Results of Geotechnical Field Investigations in Cumberland Basin During a Four-day Period in September 1989: Data and Interpretation

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Introduction and Background:

A geomechanical device has been developed to measure the shear strength of very soft surface sediment in-situ on intertidal mudflats. The reason for building this device was to measure sediment cohesion, which is equated with the surface critical shear stress for erosion. This device (INSIST - In-situ SImple Shear Test) provides reproduceable measures of sediment strengths to less than 10 Pa. The device was used from September 4 to 7, 1989 to measure the shear strength in-situ at four locations in Cumberland Basin (Figure 1).

Subsamples were also obtained from Cumberland Basin for laboratory classification testing. Analyses were then performed to determine the plasticity characteristics, the particle size distribution, pore water salinity, water content, bulk density, porosity, and specific gravity. These index properties assist in the interpretation of the results from INSIST and also establish baseline physical behaviour that determines the applicability of other in-situ tests in these sediments.

Standard geotechnical devices such as shear vanes typically produce cohesion measurements three orders of magnitude larger than values measured with INSIST. This means that standard techniques are often of no use in identifying in-situ strengths at the surface of the mudflat where the vertical stress is very low. Also, the bulk sediment strength is much greater than its ability to resist directionally-applied shear stress due to anisotropy expressed as a laminated microfabric.

INSIST applies incrementally increasing vertical loads to the uppermost few millimetres of sediment, thereby allowing an intact area to be consolidated to a higher stress and lower porosity; then it applies a horizontal shearing force, in an attempt to simulate hydrodynamic shear stresses. The end result is a complete definition of the shear strength envelope for a wide variety of applied stresses. This stress path is not possible with other types of equipment such as shear vanes. Also, shear vanes provide data that is used in "undrained" analyses and must therefore only be used in clays whereas INSIST can be used to test any sediment type since it is capable of shearing sediments in a both a drained and an undrained mode. The capability to perform drained tests is extremely important in the non-cohesive mudlats found in the Bay of Fundy, since environmental loading produces a quasi-drained or drained shearing response within the bed.

The in-situ data reported herein are inherently more reliable than similar data produced on potentially disturbed samples tested in the laboratory; this fact was recognized as being of paramount importance in determining the critical shear stress for erosion in easily disturbed sediments and was the catalyst for developing the INSIST technique. If the environmental variables can be measured in a quantitative way, then INSIST becomes a very useful tool for measuring the impact of these processes on the stability of mudflats.

Methodology:

The INSIST device consists of a weighted pad and loading gallows. The pad sits on the sediment surface inducing a vertical consolidation stress. It is attached to a yoke through the gallows and is connected to a variable loading system (Figure 2). A horizontal shear force can be applied to the pad by adding a known weight to the gallows. The sediment is interpreted to fail when the pad begins to slide over the bed. The horizontal force at sediment failure is then a measure of the shear strength integrated over the depth of influence of the pad. The shear stress is taken to be equal to the load exterted by the weights pulling on the pad divided by the contact area. This is interpreted as the condition of unlimited deformation or failure. Likewise, the vertical consolidation stress is equal to the force exerted by the total weight of the pad divided by the bed contact area.

The test is repeated at different vertical loads. In each case, the sediment is allowed sufficient time for consolidation beneath the pad to occur under the new load. Thus excess pore water pressure beneath the pad is dissipated. A least-squares regression is then drawn through a plot of the vertical stress (σ_v) versus shear stress at failure (T). The best-fit line of the data represents the possible stress state within the sediment at the point of failure and is referred to as the failure envelope. Examples of failure envelopes are shown in Appendix A. The intercept on the y axis is the sediment cohesion and the arctangent of the slope of the line is referred to as the friction angle. The failure envelope therefore defines the characteristic shear strength for the sediment at any applied stress.

Results of applied consolidation stress (a function of depth in the sediment) plotted against failure (sediment shear strength) for intertidal mudflats in Cumberland Basin gave reliable and repeatable linear relationships. Measurements of surface cohesion using INSIST were made at four locations during a 3 day period in early September, 1989 (Figure 1). The sediments tested had a water content between 40 and 160 percent by weight and a bulk density between 1.45 and 1.75 g/cm^3.

Errors in INSIST Measurements:

The standard deviation in INSIST results is generally good, depending on the experience of the operator. The depth and manner at which subsamples are taken for classification purposes is also critical in data interpretation since the various physical properties are partly interdependent and are very sensitive to sampling disturbance.

A major source of error with INSIST is the rate at which load is applied and the time given for equalization and dissipation of pore pressures generated both during consolidation and during shear. Different rates of pore pressure dissipation will exist depending on sediment texture and whether or not it is preconsolidated. When testing coarse-grained sediments, precautions must be taken to ensure that the test is performed slowly to ensure that drained conditions exist at all times. The application of load must also be uniform; high winds can cause spontaneous liquefaction of sediment by causing large cyclic variations in shear stress applied through the loading system.

Since the device cannot at present be used underwater, the operator must arrive at the site shortly after exposure and select an area for testing that is still inundated with 1 to 2 mm of water. (This represents the subtidal condition as close as possible). Terzaghi (1943) found that soil shear strength is governed by the effective stress and can be simply stated as follows:

Effective Stress = Total Stress - Pore Pressure

Subsequent measurements made later in the exposure period must be accompanied by subsamples for water content, bulk density, and specific gravity so that a calculation can be made to determine whether the mudflat is desaturating as it dries out, or whether it is simply settling. The volume of water removed by drainage and evaporation must equal the volume change if the sediment is to remain fully saturated.

This latter point is particularly important because it is extremely difficult to know what the effective stress is in an unsaturated material. So long as the sediment remains saturated there are no problems in the analysis of results. In the case of clays, it is much more difficult to ensure that undrained conditions do not develop during loading which could result in apparently high values of cohesion and low friction angles since the effective stress would be higher than one might anticipate.

The sensitivity of the device has been predetermined by the selection of the amount of area in shear beneath the pad. This translates into a sensitivity of +/- 0.5 Pascals given that the variation in weight added to the tensioning system is around 5×10^{-3} kg. The vertical weights on the pad are calibrated to a high degree of accuracy and so long as the pad is clean and dry, there is no significant error. Errors in the contact area can develop if the pad is not placed on a completely smooth portion of the mudflat, because it will initially be supported only on the topographic highs. This effect disappears once the pad begins to shear if the bed roughness is not too severe since the points of contact will undergo failure and be sheared off, thus bringing the pad into contact with more sediment.

The test is quite repeatable so long as the preceding cautions are observed, the only problem arising from the fact that the pad must be moved to a fresh surface after each test to failure so that peak shear strength behaviour is mobilized each time. This introduces a level of variability into the results because water content, grain size, amount of bioturbation, surface roughness, and structure all play a role in determining the shearing resistance. Therefore, sites must be as similar as possible and it may be necessary to repeat certain trials to achieve good linear regression and an acceptable failure envelope. The achievement of a correlation coefficient above 0.95 is easily obtained with the INSIST device (see Appendix A). If time permits, tests should be rerun at the same vertical load to determine the standard deviation of measurement.

Index property testing followed ASTM (American Society for Testing and Materials) recommendations using the following testing standards:

Procedure Performed	Designation
Sample Preparation (wet)	ASTM D2217
Water content	ASTM D2216
Salinity	ASTM D4542
Atterberg Limits	ASTM D4318
Particle Size	ASTM D421, D422
Specific Gravity	ASTM D854
Soil Classification	ASTM D2487

Bulk Density was determined from the undisturbed sample used for water content since the piston sampler used in-situ was of known volume. Water contents are uncorrected for salt since salinity tests were not performed on all samples and only represents a minor correction.

Discussion of Results:

Four locations within Cumberland Basin were tested for during the three day period and are shown in Figure 1. Pecks Cove was tested most extensively for shear strength and index properties, followed by the high intertidal area at Minudie Marsh, Mill Cove and Amherst Point. Details of particle size testing from each site are given in Table 1. Summaries of the geotechnical test results are listed in Table 2. The actual particle size distributions are shown in Appendix B. Table 3 shows the results of the Atterberg Limits testing and a summary of the soil classifications are given in Table 4 wherever sufficient data permitted.

Sampling at Pecks Cove (sites denoted with D) began approximately at the low water mark on September 4 and proceeded landwards just ahead of the flood tide. The transect was on a bearing of 288°.

Minudie mudflat was visited on September 5, and was reputed to be an area of very soft sediments at certain times of the season; however it appeared to have stabilized to a high degree by the time we arrived. It is noteworthy that Table 1 shows that Minudie sediments were very sandy and had the lowest clay content of any tested. The grain size curves for these samples show poor sorting, which could mean that under storm conditions they might be susceptible to liquefaction.

Sample station names beginning with an A and a C are samples provided by Dave DeWolfe from site work at Mill Cove and Amherst Point respectively.

1. **Pecks Cove:**

The shear strength results (Table 2) indicate that the sediments at D6.5 behave like a normally consolidated clay with a plasticity index of 7% (Kenney, 1959). This is in general agreement with the results obtained from index testing for that site. Data from the low intertidal site D8.5 shows a reduced friction angle for sediment having slightly more clay than at D6.5. Kenney (1959) predicts a higher friction angle of 37° and an examination of the INSIST results for D8.5 contained in Appendix A shows that there is significant scatter in the data and that it would be possible to redraw the failure envelope with a higher slope. The wind over the mudflat was quite strong on the day that D8.5 was visited, which could have introduced error into the INSIST measurements as previously indicated.

1. **Minudie Mudflat:**

The INSIST data agree well with values predicted after Kenney (1959). Table 3 shows that the plasticity index is about 6 to 7 percent. A remoulded test was performed at a site immediately offshore from MIN-D9 but on the sand-rippled portion of the mudflat. The ripples prevented any peak strength measurements from being made, however the remoulded friction angle agrees very well with Skempton (1964) who compiled a large body of remoulded strength data with varying clay content. The Minudie remoulded friction angle data plot in the area of random-oriented quartz with a clay content below 7 percent.

Insufficient data exists to make any statement about the INSIST data from Mill Cove other than it appears to well correlated.

Conclusions:

Results from a field program on the mudflats in Cumberland Basin during a three-day period in early September 1989 have provided further evidence that the INSIST device is a reliable device for measuring in-situ shear strength behaviour at very low applied stresses. The device is able to simulate the application of a hydrodynamic shearing stress in the horizontal plane, an improvement over other testing techniques.

It must be stressed that the device is in the development stage and any results obtained with it are subject to question until it can be shown that they are a true representation of the actual shearing behaviour at low stresses. Soil engineers have long realized the importance of confining stress on the peak friction angle (Lambe and Whitman, 1969) and it is not surprising that dilatant behaviour is observed at low stresses in sandy sediments. However, the data from this experiment appear to lie within the range of behaviour associated with normally consolidated silty clays of low plasticity.

