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PRESSUREMETER TESTS IN LEDA CLAY

by

J.H. Schmertmann

PREFACE

Professor John H. Schmertmann, Department of Civil Engineering, University of Florida, was a visiting scientist with the Geotechnical Section, Division of Building Research, from September 1971 to August 1972. During part of his stay he conducted investigations on three in situ test methods in sensitive clay; the static cone penetrometer, the hydraulic fracture method and the Menard pressuremeter.

His work on the hydraulic fracture method has subsequently been incorporated in the publication, "Minor principal stress measurements in marine clay with hydraulic fracture tests" by M. Bozozuk, Proceedings, Conference on Subsurface Exploration for Underground Excavation and Heavy Construction, Henniker, N.H., ASCE, 1974, pp. 333-349. His work with the modified Menard pressuremeter and the static cone penetrometer is now presented in DBR Reports 450 and 451 as a record for the benefit of ensuing work on these two test methods.

Ottawa
May 1979

C.B. Crawford,
Director, DBR/NRC

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF BUILDING RESEARCH

DBR INTERNAL REPORT NO. 450

PRESSUREMETER TESTS IN LEDA CLAY

by J.H. Schertmann

Checked by: E.P. **Approved by:** L.W.G. **Date:** May 1979

Prepared for: Record Purposes

INTRODUCTION

Because of the potential of the pressuremeter test for investigating the stress-strain properties of soil, this method has attractive possibilities for the Geotechnical Section of the Division of Building Research. The Menard unit purchased by the Section has been used in Leda clay. Ladanyi (1) has provided significant theoretical and practical background for the present study.

The purpose of the present study was to determine the feasibility of pressuremeter tests in the brittle, sensitive clays of the Leda type. The possibility of using pressuremeter test results to determine in situ lateral stress, p_o, undrained modulus, E, undrained shear strength, s_u, preconsolidation stress, p_c, and the general nature of undrained stress-strain behaviour in such clays was also investigated.

After some preliminary tests it seemed that it would not be possible to test satisfactorily in Leda clay with the pressuremeter then available and the calibration methods commonly used. Accordingly, several modifications were made to the meter and a different calibration procedure was devised.

An important part of this work was to find the best method of making the borehole for the pressuremeter. For the same reasons that investigators wish lab samples disturbed as little as possible, pressuremeter testing requires that the sides of the borehole are disturbed as little as possible. Three methods of making the borehole were investigated.

After modifications to the pressuremeter were complete, eleven pressuremeter tests were carried out at the trial research area behind the DBR building.

MODIFICATIONS TO THE PRESSUREMETER

Figure 1 shows the schematic of the modified pressuremeter; Figure 2 illustrates the new setup. The most important modifications consisted of the following (keyed into photos):

(a) an air-bubble bleed line at the bottom of the pressuremeter;

(b) copper tubing replacing plastic;

(c) a larger, more accurate water pressure gauge, plus a gauge for precision in the low range;

(d) high-quality pressure regulators to control the final measuring and guard cell pressures;

(e) a mercury manometer to measure the differential gas pressure between measuring and guard cells;

(f) replacing most valves with ones of the Circle Seal type;

(g) replacing the metal-sheathed outer membrane with a low-inertia rubber one;

(h) a rapid, positive valve for switching between the two burettes.

CALIBRATION METHOD

The Menard pressuremeter employs a central, water-filled cell to measure volume changes and hence volume strain. This cell is in turn covered by a longer cell, called the guard cell, which is inflated by gas pressure. The guard cell expands the borehole for some distance beyond the ends of the measuring cell and thereby better assures an approximate, two-dimensional axi-symmetric expansion of the sort required by the theory used to analyse the test results. This measuring and guard cell design requires a pressure differential between the cells to assure that the measuring cell is always expanded in contact with the inside of the enveloping guard cell.

Appendix A presents the logic and formulae for the calculation of this differential pressure, as well as the determination of K_o', pore pressure and borehole water or mud pressure. Figure 3 illustrates schematically the inner and outer membranes and the measuring and guard cell configurations discussed in the following.

The conventional method of performing a pressuremeter test involves establishing a fixed differential pressure between inner and outer membrane, held constant throughout the test. Choosing a high enough differential pressure to assure contact during the final, high-volume expansion part of the test, results in the measuring and guard cell configuration during the early part of the test shown in Figure 3(a). This is perhaps far from the ideal cylindrical shape. Choosing a differential pressure that assures a more cylindrical shape during the early, low volume expansion phase of the test (the phase from which one interprets the important early-strain stress-strain behaviour and soil deformation modulus) may mean that the inner membrane barely contacts the outer during the final stages, as shown in Figure 3(b). Note that with a constant differential pressure, the shape of the inner membrane continually changes during the test, making it difficult and perhaps impossible to interpret volume changes in terms of cylindrical-expansion volume strain. It seems clear that the problem requires a variable differential-pressure method of conducting the test to assure 1) an approximate cylindrical shape of the measuring cell membrane through all stages of the pressuremeter test, and 2) a positive contact between inner and outer membranes, over a fixed reference length, throughout the test.

For these requirements, an alternate method for pressuremeter-membrane inertia calibration was devised. During the first stage of this calibration, one tests with the inner membrane only, in a sequence of transparent plastic cylinders of different diameters (covering the range of diameters expected during the expansion phase of test). Different contact lengths were obtained between the membrane and tube wall by wetting the outside of the inner membrane and applying different levels of water pressure in the measuring cell. After conducting this series of tests, the contact length that would be held constant throughout a pressuremeter test was determined. The length of the inner cell was 21 cm for the pressuremeter used in this study. It was decided that a reasonable contact length would be 17 cm. The volume of water actually injected into the measuring cell to achieve the 17 cm contact length in the different tube diameters was compared with the volume required for a perfect right-cylinder of different lengths with the same tube diameters. It was concluded that for a contact length of 17 cm, the measuring cell was behaving, approximately, as a right-cylinder with an equivalent length of 18 cm.

The second stage of the initial calibration involved using both membranes and different values of gas pressure between the inner and outer membranes to expand the outer membrane to various diameters (within the range expected in a pressuremeter test with this equipment). The average diameter of the outer membrane over the length of the measuring cell was measured at each gas pressure of the guard cell. The pressure differential required to obtain the 17 cm contact length at each average diameter was known from the previous work. This differential was then imposed, which in turn changed the outer diameter somewhat. The cycle was repeated a sufficient number of times, usually one or two, until the outer membrane diameter had the differential pressure required for that diameter and a 17 cm contact length.

The pressuremeter test was concluded in such a way that the differential pressure between inner and outer membranes always (incrementally) remained consistent with the current expanded volume of the pressuremeter to assure the selected (17 cm) contact length. This is the reason for the differential pressure gauge in the modified pressuremeter design.

Computations for the pressuremeter test require the results of still another calibration to give the volume change observed in the burette system under conditions of no volume change at the borehole. Several laboratory-test calibrations of this type suggested, in agreement with previous experience, that the indicated volume change varies approximately as the logarithm of water pressure. It is believed this effect is not a major one and such a log approximation should usually be adequate. The following procedure is recommended in the field, just prior to each test: set a reference pressure, note the burette reading at that pressure, increase this water pressure tenfold and again note the burette reading. The difference in readings then represents the volume change per log cycle for volume correction use in that test.

LADANYI CONVERSION THEORY

Before the fieldwork reported here began, Ladanyi (1) made available a method for the direct conversion of pressuremeter test results into an equivalent stress-strain curve as obtained from an axi-symmetric compression test. His principal assumptions include: Poisson's ratio = 0.50, a plane strain radial expansion of the borehole, and homogeneous, isotropic material that does not fail in tension. In a completely independent study using a different mathematical approach, Palmer (2) arrived at a solution of the same problem which confirms part of Ladanyi's work. Both papers were reviewed in detail and, according to this writer's interpretation of the equations and assumptions used, the authors evaluate the stress-strain behaviour of the soil tested by the pressuremeter only in the immediate vicinity of the borehole. Ladanyi disagreed with this interpretation during subsequent discussions, stating that the pressuremeter sensed what was happening over a considerable distance from the borehole and that his analysis produced a stress-strain curve for the soil in the entire zone stressed. From a mathematical viewpoint this question is academic; because both Ladanyi and Palmer assumed homogeneous soil it would not matter whether the analysis method evaluated soil immediately at the surface of the borehole or some larger zone. In the field, however, this may be an important consideration because of the unknown effects of surface disturbance on boreholes.

In the analysis of subsequent field tests the Ladanyi method was used to convert the results to equivalent compression stress-strain curves. These curves are more familiar and can be more readily evaluated relevant to previous experience, sample disturbance, etc.

One observation concerning the modulus E from these field results supports the validity of the Ladanyi method. One can, of course, determine E directly from the slope of the initial portion of the equivalent compression test stress-strain curve. In all cases investigated, E determined from Ladanyi's equivalent stress-strain curve compared favourably with E determined directly by other established methods. Some difference was to be expected because each comparison involved two different graphical interpretations of test curve slopes. The values are presented in Table I.

METHOD OF MAKING BOREHOLE AND EFFECT ON TEST RESULTS

Disturbance of the soil tested represents a serious problem when one attempts to evaluate the in situ properties of brittle, sensitive Leda clays. This problem exists with the sides of the borehole for a pressuremeter test as with a sample in a laboratory test. In an attempt to make a borehole with as little wall disturbance as possible, the first approach was to wash and rotary drill, or auger, to a depth a few feet above the final test depth and then to use a cylindrical sampler to carve the final test wall. Efforts were made to sample with the best techniques that could be devised, which included the use of a thin-walled sampler with the cutting edge bevelled to the inside of the sampler, a fixed piston, and a grooved cutting shoe to reduce sampler-wall contact area and permit some relief of bottom-sample suction during withdrawal (even though the slowest possible withdrawal rate was used). Six pressuremeter tests were conducted using these borehole techniques. Figure 4 presents the 6 equivalent Ladanyi stress-strain curves. No difference was detected between making the borehole with a shoed or an unshoed sampler. Judging by the low initial moduli and the 5 to 7 per cent strain at peak strength, the test results seemed seriously affected by borehole soil disturbance. Appendix B presents the pressure-volume curves for the 11 tests; the first 6 were conducted in holes made with a sampler. A further indication of borehole disturbance was an unusual "scallop" noted at the beginning of some of the conventional pressuremeter curves. See test numbers 5, 6 and 11 for examples. Although one can perhaps account for this scallop effect in a number of ways, it most likely represents the early top-bottom extrusion failure of a badly disturbed layer at the surface of the borehole.

After the apparent failure of sampling methods for the borehole, drilling mud and augering were tried. The auger used was a simple, flat-bladed device that ejected drilling mud downward through an axial hole. It is understood that the French investigators use and recommend this design for making hand-augered, drilling mud assisted, pressuremeter holes for testing in clay.

Figure 5 presents the equivalent compressive stress-strain curves from the five tests conducted in augered holes made with drilling mud. The first three tests showed an immediate dramatic improvement in the quality of the test results, judging by the much higher initial moduli and the much lower strain to maximum strength. The last two tests using drilling mud gave poor results for unknown reasons that may be related to the drilling mud technique used. Test number 11 was completed despite an air leak from the pressuremeter observed from the beginning of the test. The leak had an unknown, but probably serious influence on the test results.

A recent paper by La Rochelle, Roy and Tavenas (3) clearly confirms the great improvement in pressuremeter test results when augering and drilling mud are used instead of sampling methods to make the borehole. In the writer's opinion researchers should perform pressuremeter tests in sensitive clays only in holes made with drilling mud and augering; refining this method should be made a matter of top priority.

POSSIBLE SIGNIFICANCE OF TESTS 7, 8, 9

The results from tests 7, 8 and 9 (see Figure 5 and detailed data in Appendix B) clearly show the bond, or cementation, strength peak at the beginning of undrained strength mobilization. This peak appears superimposed on the ordinary mobilization of the matrix strength of the clay, with a "dip" between the two mobilizations. This dip was determined only after an unusual, but seemingly consistent, "wave" pattern was noted in the log volume strain vs $p-p_o$ intermediate graph used in the Ladanyi conversion. This pattern, and the dip-results computed from it, became apparent only after carefully drawing the intermediate curve through the test points instead of assuming experimental error and drawing a smoother curve sometimes passing between the points. The data from tests 7 and 8, shown in Appendix B, include the Ladanyi conversion results with and without this data smoothing.

