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Hydraulic characterisation of the tailings associated with the abandoned mine at Frongoch, mid-Wales.

Groundwater Protection Programme

Open Report OR/11/016

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

OPEN REPORT OR/11/016

Hydraulic characterisation of the tailings associated with the abandoned mine at Frongoch, Mid-Wales

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Keywords

Report; keywords: Hydraulic testing; Unsaturated zone; Mine tailings.

Front cover

Hydraulic testing at the abandoned Frongoch Mine site, Mid Wales, 24 July 2006.

Bibliographical reference

BANKS, V.J. AND KIRKHAM, M., 2011. Commissioning of the British Geological Survey Guelph Tension Infiltrometer Equipment. *British Geological Survey Open Report*, OR/11/016. 36pp.

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Keyworth, Nottingham British Geological Survey 2011

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Foreword

This report is the published product of a study by the British Geological Survey (BGS). This work was initiated by Dr B.A. Klinck in the context of the Abandoned Mines Project.

The lead project for this work was named Unsat, which was established to develop capability in unsaturated zone process understanding and modelling. An initial review of the state of the art in unsaturated flow parameter measurement and the modelling of unsaturated flow was followed by through application to sites being investigated under the Abandoned Mines Project. This work focuses on the assessment of the permeability of the mine tailings associated with the tailings lagoon of the abandoned Frongoch lead-zinc mine, mid-Wales.

Frongoch Mine (at National Grid Reference [NGR] SN 72200 74400, Figure 1, Plate 1) is an abandoned lead-zinc mine in the Ystwyth catchment, mid- Wales, UK and is one of the fifty Welsh sites prioritised by the Environment Agency for remediation.

The objectives of the work were to:

- classify the materials (grading, moisture content and density) recovered from the tailings lagoon;
- bring together the results of in-situ field and laboratory saturated hydraulic testing;
- assess the hydraulic properties in the context of the material properties, and

consider the implications for the conceptual site model.

Acknowledgements

Thanks are extended to the following staff that have helped with the fieldwork: Dr B.A. Klinck., Mr S. Quigley, Ms D Wagner and Dr B. Palumbo-Roe. The authors would also like to thank Mr J Bray the owner of the Frongoch abandoned mine site for allowing access to the site.

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Summary

This report describes the material classification and results of field and laboratory hydraulic testing of tailings from the Frongoch Tailings Lagoon, situated immediately to the south of the abandoned Frongoch mine site in mid-Wales. The results are considered in the context of the conceptual site model.

1 Introduction

1.1 CONTEXT

This is a report on a component of the work undertaken through a project named Unsat, which received Science Budget funding under the Abandoned Mines and Contaminated Land project: http://www.bgs.ac.uk/research/environmentAndHealth_amrc.html. It is focused on the permeability of the mine tailings associated with the tailings lagoon of the abandoned Frongoch lead-zinc mine, mid-Wales. Sampling for laboratory testing and in-situ testing were carried out in July 2008.

Frongoch Mine (at National Grid Reference [NGR] SN 72200 74400, Figure 1, Plate 1) is an abandoned lead-zinc mine in the Ystwyth catchment, mid- Wales, UK and is one of the fifty Welsh sites prioritised by the Environment Agency for remediation. The mine occupies a valley setting, the trend of the valley apparently having been influenced by the east-northeast to west-southwest trending fault upon which the mine is founded. From a valley level of approximately 250 m AOD ground level rises to at least 300m AOD to the north and south of the valley.

Figure 1: Location of Frongoch Mine, mid-Wales. Figure 2: View of the former tailings lagoon, looking south-south-east.

The 1: 50 000 Series British Geological Survey Sheet 178 *Llanilar* Solid with Drift Edition indicates that the site is underlain by a solid geology comprising Silurian strata of the Devil's Bridge Formation. This formation is characterised by turbidite deposits comprising rhythmic deposits of interbedded thin sandstones and mudstones, with a basal sandstone unit. Superficial deposits are shown to overlie areas of the solid geology. Peat caps some of the higher ground and Glacial Till deposits commonly occupy valley bottoms.

The lead-zinc deposits of the mid-Wales ore field are concentrated on east-northeast trending normal faults and breccia zones, which cut the north-south trending, fold axes. The mineralised faults vary in length between 1 and 10 km or more and exhibit downthrows of up to 200m. Frongoch Mine was one of several mines established along the east-northeast trending Frongoch Fault. Frongoch was the most productive mine in Cardiganshire and the largest producer of blende (Bick, 1996). The most productive section of the fault was approximately 450 m in length at Frongoch Mine, where it was mined to a depth of 260m. The width of the vein was about 11m and this is reported to have remained relatively constant with depth. It comprised two galena rich lodes separated by barren rock, together with a sphalerite rich load along the footwall (Davies et al., 1997). The richest part of the mine coincided with a junction of the lodes (Bick, 1996). The mine was worked between 1798 and 1902. Between 1798 and 1879 the main product was galena and between 1879 and 1902 it was sphalerite. The lode is strongly associated with quartz, making it difficult to work by hand drilling methods (Bick, 1996).

An indication of the historic extent of the tailings lagoon can be found on historic maps (Kuras et al., 2011). It comprises an area of approximately 180 m (north-west to south-east) by 80 m, which occupies a peaty natural depression, indicative of restricted or enclosed drainage. The contemporary account of the ore processing at Frongoch mine that was published by Moissenet (1866) and remnants of the former processing plant indicate that crushing, jigging and separation of the ore was carried out hydraulically be gravity separation on the slope immediately to the north of the tailings lagoon, which optimised the location of the tailings lagoon at the downstream end of this process (Palumbo-Roe et al., 2009).

Examination of the Ordnance Survey 1: 25 000 Explorer Map 213 *Aberystwyth and Cwm Rheidol* reveals that the low permeability of the strata that underlie the area has given rise to a high density of surface water courses. There are two westerly flowing rivers, which capture the surface water of the area; these are the Afon Rheidol to the north and Afon Ystwyth to the south. The mine tailings at Frongoch fall within the catchment of Afon Ystwyth. Water from Llyn Frongoch, which is fed in part by the area of peat to the north, discharges southwards to the small lake at Blaenpentre and continues in a southerly direction to the waterfall at NGR SN 7243 7456. Water from another lake centred on SN 72855 74682 (Banc Llwynwnwch) flows southwest to meet the water from Blaenpentre, in the order of 70 m above the waterfall. The waterfall discharges the surface water into the Frongoch fault and thus into the mine workings.

