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Characteristic geotechnical properties of solid and drift geological units from site investigations, southern Central Belt of Scotland

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Characteristic geotechnical properties of solid and drift geological units from site investigations, southern Central Belt of Scotland

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Key words

Geotechnical properties, solid, drift Central Belt, Scotland, rock, soil, engineering behaviour.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of the strategic multidisciplinary survey of the Central Belt of Scotland. It is part of the core programme of scientific work of the BGS undertaken as part of the Integrated Geoscience Survey (North) programme.

This report collates the quantitative results of site investigations, undertaken as part of major civil engineering works, summarizes and interprets the geotechnical properties of the main solid and drift geological units in the southern part of the Central Belt of Scotland. This summary is intended as a broad to guide to planners and geotechnical engineers within the Central Belt of Scotland and gives the characteristic ground conditions that should be anticipated in the areas underlain by the units. This does not in any way replace the need for detailed site-specific investigations.

The geotechnical characteristics presented here are compiled from the site investigation results of major engineering projects. The results for a given geological unit are compiled and the characteristic value or range of values for each geotechnical property are evaluated and presented. It is not possible to attribute site-specific investigation results from the data presented here, in keeping with any requirements to ensure that data lodged with the BGS under a confidential basis is used only to further scientific understanding by BGS activites.

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Summary

This report reviews geotechnical test data from selected site investigation reports, lodged within BGS archives, from the south-western part of the Central Belt of Scotland. A database of test results was compiled from 1313 geotechnical samples. The test results are analysed statistically and presented graphically and the characteristic geotechnical properties of solid and drift geological units are summarised.

1 Introduction

The British Geological Survey is the national archive for geoscience data including scientific information within site investigation reports. The results of site investigations within the catalogued archive of data include borehole and trial pit observations that are used to assist in the understanding of subsurface geology presented as bedrock and superficial geological maps of the UK. Increasingly, with the requirement for civil engineering projects to be based on detailed high quality technical information, the site reports include quantitative geotechnical test results.

The objective of this study is to utilise data lodged within the national archive to assess the characteristic geotechnical properties of major geological units within the Central Belt of Scotland. This is in keeping with the role of the BGS to contribute to the broader scientific understanding and use of subsurface geology for the benefit of the United Kingdom.

The scope of this study is not comprehensive. Data currently lodged with BGS are reviewed and from that a subset of selected site investigation reports was used. This is not a review of all the characteristics of geological units underlying the Central Belt of Scotland but only those investigated in the selected reports. The properties and range of values indicate the likely ground conditions that should be anticipated across areas underlain by the bedrock and superficial geological units summarised here, and serve to inform those users of geotechnical information such as planners or geotechnical engineers. These results should not, in any way, replace site-specific investigations.

The area of the study is the south-western part of the Central Belt of Scotland and approximately equates with the extent of the counties of Ayrshire and south Lanarkshire.

1.1 METHOD

BGS archives were reviewed to identify major civil engineering projects within the study area that are distinguished by the most comprehensive site investigation methods and are to accepted engineering geology standards. For the most part these investigations are associated with the construction of motorways or trunk roads (Appendix). The quantitative results were collated and a database compiled. The analyses within the database were plotted, the results reviewed and the characteristic properties of each unit assessed. Graphical presentations of the results are illustrated in Figures 1 to 9, by bedrock or superficial geological unit, with a brief written summary of the characteristic properties.

1.2 GEOLOGICAL UNITS

The geological units sampled by the site investigations included in this study span bedrock and superficial deposits, natural and artificial deposits. Data from superficial deposits comprise till (or boulder clay), which was deposited by glacial ice and blankets much of the study area, and glacio-fluvial sediment deposited from glacial melt water and likely to occur in low-lying or valley areas. Bedrock geology data are from the Carboniferous Coal Measures Group and also igneous rocks. Test results from made ground were also recorded in the geotechnical properties database. Abbreviations used in the database are given in Table 1:

Table 1 Abbreviations used in the database

Bedrock Geology	
CMSC	Coal Measures
CPV	Clyde Plateau Volcanic Formation
DOLER	Dolerite
KNW	Kinnesswood Formation
LCMS	Lower Coal Measures Scotland
LLGS	Lower Limestone Formation
LSC	Limestone Coal Formation
LWM	Lawmuir Formation
MCMS	Middle Coal Measures Scotland
PGP	Passage Formation
SWAS	Swanshaw Sandstone Formation
UCMS	Upper Coal Measures Scotland
ULGS	Upper Limestone Formation
Superficial Geology	
Alluv.	Alluvium
AS	Aeolian sand
Fill	Fill
FGS	Fluvio-glacial sands
FGSG	Fluvio-glacial Sands & Gravels
GFSG	Glaciofluvial Sands and Gravels
GLLD	Glaciolacustrine Deposits
GLDD	Glaciolacustrine Deltaic Deposits
MG	Made ground
Peat	Peat
PGD	Post-glacial Deposits
Resid.	Residual soil
RMD	Raised Marine Deposits
Till	Glacial till
Till (W)	Weathered glacial till

2 Engineering geology

2.1 DATA USED

A total of 1313 geotechnical samples taken from six reported site investigations held within the BGS archive, have been recorded, and their test results analysed statistically and graphically. The data consist of stratigraphical and lithological descriptions, index tests, and strength tests. The data have been sorted according to solid and superficial stratigraphy and/or lithology in order to examine variation in geotechnical properties with geology. The dataset is divided into 'soil' and 'rock', due mainly to the fact that test methods differ between the two, and may not be directly comparable. The dataset does not cover all formations in the study area.

3 Geotechnical test data reviewed

3.1 WATER CONTENT

Water content has been determined throughout by the BS1377: 1990 method whereby water content is calculated as a proportion of dry sample weight. Plots of water content vs. depth are shown in Figures 1a, b, c. Figure 1a shows the results for alluvium and till. Both show a decrease in water content below about 5 m, but with the alluvium having a higher overall water content, compared with the till. Figure 1b shows the same relationship subdivided according to underlying solid geology (Coal Measures) and also weathering state of the till. There is little apparent distinction between the tills. Below 1.5 m depth, water contents typically lie between 10 and 20 %. The samples classed as 'weathered' do not group separately from the others. Figure 1c shows the same relationship for fluvio-glacial sands, glacio-lacustrine deposits, post-glacial deposits, and raised marine deposits. There is a wide scatter, but there are few data. The raised marine deposits have high water contents in the range 30 to 40 %. There is no detectable trend of water content with depth for these data.

3.2 PLASTICITY

Plasticity is represented for fine-grained 'soils' by means of the liquid limit and plastic limit tests (BS1377: 1990), and the Casagrande plot (Figures 2a, 2b, and 2c), where the plasticity index is the difference between the liquid and plastic limits. Figure 2a shows the plot for alluvium and till. The till data cluster mainly within the 'low' range and above the A-line, whereas the alluvium is more widely scattered from 'low' to 'high' and some points lie below the A-line, suggesting a higher organic content for these samples. Figure 2b shows the plot for tills sub-divided by underlying bedrock. There is a suggestion of two groupings of data, particularly above a liquid limit of about 32 %, but these are not distinguished by underlying solid geology, with the possible exception of till over Lower Coal Measures which lies solely in the 'upper' group (i.e. furthest from A-line). Once again the 'weathered' tills do not group apart, though there are few data. Only a small proportion of data are on or below the A-line. Figure 2c shows the plot for the glacial deposits. These fall within the range 'low' to 'high' and with some 'weathered' data lying below the A-line.

3.3 PARTICLE-SIZE

The particle-size of 'soils' is expressed as proportions by weight of 'clay', 'silt', 'sand', and 'gravel' sized components; these being defined according to BS1377: 1990: Part 2. The particle-size distribution of a soil has an important influence on other geotechnical properties and engineering behaviour, e.g. permeability, strength, density. Particle-size data are shown for alluvium in Figure 3a, till in Figure 3b, and other soils in Figure 3c, as triangular plots, each with the sand and gravel components combined. Data points are sub-divided according to the underlying solid geology. Data for the alluvium are widely scattered with little or no grouping of data. Data for till are less scattered, but again with no grouping. This is not surprising given that the source material for alluvium and till may be far removed from the deposit. Other soils tend to contain sand and clay/silt with little gravel, or sand and gravel with little clay/silt.

3.4 CHEMICAL ANALYSIS

Alluvium, till, post-glacial deposits, and aeolian sand are classified as ‘class 1’ (< 0.2 %) for sulphate content (BRE, 1996). Total sulphate contents in ‘class 2’ (0.2 – 0.5 %) were found solely within made ground, and fill, with the exception of one fluvio-glacial sand (FGS) sample. Organic content means were similar for alluvium and till, between 1.5 and 2.0 %, though the range for alluvium was much greater, probably due to the inclusion of some peat. The values for peat were high as expected with a median of 44.1 %. Values of pH for all soil types tested were slightly above 7 with the exception of peat.

3.5 COMPACTION

Compaction related data consist of Proctor test data and California Bearing Ratio (CBR) test data (BS1377: 1990: Part 4). The former test examines the relationship between dry density and water content for a soil sample reworked and compacted into a mould in layers using a standard impact. Results are shown here as a plot of maximum dry density vs. optimum water content (Figure 4). In this plot each point represents the peak of a compaction test curve. The data tend to group either above or below optimum water content of about 13 %, with the exception of till.

The California Bearing Ratio test compares relative penetration of a model footing of a sample, usually compacted in a mould, against a ‘control’ material. The median values for alluvium and till are 0.7 and 4.4 %, respectively.

3.6 STRENGTH

Strength data are represented in the database by triaxial, shear box, uniaxial compression, and laboratory shear vane test data in the case of ‘soils’, and uniaxial compression and point load tests in the case of ‘rocks’. The boundary between ‘soil’ and ‘rock’ is not universally defined, but is frequently taken at an arbitrary uniaxial compressive strength (UCS) of 1 MPa. With any arbitrary boundary there is some overlap between weak rocks and strong soils. Thus, in some circumstances a Coal Measures mudstone may be considered a ’rock’ and in others a ‘soil’. The distinction usually hinges on the practical needs of sampling and testing. The results were obtained from tests on ‘undisturbed’ specimens, though the various preparation techniques do introduce some disturbance. Strength data for ‘soils’ have been sub-divided into ‘total’ strength (from a variety undrained test conditions) and ‘effective’ strength parameters (from drained conditions, or where pore-pressure has been measured). These are represented by the shear strength values, c_u, ϕ_u (total) and c’, ϕ’ (effective), where c is cohesion and ϕ is internal friction angle. Total triaxial, shear-box, and laboratory vane tests are covered in BS1377: 1990: Part7. Effective triaxial tests are covered in BS1377: 1990: Part8. For rocks the strength parameters are uniaxial compressive strength (UCS) and point load index ($I_{S(50)}$). These tests are not covered by British Standards, but are described in Hawkes and Mellor (1970) and Chau and Wong (1996).

