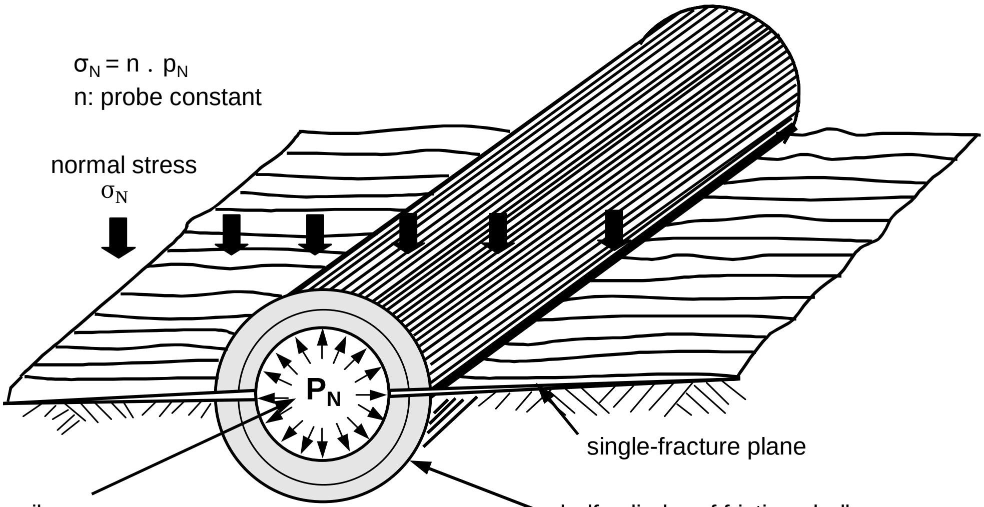
SERATA GEOMECHANICS CORPORATION

Automatic Stress/Property Measurement for Earthwork Optimization

CATEGORY **2** INVENTION OF SERATA PROBE

—Invention of Automatic Stress/Property Measurement Probe for Earthwork Optimization—



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Invention of Automatic Stress/Property Measurement Probe for Earthwork Optimization

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Serata Probe provides an accurate, quick and simultaneous measurement of in-situ stress state and material properties. It is effectively utilized as an automatic means for the measurement in surveying, design, construction and safety assurance of earthwork. It has been successfully applied to mining, tunnel, slope, underground storage and earthquake time-prediction. The principle of Probe is demonstrated in both laboratory and field work, successfully overcoming the great difficulties inherent to the conventional stress measurement methods of overcoring and hydrofracturing discussed in Category 1 (see Table 1-1).

1. Principle of Force Balance

Serata Stress Probe utilizes a single-fracture plane, created at any desired orientation, through the borehole axis by application of friction loading. A stable force balance is established between the ground stress vector (σ_N) acting normal to the fracture plane (Fig. 2-1) and the applied probe pressure (p_N) for determination of the stress state. In this process of stress measurement, a simultaneous determination of material properties of the ground is achieved automatically from behavior of the surrounding ground. Because this new method is based on direct force balance rather than the conventional elasticity assumption, the measurement is possible in complex ground, where the conventional elasticity based methods fail.

2. Mechanism of Friction Loading

The friction loading to the borehole boundary is achieved by a pair of friction shells covering an elastomer tube for the high-pressure loading. The shells are made of high strength alloy designed to create a saturation friction effect on the borehole boundary. The friction effect mechanically “freezes” all intricate deformation of the rock boundary except along a pair of gap lines between the two shells. The gap line behavior is illustrated by a computer modeling analysis of the friction effect upon the tangential stress (σ_θ) on the borehole boundary (Fig. 2-2). An intense tension stress is concentrated along the two gap lines as a reaction to the freezing effect, resulting in a single-fracture plane in the direction set by the probe orientation.

3. High Accuracy of Stress Measurement

An accurate stress determination is made possible by a direct force balance achieved between the hydraulic loading pressure (p_N) of the probe and the ground stress (σ_N) acting normal to the single-fracture plane at a moment of reopening of the plane as illustrated in Fig. 2-3. The figure shows a typical outcome of the friction loading presented in the pressure-deformation (p-d) diagram, which indicates a fracture initiation condition at F in the first cycle loading and a fracture reopening condition at N in the second cycle loading. At a moment of the reopening, the following relation is established by the force balance at the moment of the reopening.

$L \cdot \sigma_N = D \cdot p_N$
$\sigma_N = (D/L)\ p_N = n \cdot p_N$ .... (1)

where: L = length of fracture at the moment of reopening
n = D/L = f (a, b)
a = probe design factor
b = elastic rigidity of ground

Regardless of complexity of the ground, the stress state is obtained by Equation (1), in which n-value is determined automatically as illustrated from the measurement on site in real-time as discussed in the following section. Note that stresses are measured totally independent of elasticity assumptions in-situ and in real-time without requiring core specimen recovery and laboratory testing.

4. Proprietary Design of Probe

A single-fracture probe consists of two sections, viz., loading and electronics, as shown by Fig. 2-4. The loading section is made of an elastomer tube containing a set of LVDTs mounted in the direction perpendicular to the fracture plane. The loading tube is covered with a pair of semi-cylindrical friction shells made of high-strength steel. The outer surface of the shells is specially fabricated to create a saturated friction effect uniformly around the boundary by built-in flexibility of the steel shells. A cross sectional view of the loading section in the figure shows the configuration of the LVDTs in relation to the friction shells and the single-fracture plane. A diametrical expansion (d) of the shells measured by the LVDTs is related to applied oil pressure (p) in the loading tube, enabling us to monitor the p-d relation on the operating computer screen. This p-d curve is used for simultaneous determination of the stress vector σ_N acting normal to the single-fracture plane. The electronics section of the probe processes the deformation and pressure (p and d) signals to be sent to the computer operating at the surface.

The components of the portable probe system and their photos are shown in Figs. 2-5 and 2-6, respectively. It consists of components; (1) loading section, (2) electronics section, (3) extension set, (4) hydraulic pump, (5) junction box, (6) PC and (7) operation and data analysis software. The wire line probe (Fig. 2-7) has an additional remote driving hoist for accurately locating the probe in the borehole. The wireline Probe for deepwell remote application to depths to 1000m is schematically illustrated in Fig. 2-7 and shown in Fig. 2-8. We manufacture three different systems, summarized in Table 2-1, to meet global needs.