The peak undrained shear strength determined by these three tests averages about 1.57 kg/cm^2, or about 2 to 2.5 times that measured in the same area using the Geonor vane. From this comparison it seems possible that the disturbance effects of vane insertion, combined with possible serious progressive action during vane rotation, result in a computed vane undrained strength much less than the peak deduced from a pressuremeter test. Such a conclusion, while not proven, seems reasonable in view of the approximately 1.3 to 2 factor between the block sample compression test and vane shear test strengths reported by Eden (4) from the Ottawa sewage plant site. La Rochelle, Roy and Tavenas (3) also report a factor of 2 to 2.5 between pressuremeter and Geonor vane strengths.

The N_c factor was computed (Appendix C) using average results from tests 7, 8, and 9 and the Ladanyi theory for the N_c factor (using his three-slope approximation). His theory and these results predict $N_c = 5.47$. Using average Fugro cone bearing values (see Internal Report 451 and the average undrained strength (1.57) determined from tests 7, 8 and 9, an N_c factor of 5.41 is obtained. This excellent agreement provides further support for the validity of these three pressuremeter test results.

SENSITIVITY TO IN SITU LATERAL STRESS (p_o)

The computation for the equivalent compressive stress-strain curve requires the subtraction of an estimated in situ lateral total stress, p_o, from the corrected pressuremeter lateral stress, to give the excess total lateral stress acting on the sides of the borehole. The stress-strain curve seems somewhat sensitive to the value of p_o used. Table II illustrates this point by showing the computed test results from tests 2, 3, 4, using two different values for p_o. A given percentage decrease in p_o results in approximately one to two times that percentage increase in s_u, but has only a minor effect on E.

Thus, accurate estimates of s_u require accurate estimates of p_o. The hydraulic fracturing method (5) can play an important part here. For best results, these two in situ test methods should supplement each other.

Because of the relatively high membrane inertia, the high pressure of the drilling mud, and the differential pressure required for proper membrane contact, the pressuremeter test method of determining p_o by interpreting the early, reverse-curve part of the test results seems too insensitive. It was difficult to obtain more than one or two data points below p_o. In view of the greater potential of the hydraulic fracturing method, attempts to determine p_o from the pressurementer test with the present equipment should be abandoned.

SOME UNRESOLVED PROBLEMS

Some problems related to the pressuremeter test are not yet resolved. As mentioned previously, further refinement of the drilling mud and auger techniques is needed to minimize borehole wall disturbance. There is much work to be done to confirm or refute the rather revolutionary nature of the stress-strain curves obtained from tests 7, 8 and 9.

The best method of calibrating and performing the test has not yet been found. For example, the effect of the time allowed for each increment of the test should be investigated.

CONCLUSIONS

1. The Menard pressurementer requires major renovation and improvements if it is to be used in sensitive clays.

2. The conventional method of performing a test with constant inner-outer membrane pressure differential is not acceptable.

3. Making a borehole for a pressuremeter by sampling methods is not acceptable.

4. Pressuremeter tests should only be made in holes prepared using drilling mud techniques, these techniques should be refined.

5. Some of the results obtained to date suggest that pressuremeter tests will lead to a new, perhaps revolutionary, understanding of the undrained stress-strain behaviour of brittle, sensitive clays such as Leda clay.

6. Because of sensitivity of the computed results to the value of p_o used, and the possible importance of tensile strength, it appears highly advantageous to use hydraulic fracturing tests in conjunction with pressuremeter tests.

7. The present equipment and methods for pressuremeter tests do not appear to be suitable for determining p_o.

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(4) Eden, W.J. Sampler trials in overconsolidated sensitive clay. ASTM, STP 483, 1970, pp. 132-143.

(5) Bozozuk, M. Minor principal stress measurements in marine clay with hydraulic fracture test. Proceedings, Specialty Conference on Subsurface Exploration for Underground Excavation and Heavy Construction, Henniker, N.H., ASCE, 1974, pp. 333-349.

TABLE I

COMPARISON OF MODULUS E DETERMINED FROM PRESSUREMETER TEST AND LADANYI CONVERSION

DBR Test	E kg/cm^2 Test method	E kg/cm^2 Ladanyi method
1	96	87
2	47	55
3	56	82*
4	45	76*
5	59	63
6	50	58
7	212	370*
8	200	290*
9	138	235*
10	51	
11	87	93

* slope adjusted to exclude initial "seating"

TABLE II

EFFECT OF DIFFERENT ASSUMED VALUES OF p_o ON RESULTS FROM PRESSUREMETER TEST (kg/cm^2)

Assumed			Calculated from pressuremeter test			
Test	p_{o1}	p_{o2}	s_{u1}	s_{u2}	E_1	E_2
DBR-2	1.87	1.20	1.30	1.90	69	76
DBR-3	2.18	1.35	1.25	2.00	62	82
DBR-4	1.77	1.60	1.95	2.65	62	68

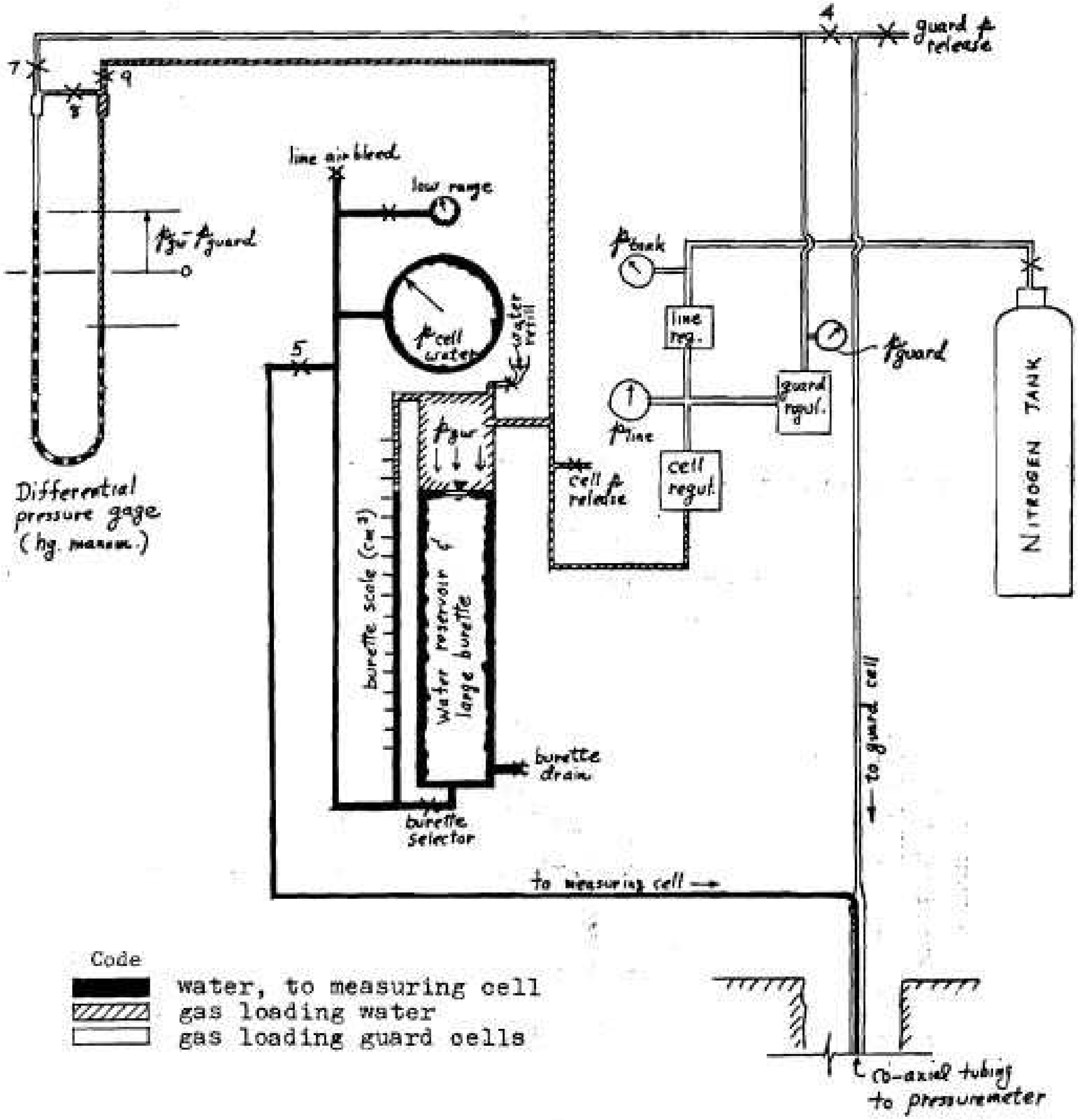
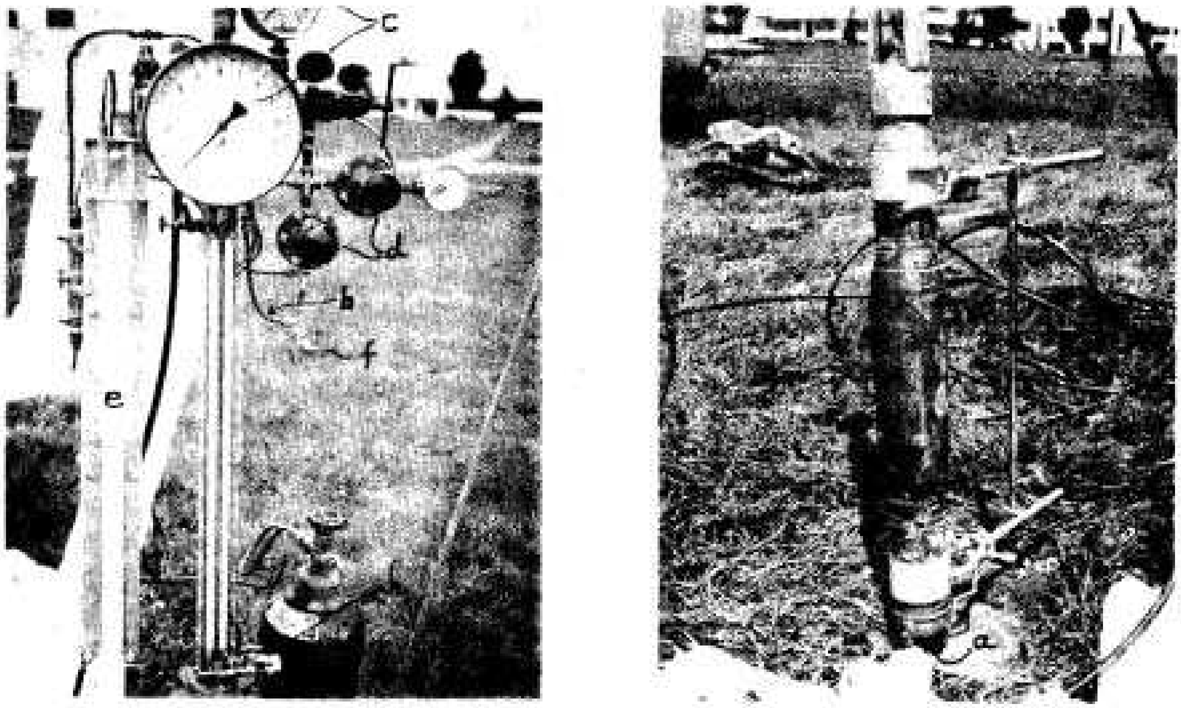