Strength is not a fundamental property of a soil or rock but is dependent on the test type, sample size, and the conditions prevailing. As a result different tests are not strictly comparable, particularly between ‘soil’ and ‘rock’ type tests. Thus, the statistical treatment should be treated with some caution. In the case of effective strength data, an estimated effective shear strength, s’, has been calculated based on the c’, ϕ‘dataset, and taking an averaged value for overburden based on bulk density data. An equivalent estimated total shear strength, s_u, has also been calculated. The calculation has included ϕ_u despite the fact that this value should theoretically equal zero in an undrained test. There are some operational reasons why it may not.

Median c_u values for alluvium and till are 32 and 97 kPa, respectively. The median s_u values estimated from triaxial tests are 32 and 107 kPa for alluvium and till, respectively. Plots of estimated shear strength vs. depth for 'soils' are shown in Figures 5, 6, and 7. Figure 5 shows the data from vane and unconfined compression tests. Figure 6 shows data from 'total' strength triaxial tests. This plot shows an apparently wider range of strength for the till near-surface than at depth. Figure 7 shows data from 'effective' strength triaxial tests. This reveals a good positive correlation of strength increase with depth. Median s_u values derived from vane and uniaxial tests for alluvium and till are 37 and 79 kPa, respectively; and for post-glacial deposits (PGD) and raised-marine deposits (RMD) 32 and 34 kPa, respectively. The equivalent plot for 'rocks' is shown in Figure 8. This does not show a clear trend. Figure 9 shows a positive correlation between uniaxial compressive strength and point load index (axial) for the limited formations tested.

3.7 DURABILITY

The 'slake durability' test is not a British Standard but is described in Franklin & Chandra (1972). A small number of 'slake durability' test data are included in the database. The test measures the sample's ability to remain intact when subject to a cycle of mechanical abrasion in water, and oven drying. Results for dolerite, Lower Coal Measures, and till (possibly erratic boulders) lie between 90 and 95 % ('very high').

4 Engineering geological assessment by geological unit

A summary of expected engineering properties, for those formations included in the geotechnical database, is given in Tables 2 to 4. (Note: where likely hazards exist for formations not included in the geotechnical database, names have been shown in grey). With the exception of dolerite, volcanic rocks are not represented in the database. It is difficult to generalise in engineering terms about the many rock types and distributions in the area.

4.1 SUPERFICIAL GEOLOGY

4.1.1 Till

Much of the area is covered in several metres thickness of glacial till. Till clasts are largely derived from local rocks (McGown et al., 1974; Mitchell and Jarvis, 1956). The tills are heavily over-consolidated and weathering extends typically to about 3 m depth. Mean strength properties for the 'Hurlford Till' have been reported (McGown et al., 1974) to be as follows: undrained cohesion, c_u of 143 kPa, effective cohesion, c' of 12 kPa, and effective friction angle, ϕ' of 30^o. Hurlford Till was also reported as being particularly well-graded. These figures compare with c_u of 97 kPa from the database for till generally. This last figure is probably intermediate when comparing with other Scottish tills (Davies et al., 1982; McGown et al., 1974). Cutting and trench instability in tills was attributed largely to the presence of fissures. Such features are common particularly in the case of heavy over-consolidation; that is where past overburden has greatly exceeded present. Shallow failures have been recorded in fresh 14 m deep cuts at 30^o slopes (McGown et al., 1974). The relative contributions of fissuring and fabric (e.g. particle-size distribution) to the mass permeability of the till have an important effect on slope stability. Till is frequently involved in instability on the slopes of deeply incised river valleys, produced by saturation and undercutting. Bearing capacity on till is generally low to moderate.

4.1.2 Glacio-fluvial deposits

Glacio-fluvial and fluvio-glacial deposits tend to be highly heterogeneous in terms of content, thickness, and distribution. They often form irregular surfaces and mounds. Otherwise unlithified deposits may contain erratic blocks of rock. Whilst consisting dominantly of coarse-grained sands, gravels, and cobbles, locally there may be lenses of soft clay and silt produced by small glacial lakes. These deposits frequently infill channels formed either within the country rock or within other superficial deposits.

4.2 BEDROCK GEOLOGY

4.2.1 Coal Measures

The majority of rock descriptions in the database are sandstones with subsidiary mudstones and siltstones. The presence of a moderate degree of weathering and clay-infilled joints is frequently referred to in sample descriptions. The geotechnical database indicates that the Middle Coal Measures sandstone is stronger than that of both the Upper and Lower Coal Measures. Igneous intrusions, in particular dykes having a dominantly NW-SE trend, and volcanic plugs and vents, represent a major engineering consideration due to the contrasting geotechnical property differences compared with the country rock.

4.2.2 Igneous rocks

The majority of igneous rock types provide a very strong material with a high bearing capacity, and slopes may be constructed to a steep angle. However, blocky spalling and larger-scale rock-fall may be persistent problems unless protective measures are applied. Hydrogeological factors may need special consideration due to perched water tables.

4.3 MADE GROUND

There is a considerable amount of made ground, often in the form of reworked or infilled mine, opencast, and quarry waste. These materials are highly heterogeneous, but may nevertheless be classified as to their origin, treatment (if any), and hence content. Using this information likely ranges of geotechnical properties may be inferred.

5 General points

• Issues of resource sterilisation may have to be considered with regard to coal, metalliferous ore, fireclay, water, sand/gravel, peat etc.

• Engineering activities should consider faulting in a dominantly NE-SW direction and the possible presence of former mine-workings.

• Active landsliding occurs in incised river valleys where the slope consist of weak, saturated glacial deposits, in particular tills.

• Minor limestones occur in some formations (e.g. Kinnesswood Formation). These may allow dissolution features to develop, possibly resulting in subsidence.

• Unweathered igneous and the older sedimentary rocks (Devonian and Silurian) tend to have the highest strengths, and hence the highest allowable bearing capacities. Carboniferous sedimentary rocks tend to have a lower capacity due to the interbedding of stronger sandstones and weaker mudstones.

• Engineering activities and site investigation may be hampered by the presence of contrasting geotechnical properties within the same formation, for example strong sandstones interbedded with weak mudstones in the Coal Measures.

• What is frequently a complex geological structure, involving folds, faults, dykes, and sills, is difficult to assess from boreholes alone. Such features can result in significant local variations in important engineering factors such as bearing capacity, mass permeability, perched water levels, and slope stability.

6. Conclusions

A small dataset of geotechnical data has been assembled and analysed for the south-western Central Belt of Scotland, as part of a larger geological study. These data have been largely obtained from highway site investigation records held at the British Geological Survey. The dataset has been analysed in order to show any variations in physical properties, and hence implications for engineering behaviour (e.g. in excavation) and engineering resource (e.g. as a fill material), and how these relate to the lithology and stratigraphy of both bedrock and superficial. As might be expected, unweathered and older rocks tend to have higher strength than weathered and younger rocks. Unfortunately, the dataset contains few identifiers for weathering state, and so this important influence on geotechnical properties often cannot be quantified. The Middle Coal Measures sandstone tends to be stronger than the Upper and Lower sandstones. Igneous intrusions provide a source of engineering problems due mainly to the contrast in properties with the host rock, and also hydrogeological factors. The tills have a relatively uniform geotechnical character, with little distinction according to parent rock type. Water content for alluvium is typically double that for till. The strength of superficial deposits was found to be extremely variable. Made ground, particularly in former industrial areas, presents a hazard principally due to the potential for pollution and ground water contamination. The possibility of landslides, particularly within thick superficial deposits such as till, must be considered. Existing landslides may be unmapped, and could undergo re-activation due to engineering or river erosion. Various mineralogical resources, for example coal and fireclay, may be sterilised by development and engineering activity. Their potential value should be considered in the early stages of planning.

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Appendix 1

Site investigation reports contributing to the database

SE 9573 Cumnock and Auchinleck Bypass (A76) Rocksoil Ltd Report No.S.86/61

SE13100 M6-M8 Fastlink Wimpey Environmental Ltd. Report No.SULZ/7493

SE10718 A76 Dumfries to Kilmarnock (Crosshands to Hollybush) Terratek Ltd Ref: 2588

SE10717 A76 Dumfries to Kilmarnock (Rodinghead to Crosshands) Terratek Ltd Ref: 2588/1

SE12864 Ayr Sewerage Scheme, proposed interceptor sewer route, GI contract No. W90575 Wimpey Environmental 1994 (SULZ/7230)

SE1962 Larkhall, Hamilton, & Uddingstone by-pass [Wimpey S/2920, Sept. 1962]

Appendix 2 Summary statistics - 'soils'

SUMMARY STATISTICS ('SOILS')