5. Accuracy Validation of Probe

High-accuracy of Serata Probe is demonstrated first in the laboratory by conducting a set of 22 single-fracture tests, which are presented in Fig. 2-9. The figure includes a summary table of the biaxial loading conditions and their corresponding fracture reopening pressure p_N. The data demonstrate the high-accuracy of the relationship $\sigma_N = n \cdot p_N$ with a constant n value. The test results are graphically shown by five lines of theoretical relationship closely matched with the corresponding measurement points in Fig. 2-10. Raw data of the 22 sets of the tests are disclosed in Reference 2 of Category 6 “Global Project Records and References”. Serata Probe has been evaluated for material property measurements by tests conducted in a wide range of ground properties as illustrated in Fig. 2-10.

The stress measurement accuracy of Serata Probe was field validated by an evaluation made at the Underground Research Laboratory (URL) of Atomic Energy of Canada at Pinawa, Manitoba, where the overburden pressure has been well established (see Fig. 2-11). The duplicate p-d relations are obtained from duplicate deformation sensors mounted in the probe demonstrating high accuracy of the fracture reopening pressure p_N. The proportional constant n is determined from the measurement of elastic rigidity of the ground automatically obtained from the measurement for each specific design as illustrated in Fig. 2-12. In each stress measurement, Serata Probe determines a wide range of material properties of ground as illustrated in Fig. 2-13 without core specimen recovery.

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TABLE 2-1

Comparison of Three Basic Types of Serata Probe

System / Category	SP-800A	SP-800B	SP-800C
Type of system	one-man portable	Custom design	deepwell wireline
Application	shallow work of mine, tunnel, dam & foundation	special cases	earthquake stress monitor, underground storage of oil & gas
Borehole Diameter	65 ~ 66 mm	open	98 ~ 110mm
Measurement Depth	0.5 ~ 500 m	open	10 ~ 1,000m and beyond
Probe Size	O.D. = 63.5 mm L = 1.85m, W = 15kg	open	O.D. = 93 mm L = 4.0m, W = 40kg
Orientation Sensor	2D/3D	2D/3D	3D
Operation	aluminum rods	aluminum rod, drill-rod or wireline	wireline with remote control
Loading Pressure Range	0 ~ 70 MPa	flexible	0 ~ 210 MPa and greater

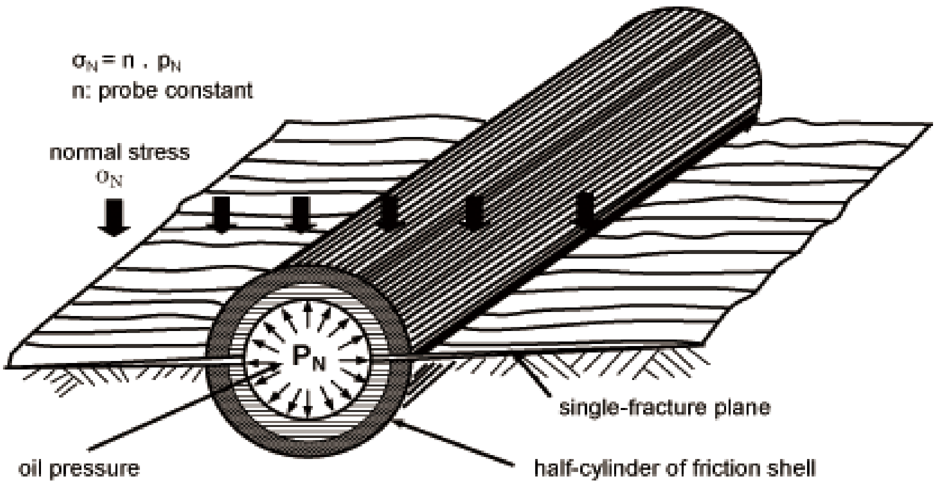


Fig. 2-1 Conceptual view of loading section of single-fracture probe, which made of elastomer loading tube covered with pair of half-cylinder friction shells, illustrating force balance between p_N and σ_N at the distinct moment of fracture reopening