For future research, it is recommended that not less than four tests be run to define each failure envelope. More research is required to properly characterize the sediment response to environmental loading.

Acknowledgements:

The author is indebted to Dave DeWolfe for soliciting his participation in this project and for helping out with the logistics of the field program.

References

ASTM. 1989. Annual Book of ASTM Standards. 4.08: Soil and Rock, Building Stones; Geotextiles. American Society for Testing and Materials, Philadephia.

Kenney, T.C. 1959. Discussion, Proceedings, American Society of Civil Engineers, Vol. 85(**SM3**), pp. 67-79.

Lambe, T.W. and Whitman, R.V. 1969. Soil Mechanics. John Wiley & Sons, New York, 553 p.

Skempton, A.W. 1964. Long term stability of clay slopes. Geotechnique, 14, p. 77.

Terzaghi, K. 1943. Theoretical Soil Mechanics. John Wiley & Sons, New York, 510 p.

Table 1. Results of grain size analysis.

Site	Date	% Gravel	% Sand	% Silt	% Clay
D6.5	4/9/89	0.0	3.4	76.6	20.0
D8.5	4/9/89	0.0	12.8	67.2	20.0
D9.0	4/9/89	2.2	25.5	59.3	13.0
EMIN-2	5/9/89	0.0	24.0	68.0	8.0
EMIN-4	5/9/89	0.0	67.2	26.3	6.5
A-1	6/9/89	0.0	3.4	76.6	20.0
A-3	6/9/89	0.0	7.2	80.5	12.3
A-4	6/9/89	0.0	3.1	78.9	18.0
A-5	6/9/89	0.0	40.2	48.5	11.3
C-1	7/9/89	0.0	0.5	71.5	28.0
C-2	7/9/89	0.0	1.5	63.5	35.0

Table 2. Summary of physical properties and shear strength.

Site	Tide	Water Content (%)	Salinity (%)	Bulk Density (g/cm^3)	Porosity (%)	Cohes -ion (Pa)	Friction Angle (deg)
D8.5	Ebb	84.6	3.15	1.475	70	60.4	24.6
D8.5	Flood	82.7	3.15	1.485	69	43.7	28.1
D6.5	Flood	40.3	3.55	1.743	52	156.0	37.9
MIN D9	Ebb	162.3	----	1.684	81	23.0	39.3
MIN SA	Ebb	----	----	-----	--	* 0.0 *	30.6
A2	Ebb	----	----	-----	--	55.0	29.1

Note: * indicates remoulded INSIST test (simulated post-failure condition)

MIN stands for Minudie; SA refers to a temporary station immdediately offshore from D9 but on the rippled sand flat.

A2 stands for Mill Cove site

Table 3. Plasticity characteristics and specific gravity results.

Site	Plastic Limit (%)	Liquid Limiit (%)	Plasticity Index (%)	Specific Gravity
D8.5	21.6	29.2	7.6	2.74
D9.0	22.2	28.4	6.2	2.66
EMIN-2	----	----	---	2.67

Table 4. Classification of sediments.

Site	USC Code	Decsription
D6.5	CL	silty clay with sand
D8.5	CL	silty clay with sand
D9.0	ML	silt with sand
EMIN-2	OL	organic silt with sand
EMIN-4	SM/SC	silty sand/clayey sand
A-1	*	*
A-3	*	*
A-4	*	*
A-5	*	*
C-1	*	*
C-2	*	*

Note: * indicates unable to classify due to lack of sample.

Appendix A

Shear Strength Data from INSIST

Appendix B

Particle Size Distribution Curves

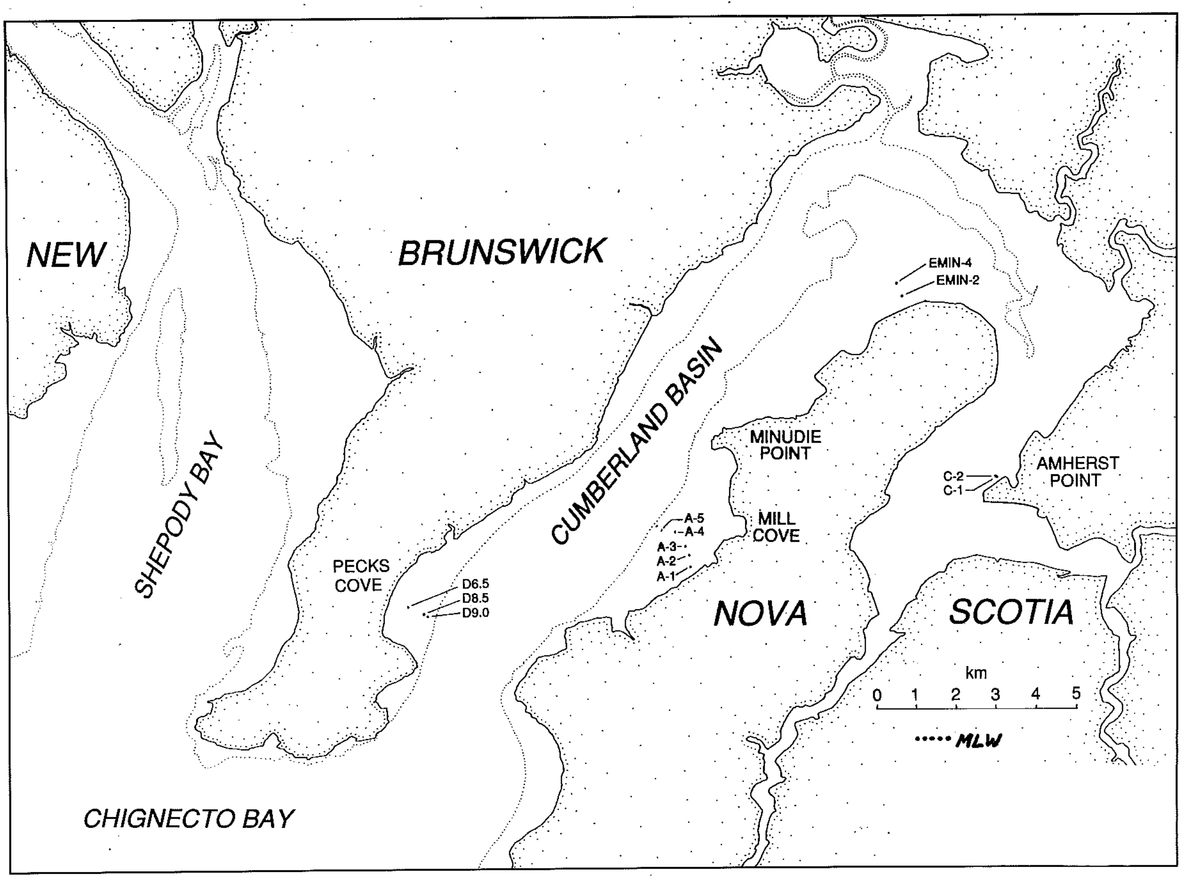


Figure 1. Location map of Cumberland Basin showing the geotechnical test sites.