										STRENGTH										
			PLASTICITY			PARTICLE SIZE				TRIAXIAL				Vane	CHEMICAL			COMPACTION		
		w	**LL**	**PL**	**PI**	**CLAY**	**SILT**	**SAND**	**GRAV**	c_u	ϕ_u	**c'**	ϕ'	s_u	SO_3	**pH**	**ORG.**	**OMC**	**MDD**	**CBR**
		(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(kPa)**	**(degr)**	**(kPa)**	**(degr)**	**(kPa)**	**%**		**%**	**(%)**	**(Mg/m^3)**	**(%)**
All data	min	6.0	19.0	10.0	2.0	0.0	0.0	0.0	0.0	0	0	0	20	3	0.01	3.3	0.2	5.0	1.5	0.2
	max	166.0	192.0	129.0	63.0	43.0	69.0	100.0	96.0	369	34	28	41	297	0.53	10.9	89.5	26.0	2.2	48.0
	median	16.0	30.0	17.0	13.0	6.5	17.5	34.0	17.5	66	2	9	32	44	0.03	7.4	2.2	9.5	2.0	3.6
	mean	19.7	32.0	18.4	13.6	9.8	19.7	41.9	26.2	91	5	9	31	63	0.07	6.9	13.8	11.4	1.9	6.5
	count	335	351	351	351	330	344	344	344	247	247	21	21	152	74	112	39	59	59	59
Alluvium	min	6.0	19.0	14.0	2.0	0.0	0.0	1.0	0.0	0	0	0	28	10	0.01	3.6	0.3	7.0	1.7	0.2
	max	67.0	118.0	81.0	37.0	43.0	69.0	98.0	93.0	196	32	28	38	146	0.16	8.6	89.5	12.0	2.2	36.0
	median	26.0	32.0	19.0	12.0	0.0	2.0	41.0	25.0	32	2	8	32	37	0.04	7.3	1.6	8.3	2.0	0.7
	mean	26.4	34.7	21.4	13.3	5.5	13.2	45.2	32.5	45	6	8	33	47	0.05	6.8	8.6	8.9	2.0	7.3
	count	75	75	75	75	139	145	145	145	50	50	11	11	30	19	36	15	4	4	16
Till	min	7.3	19.0	10.0	5.0	0.0	0.0	0.0	1.0	11	0	3	26	19	0.01	3.5	0.2	8.0	1.7	0.6
	max	41.1	75.0	31.0	44.0	33.0	60.0	85.0	96.0	369	30	12	34	297	0.21	10.9	16.8	19.0	2.1	20.0
	median	14.0	29.0	16.0	13.0	18.0	32.5	30.5	16.5	97	1	8	28	79	0.02	7.6	2.0	12.0	2.0	4.4
	mean	15.7	29.9	16.7	13.2	17.1	31.5	30.9	19.0	115	4	8	29	95	0.05	7.0	4.1	12.0	1.9	5.5
	count	236	250	250	250	134	134	134	134	165	165	4	4	46	23	26	11	15	15	30
FGS	min	11.0	21.0	13.0	8.0	2.0	8.0	55.0	13.0	17	2							5.0	1.7	0.4
	max	20.0	47.0	25.0	22.0	4.0	27.0	71.0	27.0	150	11							12.0	2.2	48.0
	median	16.0	27.0	16.0	11.0	3.0	13.0	59.0	16.0	66	6							8.5	2.0	5.4
	mean	15.8	30.5	17.5	13.0	3.0	16.0	61.7	18.7	72	7							8.6	2.0	14.5
	count	4	4	4	4	3	3	3	3	5	5							19	19	6
GLLD/ GLDD	min	21.0	22.0	20.0	2.0	0.0	0.0	48.0	0.0	0	0			19				13.0	1.5	
	max	39.0	60.0	25.0	35.0	0.0	25.0	100.0	47.0	108	34			273				26.0	1.8	
	median	28.0	38.0	20.0	18.0	0.0	3.5	91.5	1.5	29	3			41				15.5	1.7	
	mean	29.0	39.5	21.3	18.3	0.0	6.7	83.7	9.7	39	9			65				17.3	1.7	
	count	4	4	4	4	6	6	6	6	9	9			19				8	8	

Appendix 2 Summary statistics - 'soils'

			PLASTICITY			PARTICLE SIZE				STRENGTH TRIAXIAL				STRENGTH Vane	CHEMICAL			COMPACTION		
		w (%)	**LL (%)**	**PL (%)**	**PI (%)**	**CLAY (%)**	**SILT (%)**	**SAND (%)**	**GRAV (%)**	**c_u (kPa)**	**ϕ_u (degr)**	**c' (kPa)**	**ϕ' (degr)**	**s_u (kPa)**	**SO_3 %**	**pH**	**ORG. %**	**OMC (%)**	**MDD (Mg/m^3)**	**CBR (%)**
Peat	min	29.0	29.0	20.0	9.0					2	0					3.3	1.9			
	max	166.0	192.0	129.0	63.0					18	0					7.0	70.5			
	median	144.0	79.0	42.0	37.0					7	0					4.3	44.1			
	mean	113.0	100.0	63.7	36.3					9	0					4.6	39.5			
	count	3	3	3	3					3	3					7	9			
PGD	min	18.0	20.0	13.0	7.0	0.0	0.0	13.0	0.0					28	0.01	7.6				
	max	34.0	39.0	21.0	18.0	37.0	59.0	98.0	82.0					126	0.15	8.5				
	median	25.0	26.0	17.0	8.0	0.0	2.5	45.5	25.0					32	0.09	7.7				
	mean	25.2	27.6	16.8	10.8	4.6	12.7	47.7	31.3					47	0.09	7.8				
	count	5	5	5	5	28	30	30	30					6	4	6				
RMD	min	29.0	32.0	22.0	9.0	0.0	0.0	5.0	0.0	18	0	0	20	7				16.0	1.6	
	max	42.0	57.0	27.0	31.0	0.0	28.0	100.0	77.0	70	3	19	41	194				22.0	1.7	
	median	36.0	40.0	25.5	14.5	0.0	2.5	47.0	38.0	21	0	14	31	34				21.0	1.7	
	mean	34.9	42.0	24.8	17.2	0.0	8.3	49.8	38.3	28	1	11	31	45				20.0	1.6	
	count	8	10	10	10	3	4	4	4	12	12	6	6	48				5	5	
AS	min														0.01	7.1				
	max														0.01	7.8				
	median														0.01	7.4				
	mean														0.01	7.4				
	count														1	5				
FGSG	min																	5.0	2.0	0.2
	max																	9.0	2.2	9.4
	median																	7.3	2.1	1.1
	mean																	7.1	2.1	2.5
	count																	8	8	7

Appendix 3 Summary statistics - 'rocks'

		PL (ax)	PL (dia)	UCS	w	BD	SLAKE
ALL DATA	min	0.0	0.0	12.0	0.3	2.2	92.4
	max	12.2	9.9	148.4	5.2	3.0	97.6
	median	1.4	0.5	41.8	1.3	2.7	95.6
	mean	2.2	1.3	47.4	1.7	2.6	95.3
	count	105	71	54	22	22	4
Dolerite	min	2.6	0.7	21.1	0.3	2.7	
	max	7.1	6.0	142.6	2.4	3.0	
	median	5.0	3.5	48.8	1.3	2.8	
	mean	4.8	3.3	59.1	1.3	2.8	
	count	13	11	8	8	8	
KNW	min			27.4			
	max			129.1			
	median			33.4			
	mean			55.8			
	count			4			
LCMS	min	0.6		19.8	0.8	2.2	
	max	1.9		55.0	3.6	2.8	
	median	1.2		29.3	1.1	2.2	
	mean	1.2		31.1	1.7	2.4	
	count	14		8	4	4	
LSC	min			16.9			
	max			67.1			
	median			43.4			
	mean			42.9			
	count			6			
MCMS	min	0.0	0.0	33.2	0.6	2.3	
	max	11.8	3.9	148.4	5.2	2.7	
	median	1.5	0.6	55.0	2.2	2.5	
	mean	1.8	1.0	68.2	2.3	2.5	
	count	38	23	10	8	8	
UCMS	min	0.0	0.0	12.0			
	max	12.2	3.9	54.0			
	median	0.4	0.1	17.0			
	mean	2.0	0.5	26.6			
	count	38	32	7			

Glossary

(Refer to BS1377:1990)

BD, γ_b	Bulk unit weight or density (Mg/m^3)
CBR	California Bearing Ratio
CLAY	Clay size fraction (%)
c_u	Undrained cohesion – total shear strength (kPa)
c'	Drained cohesion – effective shear strength (kPa)
DD, γ_d	Dry unit weight or density (Mg/m^3)
GRAVEL	Gravel size fraction (%)
LL, w_L	Liquid limit (%)
MDD	Maximum dry density, compaction test (Mg/m^3)
OMC	Optimum water content, compaction test (Mg/m^3)
ORG	Organic content (%)
PI, I_p	Plasticity index (%)
PL, w_P	Plastic limit (%)
$PL_{(ax)}$	Point Load Index (axial)
$PL_{(dia)}$	Point Load Index (diametral)
SAND	Sand size fraction (%)
SLAKE	Slake durability Index
SO_3	Total sulphate content (%)
SILT	Silt size fraction (%)
s_u	Estimated undrained shear strength
UCS	Uniaxial compressive strength (kPa)
w	Water content (%)
ϕ_u	Drained, effective angle of internal friction (degrees)
ϕ'	Drained, effective angle of internal friction (degrees)

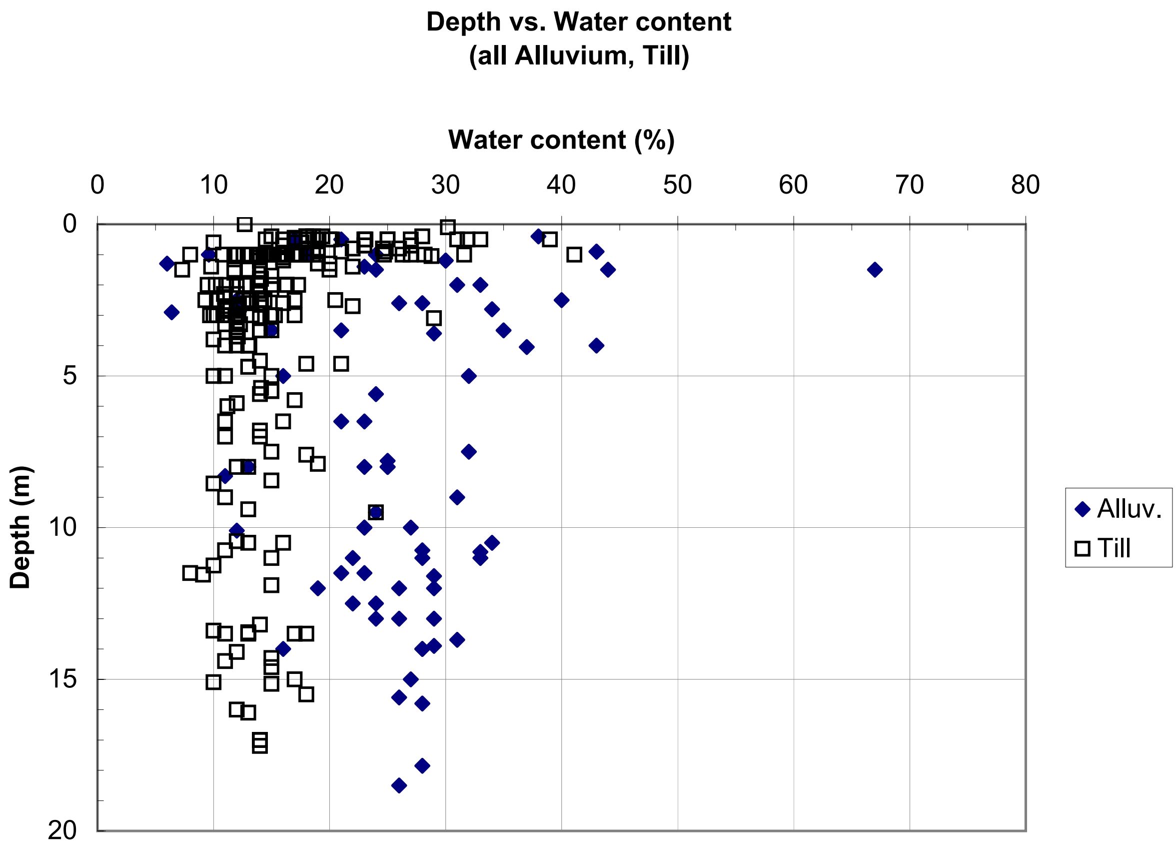

Figure 1a – Plot of water content versus depth for all samples of alluvium and till