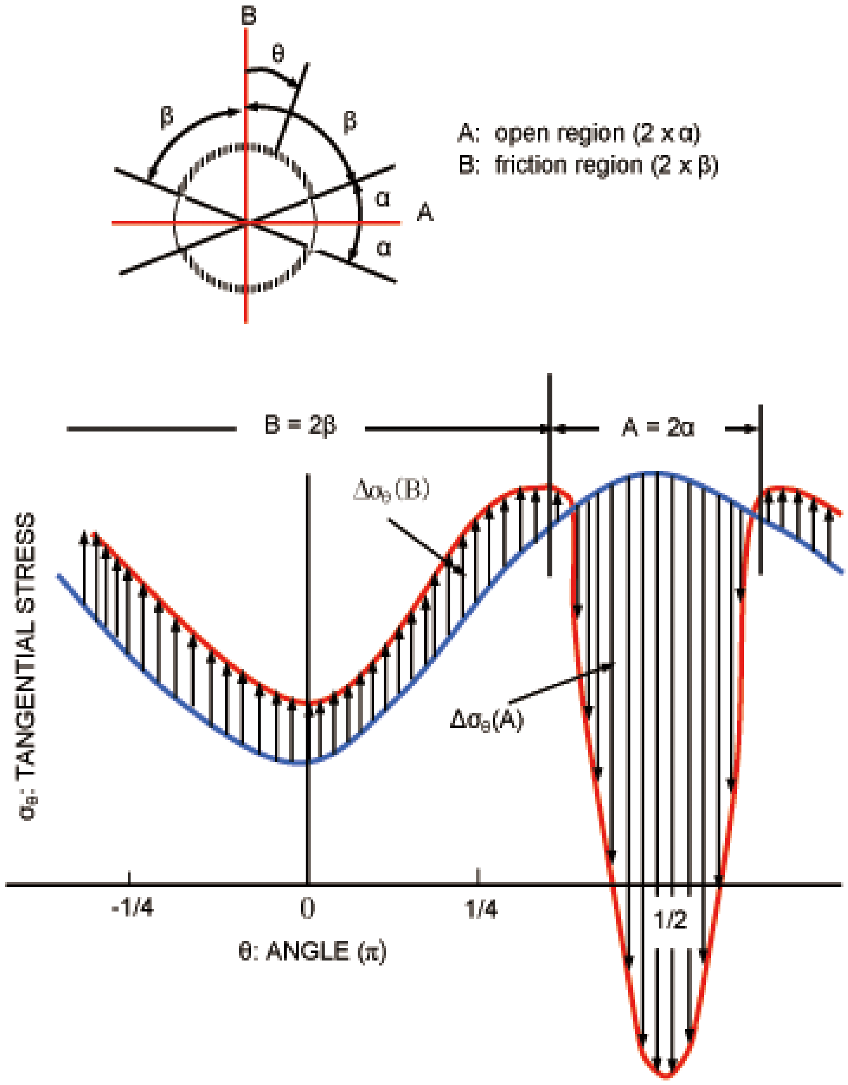
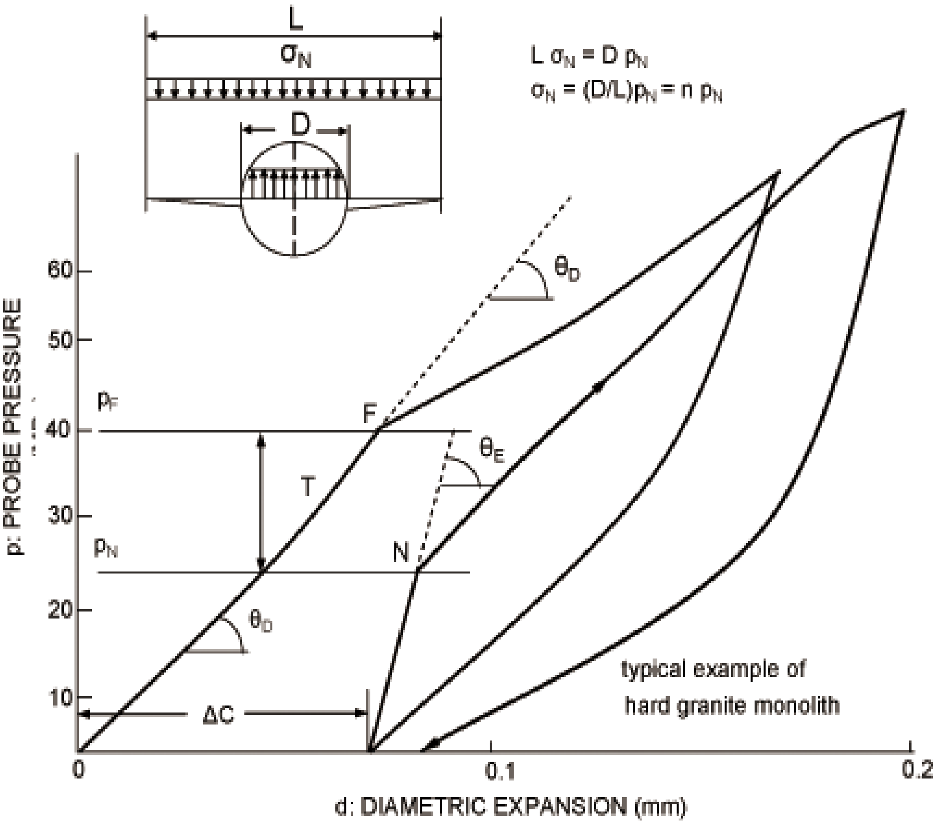


Fig. 2-2 Friction induced tangential stress ($\Delta\sigma_\theta$) by single-fracture loading super imposed upon elastic distribution of tangential stress (σ_θ) around borehole boundary, obtained by finite element model analysis for β = 70°, illustrating creation of tensile stress developed along the fracture plane



E_E = elastic modulus	where	
$= D(1 + \nu) \tan \theta_E$	D	= borehole I.D.
E_D = deformation modulus	ν	= poisson ratio
C = consolidation coefficie	$\tan \theta_E$	= elastic rigidity
$= \Delta C/D/p_{max}$	p_F	= fracture initiation pressure
T = tensile strength	p_N	= fracture reopening pressure
$= n\ (p_F - p_N)$	ΔC	= ground consolidation

Fig. 2-3 Typical p-d curve of single-fracture probe showing fracture reopening pressure p_N at deviation point N and in-situ material properties along the fracture plane