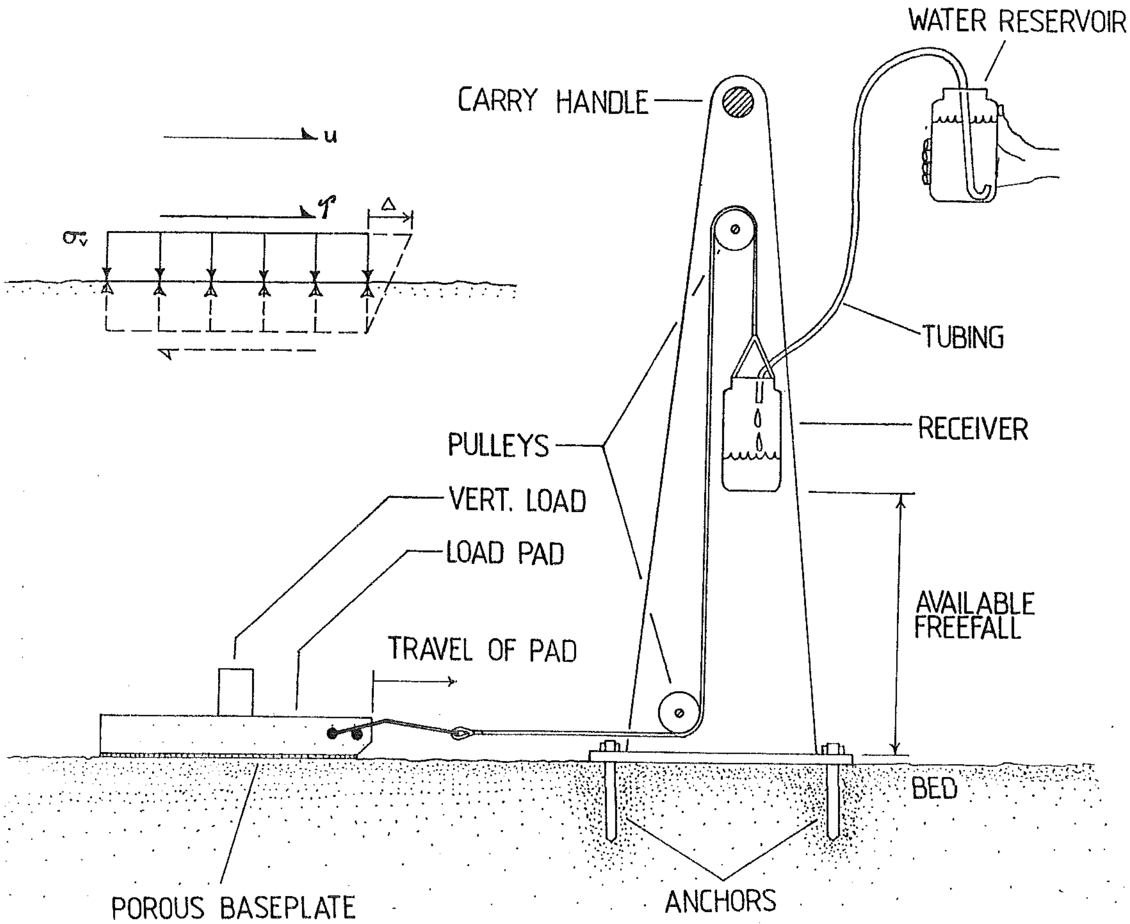
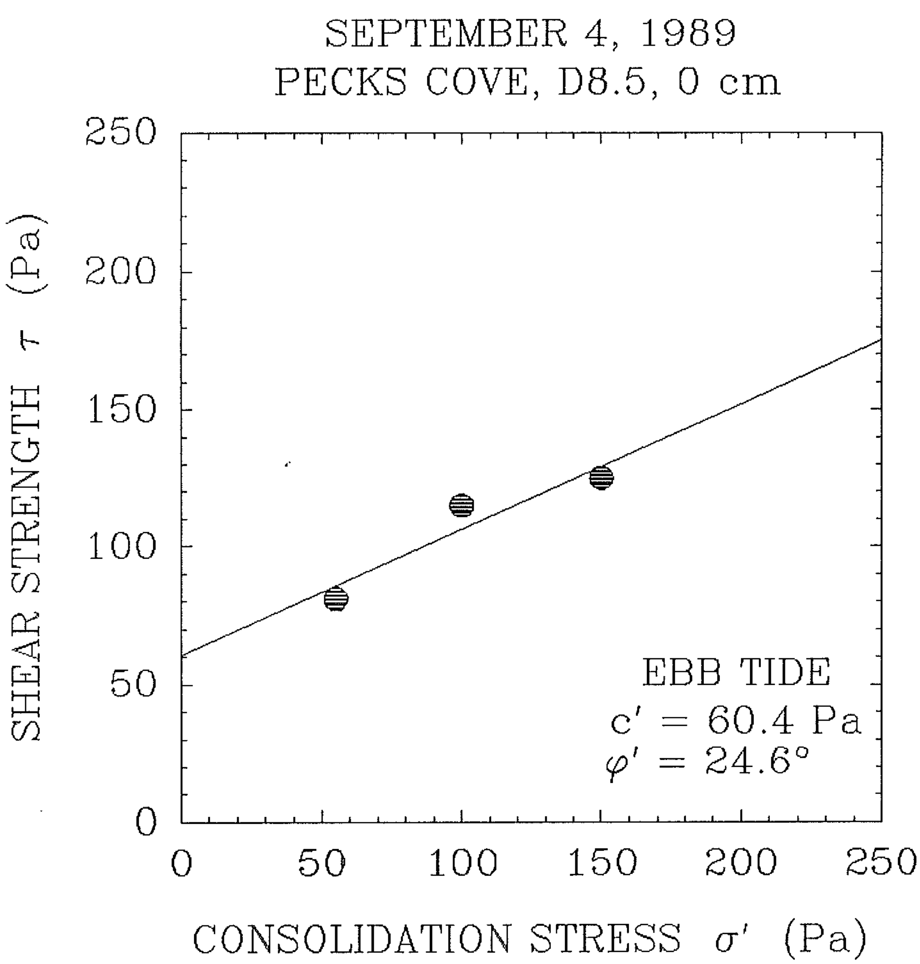
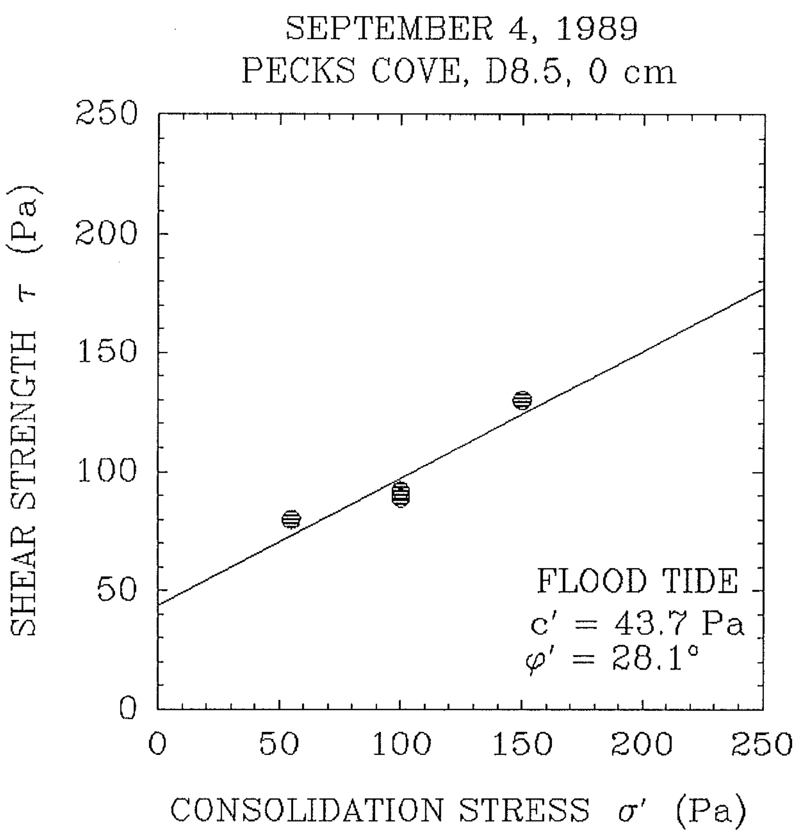
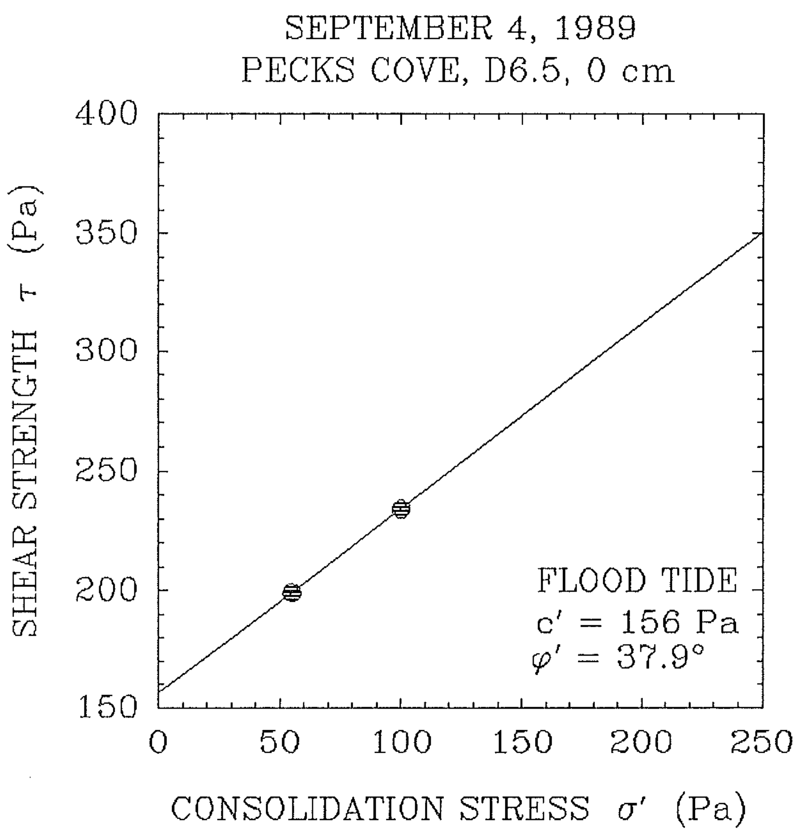


Figure 2. Diagram showing the design and operation of the INSIST device.

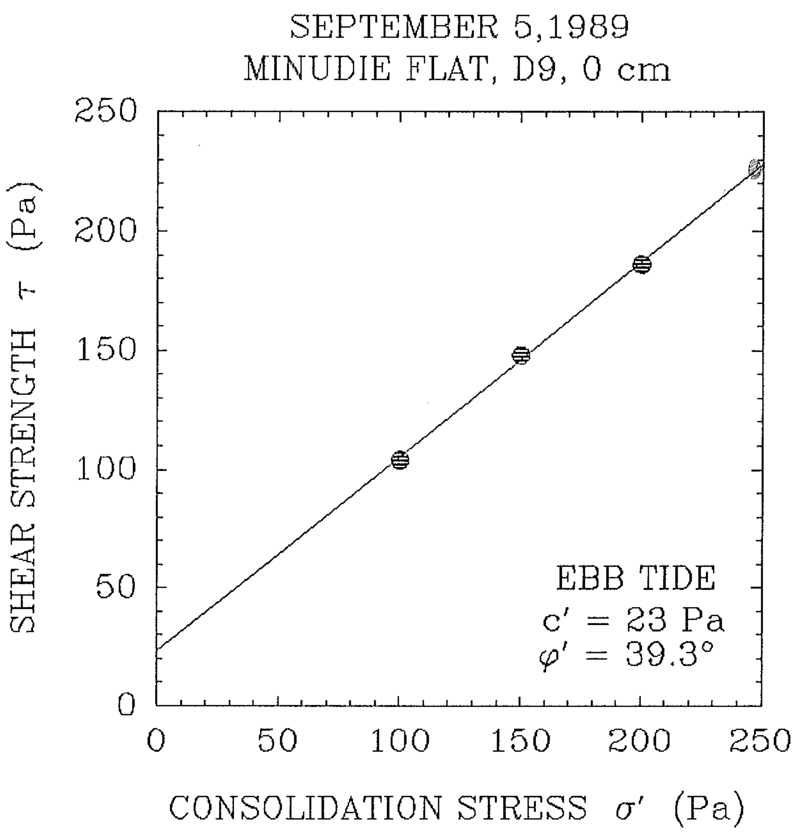


SEPTEMBER 4, 1989
PECKS COVE, D8.5, 0 cm
SHEAR STRENGTH τ (Pa)
CONSOLIDATION STRESS σ' (Pa)
0
50
100
150
200
250
EBB TIDE
c' = 60.4 Pa
φ' = 24.6°