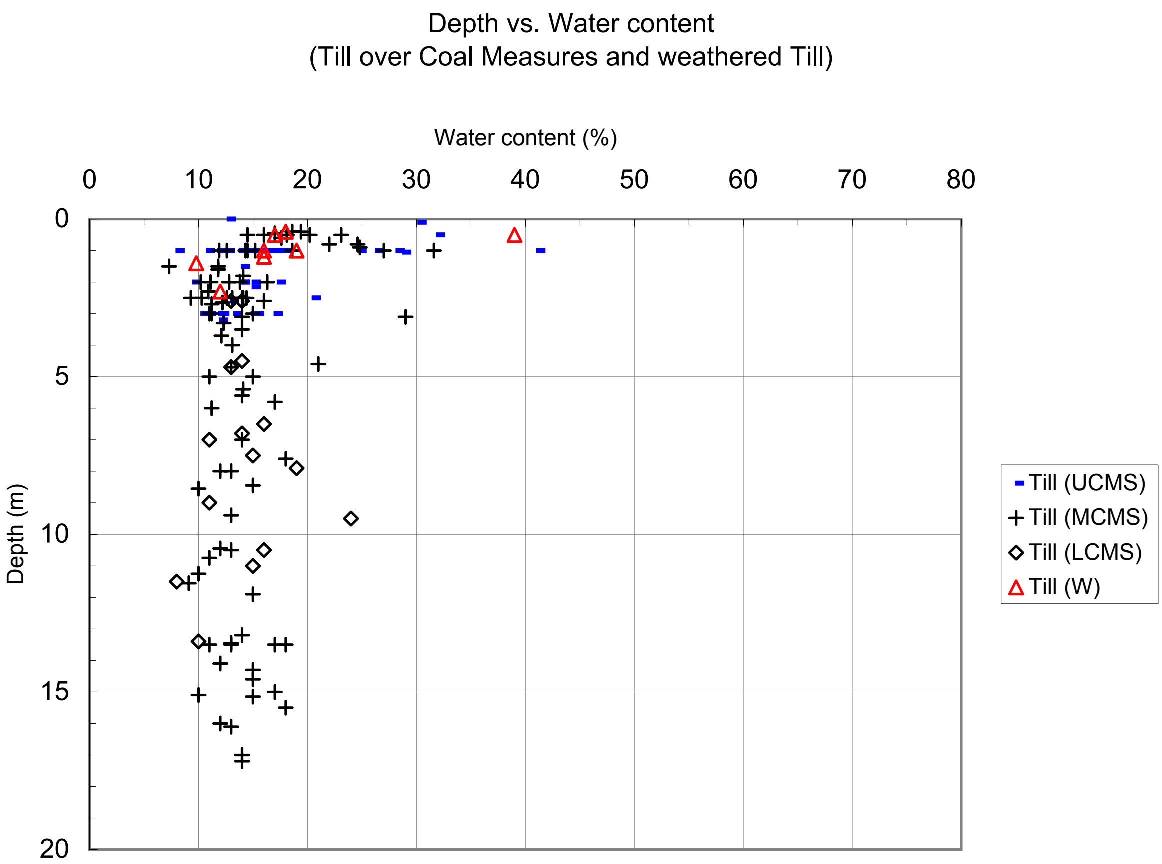

Figure 1b – Plot of water content versus depth for weathered till and till overlying Coal Measures Group

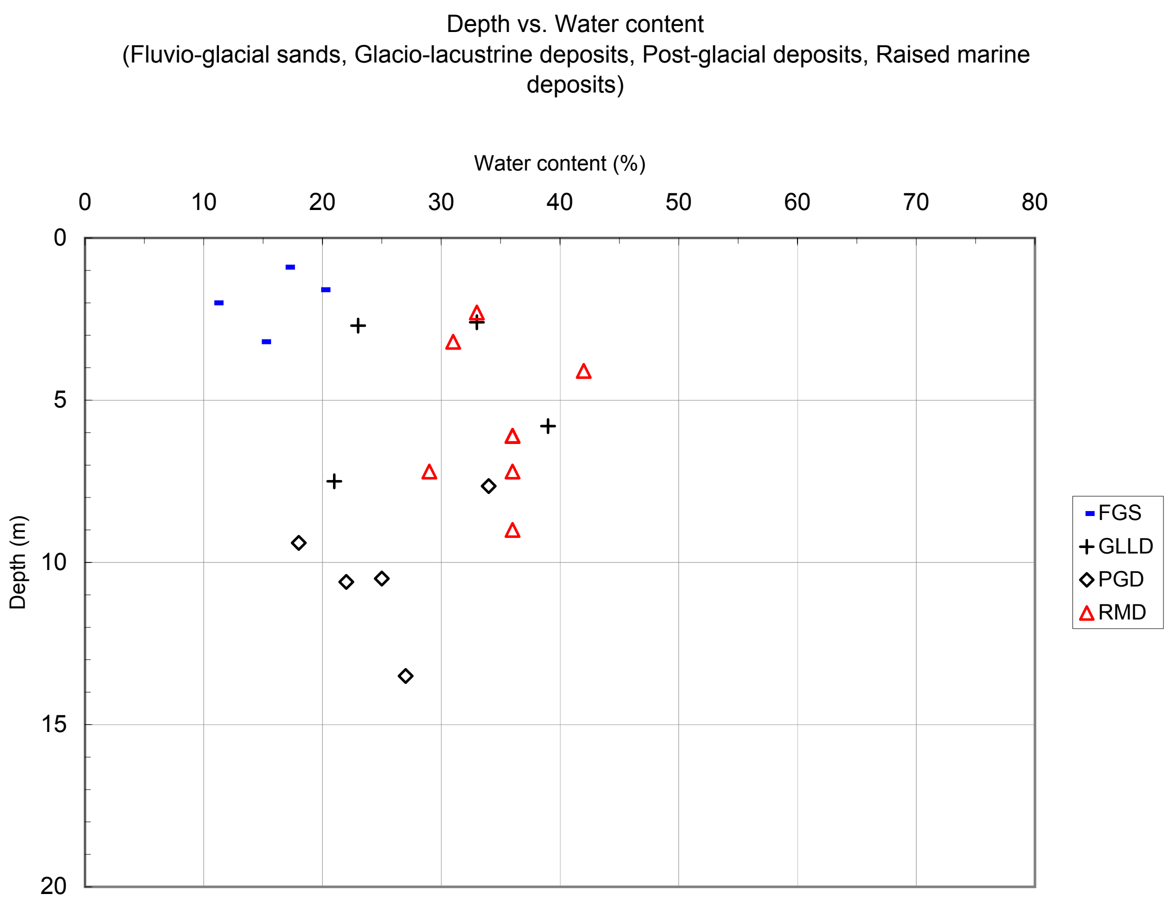

Figure 1c - Plot of water content versus depth for test samples of fluvio-glacial sands, glacio-l;acustrine deposits, post-glacial deposits and raised marine deposits