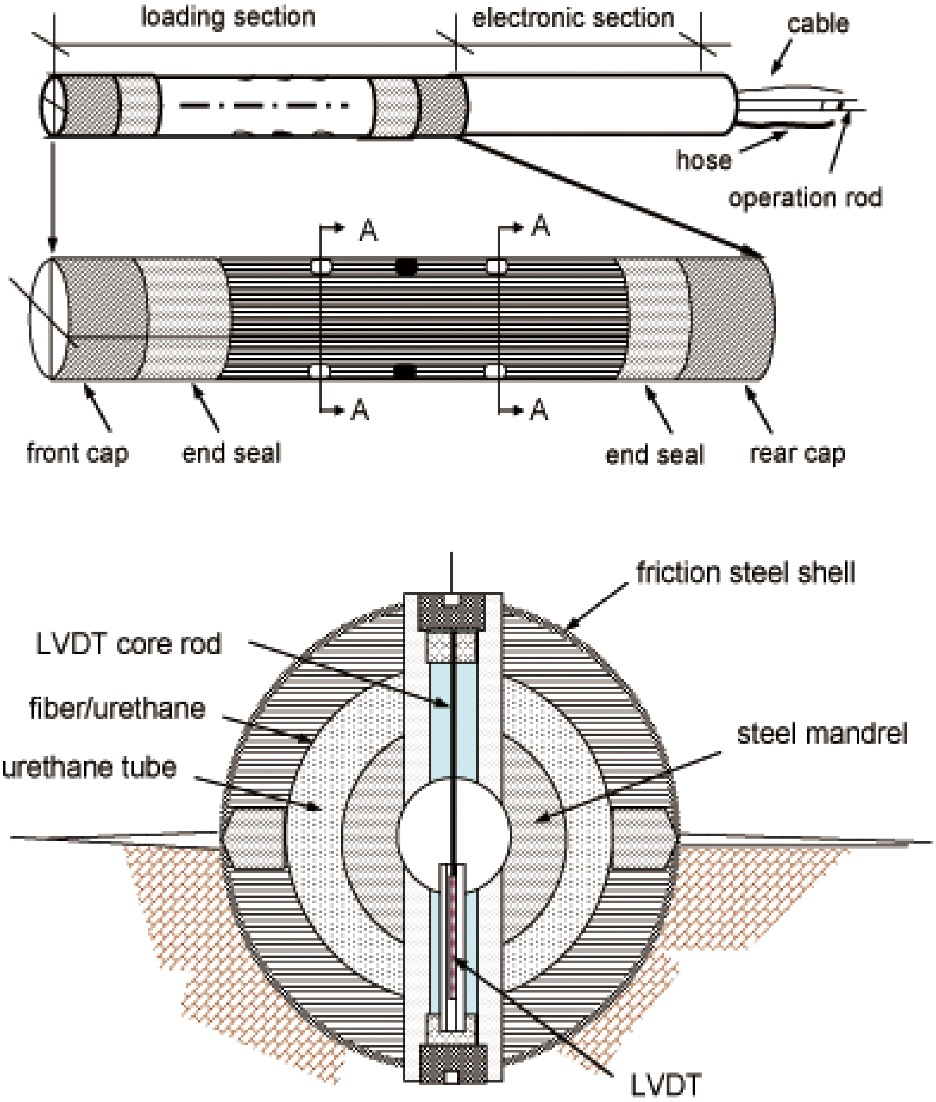


Fig. 2-4 Loading section of single-fracture probe with cross-sectional view showing critical components of the friction loading in relation to single-fracture plane