The mine tailings have been shown to be underlain by peat resting on glacial till (Bearcock et al., 2010; Kuras et al., 2011). To the south of the area of mine tailings there are short streams and areas of alluvium associated with the Nant Cwmnewydion, a southeasterly draining stream, discharging into Afon Ystwyth at Abermagwr (SN 6590 7400).

It is difficult to determine the detailed hydrogeology of the site without further investigation. Clearly the waterfall currently carries surface water into the Frongoch Fault and the mine drains to Nant Cwynewydion via the Frongoch adit (SN 713 741). It is suspected that groundwater storage outside of the mine workings is very limited in the bedrock.

Three trial pits were excavated in the tailings lagoon in August 2006 (Appendix 2 and Bearcock et al., 2010). The logs indicate that the tailings are underlain by a layer of peat (20 to 30 cm thick) that sits on a thin clay layer apparently resting on angular, gravel grade bedrock. It is not clear whether this comprises scree material derived from the adjacent high ground, shattered bedrock, or locally derived till. Groundwater was encountered in both the mine tailings and the shattered bedrock. This indicated recharge to a shallow aquifer beneath the peat as well as infiltration to the tailings, which has informed the conceptual model presented by Bearcock et al. (2010). Comparable shallow fractured bedrock aquifers were encountered in the Plynlimon investigations (Shand et al., 2005). It is considered that the water level in the tailings is controlled by the outlet via drainage pipe and a culvert at SN 723 741.

1.2 AIM

The aim of this component of the work was to undertake preliminary hydraulic characterisation of the mine tailings to contribute to the conceptual site model for the abandoned Frongoch mine. The fieldwork was carried out in July 2008, during a period of showery weather.

1.3 OBJECTIVES

The key objectives for the July 2008 fieldwork were to:

- classify the materials (grading, moisture content and density) recovered from the tailings lagoon;
- bring together the results of in-situ field and laboratory saturated hydraulic testing;
- assess the hydraulic properties in the context of the material properties, and
- consider the implications for the conceptual site model.

1.4 METHODS

Eight locations that were considered to be representative of the mine tailings, and two locations representative of the underlying peat layer, were selected for hydraulic testing (Table 1). At each location where it was possible the following was carried out:

- sample for moisture content and density determinations,
- moisture content determination with moisture content probe,
- tension infiltrometer testing,
- sample for post-testing moisture content,
- sample for particle size distribution analysis,
- undisturbed sample for laboratory testing (at six locations) and
- adjacent pressure infiltrometer testing

The tension infiltrometer testing was carried out using the procedure described in Banks et al. (2009); field moisture content determinations were carried out using a Theta Probe (section 2.1); samples for particle size distribution comprised disturbed samples; the undisturbed samples were cut into the tailings surface with every effort being made to minimise the disturbance and samples were sealed and wrapped with end caps and cling film; the pressure infiltrometer testing was carried out using the procedure described in Banks et al. (2009).

Table 1: Sampling and testing at each of the selected locations.

Sample Ref.	**AA**	**BB**	**CC**	**DD**	**EE**	**FF**	**GG**	**HH**	**II**
National Grid Ref. (SN)	27179 74307	72197 74286	72228 74266	72228 74266	72242 74248	72250 74221	72256 74279	72284 74269	72307 74284
Field Description	Medium dense, slightly olive grey, with dark flecks, sandy SILT with localised clay pockets. Becoming steel grey and orange brown below 1 cm depth	Medium dense, slightly olive grey with dark flecks, fine to medium SAND and SILT with localised clay pockets. Becoming steel grey and orange brown below 1 cm depth	Medium dense, medium greyish brown with dark flecks, silty crust of 5 mm underlain by silty fine to coarse, predominantly medium SAND with some fine to medium shale fragments at surface.	Stiff slightly purplish grey clayey SILT underlain by steel grey slightly silty fine to coarse SAND.	Dense crust: Greyish and yellowish brown silty fine to medium SAND with depth becoming brown and dark brown to black silty organic CLAY with occasional roots and rootlets.	Stiff greyish brown, locally dark flecked, becoming brown and steel grey with pinkish brown and orange brown mottling, very silty CLAY.	Firm brown and dark brown amorphous and fibrous PEAT with some flattened plant (reed?) stems.	Medium dense slightly greyish brown locally dark flecked silty fine SAND with depth becoming steel grey mottled orange brown.	Firm chestnut brown and dark brown amorphous and fibrous PEAT, close to saturation.
In-situ moisture content	/	/	/	/	/	/	/	/	/
Initial moisture content and density (laboratory)	/	/	/	/	/	/	/	/	/
Final moisture content (laboratory)	/	/	/	/	/	/	/	/	/
Particle size distribution analysis	/	/	/	/	/	/		/	
Tension infiltrometer	/	/	/	/	/	/			
Pressure Infiltrometer	/	/			/				
Sample for laboratory determined permeability	/	/	/	/	/	/			

2 Results

2.1 IN-SITU TESTING

2.1.1 Description

Determination of the initial and final moisture contents is fundamental to the interpretation of the tension infiltrometer test results. Moisture content was determined using a *ThetaProbe* (Delta-T Devices Limited, 1999). The calculations are based on volumetric moisture contents. The soil moisture probe gives direct readings of the volumetric moisture content. However, it requires prior calibration at two different moisture contents, which is not viable in material of variable density and grading, as encountered in the mine tailings. Accordingly, it was been necessary to resort to more traditional, laboratory-based methods of sampling and moisture content determination for analytical purposes.

It should also be noted that the wetted front associated with the test zone extends to limited depth and the samples obtained for moisture content determination need to be limited to this zone. Soil density determinations have been made by taking core samples of known volume, from immediately adjacent to the test site, for weighing and moisture content determination.