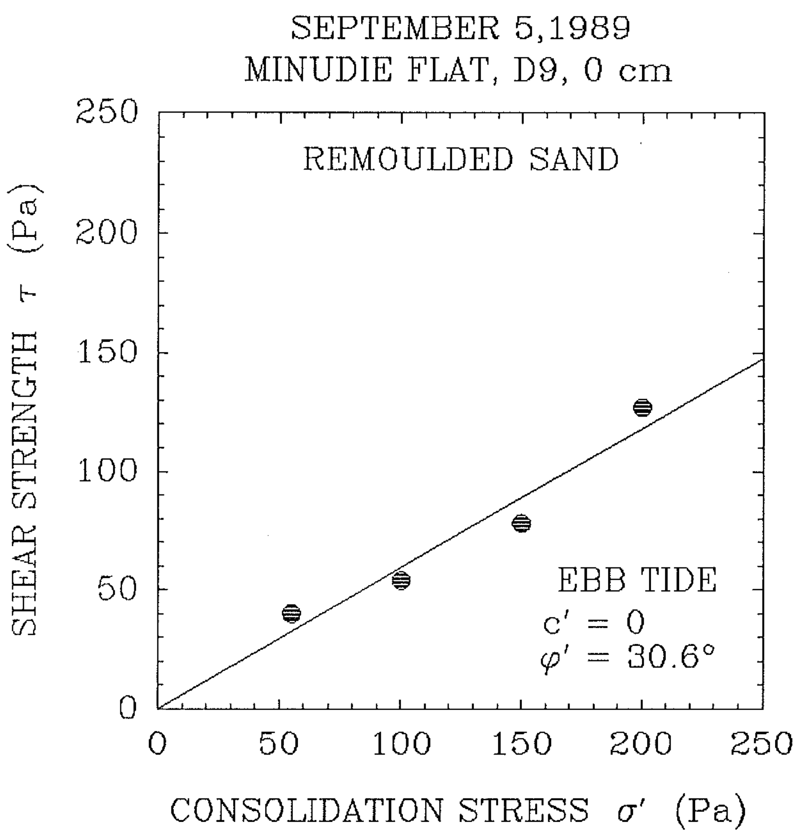

SEPTEMBER 4, 1989
PECKS COVE, D8.5, 0 cm
SHEAR STRENGTH τ (Pa)
CONSOLIDATION STRESS σ′ (Pa)
FLOOD TIDE
c′ = 43.7 Pa
φ′ = 28.1°
0
50
100
150
200
250

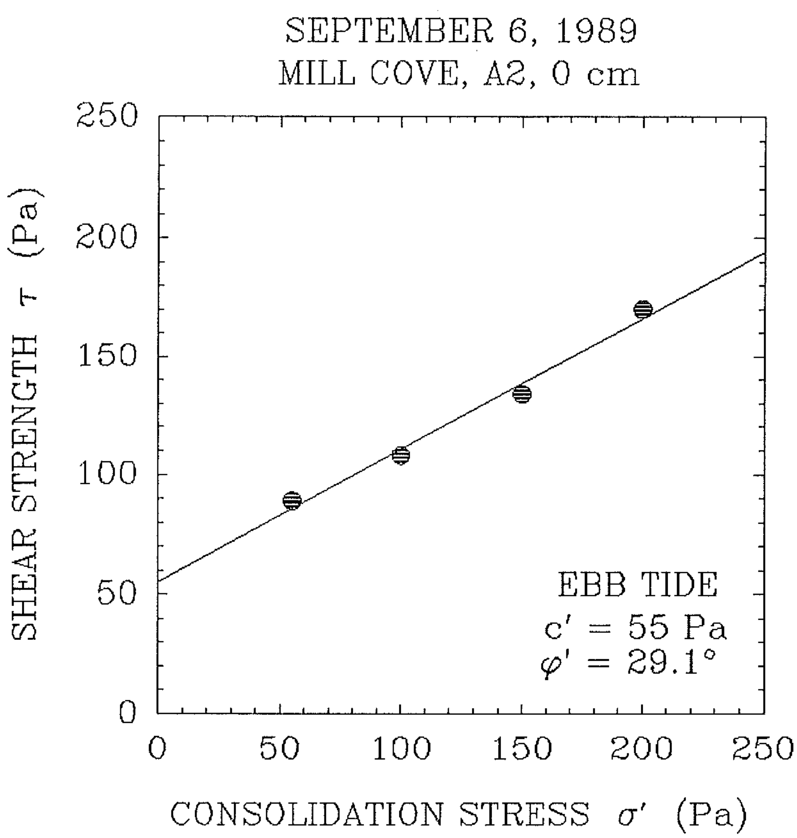


SEPTEMBER 4, 1989
PECKS COVE, D6.5, 0 cm
SHEAR STRENGTH τ (Pa)
CONSOLIDATION STRESS σ' (Pa)
FLOOD TIDE
c' = 156 Pa
φ' = 37.9°
400
350
300
250
200
150
0
50
100
150
200
250



SEPTEMBER 5,1989
MINUDIE FLAT, D9, 0 cm
SHEAR STRENGTH τ (Pa)
250
200
150
100
50
0
0
50
100
150
200
250
CONSOLIDATION STRESS σ′ (Pa)
EBB TIDE
c′ = 23 Pa
φ′ = 39.3°


SEPTEMBER 5,1989
MINUDIE FLAT, D9, 0 cm
REMOULDED SAND
EBB TIDE
c' = 0
φ' = 30.6°
SHEAR STRENGTH τ (Pa)
CONSOLIDATION STRESS σ' (Pa)
0
50
100
150
200
250



SEPTEMBER 6, 1989
MILL COVE, A2, 0 cm
SHEAR STRENGTH τ (Pa)
250
200
150
100
50
0
EBB TIDE
c' = 55 Pa
φ' = 29.1°
0
50
100
150
200
250
CONSOLIDATION STRESS σ' (Pa)

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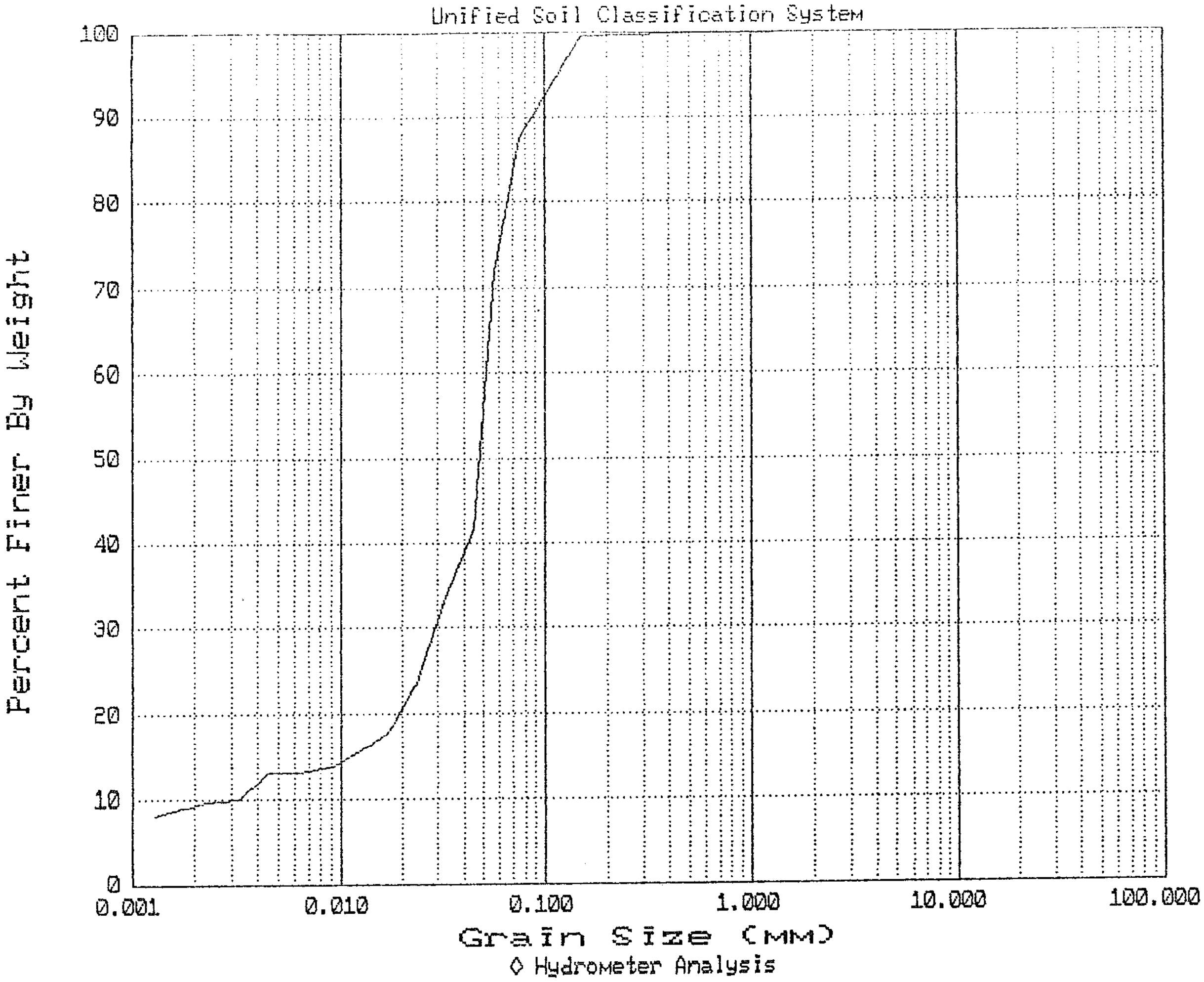
Unified Soil Classification System



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Sample	:CUMB 89 D-6.5	D10 :	0.0026 mm
Date Rec'd	:90\01\26	D30 :	0.029 mm
Date Tested	:90\02\07	D50 :	0.049 mm
Technician	:PR	D60 :	0.051 mm
Method	:ASTM D422	D70 :	0.056 mm
		D90 :	0.09 mm

Gravel	: + No. 4 (4.75mm)	=	0 %
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	12.5 %
Silt	: (0.075 to 0.002 mm)	=	78 %
Clay	: (- 0.002 mm)	=	9.5 %

Remarks :

FIGURE :