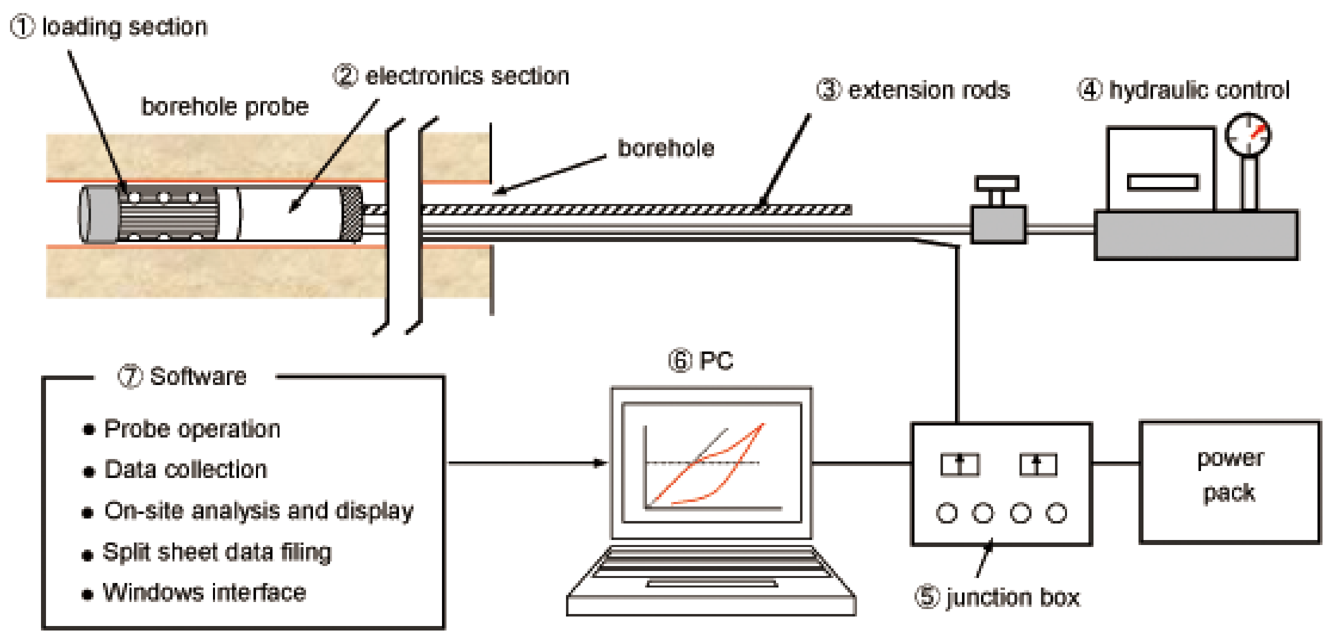


Fig. 2-5 Portable system of Serata Probe S800-A with basic components

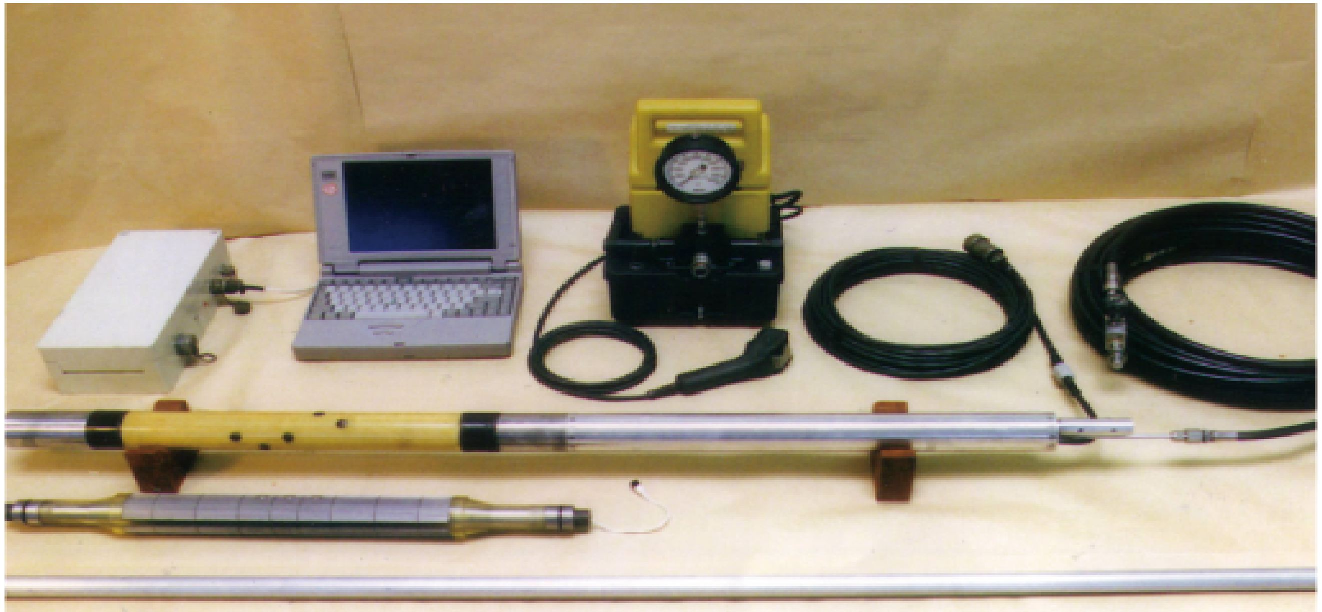


Fig. 2-6 Layout of Stress/Property measurement system (S&P800-A), including (1) S & P loading sections, (2) electronic section, (3) PC, (4) power pump, (5) hydraulic hose, (6) electric cable

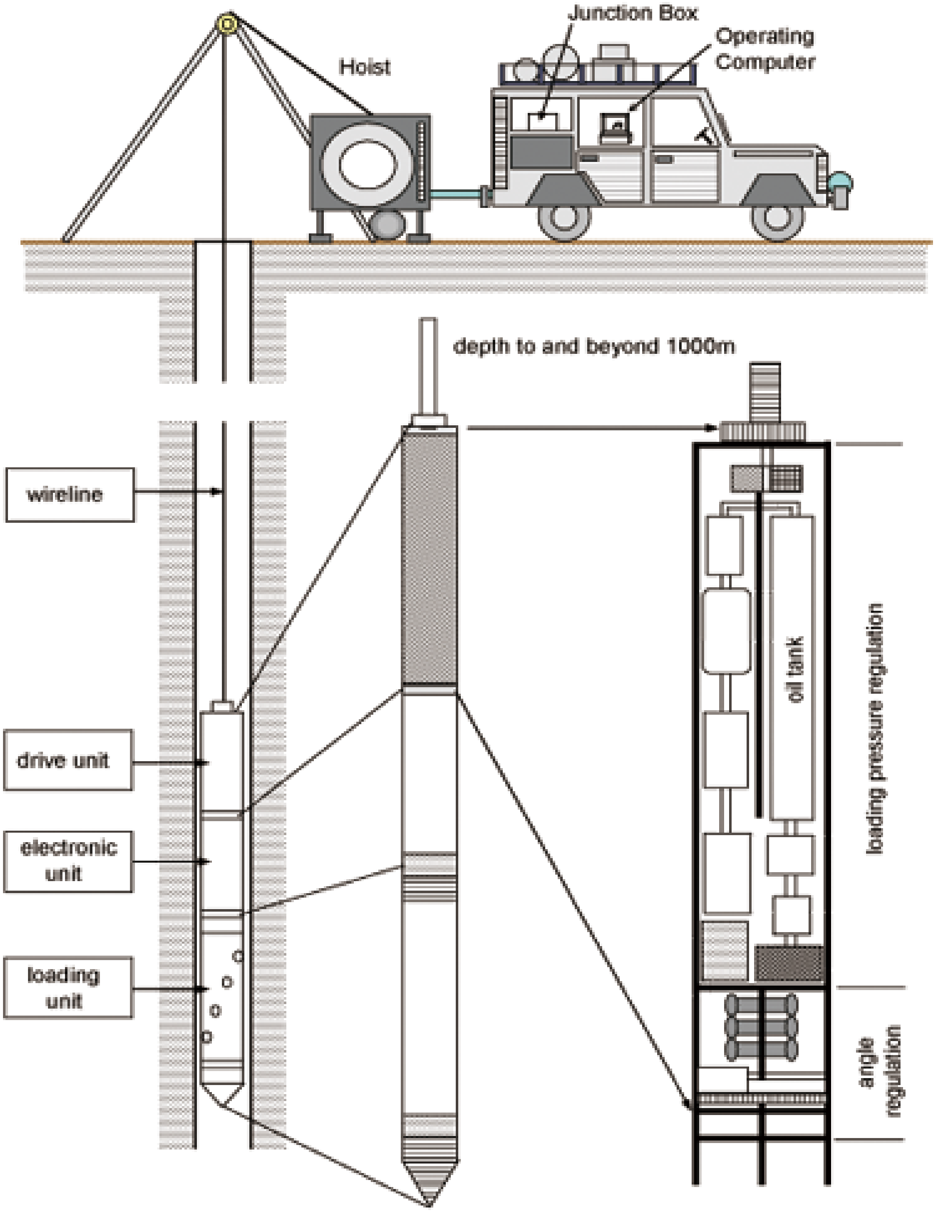
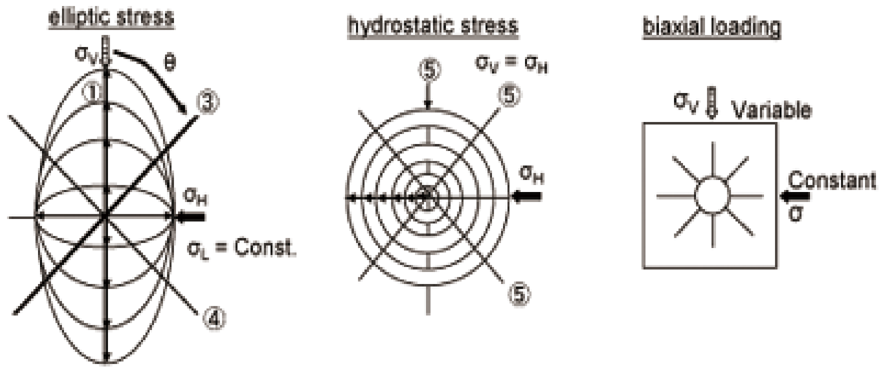


Fig. 2-7 Wireline probe of deepwell stress/property measurement system to depth to and below 1000m

Fig. 2-8 Serata Probe used as deep well remote system for repeated automatic measurement of stress/properties in-situ on site in real-time to 1000m at Sakuma Dam Site for the Japanese government program (details in Ref. No. 2 in Category 6.