The Guelph Permeameter is used to perform in-situ, constant head borehole infiltration tests (Reynolds, 1993a; Reynolds and Elrick, 1985 and 1986) on soils with field saturated permeabilities (K_{fs}) in the range 10^{-4} to 10^{-8} m/ sec. Reynolds and Elrick (1985) found the K_{fs} values effectively average the vertical and horizontal K_s values and established that using the Richards equation, which allows for capillarity gives a more representative estimate of K_{fs} than the Laplace analysis, which overestimates it. An adaptation of this, the Guelph Pressure Infiltrometer is a means of determining field saturated hydraulic conductivity at surface, utilising constant head testing, via a surface infiltrometer (Soil Moisture Equipment Corp., 1992). The tests were conducted with heads of between 1.75 and 10 cm.

The BGS Guelph tension infiltrometer is of the crust-imposed steady state category (Banks et al., 2009). It incorporates a circular disc (~20 cm diameter) comprising nylon membrane (infiltrometer foot assembly), over which the Guelph permeameter reservoir assembly and Mariotte siphon head control device (bubble tower) are seated. The tension is determined by the height of water column in the bubbler tower (to a maximum tension of 25 cm). The test is continued until the rate of fall is constant. Infiltration rates are measured for periods of a few minutes to ~ 2 hours (Stephens, 1996) to determine the steady state flow rate of water into the soil. The initial readings (capillary dominated infiltration) are crucial to the interpretation of the results. Once steady state conditions are reached gravity dominates infiltration. Tests were carried out at a range of tensions, broadly -25, -15, -10, -5 and 0.

2.1.2 Results

Steady, ponded infiltration from within the pressure infiltrometer into unsaturated soil can be approximated by a standardised approach to the Richards equation presented by Reynolds (1993) and Reynolds and Elrick (1990):

$$Q_s = (a/G)(K_{fs}H+\varphi_m)+\pi a^2K_{fs}$$

Where:

a is the ring radius; G a dimensionless shape factor; H is the steady depth of ponding in the ring and φ_m is the matrix flux potential.

Reynolds and Elrick (1990) define G:

$G = 0.316(d/a) + 0.184$

Where:

d is the depth of ring insertion.

Soil Moisture Equipment Corporation (1992) recommend the simultaneous equation, or regression approach to the Richards analysis and provide a simple, standardised approach to interpretation of steady state flow conditions:

$Kfs = (G/a)[\Delta(AR)/\Delta H]$

Where:

$\Delta(AR/\Delta H$ is the slope of the linear least squares regression line through a plot of AR vs H); A is the cross-sectional area [cell constant, cm^2]; R is the steady rate of fall of the water level in the reservoir, and a (cm) is the inner ring radius.

Using the standardised approach the following results were obtained:

Table 2: Field saturated permeability determined with the Pressure Infiltrometer.

Location Reference	NGR	Field saturated permeability (m/s)
AA	72179 74307	1.3E-04
BB	72197 74286	3.8E-06
EE	72242 74248	1.4E-04

Analysis of the tension infiltrometer test results was undertaken using the computer programme DISC (Šimůnek and van Genuchten, 2000). There were insufficient data for hydraulic parameter optimisation for each of the tests that were undertaken. It is considered that this is attributable to the very low permeability of the tailings under negative heads. A component of the DISC programme comprises parameter prediction from: the bulk density and percentage of sand, silt and clay in the soil. The resultant moisture retention curves are considered in section 3.2.

2.2 LABORATORY TESTING

The laboratory testing was undertaken in the BGS Keyworth Soils Testing Laboratory. Testing included the following:

- Moisture content analyses;
- Bulk and dry density determinations;
- Particle density determinations;
- Particle Size distribution analyses, and
- Falling head permeability testing.

Moisture content was determined through oven drying of the samples using BSI:1377:1990: Test 3 (BSI, 1990). A representative sub-sample of the main test sample was taken and placed into a clean, dry tin of known weight, m_1, to the nearest 0.01 g. The size of the sub-sample was dependent upon the size of the particles present, usually greater than 100 g. Large gravel or cobbles were removed. The sub-sample and the tin were reweighed, m_2, and placed into an oven at 105°C to 110°C until it attained a constant weight, usually 24 hours. The tin and oven dry sample were allowed to cool in a desiccator which contained dry silica gel and reweighed, m_3. The moisture content of the soil, w, was calculated as a percentage of the dry soil mass to the nearest 0.1%, from the equation:

$$w_i \quad \% \quad = \quad 100 \times (m_2 - m_3)/(m_3 - m_1)$$

where m_1 mass of the container (g);
m_2 mass of the container and wet soil (g);
m_3 mass of the container and dry soil (g).

Soil density determinations have been made by taking core samples of known volume, from immediately adjacent to the test site, for weighing and moisture content determination. Particle density analyses were determined using the Pyknometer technique detailed in BS 1377 (1990), Part 2, Test 8.4. Particle size distribution analyses were carried out using sieving (for the coarser fraction) and X-ray sedigraph (for the finer fraction) techniques. The falling head tests were carried out following the procedure outlined in Head (1994) Volume 2.

The results of the laboratory testing are presented in Appendix 1 and have been summarised in Table 3.

Some of the samples indicate a decrease in moisture content following the in-situ hydraulic testing. It is suggested that this difference (initial to final) reflects the highly variable properties of the materials tested.

Table 3: Summary of laboratory test results.

National Grid Reference	Sample	Laboratory sample description	Moisture Content (%)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)	Permeability (m/s)
27179 74307	AA (initial)	Very silty SAND	12.21	1850	1649	2.2E-06
	AA (post test)		21.23	1825	1505	
72197 74286	BB (initial)	Very silty SAND	23.21	1985	1611	4.7E-06
	BB (post test)		21.50	2077	1710	
72228 74266	CC (initial)	Silty SAND	14.53	2317	2023	2.1E-06
	CC (post test)		15.42	2176	1885	
72228 74266 At 0.25 m depth	DD (initial)	Silty SAND	22.42	2199	1796	4.0E-07
	DD (post test)		24.43	2084	1675	
72242 74248	EE (initial)	Slightly clayey, very silty, SAND	16.80	2355	2016	2.9E-06
	EE (post test)		14.26	2227	1949	
72250 74221	FF (initial)		21.49	1933	1591	
	FF (post test)		23.54	2163	1751	
72256 74279	GG (initial)		214.95	1077	342	
	GG (post test)		200.00	1064	355	
72284 74269	HH (initial)		10.84	2026	1828	
	HH (post test)		13.84	2234	1962	
72307 74284	II (initial)		250.98	1144	326	
	II (post test)		265.98	1134	310	

3 Tailings characterisation

3.1 SUMMARY AND COMPARISON OF RESULTS

The results of this phase of field work indicate that the saturated permeability of the mine tailings ranges between 3.8 E -06 and 1.4 E -04 m/s, as determined by the pressure infiltrometer.