FIGURE 1

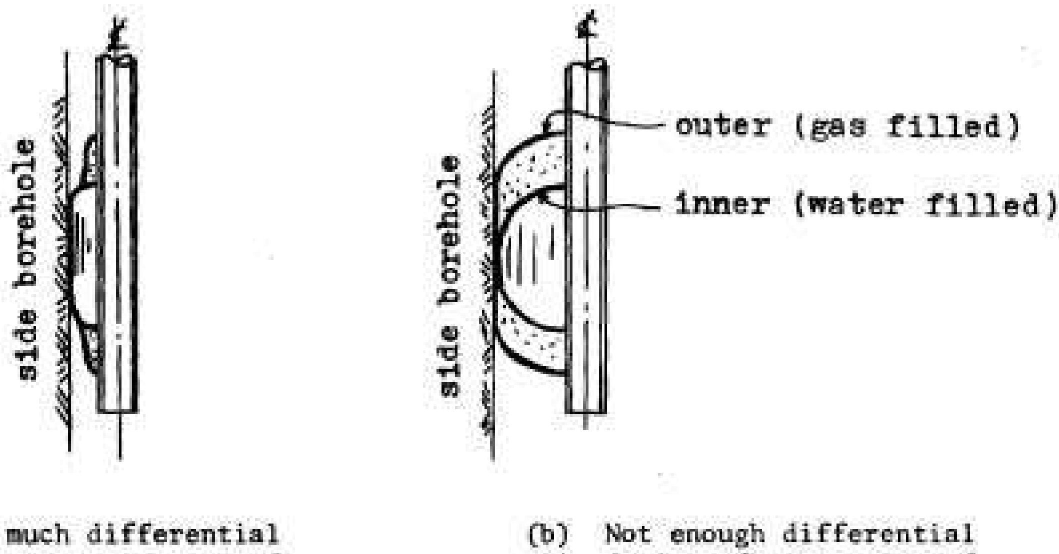
SCHEMATIC DIAGRAM OF PRESSUREMETER



(a) Rebuilt pressuremeter controls (b) Rebuilt pressuremeter probe

FIGURE 2

REMODELLED PRESSUREMETER USED IN THIS RESEARCH



(a) Too much differential during early part of pressuremeter test

(b) Not enough differential during final part of pressuremeter test

FIGURE 3

POSSIBLE CONSEQUENCES OF USING A CONSTANT PRESSURE DIFFERENTIAL BETWEEN INNER AND OUTER MEMBRANES THROUGHOUT PRESSUREMETER TEST

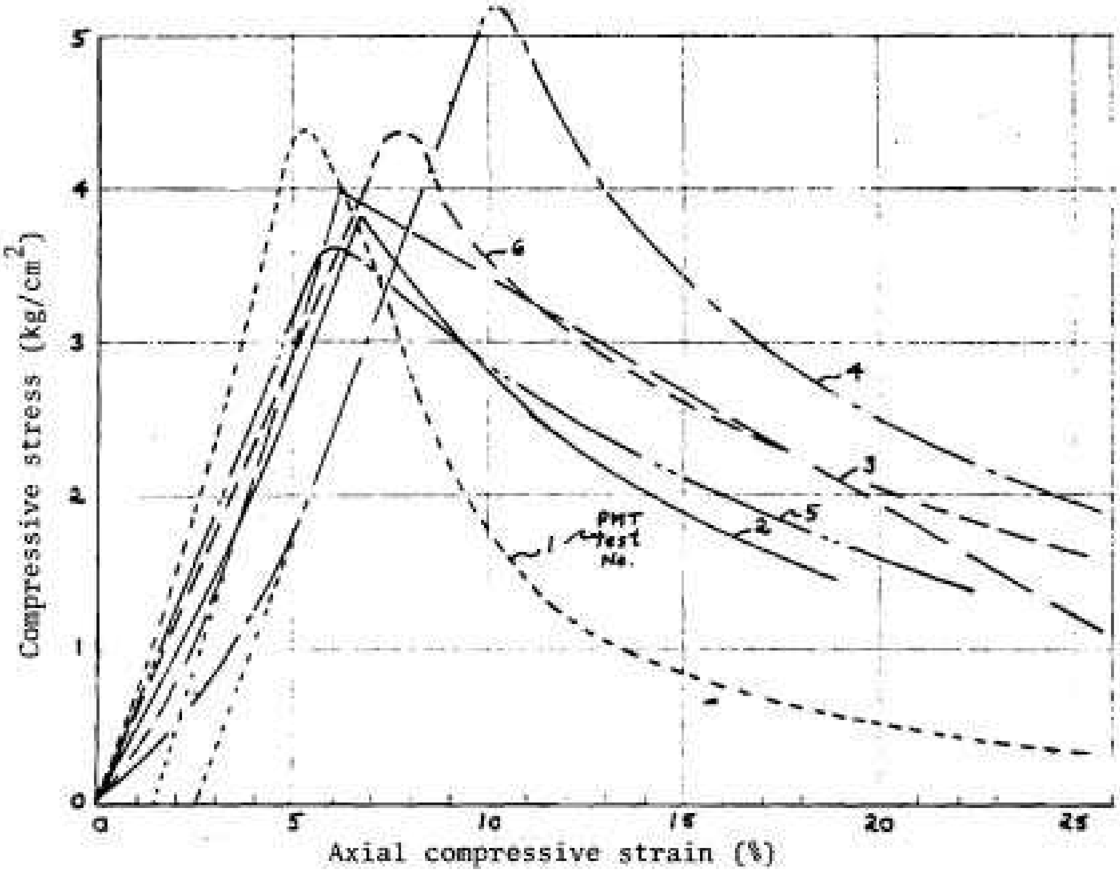


FIGURE 4

LADANYI EQUIVALENT COMPRESSION TEST CURVES FROM PRESSUREMETER TESTS MADE IN BOREHOLES MADE WITH FIXED-PISTON SAMPLING

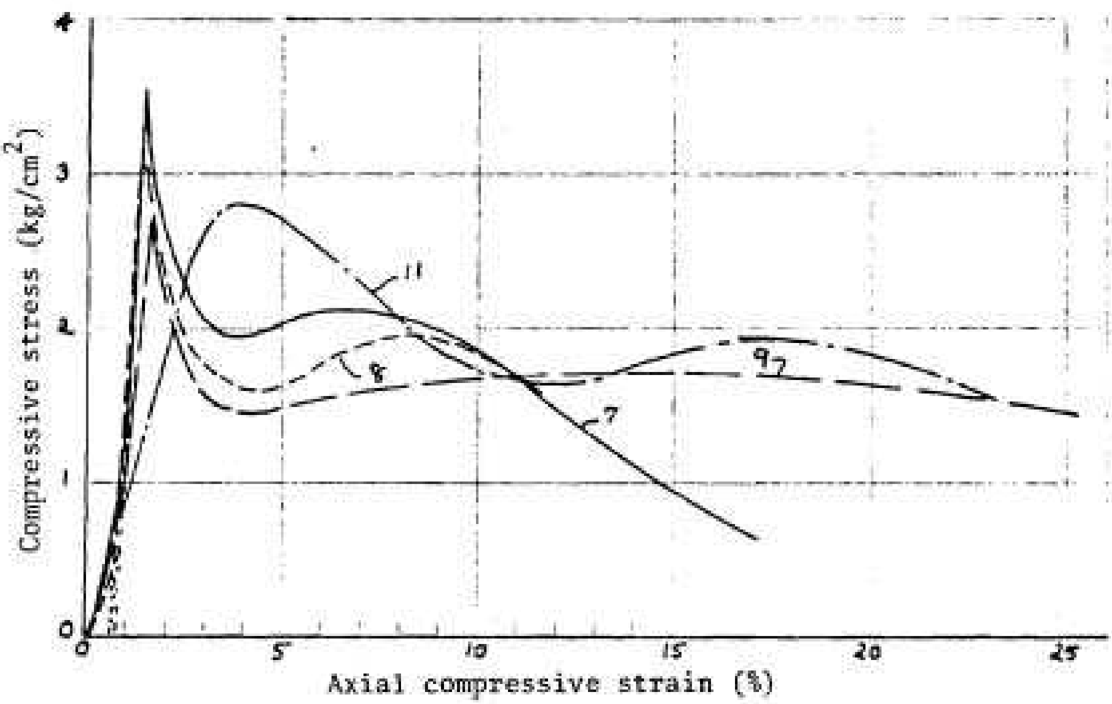
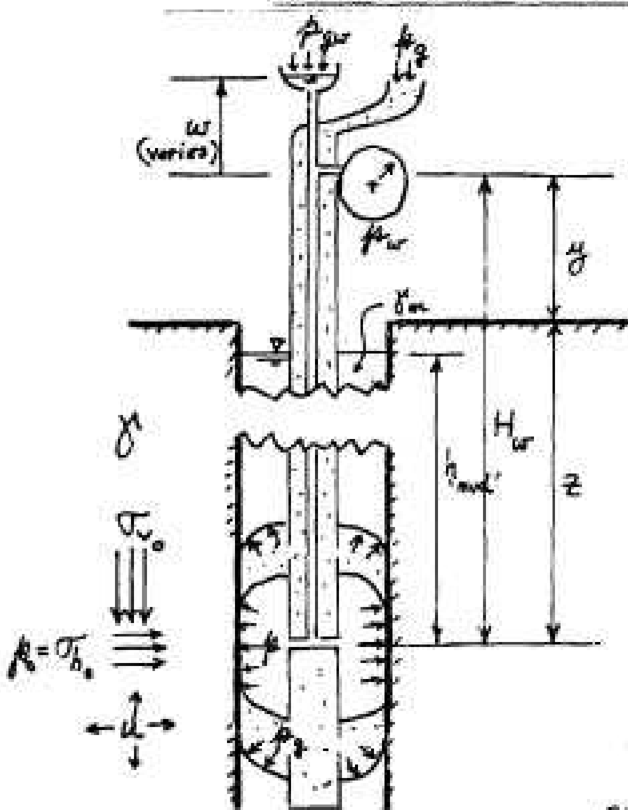


FIGURE 5

LADANYI EQUIVALENT COMPRESSION TEST CURVES FROM PRESSUREMETER TESTS MADE IN BOREHOLES MADE WITH DRILLING MUD AND AUGERING

APPENDIX A

How to evaluate different water pressure effects in test?



press. control expansion of inner membrane = $\Delta p'$

$$\Delta p' = p - p_g = p_w + \gamma_w H_w - p_g$$

$$p_w = p_{gw} + w\gamma_w$$

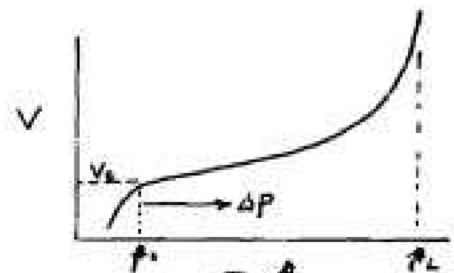
$$p_{gw} = p_g + \Delta p_g$$

$$p_w = p_g + \Delta p_g + w\gamma_w$$

$$\Delta p' = \cancel{p_g} + \Delta p_g + w\gamma_w + \gamma_w(z+y) - \cancel{p_g}$$

$$\boxed{\Delta p' = \underbrace{\Delta p_g}_{+\ \text{if}\ (p_{gw} > p_g)} + (w+y+z)\gamma_w}$$

pressure controlling PMT graph = Δp



all total stresses in clay

$$\Delta p = p - p_0$$

$$p = p_w + H_w\gamma_w = p_w + (y+z)\gamma_w$$

$$p_0 = K'(\sigma_{v_0} - u) + u$$

$$\sigma_{v_0} = \gamma z$$

$$p_0 = K'\gamma z - K'u + u$$

$$= K'\gamma z + u(1-K')$$

$$\Delta p = \underbrace{p_w + (y+z)\gamma_w}_{\text{plot}} - \underbrace{K'\gamma z - u(1-K')}_{\text{try to determine by other means}}$$