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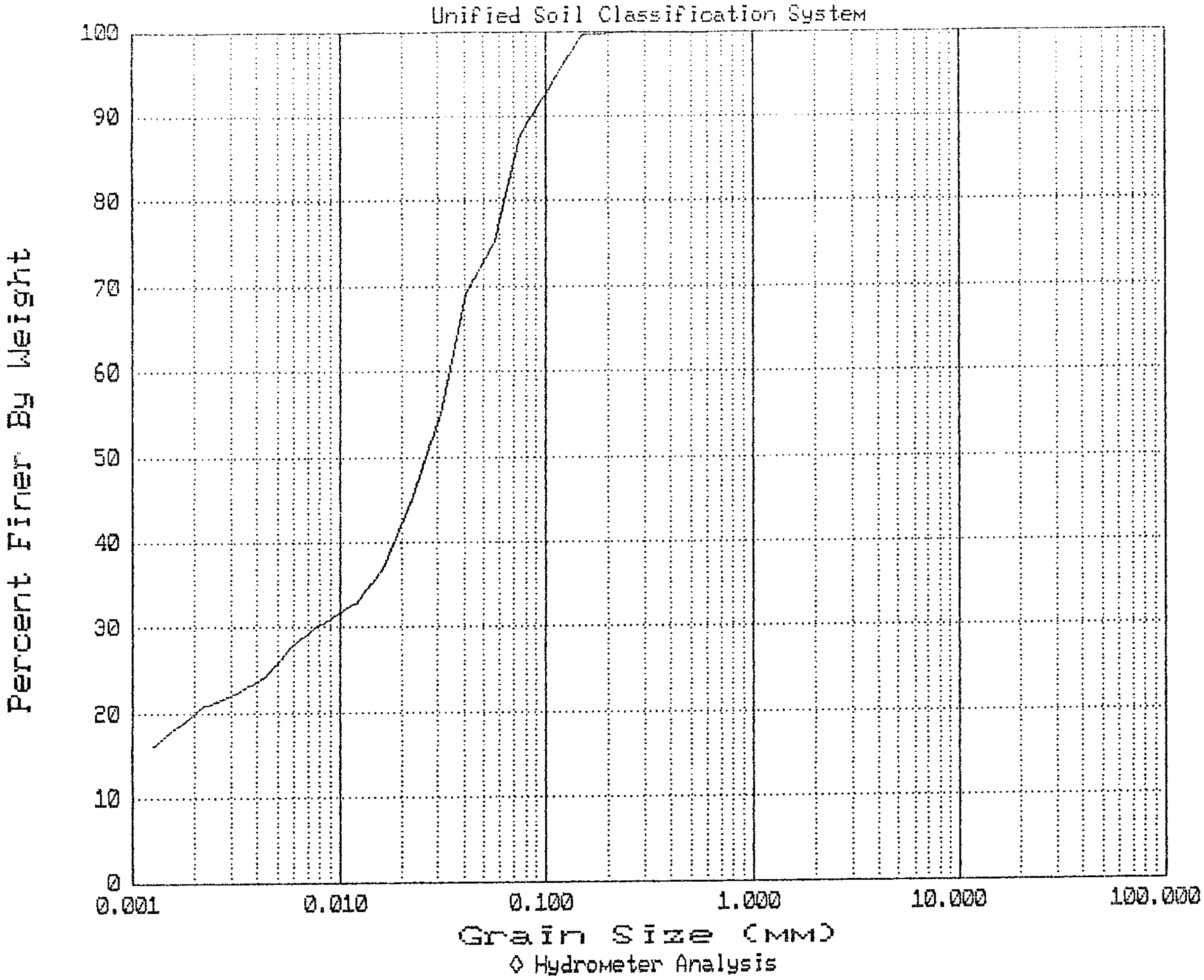
Unified Soil Classification System



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Client :DSS

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Date Rec'd	:90\01\26	D30 :	0.0075	mm
Date Tested	:90\02\07	D50 :	0.025	mm
Technician	:PR	D60 :	0.032	mm
Method	:ASTM D422	D70 :	0.04	mm
		D90 :	0.089	mm

Gravel	: + No. 4 (4.75mm)	=	0
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	12.8
Silt	: (0.075 to 0.002 mm)	=	67.2
Clay	: (- 0.002 mm)	=	20

Remarks :

FIGURE :

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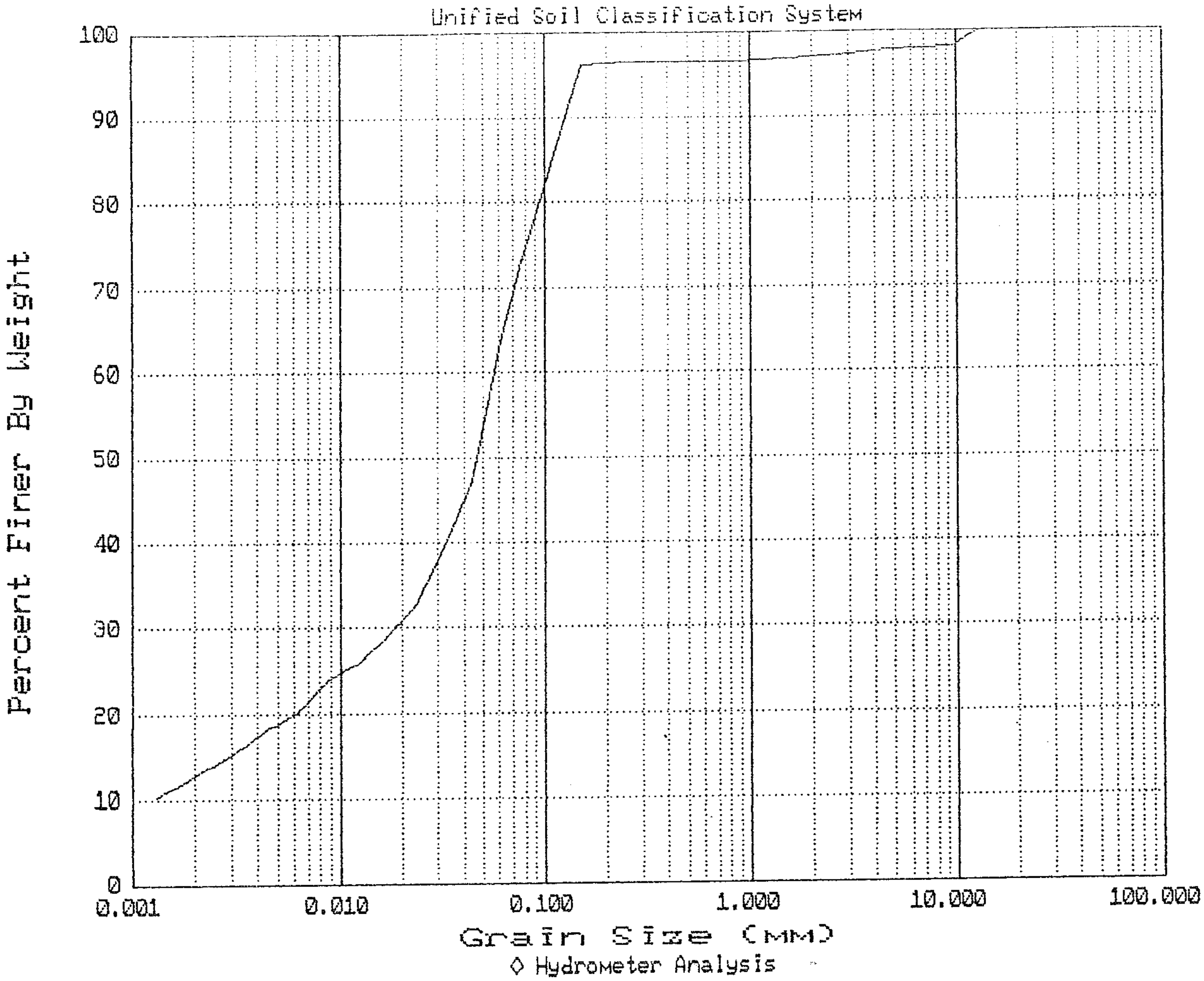

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Client :DSS

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Date Rec'd	:90\01\26	D30 :	0.019 mm
Date Tested	:90\02\09	D50 :	0.047 mm
Technician	:PR\TS	D60 :	0.056 mm
Method	:ASTM D422	D70 :	0.07 mm
		D90 :	0.14 mm

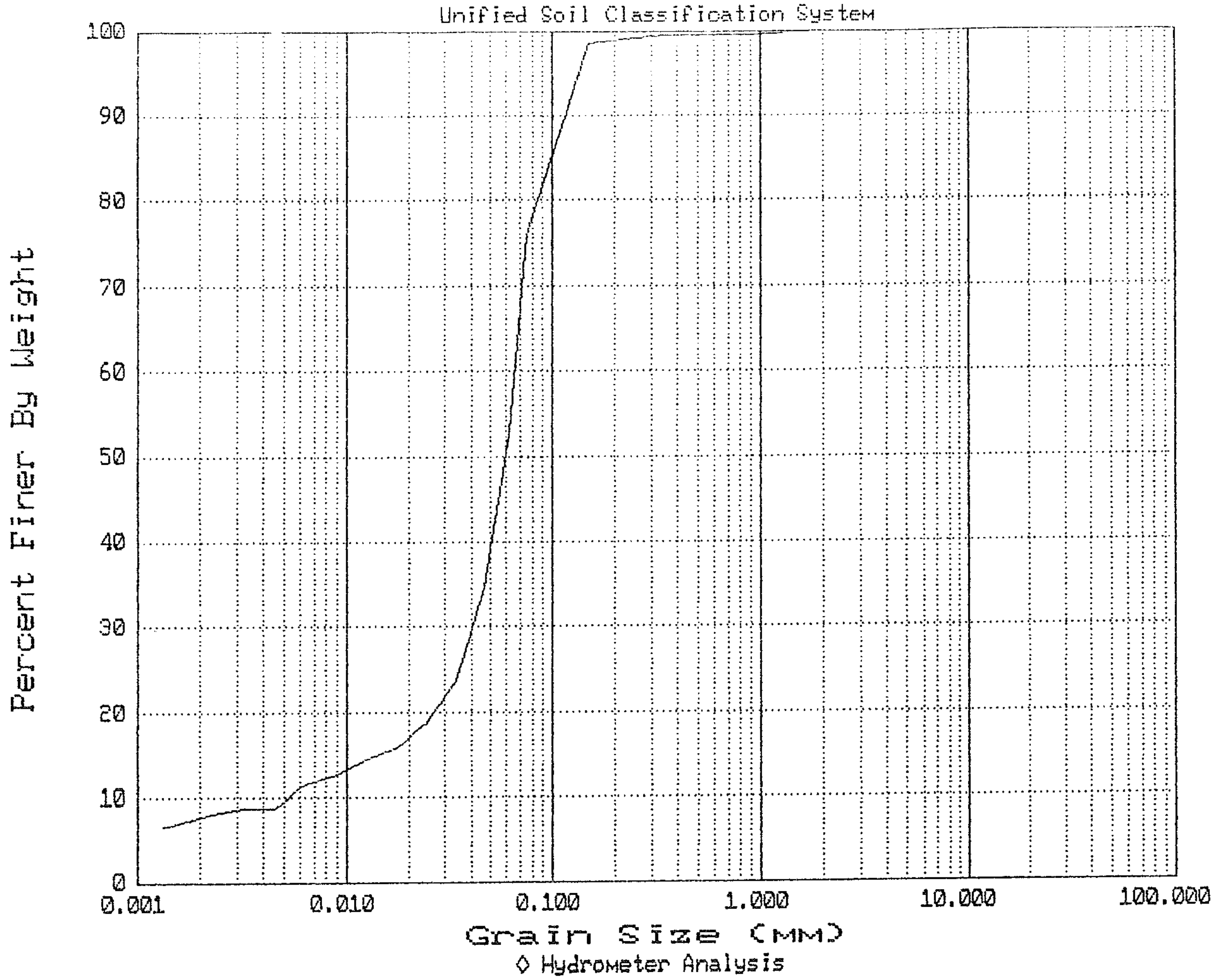
Gravel	: + No. 4 (4.75mm)	=	2.2 %
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	25.5 %
Silt	: (0.075 to 0.002 mm)	=	59.3 %
Clay	: (- 0.002 mm)	=	13 %

Remarks :

FIGURE :

NOLAN, DAVIS & ASSOCIATES LTD.