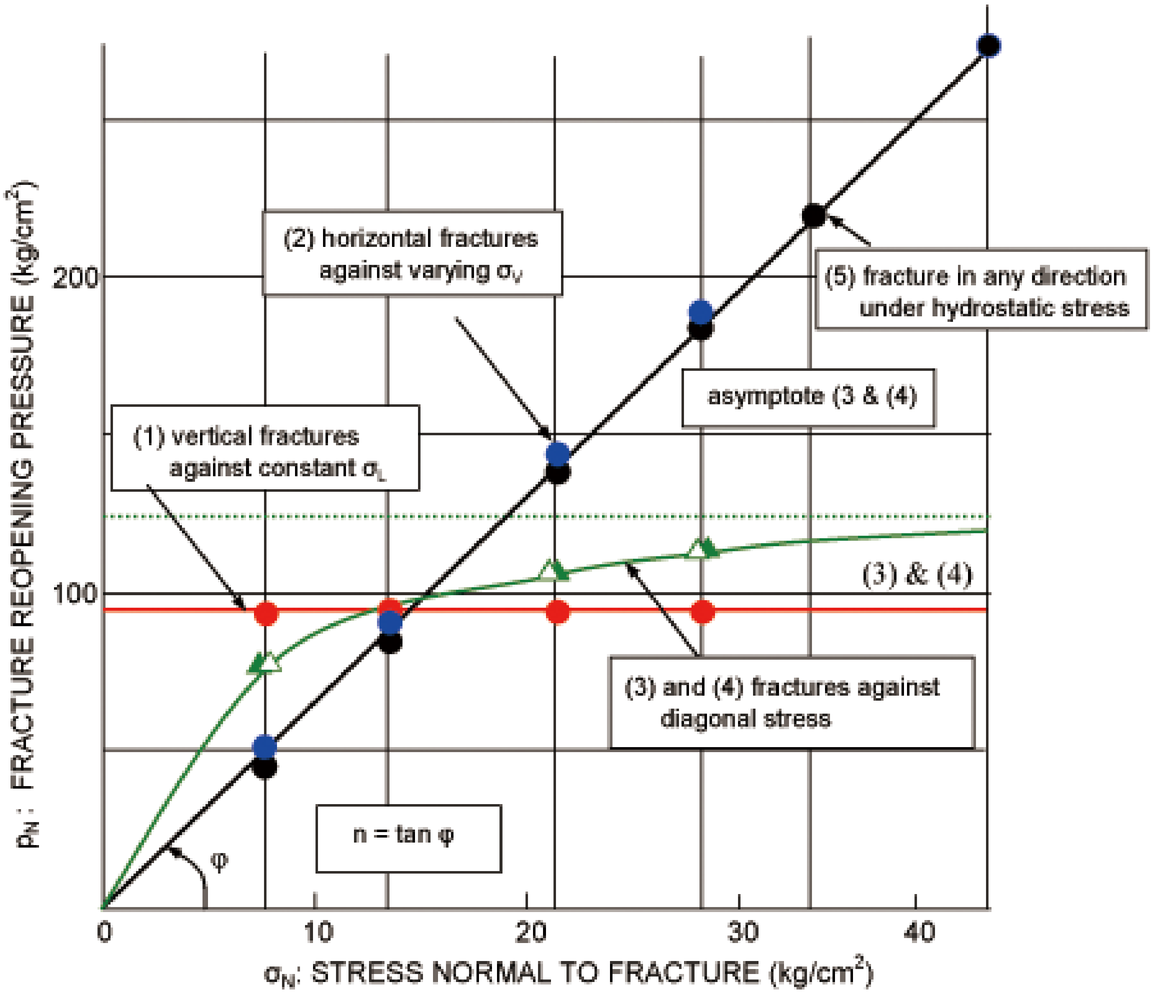


TEST		LOADING CONDITION				MEASUREMENT RESULTS	
series	No.	fracture direction	σ (MPa)	σ_H (MPa)	σ_N (MPa)	p_N (MPa)	n
1	1	0°	7.04	14.08	14.08	90	0.16
	2		14.08	14.08	14.08	90	0.16
	3		21.12	14.08	14.08	90	0.16
	4		28.16	14.08	14.08	90	0.16
2	1	90°	7.04	14.08	11.09	50	0.14
	2		14.08	14.08	14.08	90	0.16
	3		21.12	14.08	17.50	135	0.16
	4		28.16	14.08	18.75	180	0.16
3	1	45°	7.04	14.08	11.09	70	0.16
	2		14.08	14.08	14.08	90	0.16
	3		21.12	14.08	17.50	110	0.16
	4		28.16	14.08	18.75	120	0.16
4	1	- 45°	7.04	14.08	11.09	70	0.16
	2		14.08	14.08	14.08	90	0.16
	3		21.12	14.08	17.50	110	0.16
	4		28.16	14.08	18.75	120	0.16
5	1	0°, 45°, 90°	7.04	7.04	7.04	50	0.15
	2		14.08	14.08	14.08	90	0.16
	3		21.12	21.12	21.12	135	0.16
	4		28.16	28.16	28.16	180	0.16
	5		32.20	32.20	32.20	225	0.16
	6		42.25	42.25	42.25	270	0.16

relationship established: $\boxed{\sigma_N = n \cdot p_N}$

θ = angle of fracture
σ_V = increasing vertical stress
σ_H = constant horizontal stress
σ_N = stress normal to fracture
p_N = fracture reopening pressure
$n = \sigma_N/p$ = proportionality constant

Fig. 2-9 Laboratory testing setup where five biaxial loading series produced 22 different test results, clearly disclosing linear relationship between σ_N and p_N