pore + hydraulic fracturing or break in PMT curve

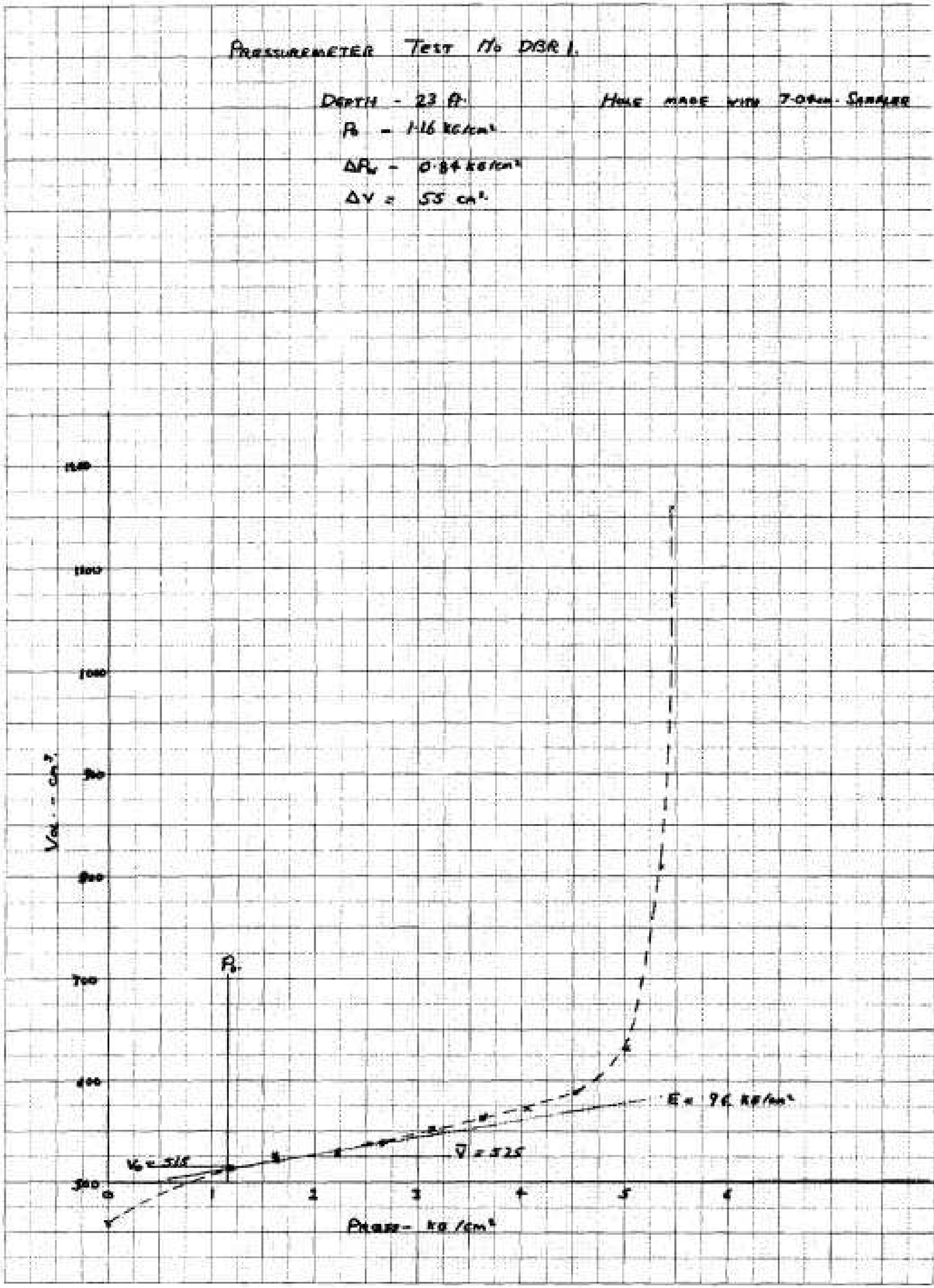
$$\boxed{p = p_w + (y+z)\gamma_w}$$

Note: Effect of water or mud in the hole

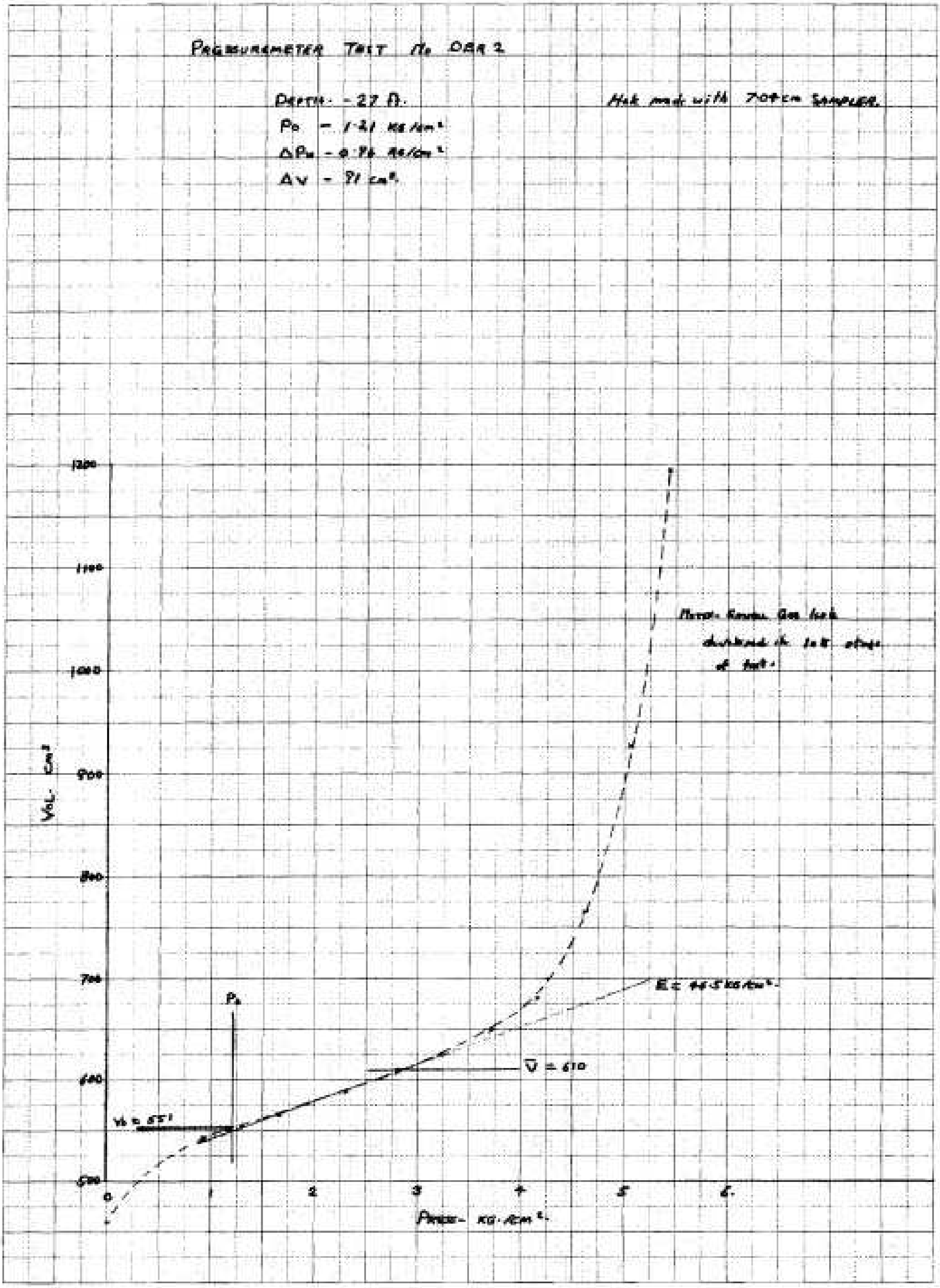
1. To expand the outer membrane at all, p_g must exceed the effective "mud" pressure $(h_m \cdot \gamma_m)$ + membrane inertia. This, plus the differential pressure $\Delta p'$ required to assure inner-outer membrane contact over the standard length chosen, establishes the least value of p at which test can begin.

2. Whether to use u in situ before the hole, or $h_m \cdot \gamma_m$ for u seems uncertain. Does mud in hole raise pore pressures in zone a few diameters from hole? Don't know but assume so. Use whichever is greater in the calculation for p_o.

A P P E N D I X   B



PRESSUREMETER TEST No DBR 1.
DEPTH - 23 ft.
HOLE MADE WITH 7.04cm. SAMPLER
P0 - 1.16 KG/cm²
ΔPv - 0.84 KG/cm²
ΔV = 55 cm³
1200
1100
1000
900
800
700
600
500
Vol. - cm³
P0
V0 = 515
V̄ = 525
E = 96 KG/cm²
0
1
2
3
4
5
6
PRESS - KG/cm²


PRESSUREMETER TEST No DBR 2
DEPTH - 27 ft.
Po - 1·21 KG/cm²
ΔPu - 0·96 KG/cm²
ΔV - 91 cm³
Hole made with 7·04 cm SAMPLER.
E = 44·5 KG/cm²
V̄ = 610
Vo = 551
Po
VOL. cm³
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6
PRESS- KG/cm²