Unified Soil Classification System



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Client :DSS

Sample :CUMB 89 EMIN-2
Date Rec'd :90\01\26
Date Tested :90\02\09
Technician :PR/TS
Method :ASTM D422

D10 : 0.005 mm
D30 : 0.04 mm
D50 : 0.06 mm
D60 : 0.065 mm
D70 : 0.07 mm
D90 : 0.12 mm

Gravel : + No. 4 (4.75mm) = 0 %
Sand : No. 4 to No. 200 (4.75 to 0.075 mm) = 24 %
Silt : (0.075 to 0.002 mm) = 68 %
Clay : (- 0.002 mm) = 8 %

Remarks :

FIGURE :

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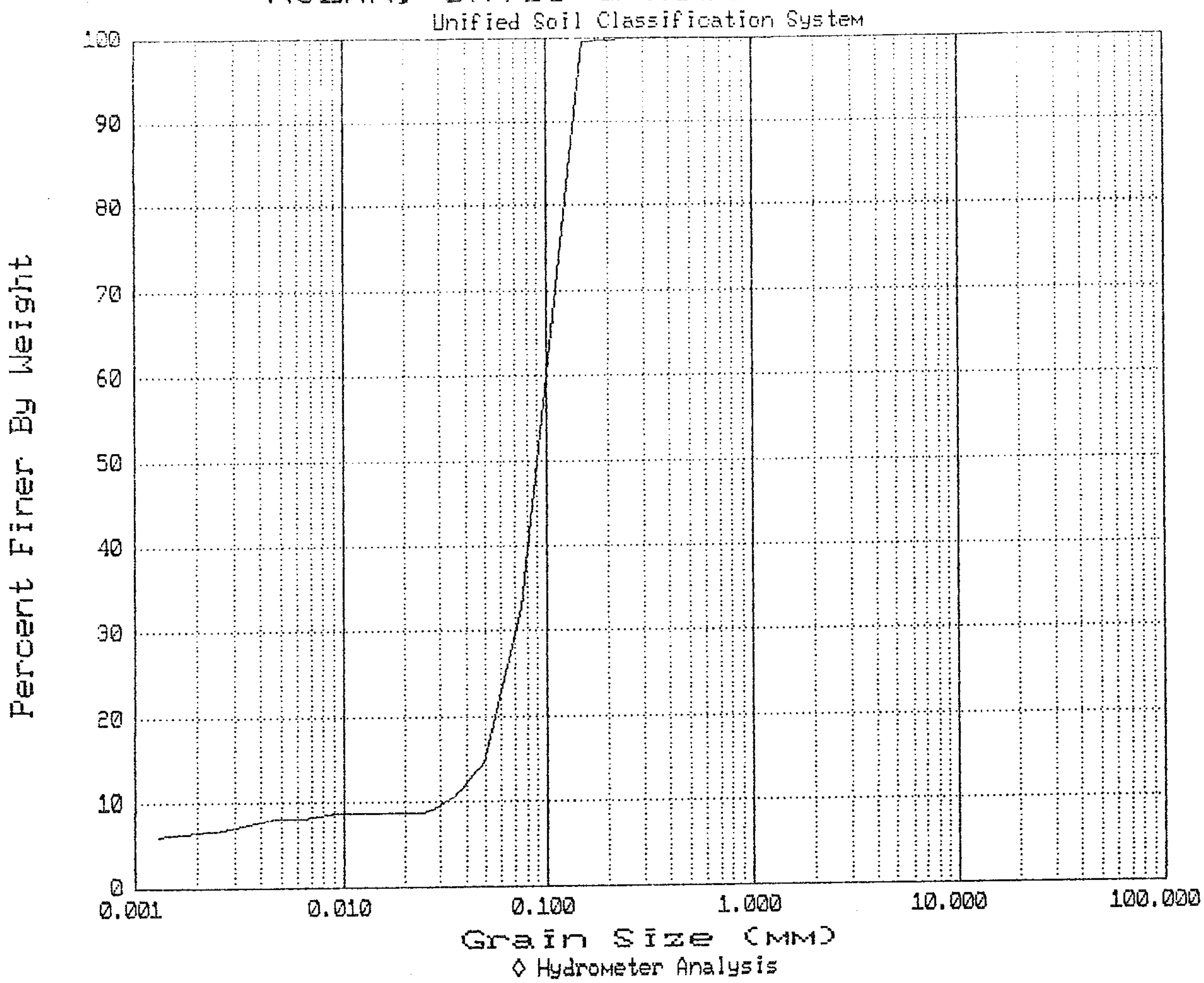

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Date Rec'd	:90\01\26	D30 :	0.07 mm
Date Tested	:90\02\07	D50 :	0.09 mm
Technician	:PR	D60 :	0.1 mm
Method	:ASTM D422	D70 :	0.11 mm
		D90 :	0.14 mm

Gravel	: + No. 4 (4.75mm)	=	0
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	67.2
Silt	: (0.075 to 0.002 mm)	=	26.3
Clay	: (- 0.002 mm)	=	6.5

Remarks :

FIGURE :

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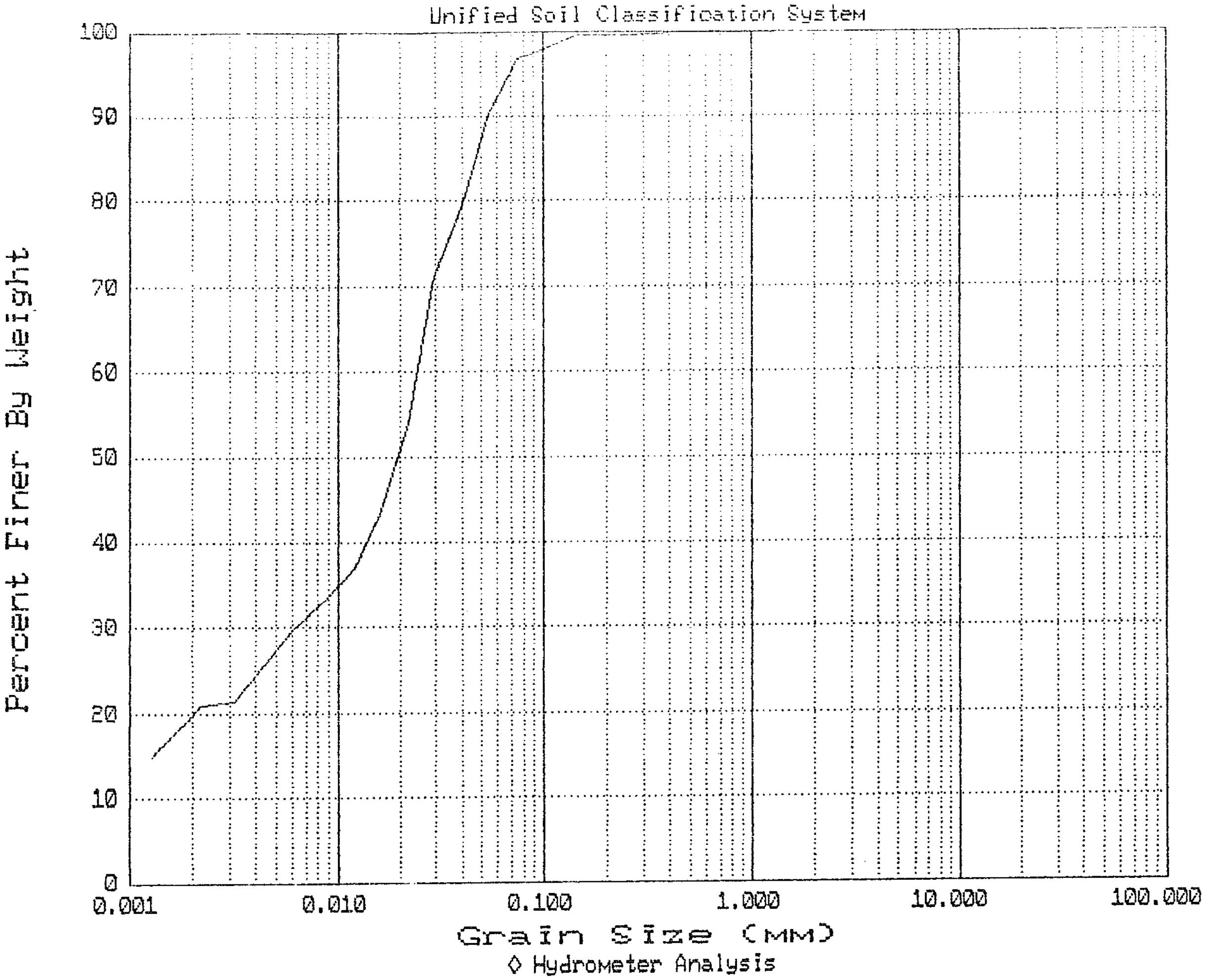

