deformation graph from one test with two completed loading cycles. The secant moduli for low loads are indicated.

Table 1. Modulus of deformation for low loads. Mean values and standard deviation for the different rock types.

Rock type	No. of tests	Modulus of deformation (GPa) Mean value	Standard deviation
Gneiss granite . .	24	12	11
Granite	10	17	10
Leptite	11	16	6

from determinations of the modulus of elasticity obtained from drill cores.

It may be seen that the variation of the storage coefficients and the deformation moduli is great. For gneiss granite, the modulus of deformation varies from 0,65 GPa up to 40 GPa, i.e. 0,8 per cent to 50 per cent of the modulus of elasticity for unfractured rock. For the tests at Seitevaare, the variation is smaller and in general the values of the modulus of deformation are higher — 5 to 50 per cent of the modulus of elasticity.

Conclusions

The tests have shown that the variation in storage coefficient is much greater than that obtained from the empirical relationship. In general, the storage coefficient may be much greater than expected from the modulus of elasticity. The varia-

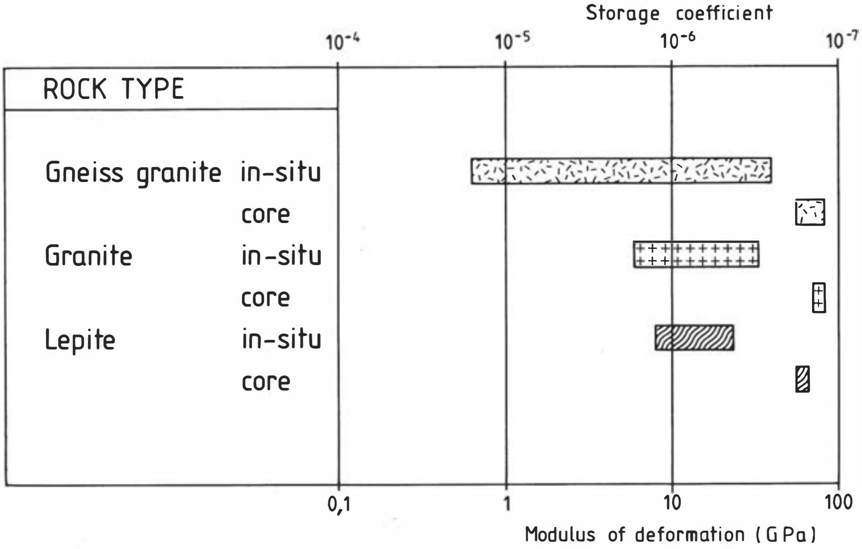

Fig. 8. Modulus of deformation and corresponding values of the storage coefficient for different rock types. The compilation is based on 24 tests in geniss granite, 10 in granite and 11 in leptite. It should be noted that the tests in granite and leptite were made using a different technique.

tions in the same type of rock, in the same area may be as much as 100 times the lowest value. It is therefore important to determine as carefully as possible the actual deformation properties of the hydraulically tested rock mass and not to use only empirical rules as a base for the determination of hydraulic tests.

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