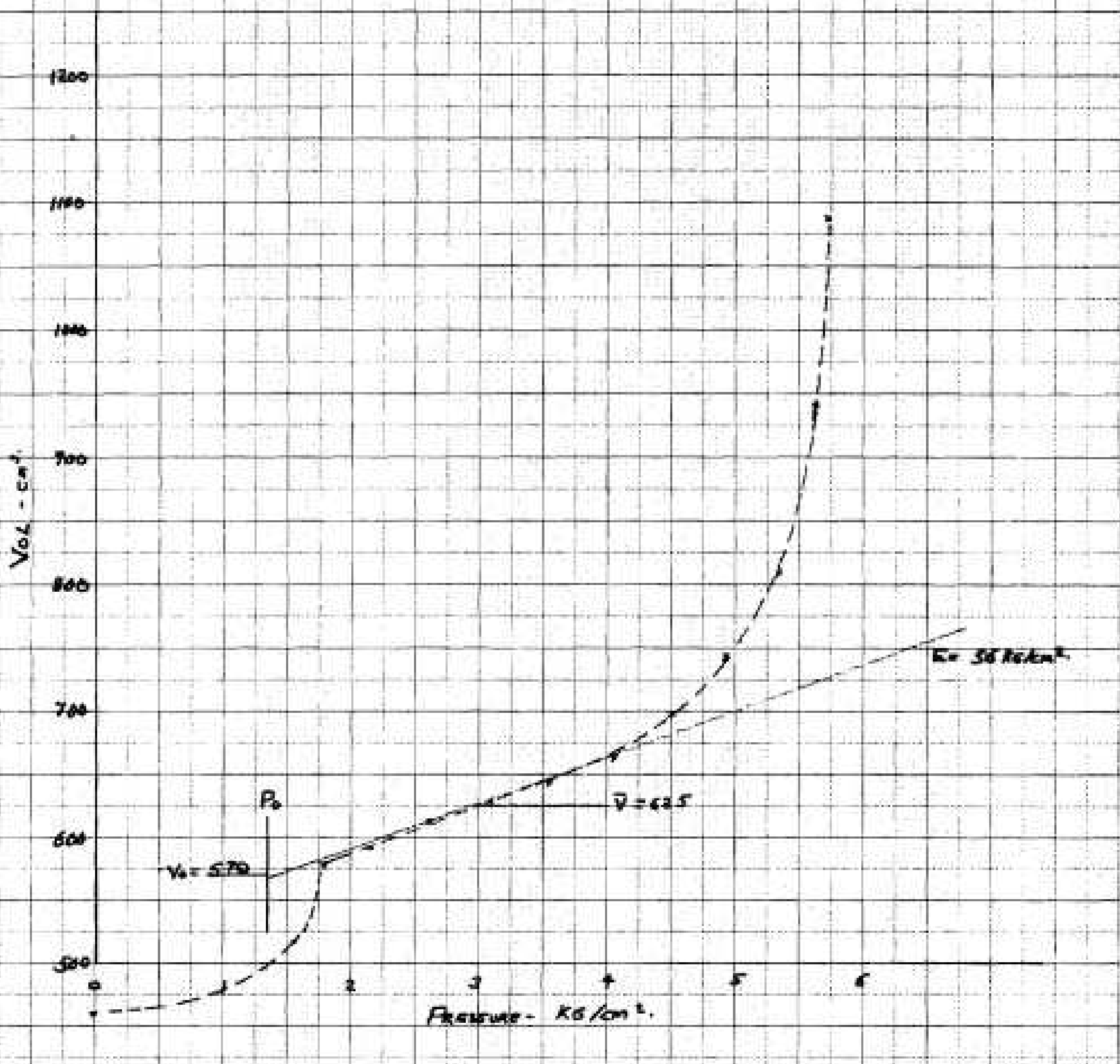
PRESSUREMETER TEST No. DBR 3

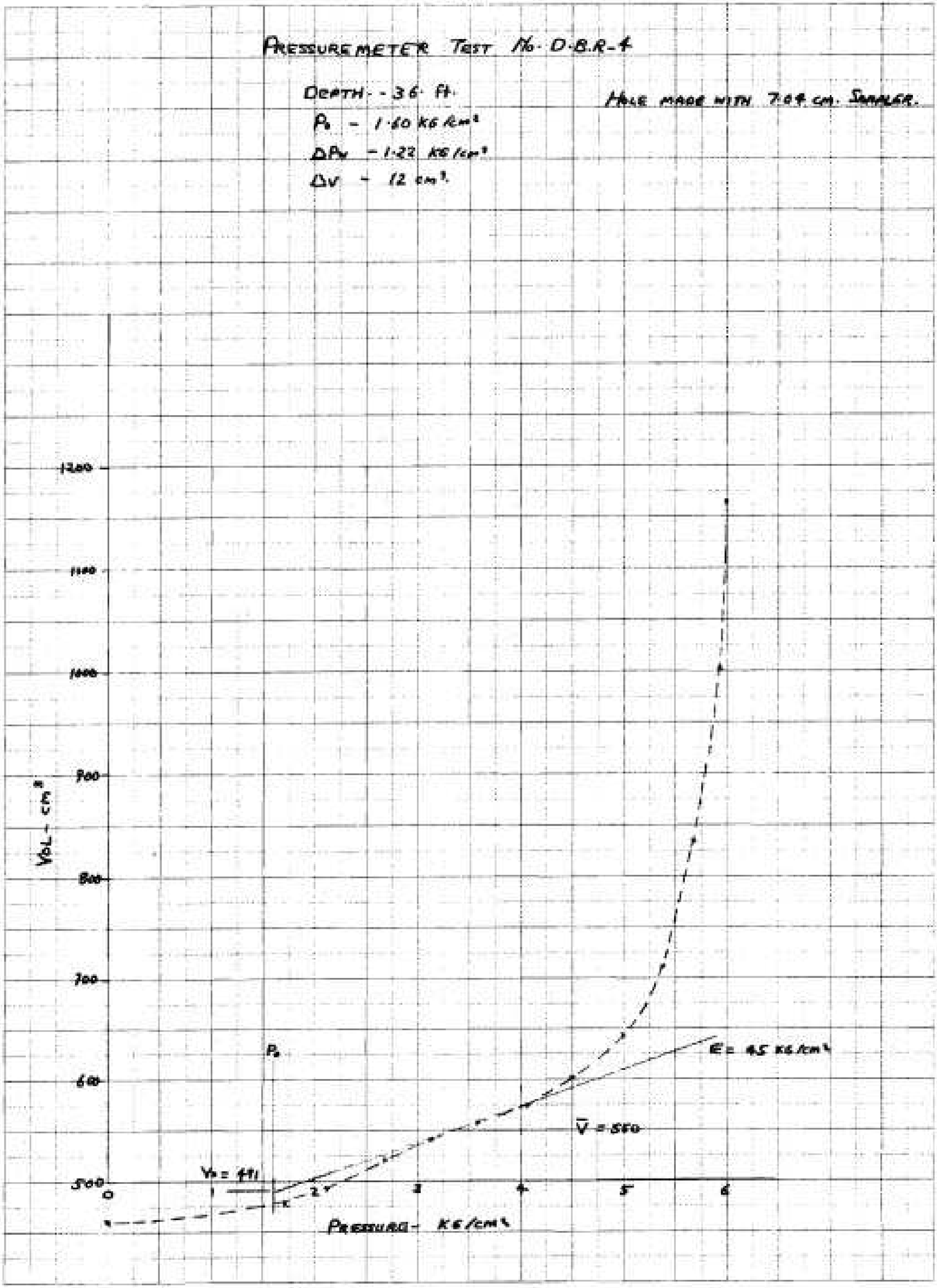
DEPTH - 31.0 ft.   Hole made with 7.98cm. Sampler.