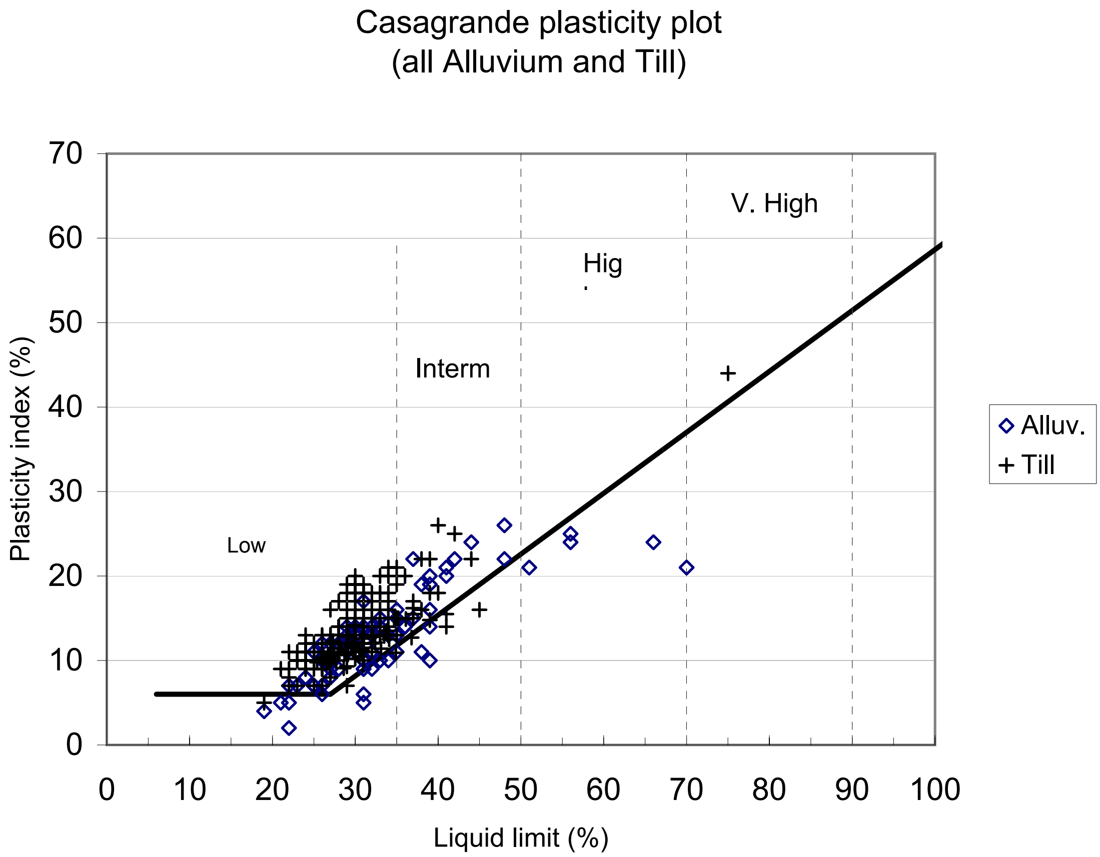

Figure 2a – Casagrande plasticity plot of samples of alluvium and till

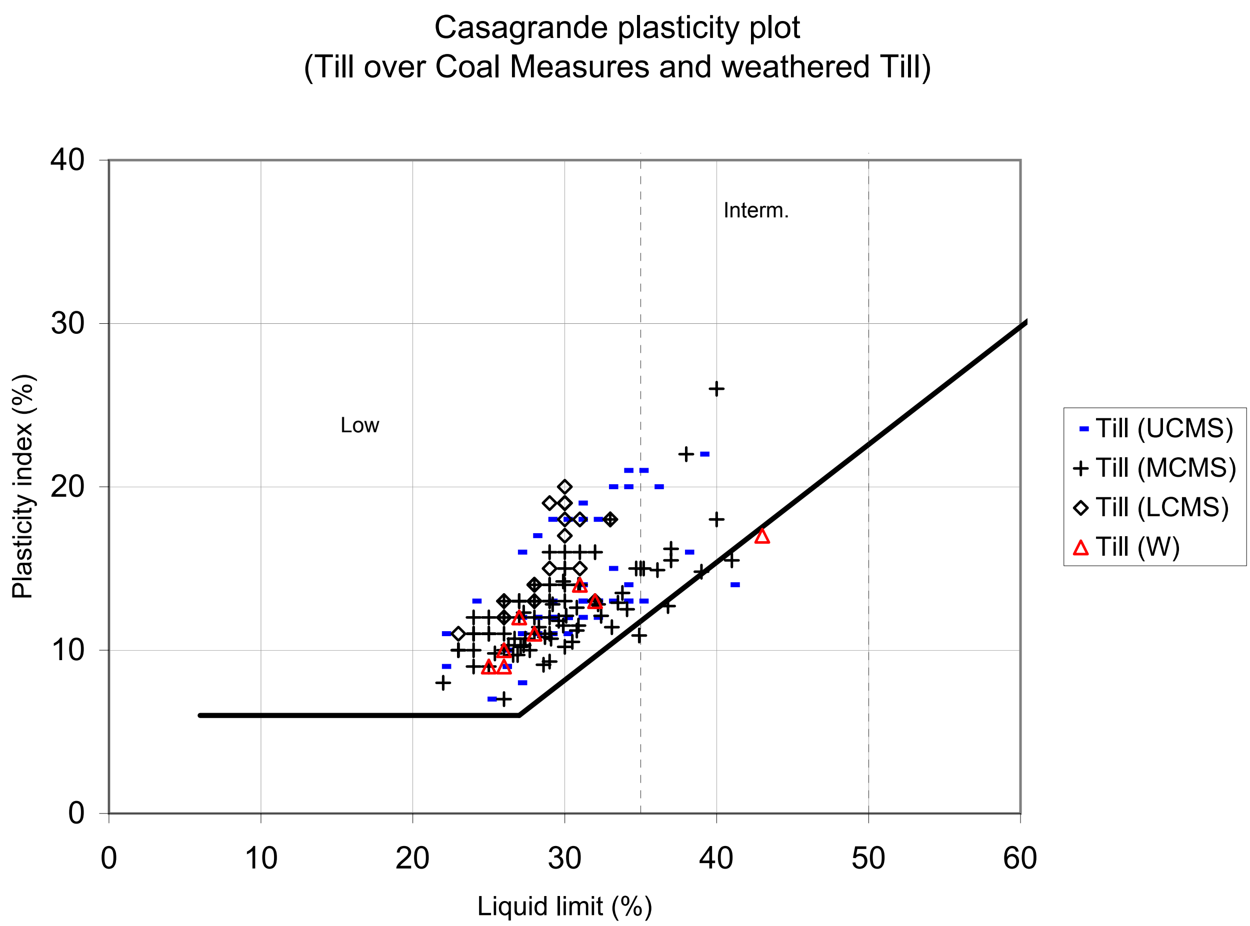

Figure 2b – Casagrande plasticity plot of samples of weathered till and till overlying Coal Measure Group, W weathered till

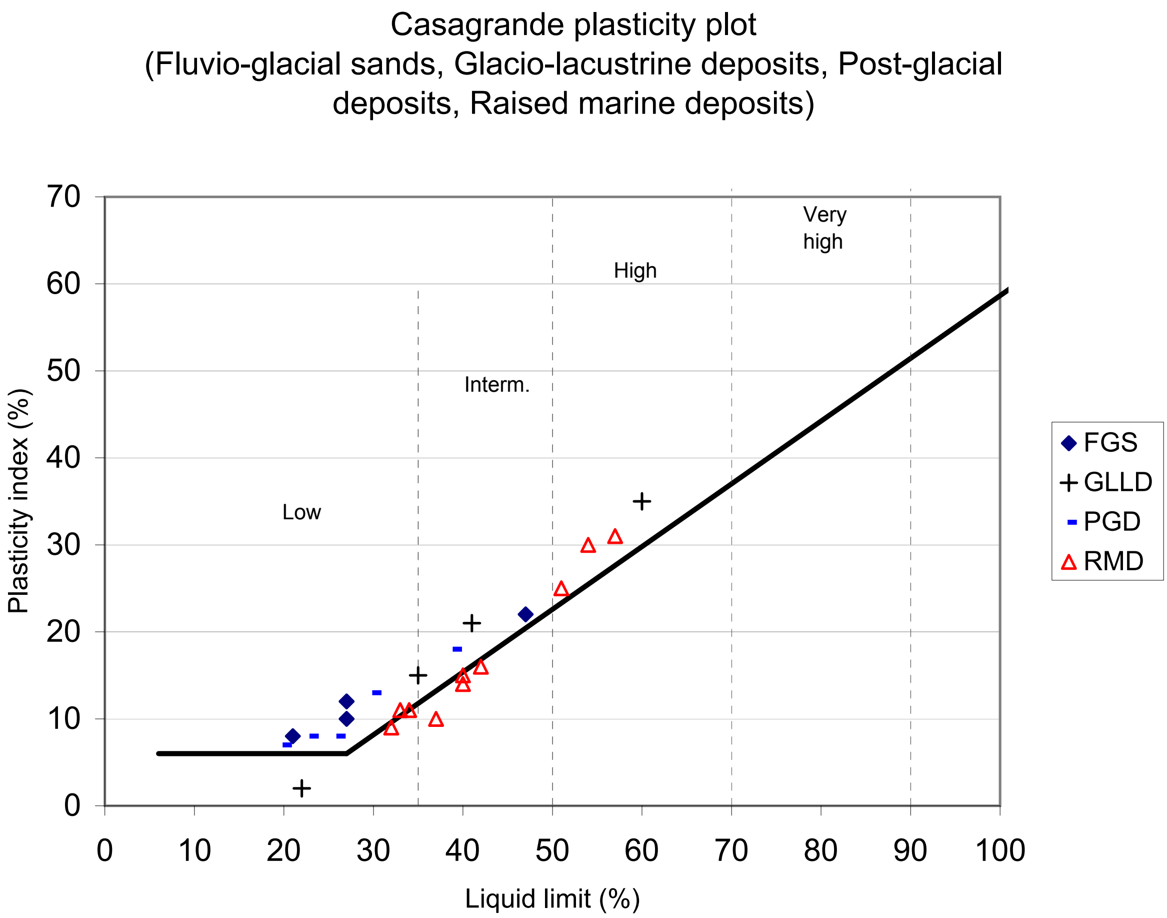

Figure 2c – Casagrande plasticity plot of samples of fluvio-glacial sands FGS, glacio-lacustrine deposits GLLD, post-glacial deposits PGD and raised marine deposits RMD

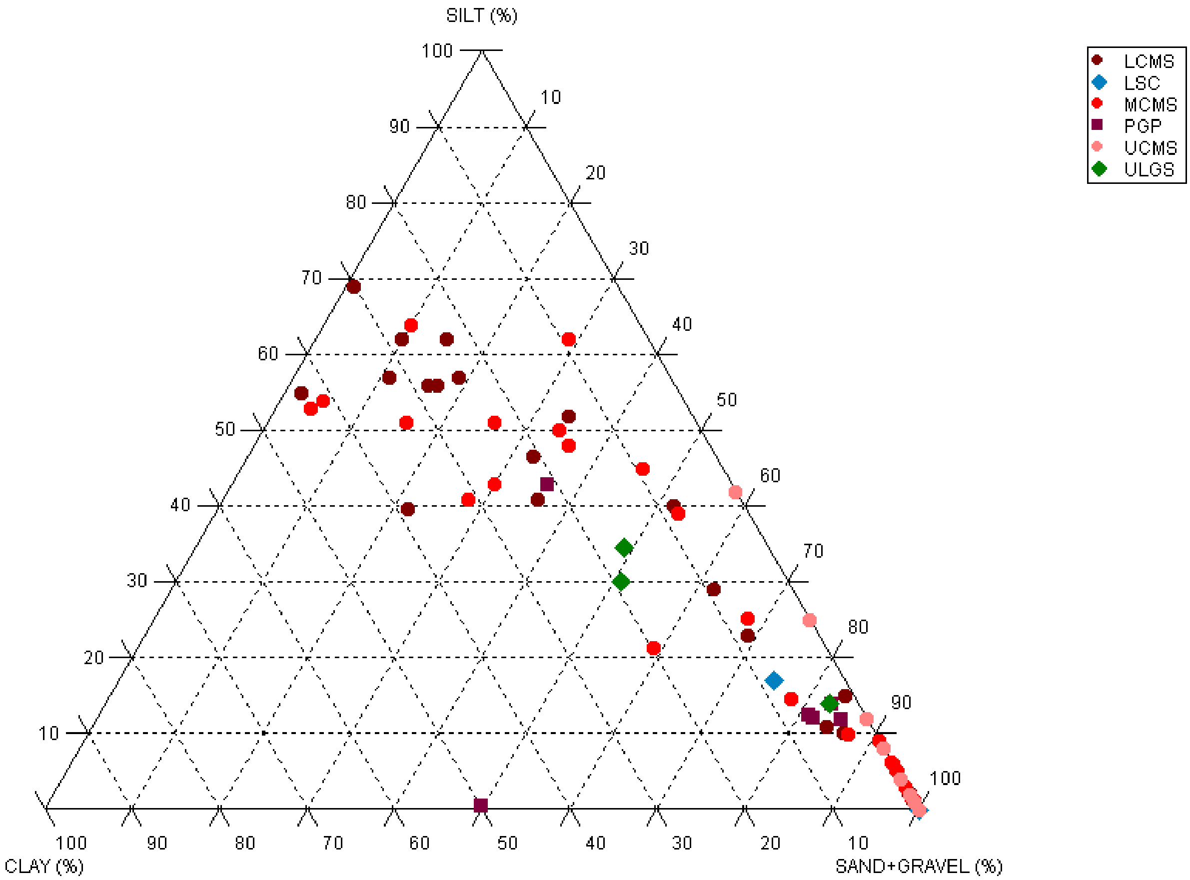

Figure 3a – Triangular diagram of sand, clay and sand + gravel for alluvial deposits overlying UCMS Upper Coal Measures, MCMS Middle Coal Measures, LCMS Lower Coal Measures, PGP Passage Formation, ULGS Upper Limestone Formation and LSC Limestone Coal Formation