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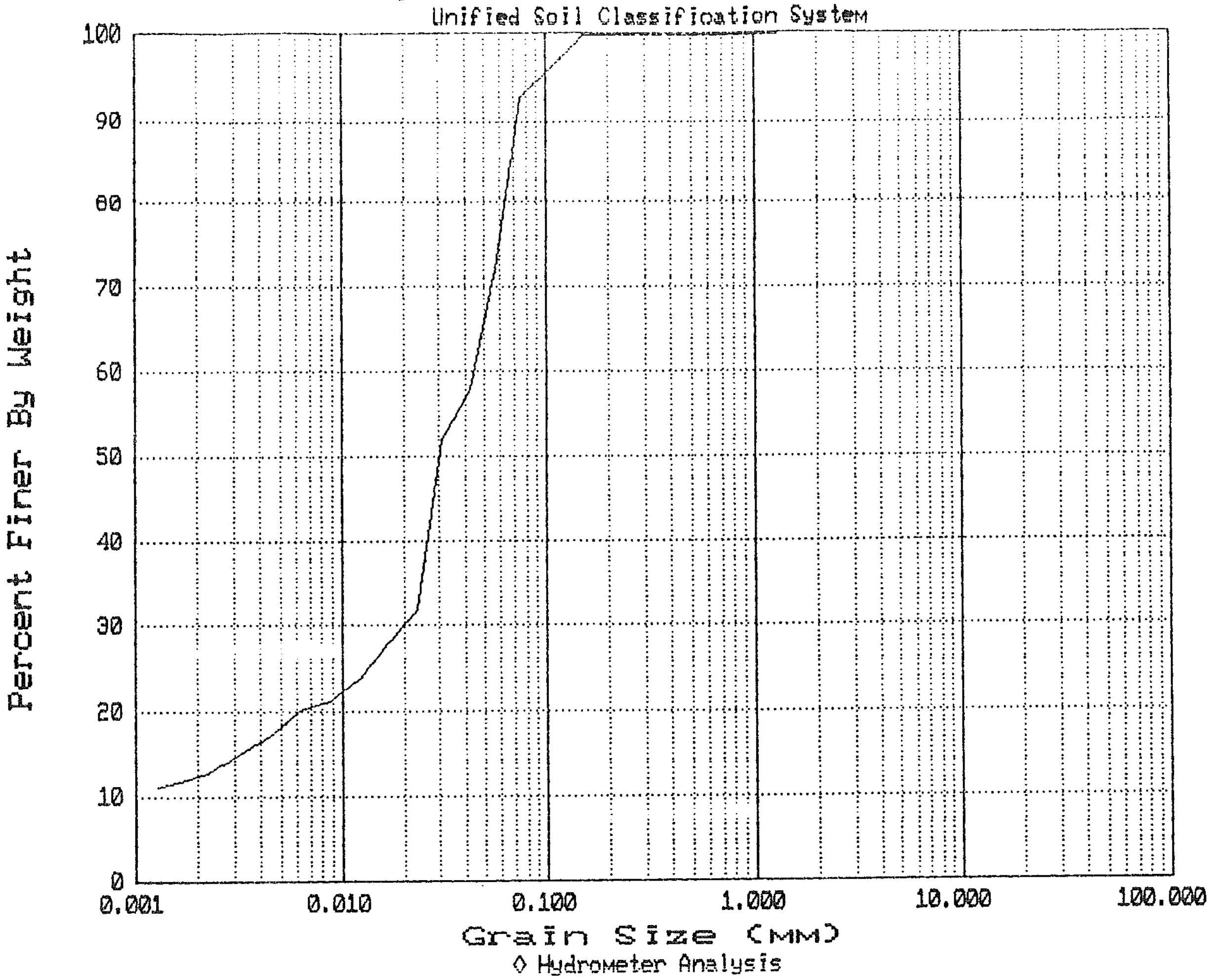
Sample	:CUMB 89 A-1	D10 :	0.0009 mm
Date Rec'd	:90\01\26	D30 :	0.006 mm
Date Tested	:90\02\07	D50 :	0.02 mm
Technician	:PR	D60 :	0.024 mm
Method	:ASTM D422	D70 :	0.029 mm
		D90 :	0.053 mm

Gravel : + No. 4 (4.75mm)	=	0
Sand : No. 4 to No. 200 (4.75 to 0.075 mm)	=	3.4
Silt : (0.075 to 0.002 mm)	=	76.6
Clay : (- 0.002 mm)	=	20

Remarks :
D10 is extrapolated

FIGURE :

NOLAN, DAVIS & ASSOCIATES LTD.



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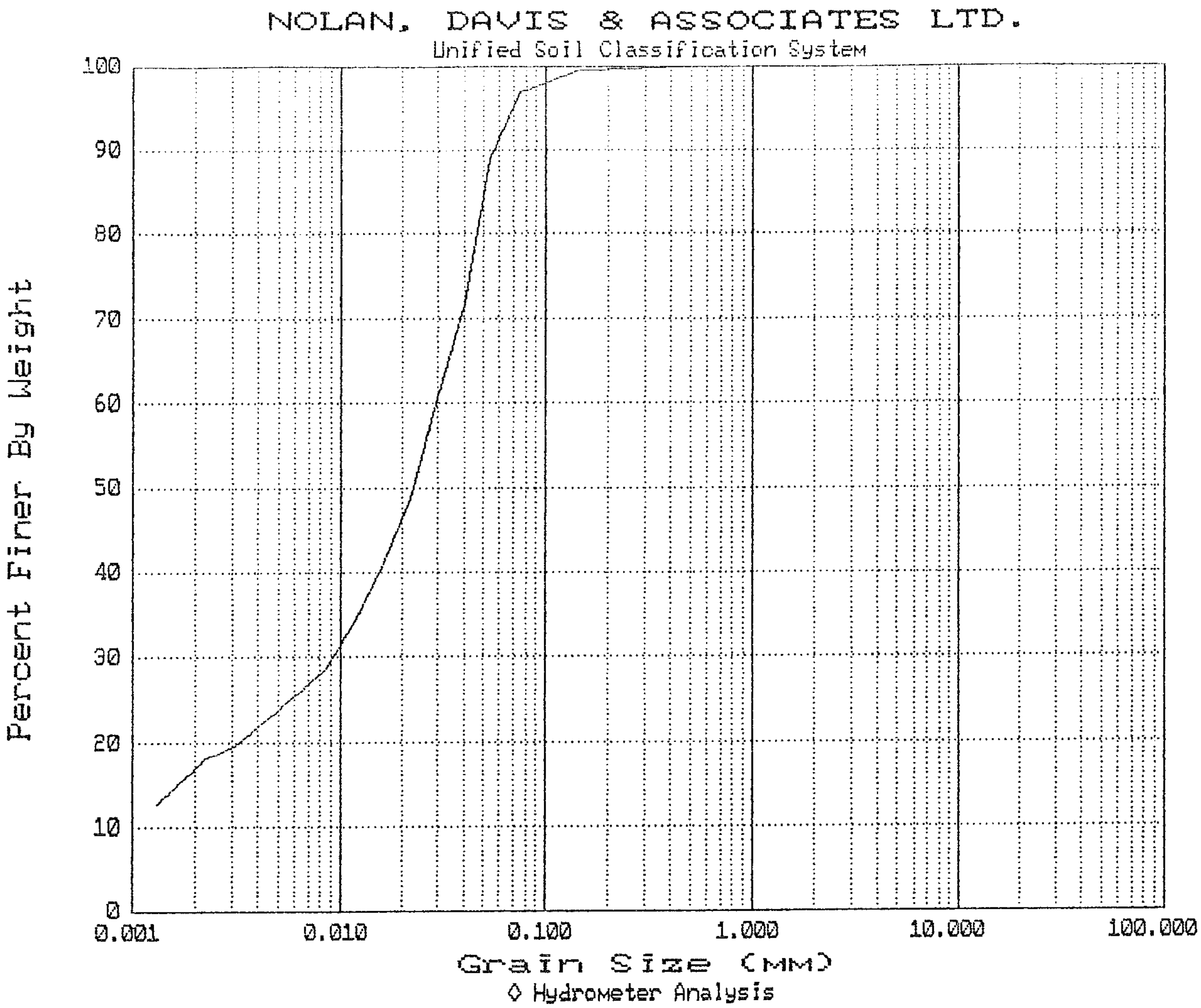
Date Rec'd	:90\01\26	D30 :	0.02 mm
Date Tested	:90\02\07	D50 :	0.03 mm
Technician	:PR	D60 :	0.045 mm
Method	:ASTM D422	D70 :	0.053 mm
		D90 :	0.07 mm

Gravel	: + No. 4 (4.75mm)	= 0
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	= 7.2
Silt	: (0.075 to 0.002 mm)	= 80.5
Clay	: (- 0.002 mm)	= 12.3

Remarks :

FIGURE :



Project No. :H89254
Client :DSS

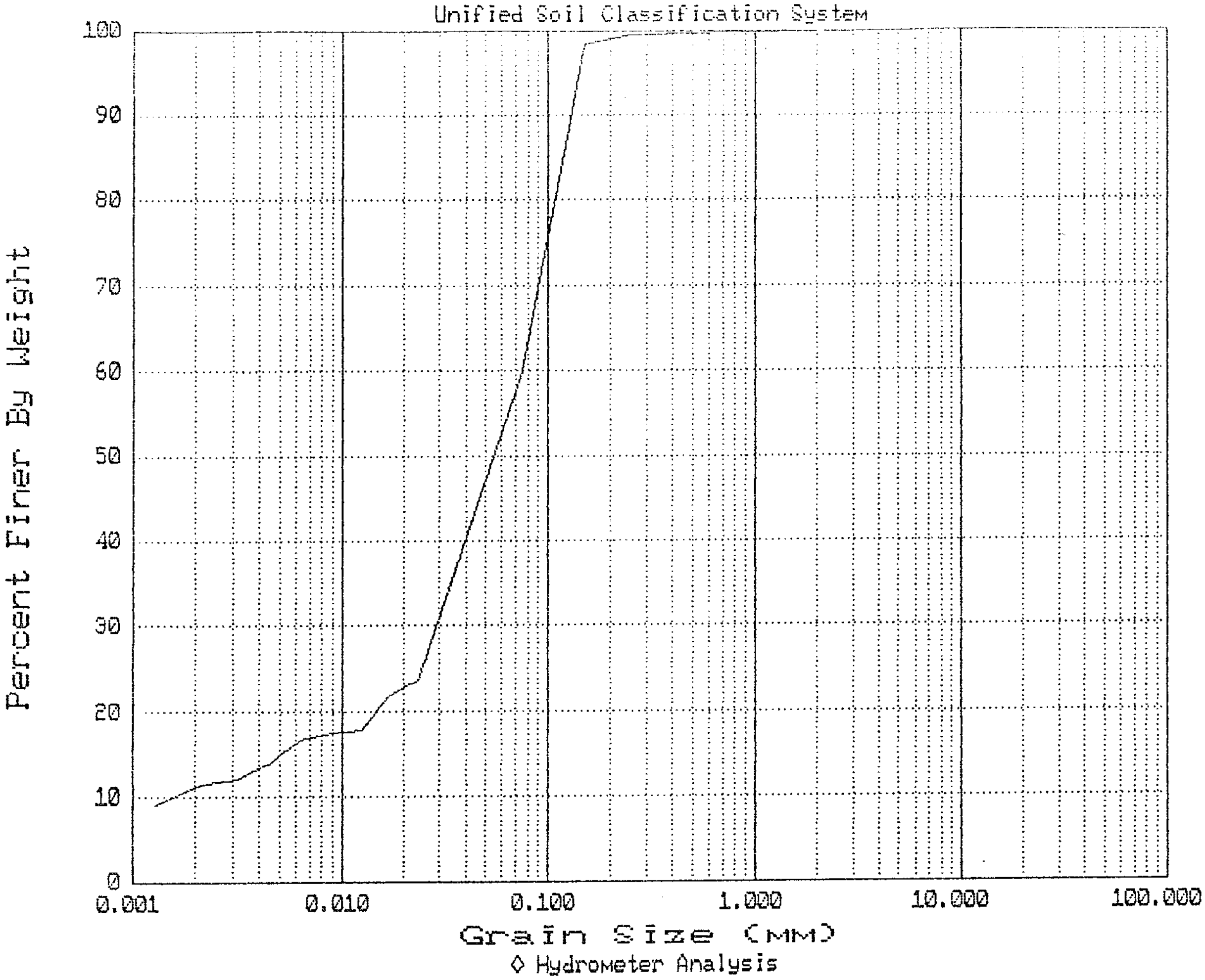
Sample	:CUMB 89 A-4	D10 :	0.001 mm
Date Rec'd	:90\01\26	D30 :	0.009 mm
Date Tested	:90\02\09	D50 :	0.024 mm
Technician	:PR\TS	D60 :	0.03 mm
Method	:ASTM D422	D70 :	0.039 mm
		D90 :	0.057 mm

Gravel	: + No. 4 (4.75mm)	=	0 %
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	3.1 %
Silt	: (0.075 to 0.002 mm)	=	78.9 %
Clay	: (- 0.002 mm)	=	18 %

Remarks :

FIGURE :

NOLAN, DAVIS & ASSOCIATES LTD.