The laboratory determined saturated permeabilities ranged between 4.0 E -07 and 4.7 E -06 m/s.

Field and laboratory determined permeabilities for samples AA, BB and EE have been presented in Table 4 for comparative purposes. The higher permeabilities determined for samples AA and EE indicate more sandy material, which would not have been suitable for undisturbed sampling. The range in permeabilities reflects the lateral and horizontal variability in the grain size of the tailings.

Table 4: Comparison of field and laboratory determined permeabilities.

Location Reference	**Field determined saturated permeability (m/s)**	**Laboratory determined saturated permeability (m/s)**
AA	1.3E-04	2.2E-06
BB	3.8E-06	4.7E-06
EE	1.4E-04	2.9E-06

The variability in the permeability confirms the finding of the results determined during the commissioning of the tension infiltrometer equipment (Banks et al., 2009), when field saturated permeabilities were found to range between 3.0 E -06 and 5.2 E -04 m/s with DISC modelled values ranging from 1.5 E -07 to 1.7 E -04 m/s.

During the borehole investigation described by Bearcock et al. (2010) falling head tests were attempted in two of the open boreholes, but the rate of drainage (~1 m of head draining in <10 s) was too great for the calculation of permeability. This further supports the concept of a high horizontal permeability.

3.2 EMPIRICAL DERIVATIONS OF HYDRAULIC CONDUCTIVITY

Particle size distribution analyses are commonly used as a means of empirical derivation of hydraulic conductivity. Comparison of the grading analyses (Appendix 2) with the laboratory and field determined permeabilities would suggest that there are other factors that influence the hydraulic conductivity of the mine tailings. Examination of the materials would suggest that the key influence is the structured nature of the tailings. It is suspected by the authors that there is a significant difference in the vertical and horizontal permeability of these materials, which can be attributed to the method of placement, essentially settling out from suspension in the lagoon, which results in a preferential alignment of the particles as they settle. The structured nature of the deposits can be seen in Figure 3 and results in a higher horizontal than vertical permeability.

Notwithstanding the observations above, the DISC programme for analysing the results of the tension infiltrometer testing incorporates the pedotransfer functions of Schaap et al. (1999), thereby generating soil moisture retention curves derived from the particle size distribution, gradings. The results have been appended to this report (Appendix 3) for completeness, but given the information presented above, it is considered that they should only be treated as a guide and indication of the range of permeability with changes in moisture content.

3.3 IMPLICATIONS FOR THE CONCEPTUAL SITE MODEL

Three trial pits were excavated in the tailings lagoon in August 2006 (Appendix 2). The logs indicate that the tailings are underlain by a layer of peat (Figure 4), in the order of 20 to 30 cm thick that sits on a thin clay layer resting on shattered bedrock. Groundwater was encountered in both the mine tailings and the shattered bedrock. This indicated recharge to a shallow aquifer beneath the peat as well as infiltration to the tailings, which has informed the conceptual model presented by Bearcock et al. (2010). It is considered that the water level in the tailings is controlled by the outlet via drainage pipe and a culvert at SN 723 741. There is no instrumentation extending down into the shattered bedrock, so groundwater levels in the shallow bedrock remain unknown. The extent and orientation of the drainage associated with the drainage culvert is not known.

Figure 3: Kubiena tin sample showing variation in grading of the tailings. Figure 4: Peat exposed beneath the tailings.

The hydrogeology of the tailings lagoon is clearly more complex than might be anticipated. The evidence suggests that the structured (layered) nature of the lagoon exerts a strong influence on the ratio of the vertical to horizontal hydraulic conductivity. The results from the “falling head tests” in the boreholes indicate a high hydraulic conductivity. By contrast observations made during a storm event during the July 2008 fieldwork suggest a significant proportion of overland flow. This observation is supported by the extensive channelling over the surface of the lagoon with channels reaching in the order of 1.0 m in depth and 0.5 m in width (Figure 5).

The implications are that recharge to the shallow bedrock aquifer occurs around the edges of the lagoon. It is also likely that recharge to the tailings is strongly guided by the structured (laminated to bedded) nature of the deposits.

Figure 5: Channelling in the tailings. Figure 6: Bianchite on tailings, August 2006.

It should also be noted that the drainage pipe discharging to surface water via the culvert at SN 723 741is unlikely to drain from the base of the tailings. The artificial lowering of the water table with impeded drainage below this level in the tailings has resulted in a supply of water and a depth of unsaturated zone that provides the right conditions for capillary rise during periods of prolonged dry weather, as observed in August 2006, when the efflorescent mineral bianchite was observed on the surface of the tailings (Figure 6).

4 Conclusions.

The results of field and laboratory testing suggest that hydraulic permeability of the tailings ranges between 1.5 E -07 m/s and 5.2 E -04 m/s.

It is suspected that the horizontal permeability significantly exceeds the vertical permeability. This is a consequence of the laminated nature of the tailings that results from the depositional processes.

In the event that it is decided to cap the tailings lagoon, careful consideration will need to be given to the design of the cap in terms of: its material properties; its gradient and drainage. This area serves as a collector for much of the surface runoff from the surrounding areas, particularly from the north and west.

Field observations have provided evidence of evapotranspiration in the tailings, which should also be mitigated for in any proposed remediation.

Water balance calculations would be useful to further develop the conceptual site model for this site.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://envirolib.bgs.ac.uk.