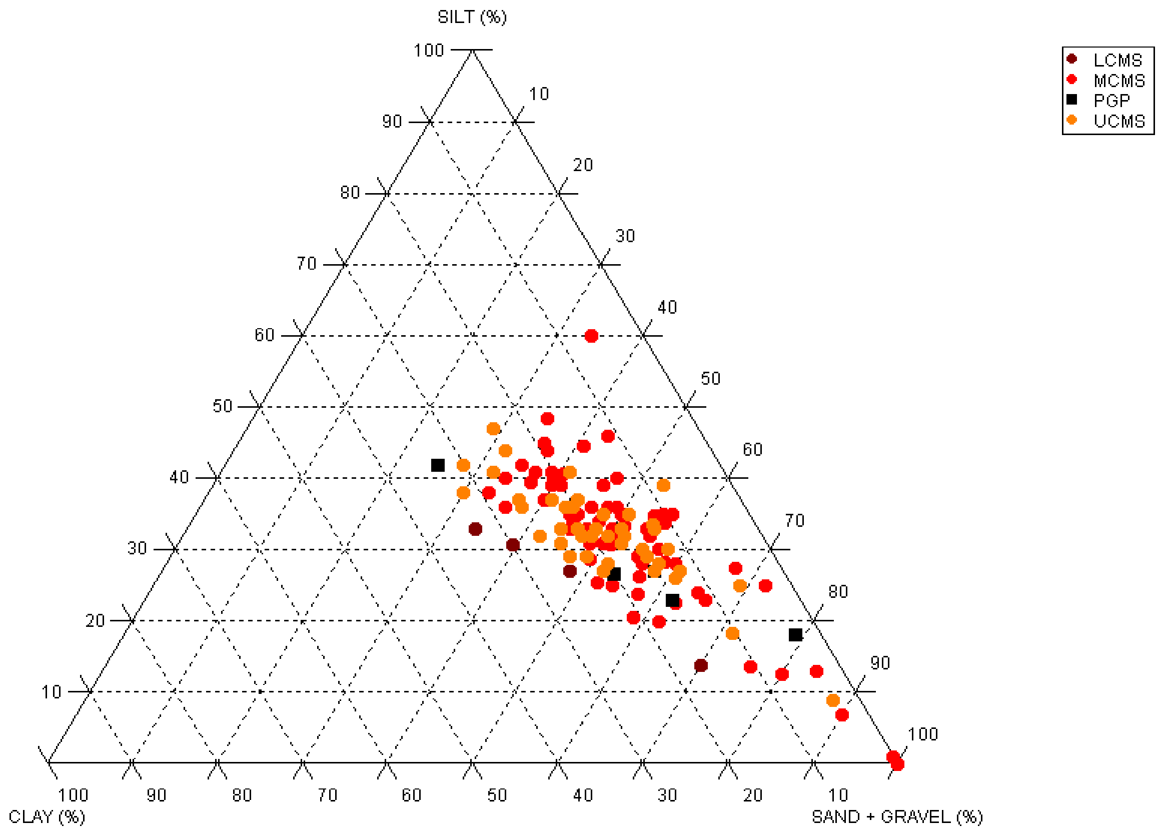

Figure 3b – Triangular diagram of sand, clay and sand + gravel for till deposits overlying UCMS Upper Coal Measures, MCMS Middle Coal Measures, LCMS Lower Coal Measures, PGP Passage Formation

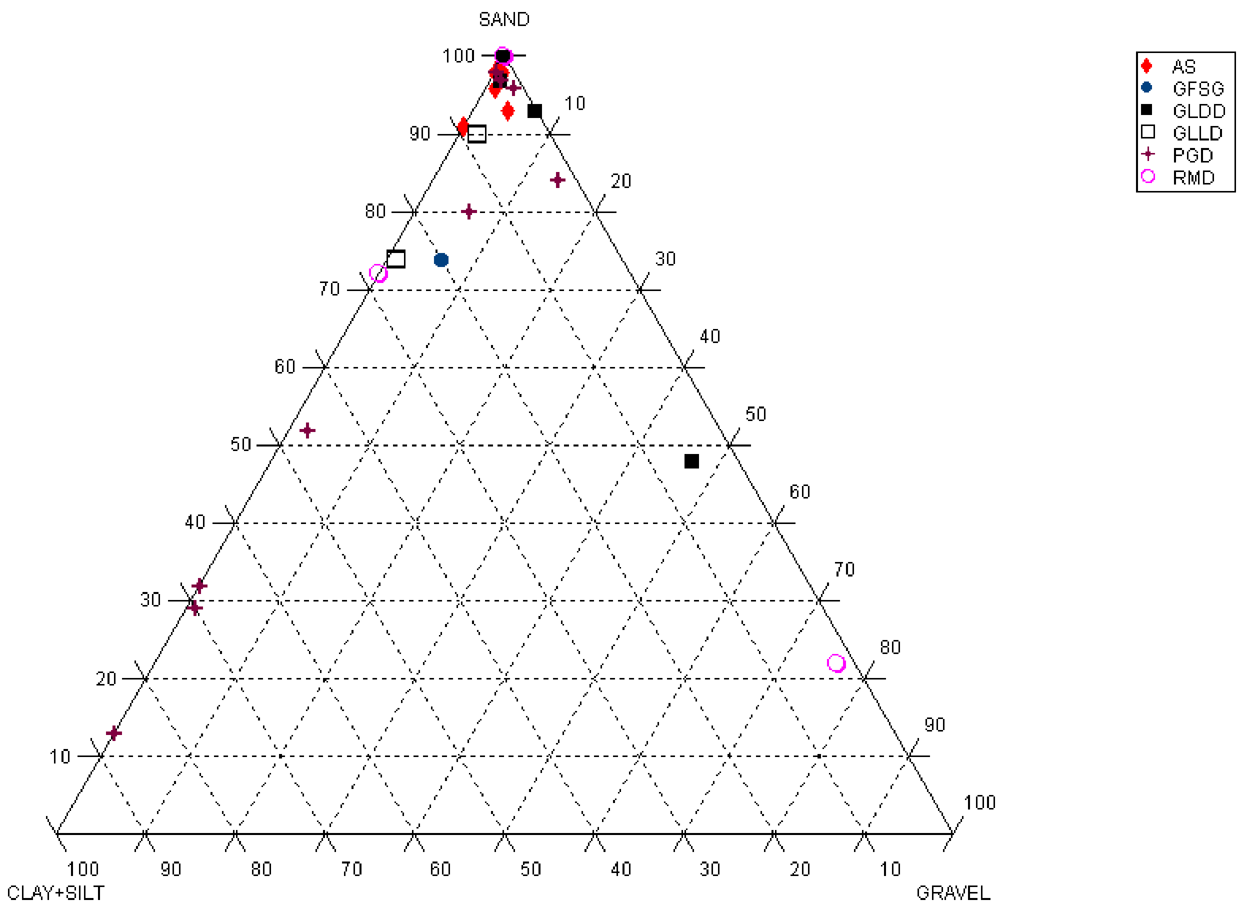

Figure 3c – Triangular diagram of clay+silt, sand, and gravel particle-size of fluvio-glacial sand and gravel FGSG, glacio-lacustrine deposits GLLD, post-glacial deposits PGD and raised marine deposits RMD