Five different fracture planes analyzed

1) vertical fractures: reopening at constant p_N independent of σ_V
2) horizontal fracture: reopening at increasing p_N proportional to
3) & 4): ± diagonal fracture: reopening at increasing p_N proportional to elliptical stress
5) under uniform loading: reopening at increasing p_N proportional to the elliptic stress loading

Fig. 2-10 Experimental validation of single-fracture probe demonstrated by close agreement between measurement results (points) and the theory (solid lines). Closeness of the agreement is verified by 22 laboratory test results conducted under five different loading patterns

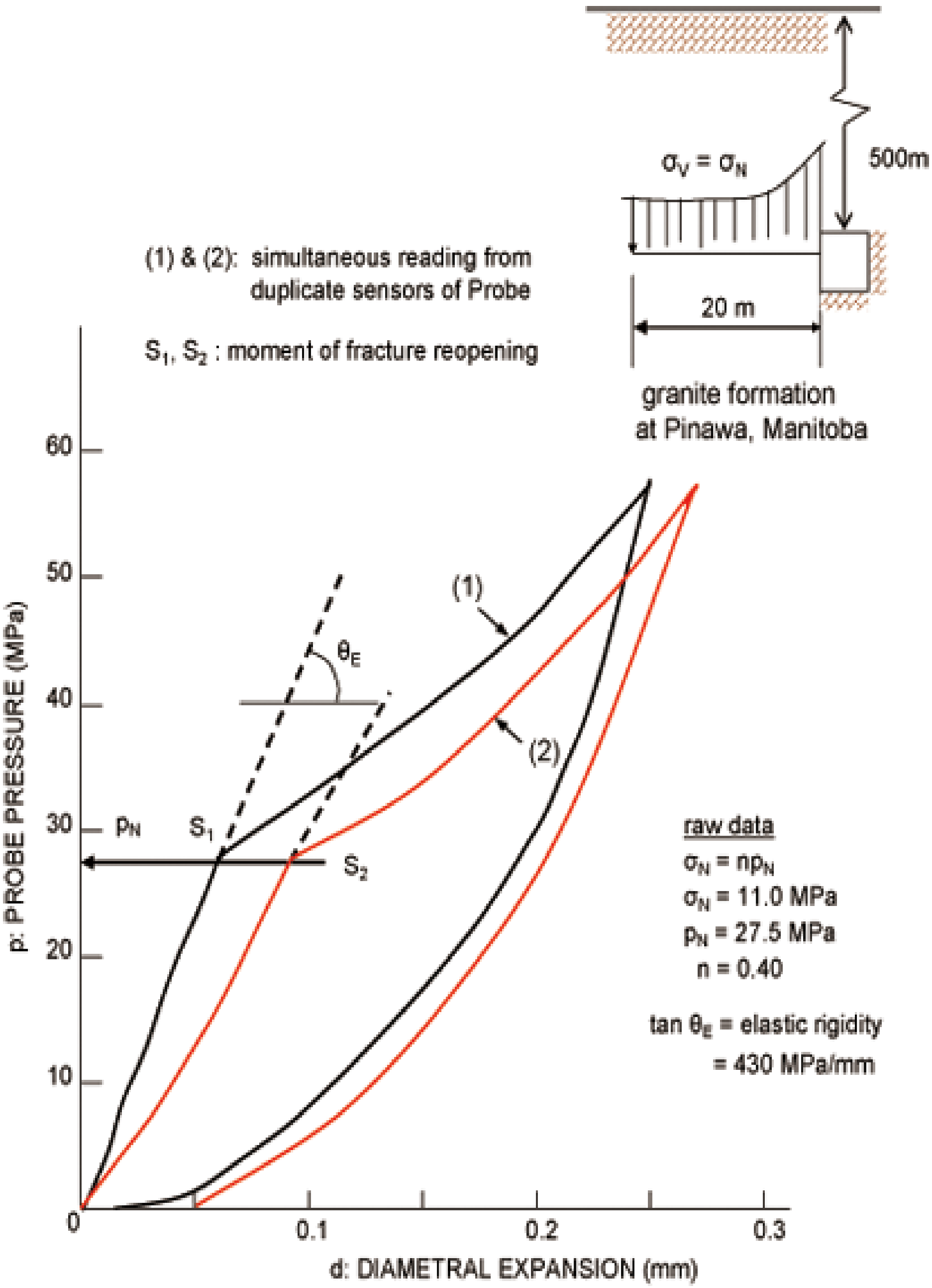


Fig. 2-11 p-d diagram obtained in hard granite monolith of Underground Research Laboratory of Atomic Energy of Canada, Pinowa, Manitoba with fracture reopening pressure (p_N) against known vertical stress vector σV = σN = 11.0 MPa used for field validation of n-value