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Appendix 1 Laboratory test results

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site AA	
Pyknometer Number			160	39
Mass of Bottle	m1	g	30.824	25.126
Mass of Bottle + Soil	m2	g	40.172	34.189
Mass of Bottle+Soil+Water	m3	g	88.490	80.638
Mass of Bottle full of Water	m4	g	82.586	74.912
Mass of Soil	m2-m1	g	9.348	9.063
Mass of Water in full Bottle	m4-m1	g	51.762	49.786
Mass of Water used	m3-m2	g	48.318	46.449
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	3.444	3.337
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.714	2.716
Average Value, Þs		Mg/m^3	2.72	
		Operator	**Checked**	**Approved**
		MK		

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site BB	
Pyknometer Number			14	12
Mass of Bottle	m1	g	25.530	25.234
Mass of Bottle + Soil	m2	g	34.408	37.540
Mass of Bottle+Soil+Water	m3	g	81.604	82.465
Mass of Bottle full of Water	m4	g	75.946	74.630
Mass of Soil	m2-m1	g	8.878	12.306
Mass of Water in full Bottle	m4-m1	g	50.416	49.396
Mass of Water used	m3-m2	g	47.196	44.925
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	3.220	4.471
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.757	2.752
Average Value, Þs		Mg/m^3	2.75	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site CC	
Pyknometer Number			41	122
Mass of Bottle	m1	g	25.324	35.680
Mass of Bottle + Soil	m2	g	33.279	43.609
Mass of Bottle+Soil+Water	m3	g	79.877	90.196
Mass of Bottle full of Water	m4	g	74.827	85.164
Mass of Soil	m2-m1	g	7.955	7.929
Mass of Water in full Bottle	m4-m1	g	49.503	49.484
Mass of Water used	m3-m2	g	46.598	46.587
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	2.905	2.897
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.738	2.737
Average Value, Þs		Mg/m^3	2.74	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site DD (1)	
Pyknometer Number			478	15
Mass of Bottle	m1	g	27.856	24.064
Mass of Bottle + Soil	m2	g	37.209	33.417
Mass of Bottle+Soil+Water	m3	g	83.738	80.568
Mass of Bottle full of Water	m4	g	77.625	74.457
Mass of Soil	m2-m1	g	9.353	9.353
Mass of Water in full Bottle	m4-m1	g	49.769	50.393
Mass of Water used	m3-m2	g	46.529	47.151
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	3.240	3.242
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.887	2.885
Average Value, Þs		Mg/m^3	2.89	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site DD (2)	
Pyknometer Number			14	41
Mass of Bottle	m1	g	25.531	25.323
Mass of Bottle + Soil	m2	g	35.552	35.967
Mass of Bottle+Soil+Water	m3	g	82.375	81.638
Mass of Bottle full of Water	m4	g	75.947	74.826
Mass of Soil	m2-m1	g	10.021	10.644
Mass of Water in full Bottle	m4-m1	g	50.416	49.503
Mass of Water used	m3-m2	g	46.823	45.671
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	3.593	3.832
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.789	2.778
Average Value, Þs		Mg/m^3	2.78	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site EE	
Pyknometer Number			15	122
Mass of Bottle	m1	g	24.064	35.680
Mass of Bottle + Soil	m2	g	32.642	44.361
Mass of Bottle+Soil+Water	m3	g	79.915	90.679
Mass of Bottle full of Water	m4	g	74.457	85.162
Mass of Soil	m2-m1	g	8.578	8.681
Mass of Water in full Bottle	m4-m1	g	50.393	49.482
Mass of Water used	m3-m2	g	47.273	46.318
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	3.120	3.164
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.749	2.744
Average Value, Þs		Mg/m^3	2.75	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site FF	
Pyknometer Number			160	478
Mass of Bottle	m1	g	30.828	27.856
Mass of Bottle + Soil	m2	g	38.809	35.435
Mass of Bottle+Soil+Water	m3	g	87.703	82.488
Mass of Bottle full of Water	m4	g	82.590	77.625
Mass of Soil	m2-m1	g	7.981	7.579
Mass of Water in full Bottle	m4-m1	g	51.762	49.769
Mass of Water used	m3-m2	g	48.894	47.053
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	2.868	2.716
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.783	2.791
Average Value, Þs		Mg/m^3	2.79	

Particle Density (Pyknometer). BS 1377: Part 2: 1990, Test 8.4

Specimen Reference			Frongoch Site HH	
Pyknometer Number			12	39
Mass of Bottle	m1	g	25.230	25.126
Mass of Bottle + Soil	m2	g	33.317	33.844
Mass of Bottle+Soil+Water	m3	g	79.944	80.632
Mass of Bottle full of Water	m4	g	74.626	74.910
Mass of Soil	m2-m1	g	8.087	8.718
Mass of Water in full Bottle	m4-m1	g	49.396	49.784
Mass of Water used	m3-m2	g	46.627	46.788
Volume of Soil Particles	(m4-m1)-(m3-m2)	mL	2.769	2.996
Particle Density, Þs =	$\frac{m2-m1}{(m4-m1)-(m3-m2)}$	Mg/m^3	2.921	2.910
Average Value, Þs		Mg/m^3	2.92	

Moisture content and bulk density analyses.

Sample	Moisture Content (%)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)
AA (initial)	12.21	1850	1649
AA (post test)	21.23	1825	1505
BB (initial)	23.21	1985	1611
BB (post test)	21.50	2077	1710
CC (initial)	14.53	2317	2023
CC (post test)	15.42	2176	1885
DD (initial)	22.42	2199	1796
DD (post test)	24.43	2084	1675
EE (initial)	16.80	2355	2016
EE (post test)	14.26	2227	1949
FF (initial)	21.49	1933	1591
FF (post test)	23.54	2163	1751
GG (initial)	214.95	1077	342
GG (post test)	200.00	1064	355
HH (initial)	10.84	2026	1828
HH (post test)	13.84	2234	1962
II (initial)	250.98	1144	326
II (post test)	265.98	1134	310

Particle Size Distribution Analyses

Sample AA

Type	%
Gravel	1.1
Sand	59.8
Silt	30.3
Clay	8.8

Sample BB

Type	%
Gravel	0.3
Sand	76.4
Silt	18.7
Clay	4.6

Sample CC

Type	%
Gravel	3.1
Sand	82.3
Silt	10.1
Clay	4.6

Sample DD

Type	%
Gravel	0.0
Sand	19.3
Silt	73.0
Clay	7.6

Sample EE

Type	%
Gravel	2.7
Sand	58.6
Silt	29.4
Clay	9.3

Sample FF

Type	%
Gravel	0.4
Sand	10.8
Silt	66.6
Clay	22.2

Sample HH

Type	%
Gravel	3.1
Sand	55.7
Silt	32.6
Clay	8.6

Appendix 2 Trial Pit Logs.