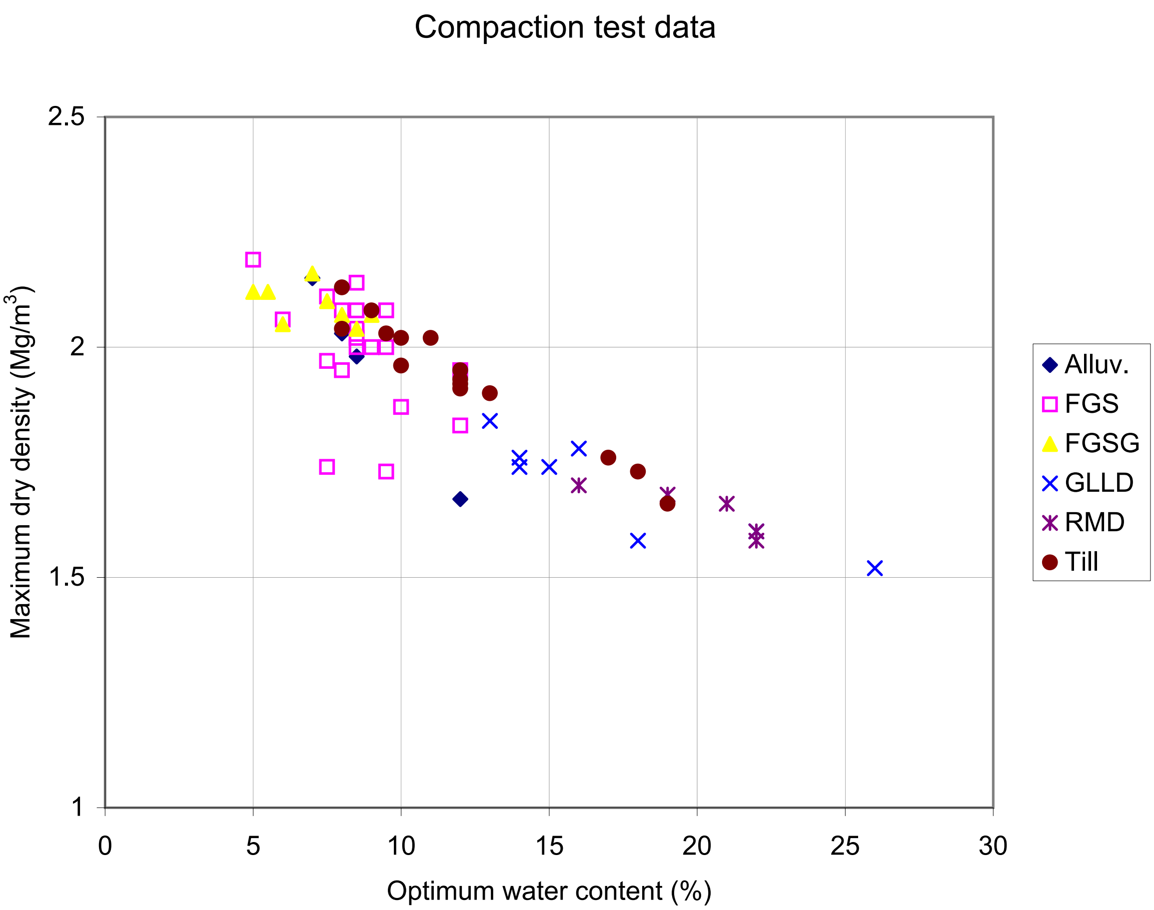

Figure 4 – Compaction test plot, dry density versus water content for alluvium Alluv., fluvio-glacial sands FGS, fluvio-glacial sand and gravel FGSG, glacio-lacustrine deposits GLLD, raised marine deposits RMD and till

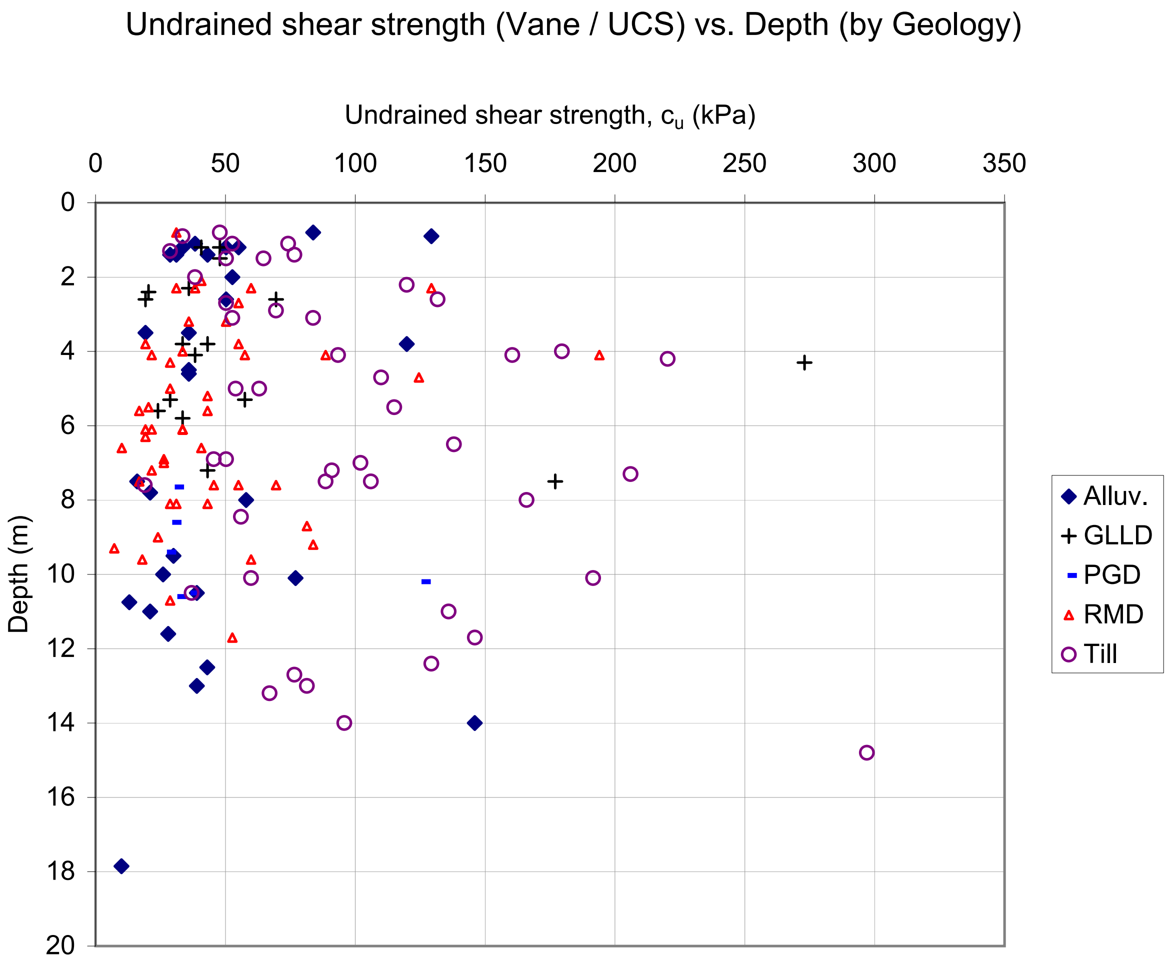

Figure 5 – Undrained shear strength versus depth for samples of alluvium Alluv., glacio-lacustrine deposits GLLD, post-glacial deposits PGD, raised marine deposits RMD and till

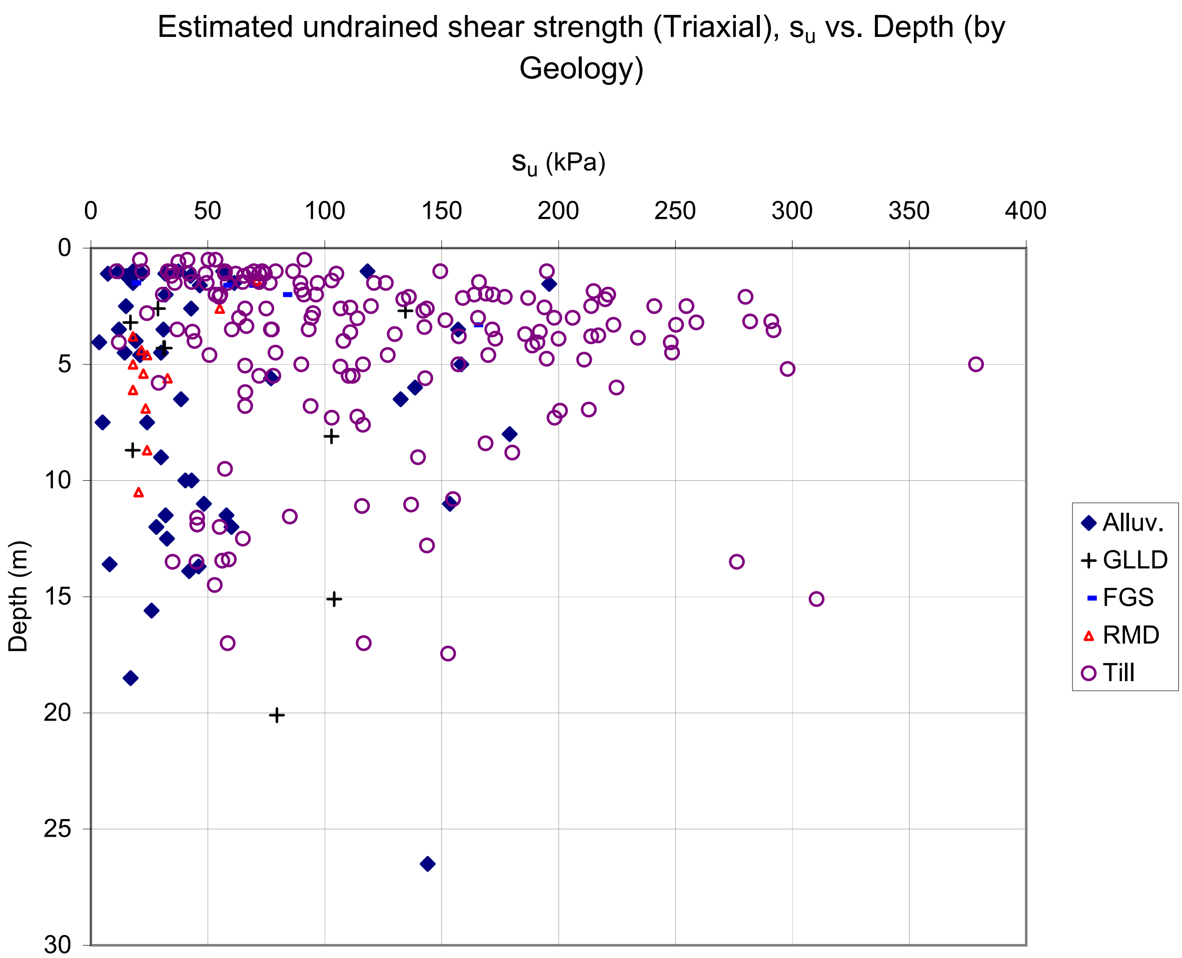

Figure 6 – Estimated undrained shear strength versus depth for samples of alluvium Alluv., glacio-lacustrine deposits GLLD, post-glacial deposits PGD, raised marine deposits RMD and till