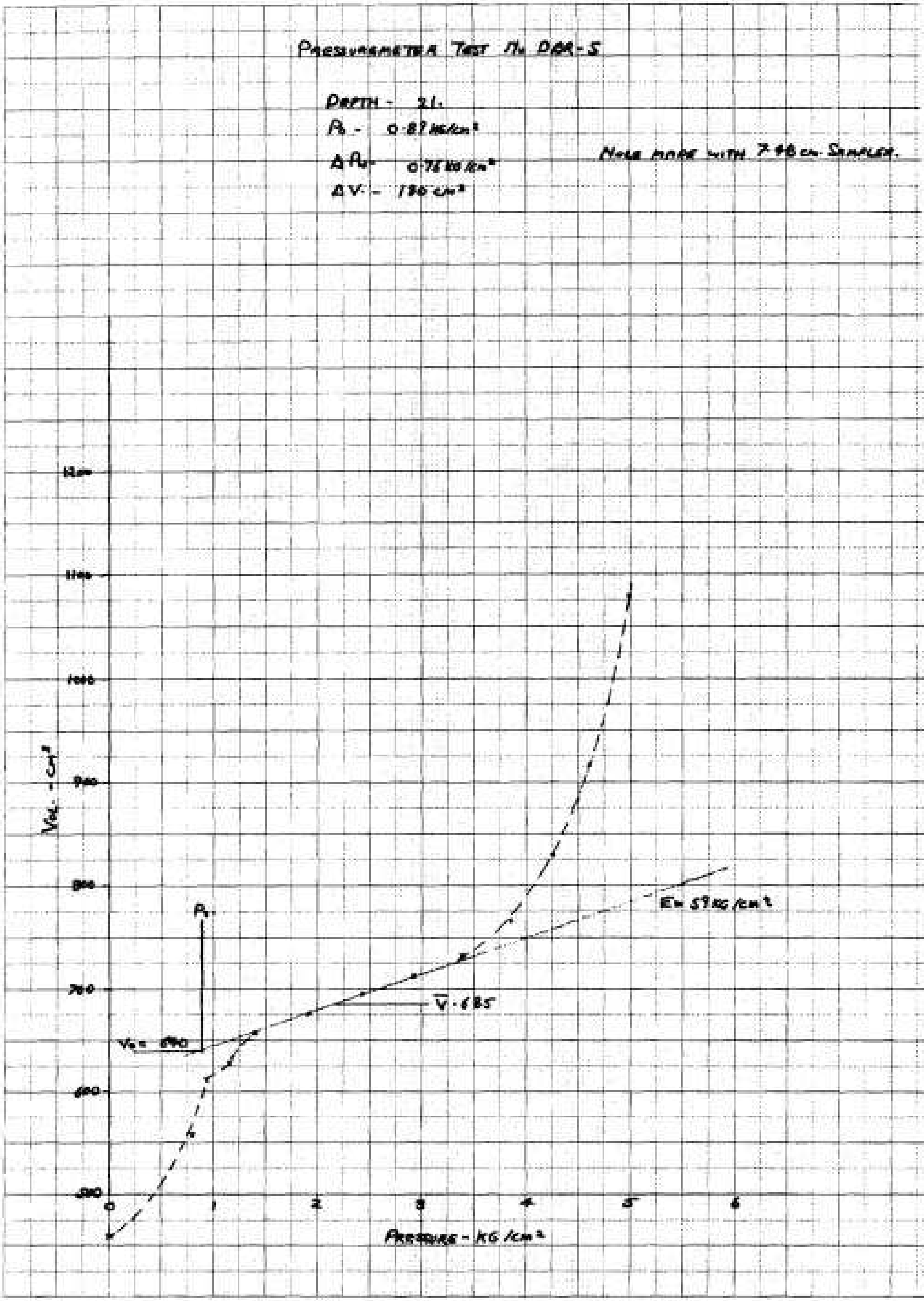
P_o - 1.35 KG/cm²

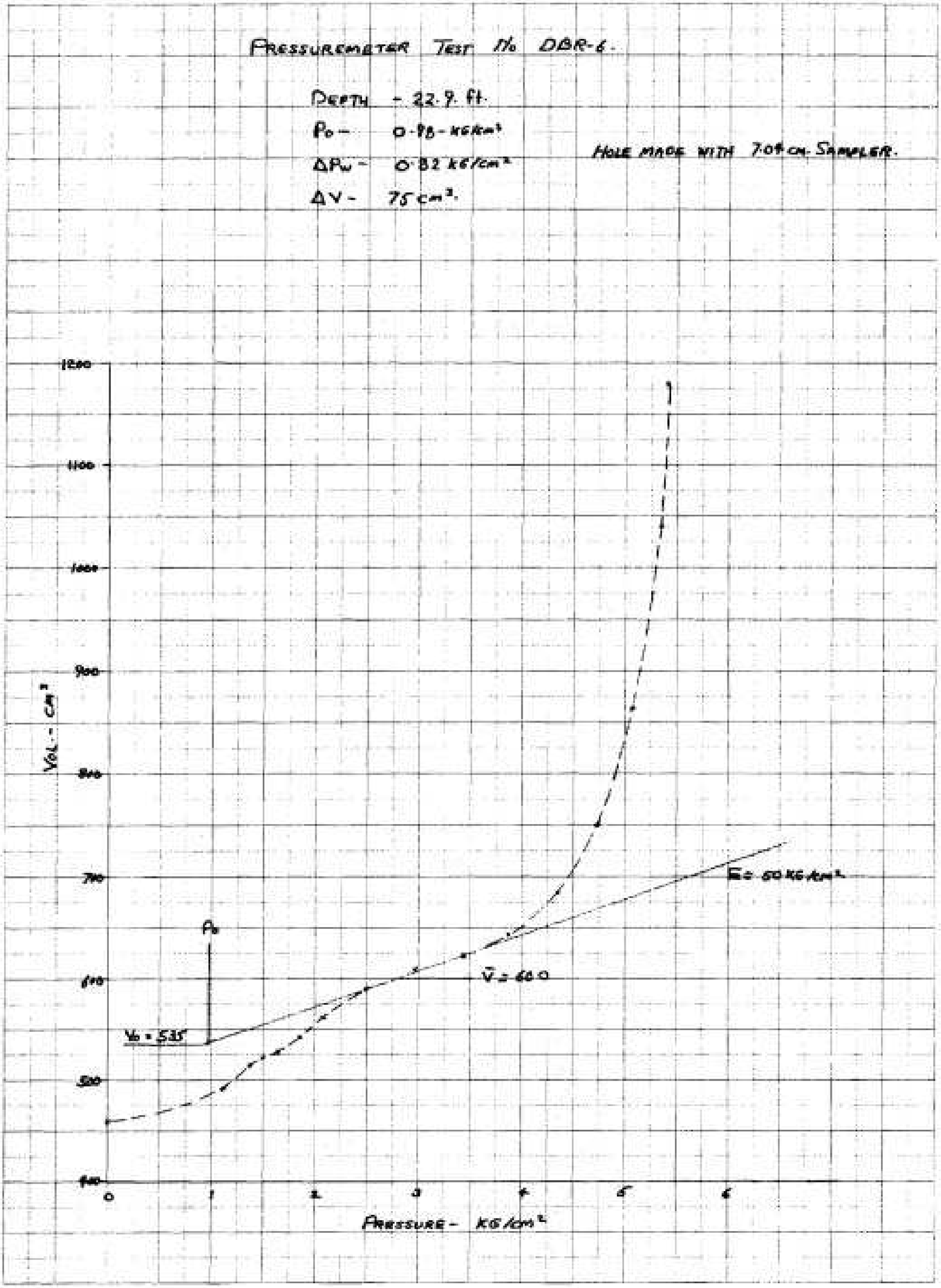
ΔP_o - 1.08 KG/cm²

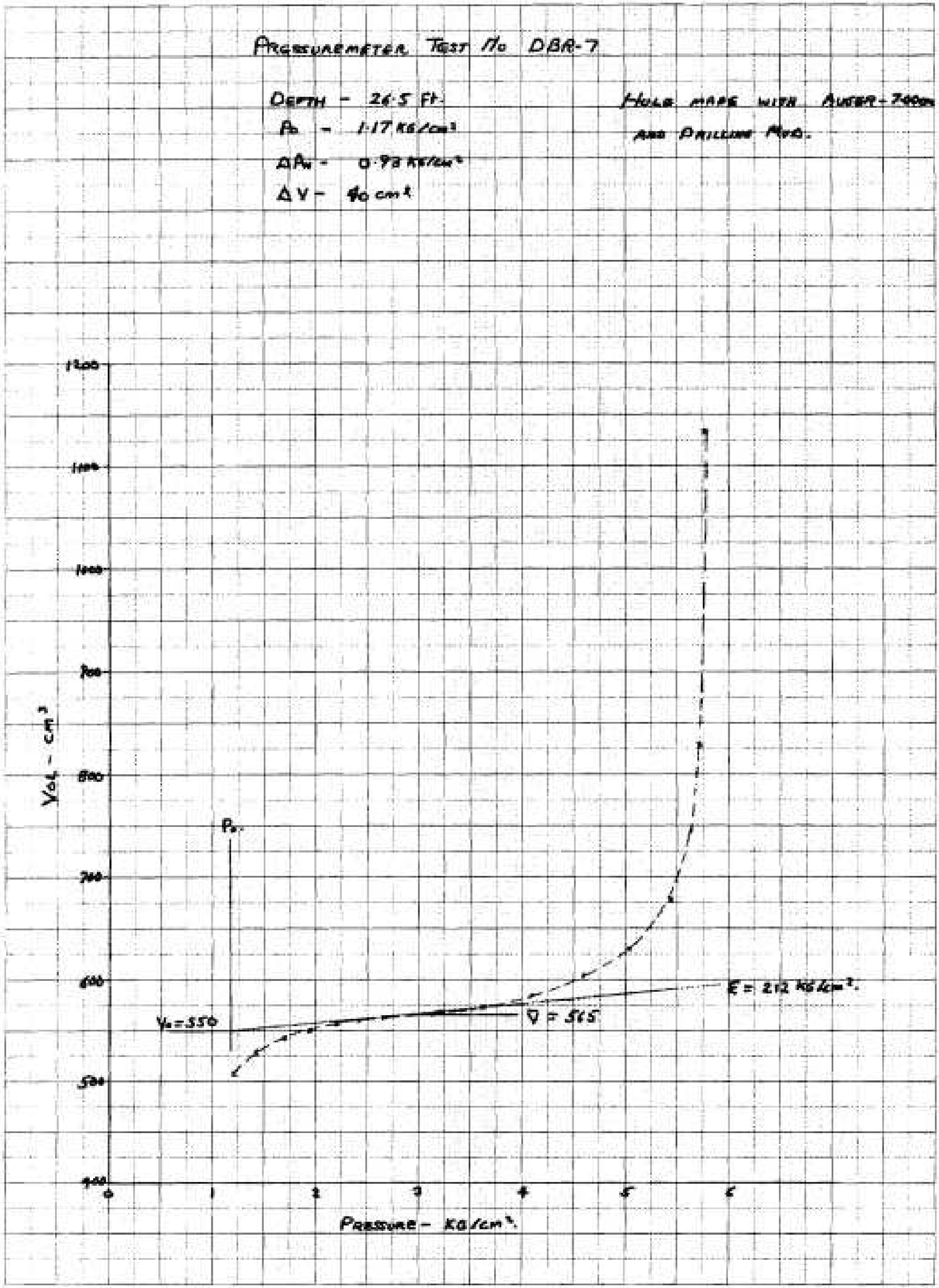
ΔV - 110 cm²




PRESSUREMETER TEST No. D.B.R-4
DEPTH - 36 ft.
Po - 1.60 KG/cm²
ΔPv - 1.22 KG/cm²
ΔV - 12 cm³
HOLE MADE WITH 7.04 cm. SAMPLER.
1200
1100
1000
900
800
700
600
500
VOL - cm³
Po
E = 45 KG/cm²
V̄ = 550
Vo = 491
0
1
2
3
4
5
6
PRESSURE - KG/cm²


PRESSUREMETER TEST IN DBR-5
DEPTH - 21.
P0 - 0.87 KG/cm²
ΔP - 0.75 KG/cm²
ΔV - 190 cm³
HOLE MADE WITH 7.90 cm. SAMPLER.
E = 59 KG/cm²
V̄ = 685
V0 = 640
VOL. - cm³
PRESSURE - KG/cm²


PRESSUREMETER TEST NO DBR-6.
DEPTH - 22.9 ft.
Po - 0.98 - KG/cm²
ΔPw - 0.82 KG/cm²
ΔV - 75 cm³.
HOLE MADE WITH 7.0⁴ cm. SAMPLER.
1200
1100
1000
900
800
700
600
500
400
VOL. - CM³
Po
Vo = 535
V̄ = 600
E = 60 KG/cm²
0
1
2
3
4
5
6
PRESSURE - KG/CM²


PRESSUREMETER TEST NO DBR-7
DEPTH - 26.5 Ft.
P0 - 1.17 KG/cm²
ΔPN - 0.93 KG/cm²
ΔV - 40 cm³
HOLE MADE WITH AUGER-74mm
AND DRILLING MUD.
VOL - cm³
1200
1100
1000
900
800
700
600
500
400
P0
V0=550
V̄ = 565
E = 212 KG/cm²
0
1
2
3
4
5
6
PRESSURE - KG/cm²

PRESSUREMETER TEST No DBR-8

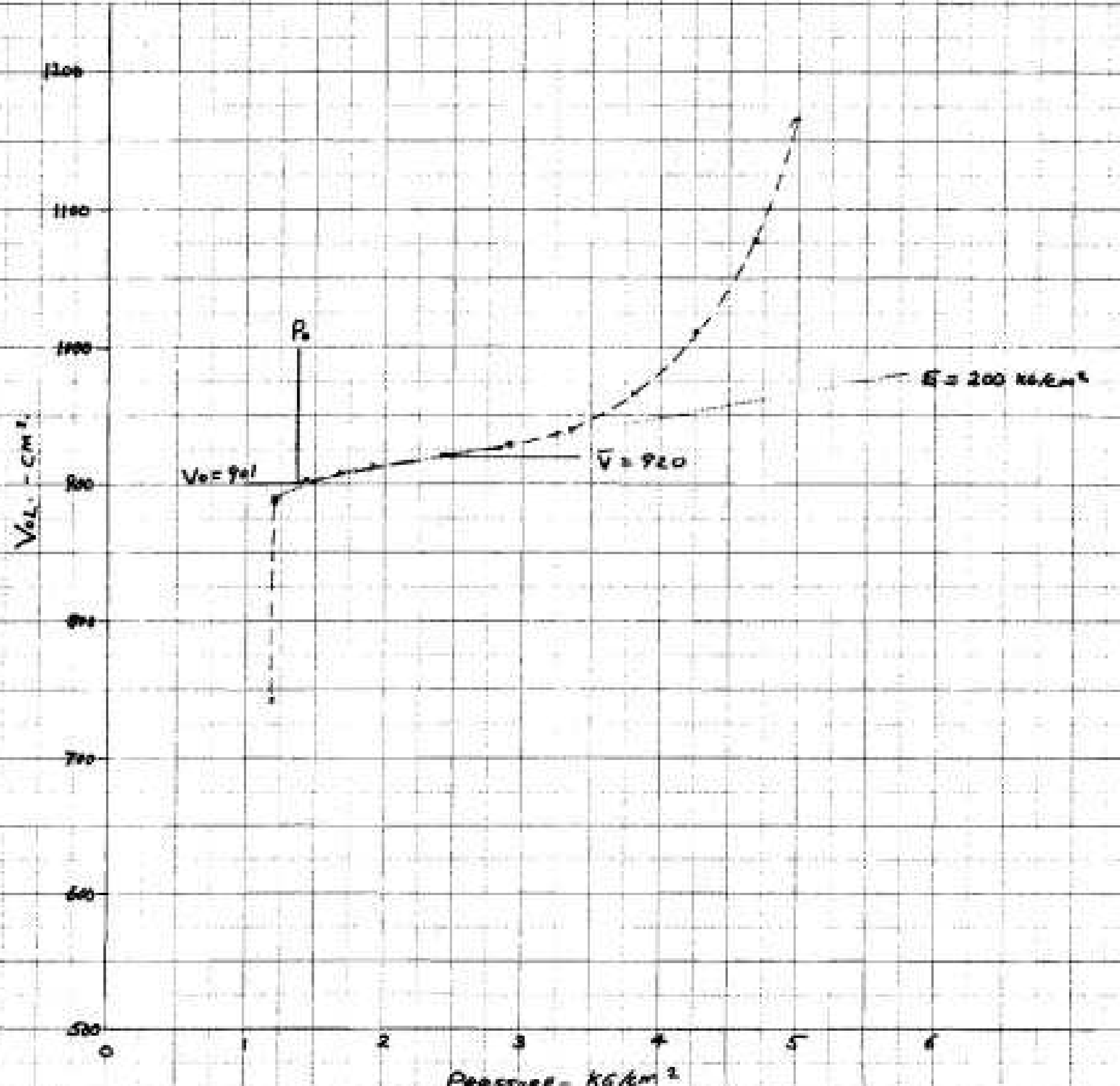
DEPTH - 32'