Trial Pit Ref:	**FRS 3001 (SN 72196 74292), 09/08/06**				
Depth (m)	**Description**	**Groundwater detail**	**Sample depth (m)**	**mc (%)**	**Notes**
0.00 - 0.17	Light olive brown (2.5Y 5/3) sandy SILT, with orange brown mottling towards the base		0.00 - 0.17		Sampling: 2 No. paper envelopes and one plastic bag
0.17 - 0.74	Dark grey (7.5YR 4/1) fine silty SAND		0.17 - 0.74		
0.74 - 1.00	Dark reddish grey (2.5YR 4/1) finely laminated silty CLAY, with brown to grey and orange laminae, orange brown mottling and organic fibres		0.74 - 1.00		
1.00 - 1.40	Dark grey to black (2.5Y 2.5/1) fine gravelly coarse SAND, with occasional organic fibres and including quartz grains	Groundwater encountered at 1.20m depth, standing at 1.50m	1.00 - 1.40		Groundwater: eH 217 mV; pH 5.33; Electrolytic Conductivity 686 uS; Temperature 18.6 C and Alkalinity 0 mg/kg
1.40 - 1.65	Soft dark slightly brownish grey and dark grey (GLEY 3/1) finely laminated clayey SILT		1.40 - 1.65		Pit sides starting to fail
1.65 - 2.20	Soft light brown and grey silty CLAY with fragments of slate and occasional pockets of dark brown amourphous peat towards the base of the stratum		1.65 - 1.95		
2.20 - 2.50	Brown, becoming dark brown firm amorphous with some fibrous PEAT				
2.50 - 2.70	Soft bluish grey clayey SILT with slate fragments				Pit dimensions approximately 1.0 x 3.00m, orientated approximately east-west and backfilled with arisings upon completion.

Trial Pit Ref:	**FRS 3002 (SN 722228 74266), 09/08/06**				
Depth (m)	**Description**	**Groundwater detail**	**Sample depth (m)**	**mc (%)**	**Notes**
0.00 - 0.80	Tailings				No samples taken
0.80 - 1.0	Peat, with tree trunk				Assumed to be disturbed ground pit relocated to position 3003. Pit dimensions 1 x 2m, oriented approximately east to west

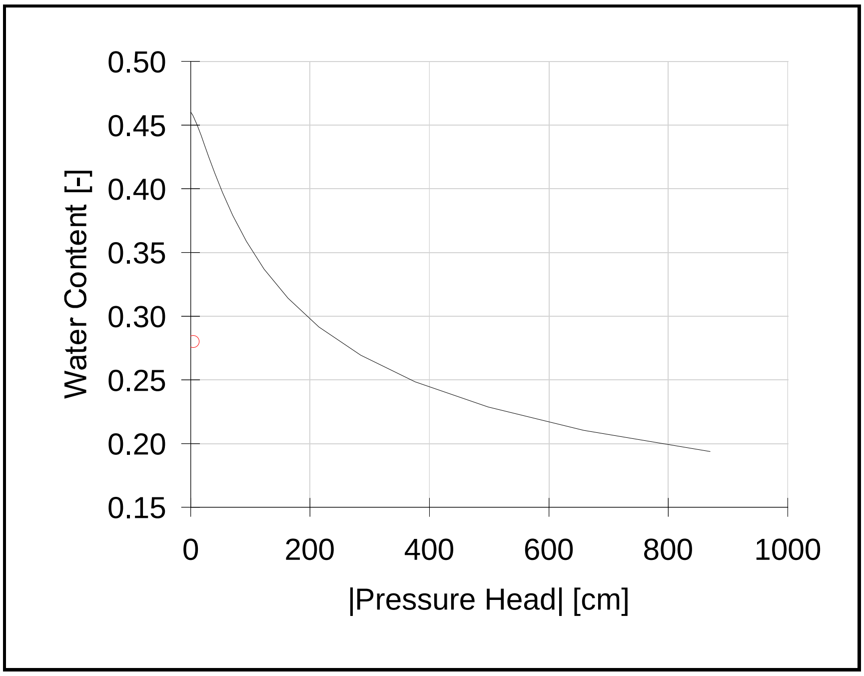
Trial Pit Ref: **FRS 3003 (SN 72213 74254), 09/08/06**

Depth (m)	Description	Groundwater detail	Sample depth (m)	mc (%)	Notes
0.00 - 0.18	Slightly yellowish brown (5Y 4/4 and 5/4) silty fine to coarse SAND with occasional clay laminae		0.00 - 0.18		Sampling: 2 No. paper envelopes
0.18 - 0.28	Laminated dark grey and light brown (10YR 3/1 and 5/2) fine clayey SILT		0.18 - 0.28		
0.28 - 0.87	Dark grey (GLEY 3/1) slightly silty, sandy fine GRAVEL		0.28 - 0.87		
0.87 - 1.15	Dark brownish grey to black (5Y 2.5/1) finely laminated silty CLAY tailings	Groundwater standing at 1.10m depth	0.87 - 1.15		Groundwater: eH 199 mV; pH 4.84; Electrolytic Conductivity 702 uS; Temperature 21.3 C and Alkalinity 0 mg/kg
1.15 - 2.40	Firm brown amorphous and fibrous (particularly on partings) PEAT, becoming darker in colour below 1.70m depth		1.15 - 1.50		Additional plastic bag sample of peat. Pit sides starting to fail, necessary to lengthen pit to achieve depth of excavation
2.40 - 3.35m	Soft to firm grey silty CLAY, becoming wet with much fragmented slate at 2.50m		2.40 - 2.50 3.25		Sample at 3.25m plastic bag. Second groundwater strike at 3.35m depth: eH 183 mV; pH 4.88; Electrolytic Conductivity 653 uS; Temperature 13.6 C and Alkalinity 0 mg/kgPit dimensions approximately 1.0 x 3.00m, orientated approximately east-west and backfilled with arisings upon completion.