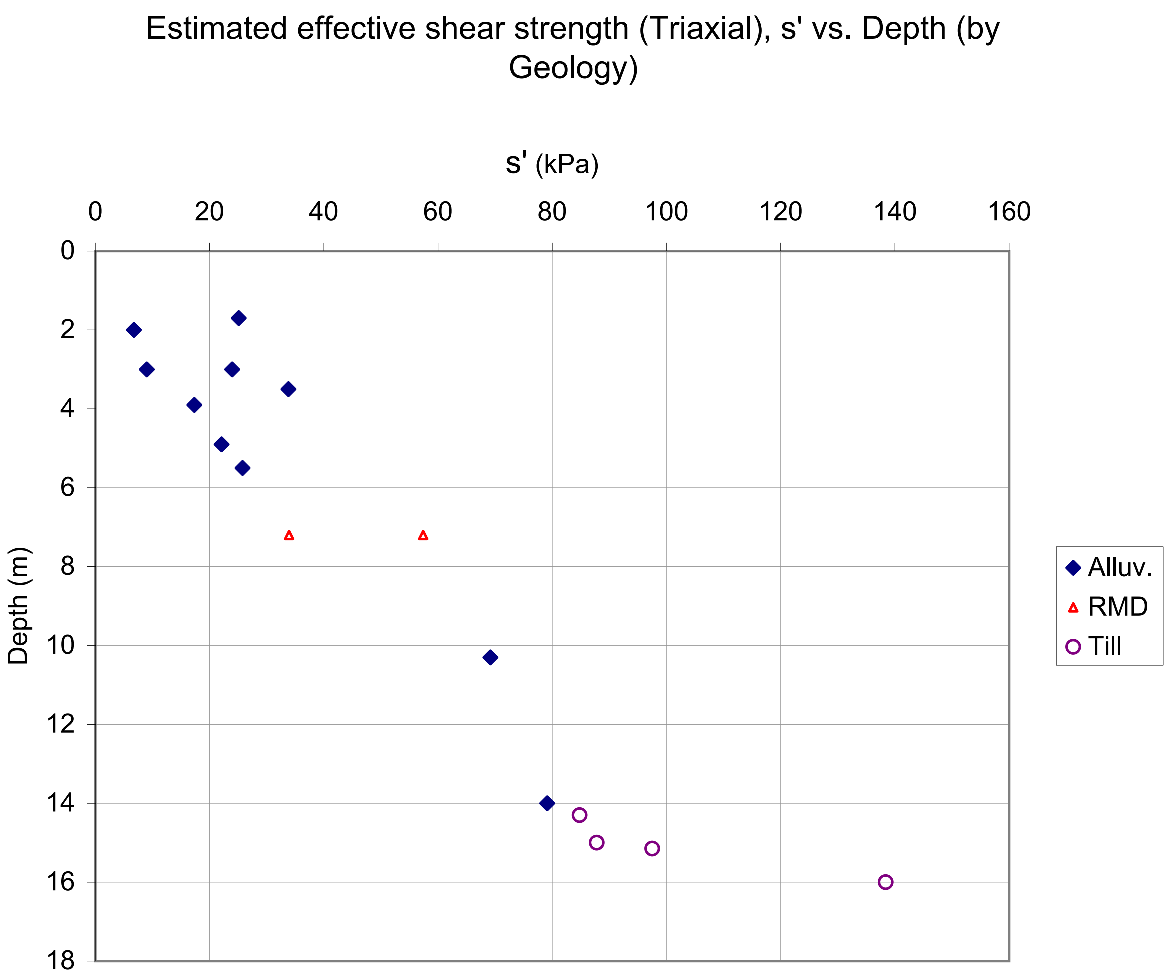

Figure 7 – Estimated effective shear strength versus depth for samples of alluvium Alluv., raised marine deposits RMD and till

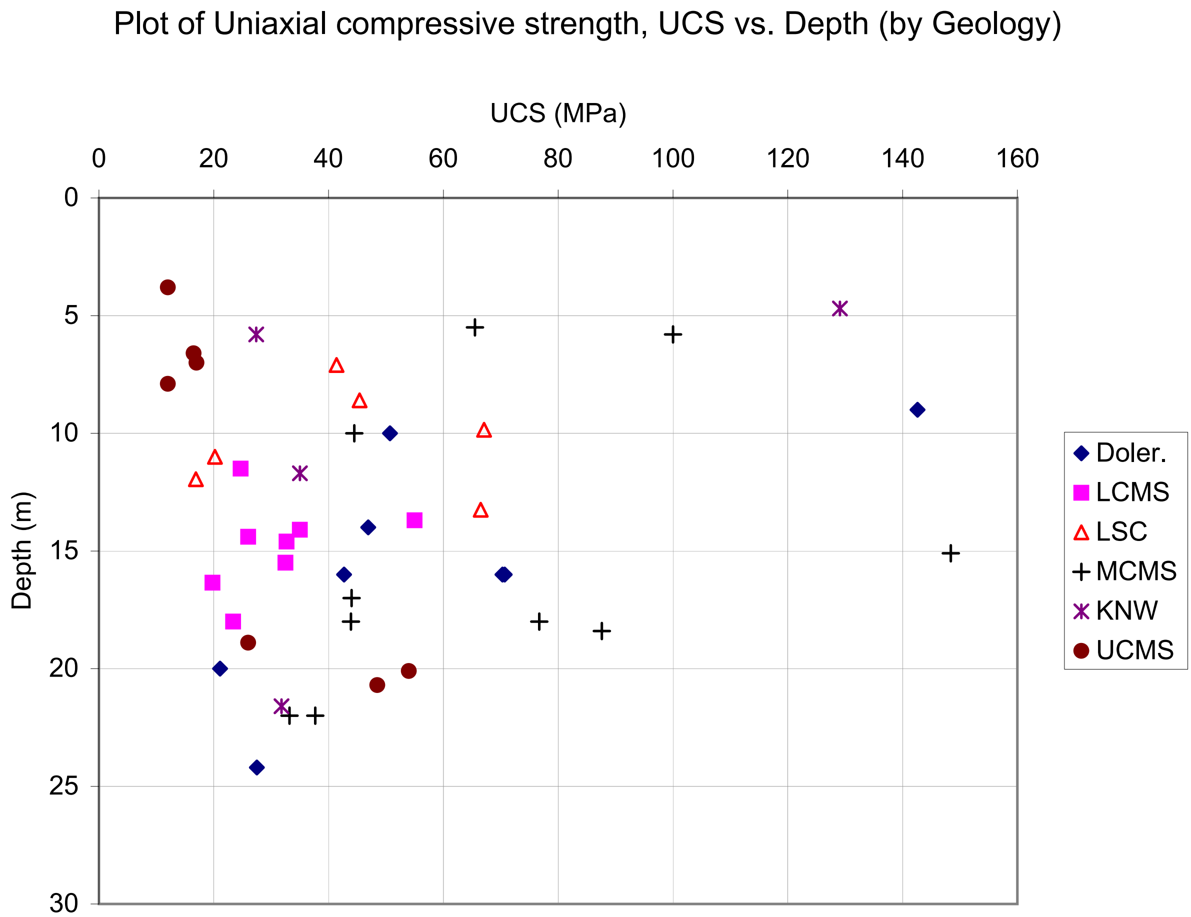

Figure 8 – Plot of uniaxial compressive strength versus depth for Doler. dolerite, UCMS Upper Coal Measures, MCMS Middle Coal Measures, LCMS Lower Coal Measures, LSC Limestone Coal Formation, KNW Kinnesswood Formation

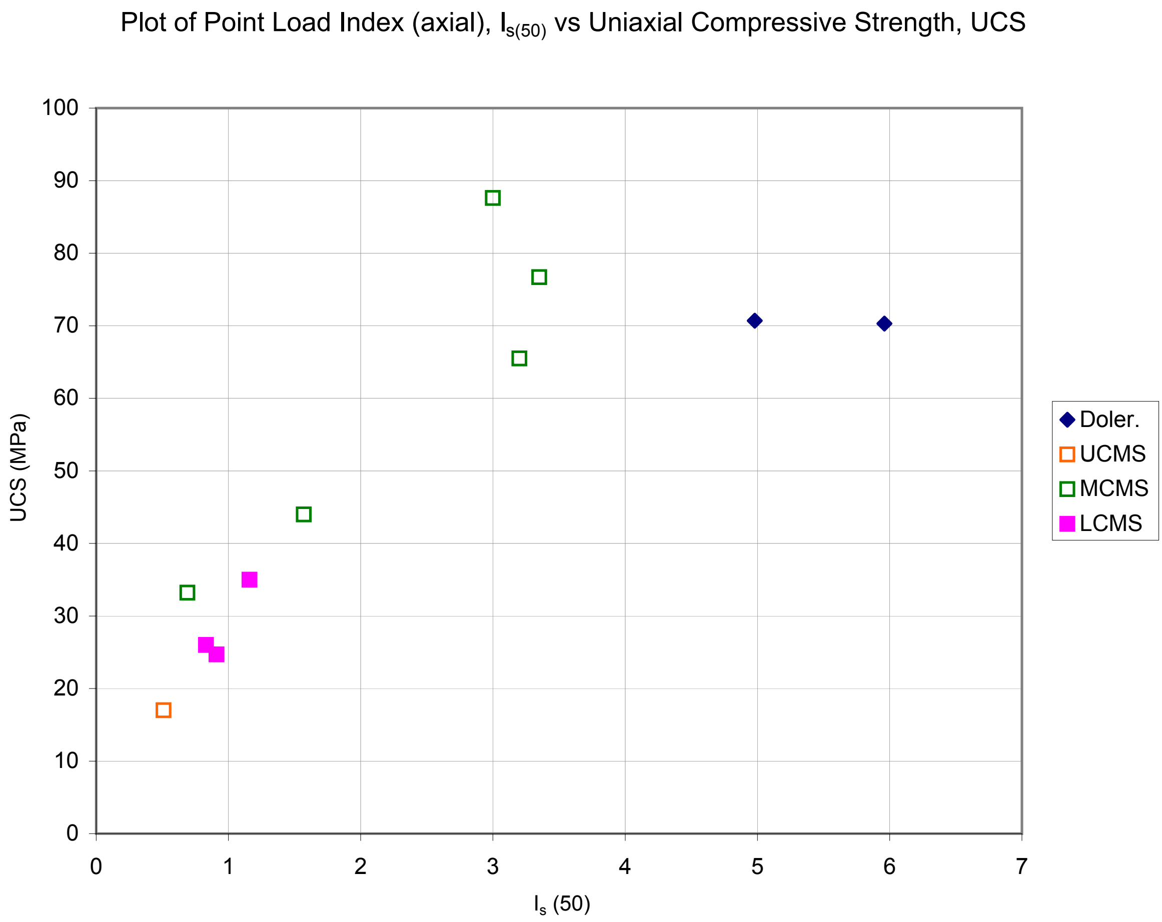

Figure 9 – Plot of point load index versus uniaxial compressive strength for Doler. dolerite, UCMS Upper Coal Measures, MCMS Middle Coal Measures, LCMS Lower Coal Measures