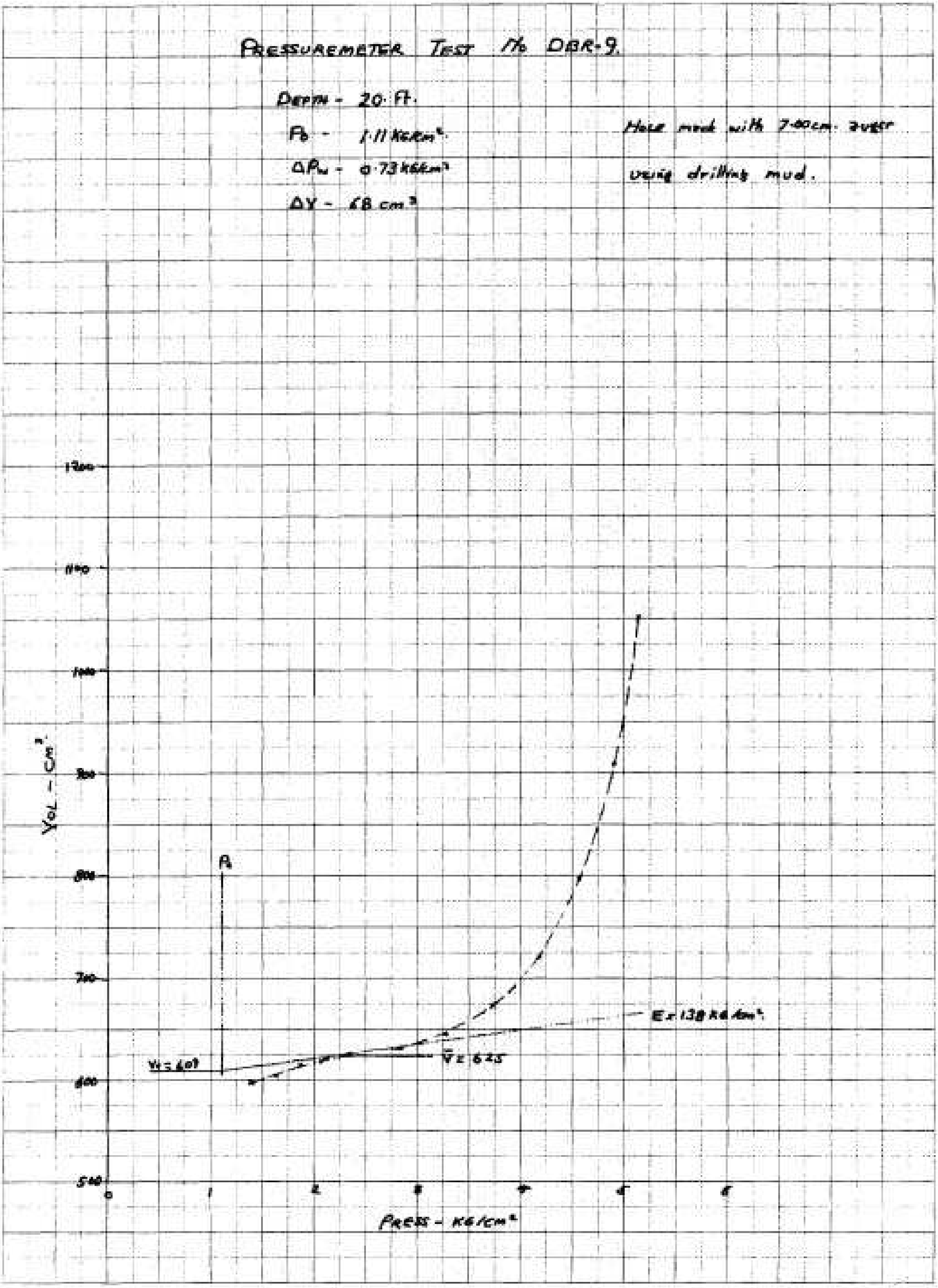
P_0 - 1.37 KG/cm²

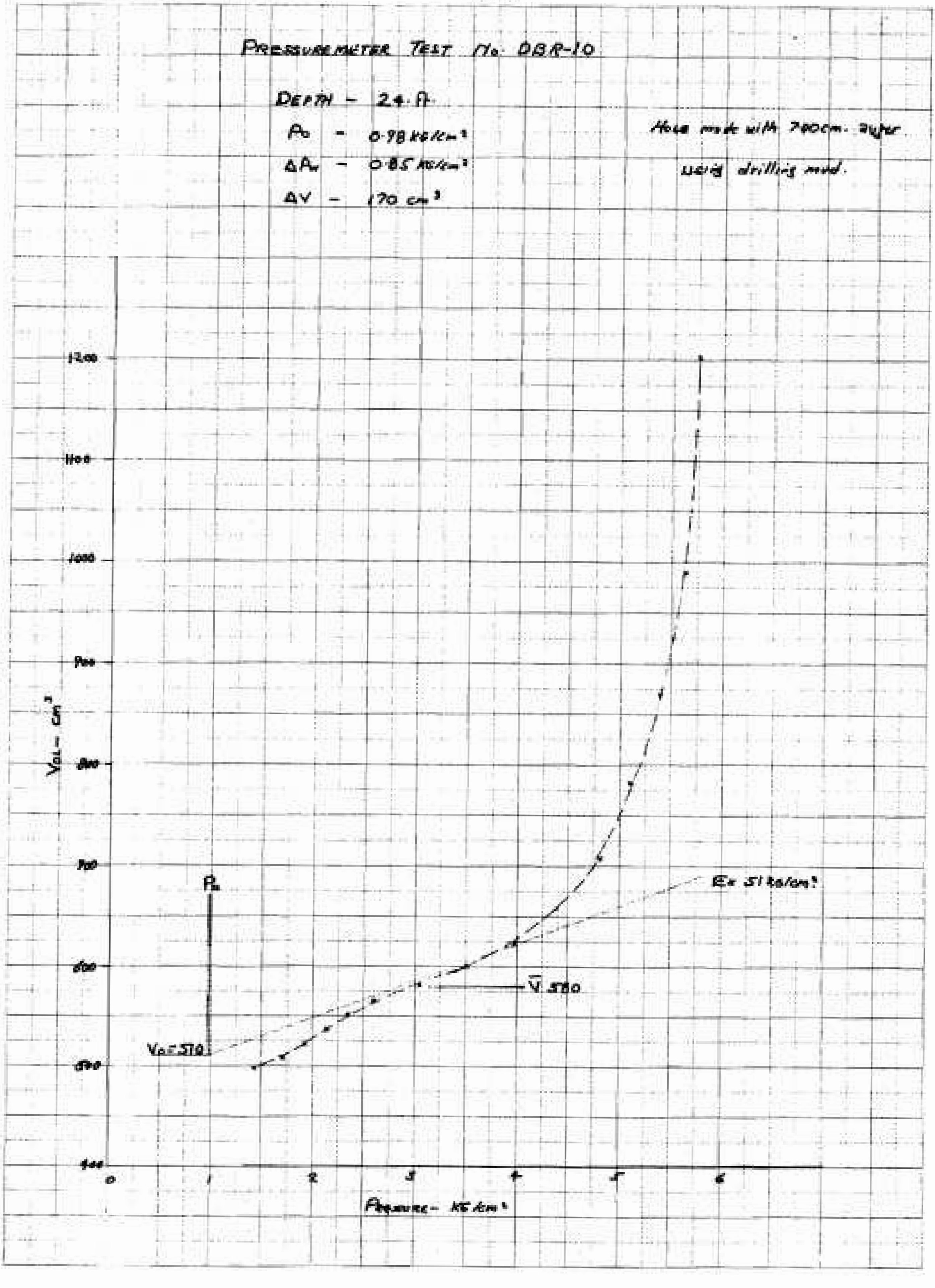
ΔP_w - 1.10 KG/cm²

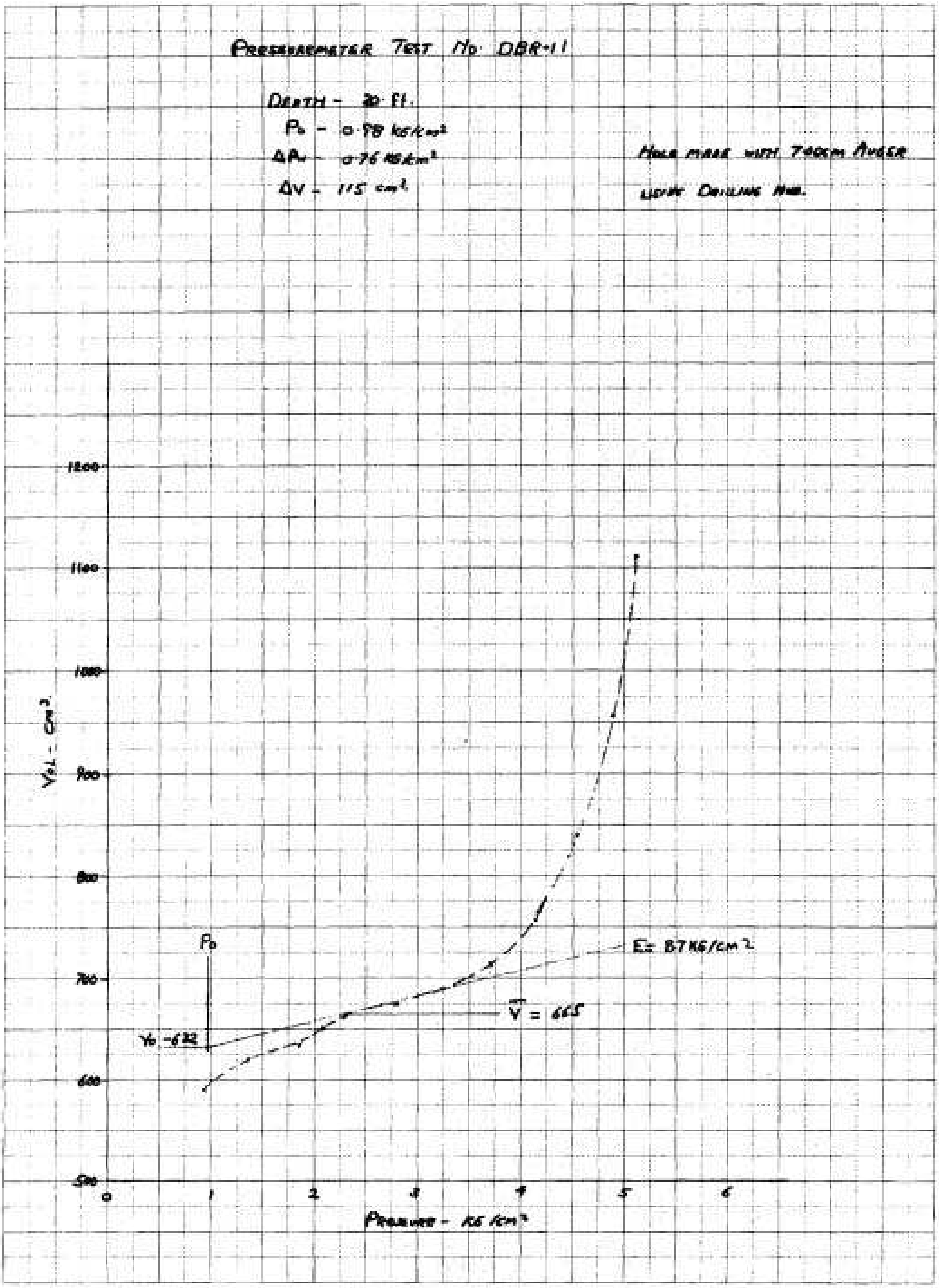
ΔV - 69 cm³.

HOLE MADE WITH 700cm AUGER USING DRILLING MUD.

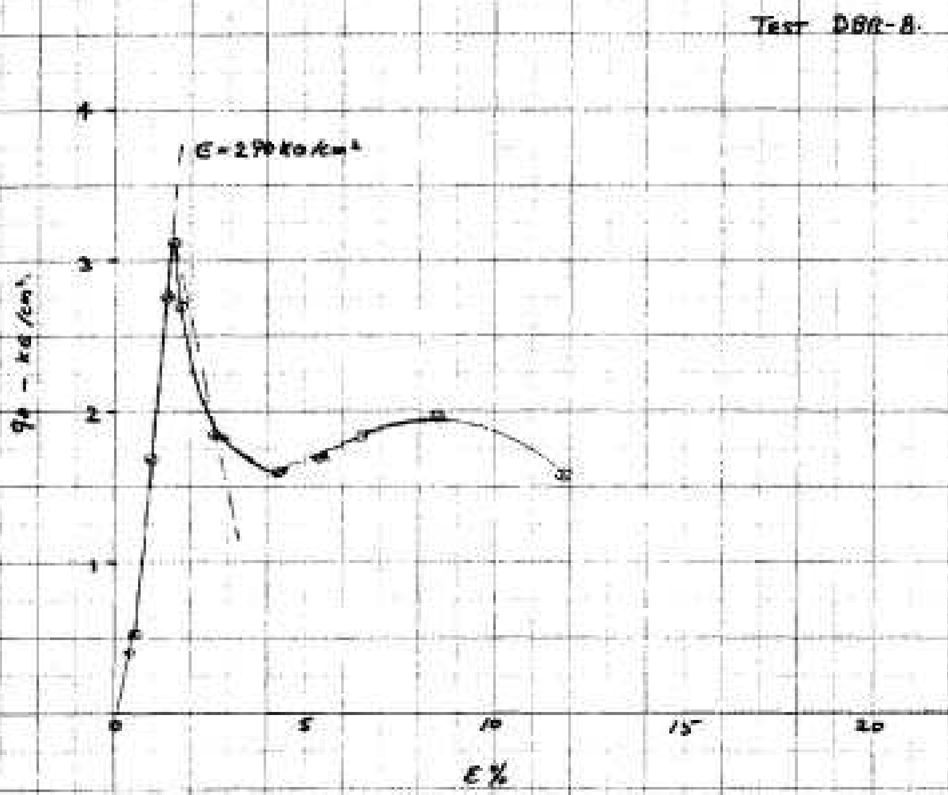


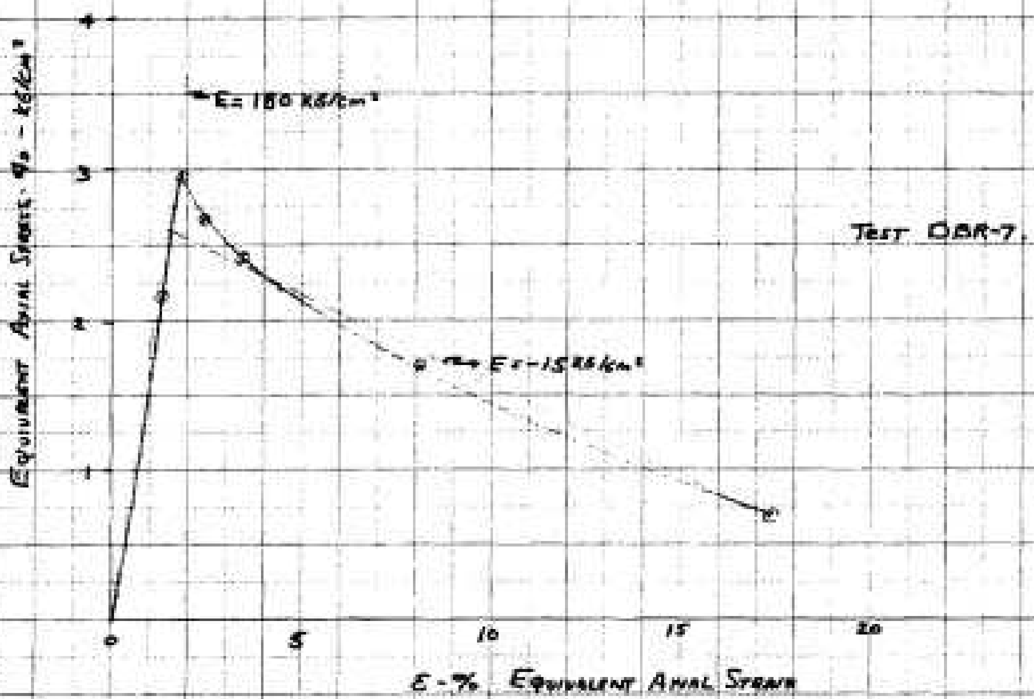

PRESSUREMETER TEST No DBR-9.
DEPTH - 20 Ft.
P0 - 1.11 KG/cm².
ΔPm - 0.73 KG/cm²
ΔV - 68 cm³
Hole made with 7.00cm. auger
using drilling mud.
VOL - CM³.
1200
1100
1000
900
800
700
600
500
P1
Vi = 607
V̄ = 625
E = 138 KG/cm².
0
1
2
3
4
5
6
PRESS - KG/CM²