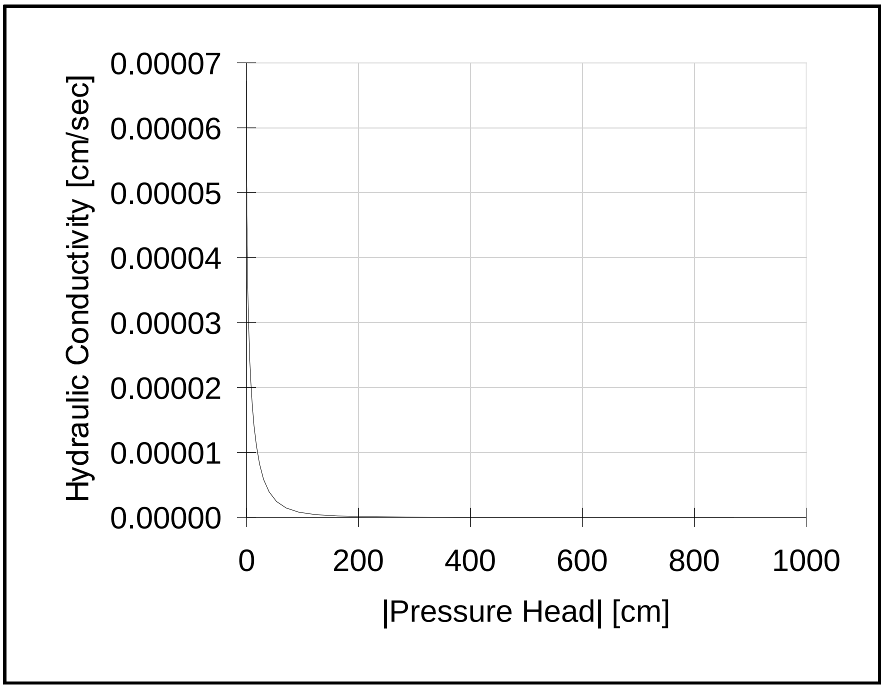
Appendix 3 Plots of moisture retention and hydraulic conductivity against head, derived from DISC.