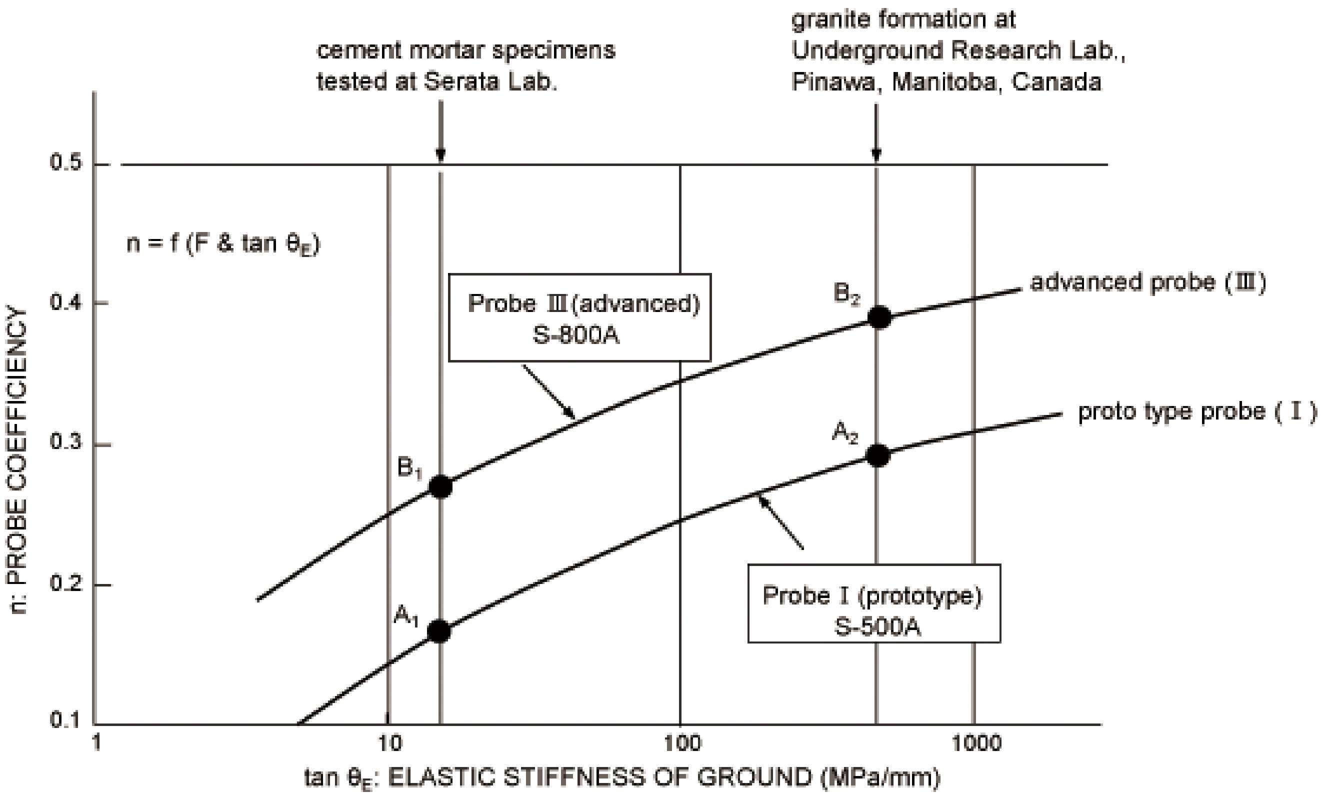


Fig. 2-12 Probe coefficient n-value determined on site by combination of Probe design parameter (F) and ground elastic stiffness (tan θ_E), which are automatically obtained by each field measurement as shown in Fig. 2-3. Raw data of laboratory and field test can be made available upon request

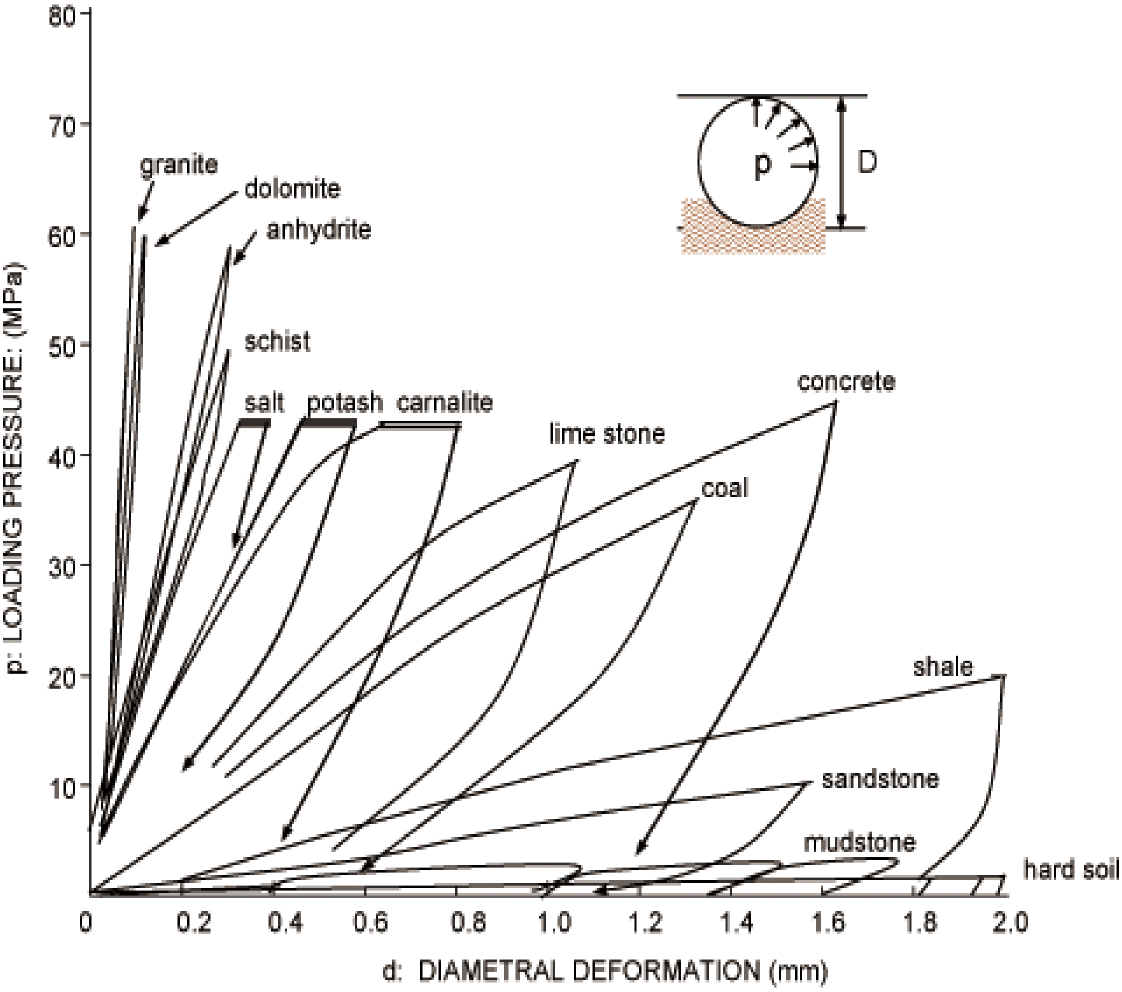


Fig. 2-13 In-situ properties of various ground media identified from p-d curves obtained on computer screen on site in realtime