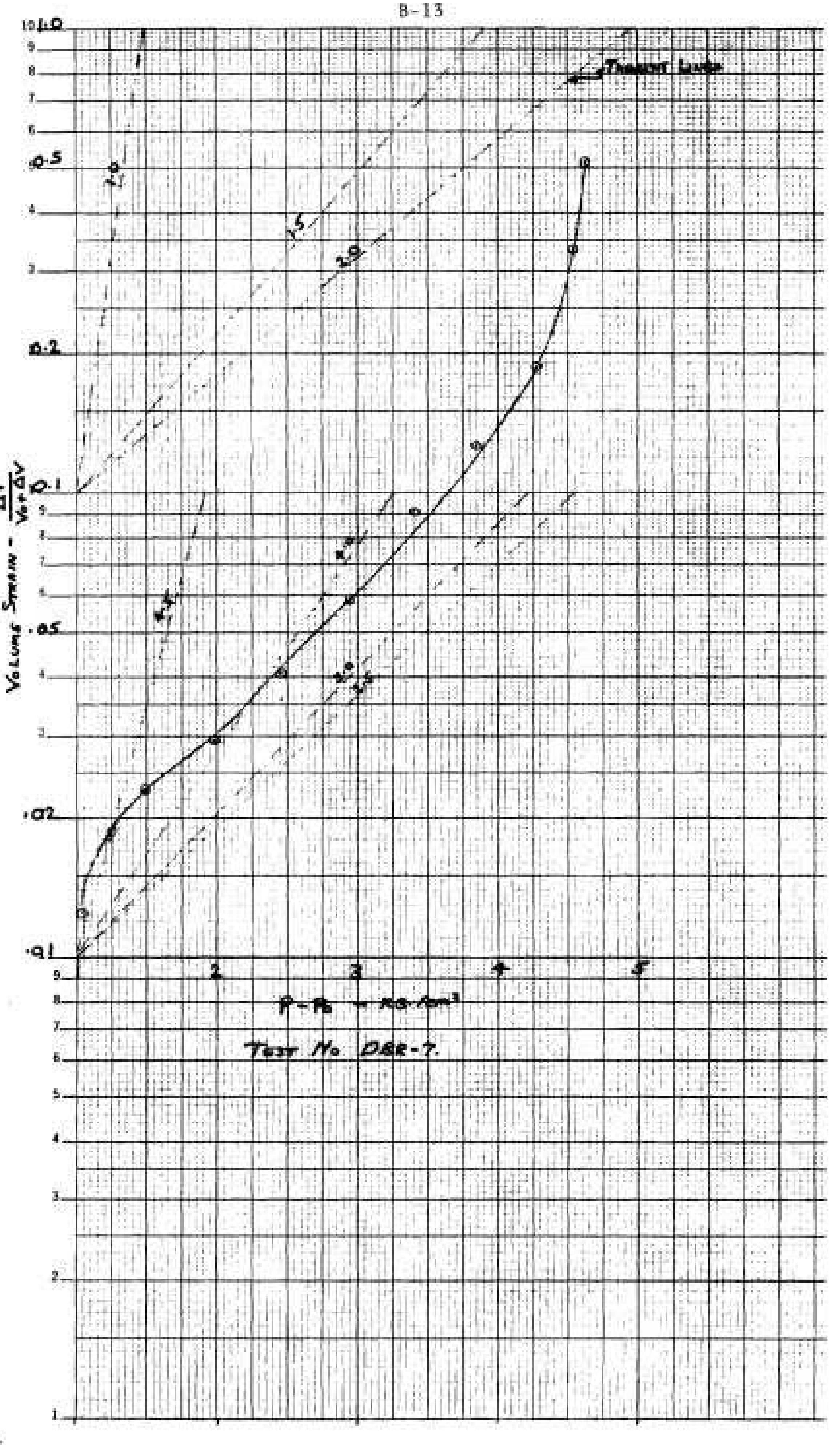

PRESSUREMETER TEST NO. DBR-10
DEPTH - 24 ft.
Po - 0.98 KG/cm²
ΔPu - 0.85 KG/cm²
ΔV - 170 cm³
Hole made with 700cm. auger using drilling mud.
E= 51 KG/cm²
V̄ 580
Vo=510
Pu
Vol - cm³
Pressure - KG/cm²

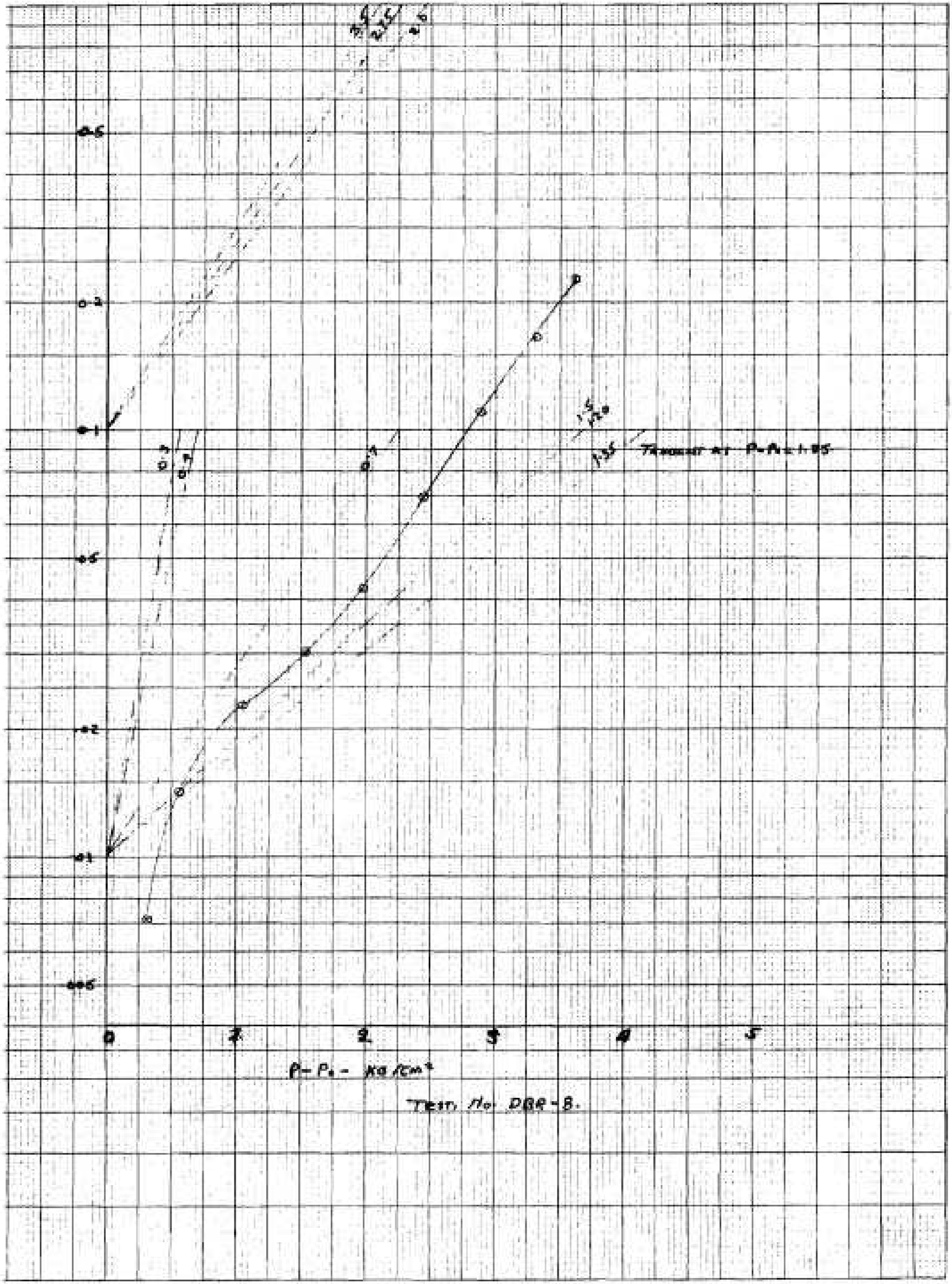


PRESSUREMETER TEST No. DBR-11
DEPTH - 20 Ft.
Po - 0.98 KG/cm²
ΔPm - 0.76 KG/cm²
ΔV - 115 cm³
HOLE MADE WITH 7.40CM AUGER
USING DRILLING RIG.
VOL - CM³
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6
PRESSURE - KG/CM²
Po
Vo - 632
V̄ = 665
E = 87 KG/CM²


TEST DBR-8.
E=290 KG/cm²
q_o - KG/cm²
4
3
2
1
0
5
10
15
20
E %


TEST DBR-7.
E= 180 KG/cm²
E=-15 KG/cm²
EQUIVALENT AXIAL STRESS q_o - KG/cm²
4
3
2
1
0
5
10
15
20
E - % EQUIVALENT AXIAL STRAIN


Volume Strain - $\frac{\Delta V}{V_0+\Delta V}$
1.0
0.5
0.2
0.1
.05
.02
.01
2
3
4
5
$P - P_0$ = KG/cm²
Test No DBR-7.
Tangent lines
1.5
2.0


0.5
0.2
0.1
0.05
0.02
0.01
0.005
0
1
2
3
4
5
P - P₀ - KG/CM²
TEST. NO. DBR-8.
TANGENT AT P-P₀=1.95
1.35

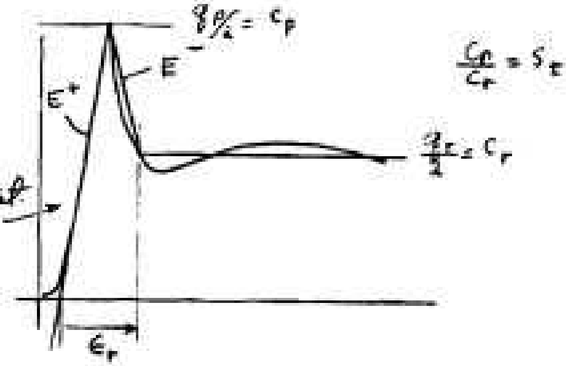
A P P E N D I X   C

Using the best 3 pressuremeter tests

$$N_c = \frac{1}{S_t} + \frac{4}{3S_t}\left[1+\ln\frac{2}{3\epsilon_r}\right] + \frac{4}{3}\left[1+\frac{E^-}{E^+}\right]\ln\left[\frac{E^+}{E^-}\left(1-\frac{1}{S_t}\right)+1\right]$$

Test No.	$\frac{C_p}{C_r} = S_t$	ϵ_r	E^+	E^-	E^+/E^-
7	$\frac{3.5}{2} = 1.75$	.022	370	100	3.7
9	$\frac{2.8}{1.6} = 1.75$	.023	235	85	2.8
8	$\frac{3.0}{1.75} = 1.71$	.025	295	80	3.7
ave	1.74	.023			3.4

interpretation used



$\frac{C_p}{C_r} = S_t$

$$\text{then}\quad N_c = \underbrace{\frac{1}{1.74}}_{.576} + \underbrace{\frac{4}{3(1.74)}}_{.765}\underbrace{\left[1+\ln\underbrace{\frac{2}{3(.023)}}_{29}\right]}_{4.367} + \frac{4}{3}\underbrace{\left[1+\frac{1}{3.4}\right]}_{1.294}\ln\underbrace{\left[3.4\underbrace{\left(1-\frac{1}{1.74}\right)}_{.424}+1\right]}_{2.44}$$

$$= 0.576 + \underbrace{0.765\,[4.367]}_{3.35} + \underbrace{1.33\,(1.294)\,\underbrace{\ln 2.44}_{0.892}}_{1.54}$$

$$= \begin{array}{r} 0.58 \\ 3.35 \\ 1.54 \\ \hline 5.47 \end{array}$$

$\overline{N_c}$ meas by Fugro cone $= \frac{\overline{q_c}}{\overline{S_u}}$

$= \frac{8.5}{1.57}$

$= 5.41$

$\overline{S_u} = 3.6 + 2.9 + 3.0$; $3 \times 2 \,\overline{)\,9.5} = \frac{3.15}{2} = 1.57$

$\overline{q_c} = 7.5 \to 9.5$
Say 8.5 kg/cm²

excellent agreement

COMPARISON OF N_c PREDICTED BY LADANYI'S 3-SLOPE THEORY

AND AS MEASURED BY FUGRO CONE AND PRESSUREMETER