Project No. :H89254
Client :DSS

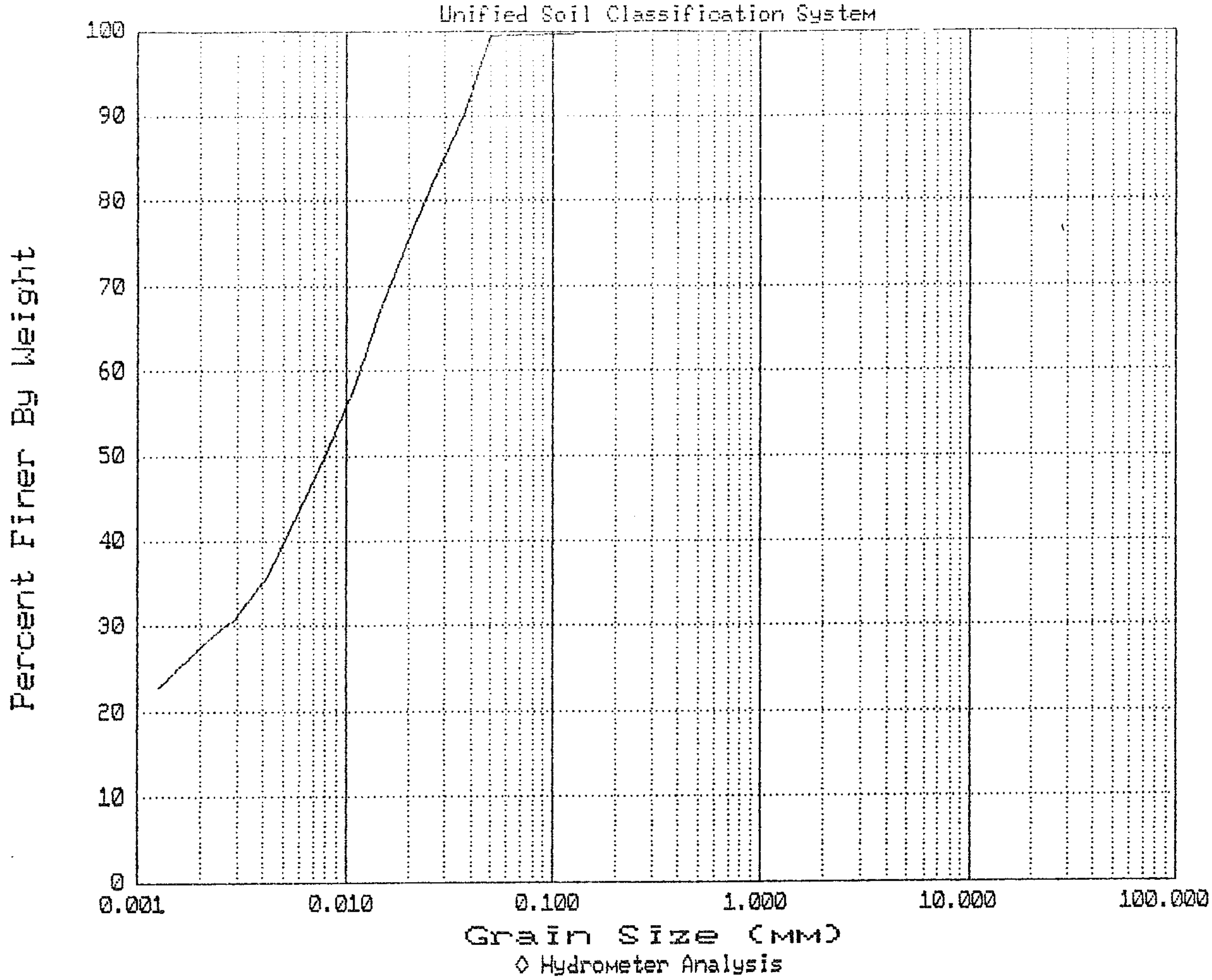
Sample	:CUMB 89 A-5	D10 :	0.0014 mm
Date Rec'd	:90\01\26	D30 :	0.029 mm
Date Tested	:90\02\07	D50 :	0.065 mm
Technician	:PR	D60 :	0.075 mm
Method	:ASTM D422	D70 :	0.09 mm
		D90 :	0.14 mm

Gravel	: + No. 4 (4.75mm)	=	0
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	40.2
Silt	: (0.075 to 0.002 mm)	=	48.5
Clay	: (- 0.002 mm)	=	11.3

Remarks :

FIGURE :

NOLAN, DAVIS & ASSOCIATES LTD.



Project No. :H89254
Client :DSS

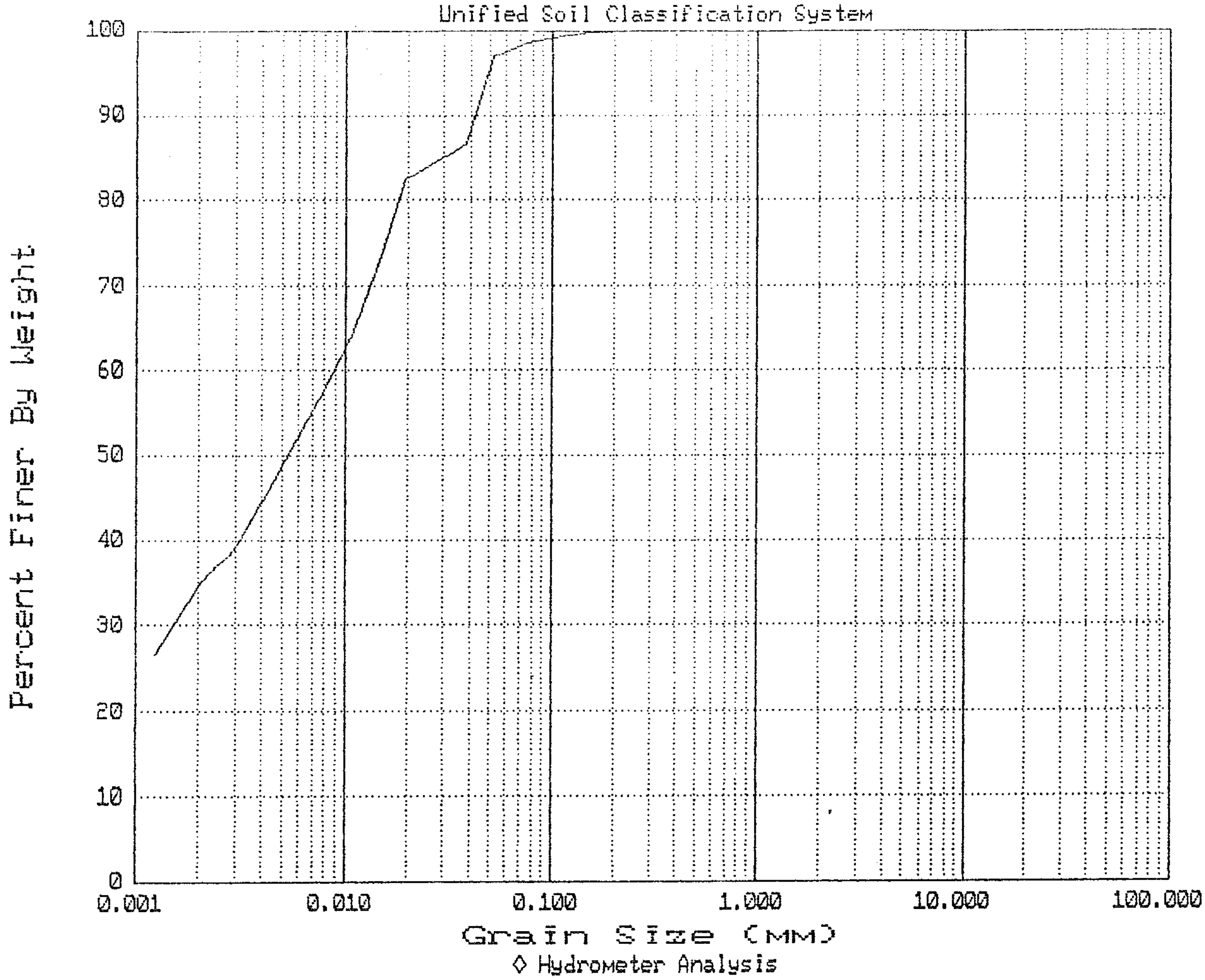
Sample	:CUMB 89 C-1	D10 :	-- mm
Date Rec'd	:90\01\26	D30 :	0.0027 mm
Date Tested	:90\02\09	D50 :	0.008 mm
Technician	:PR\TS	D60 :	0.012 mm
Method	:ASTM D422	D70 :	0.017 mm
		D90 :	0.037 mm

Gravel	: + No. 4 (4.75mm)	=	0 %
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	0.5 %
Silt	: (0.075 to 0.002 mm)	=	71.5 %
Clay	: (− 0.002 mm)	=	28 %

Remarks :

FIGURE :

NOLAN, DAVIS & ASSOCIATES LTD.



Project No. :H89254
Client :DSS

Sample	:CUMB 89 C-2	D10 :	--	mm
Date Rec'd	:90\01\26	D30 :	0.0016	mm
Date Tested	:90\02\07	D50 :	0.0055	mm
Technician	:PR	D60 :	0.009	mm
Method	:ASTM D422	D70 :	0.014	mm
		D90 :	0.041	mm

Gravel	: + No. 4 (4.75mm)	=	0 %
Sand	: No. 4 to No. 200 (4.75 to 0.075 mm)	=	1.5 %
Silt	: (0.075 to 0.002 mm)	=	63.5 %
Clay	: (- 0.002 mm)	=	35 %

Remarks :

FIGURE :