Position AA

Hydraulic Properties: Theta vs. h

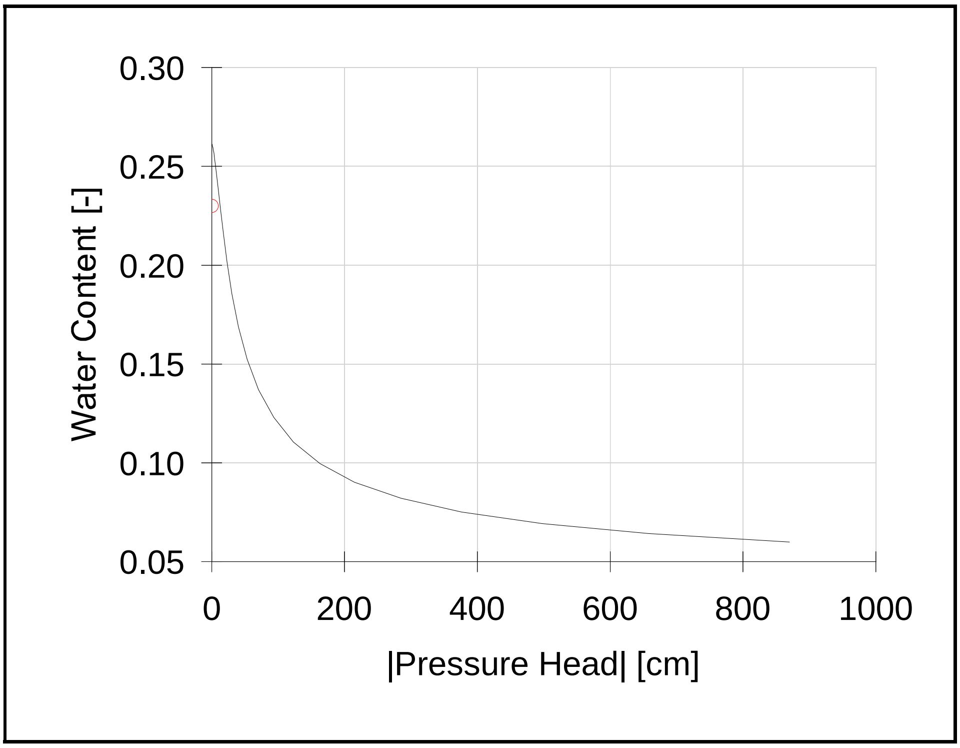


Hydraulic Properties: K vs. h

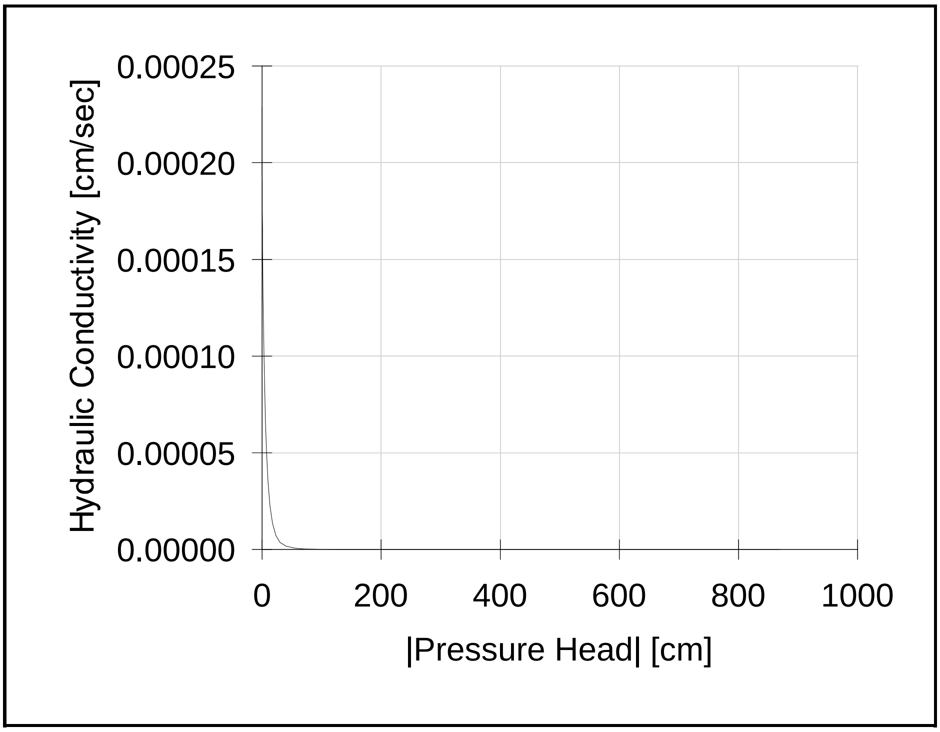


Position BB

Hydraulic Properties: Theta vs. h

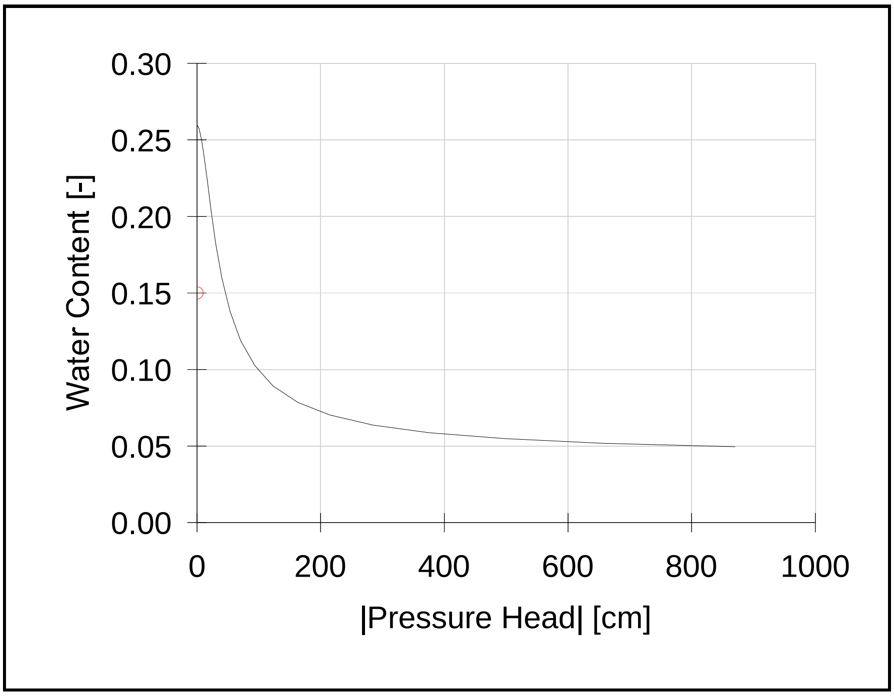


Hydraulic Properties: K vs. h

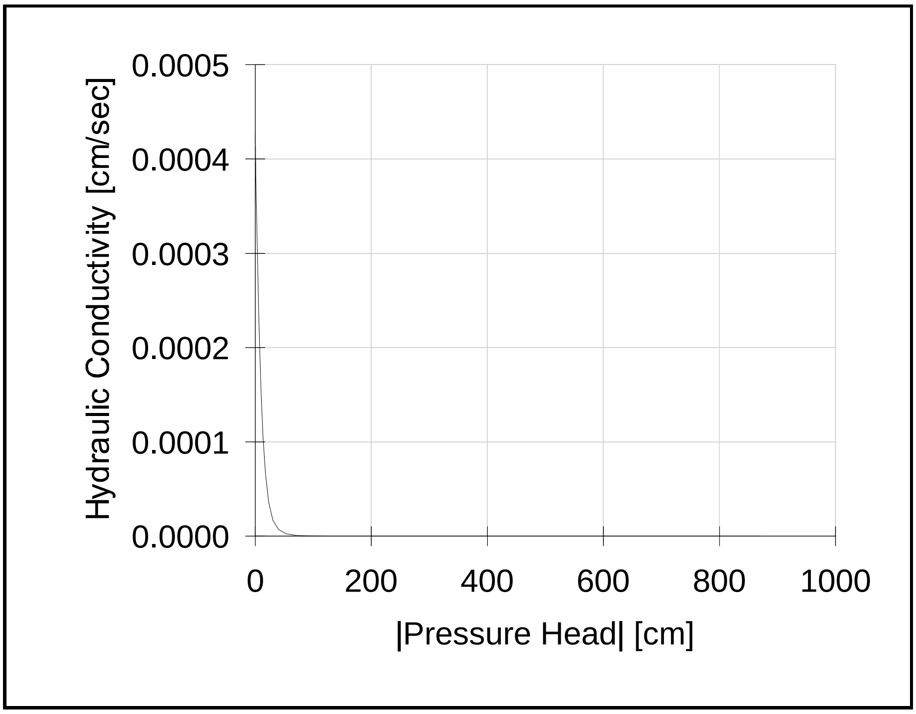


Position CC

Hydraulic Properties: Theta vs. h

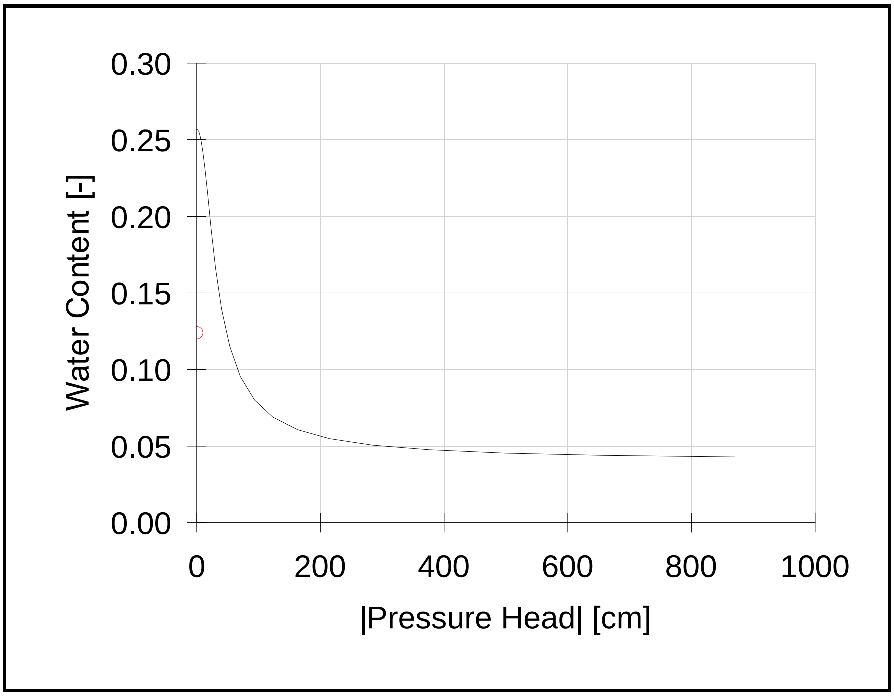


Hydraulic Properties: K vs. h

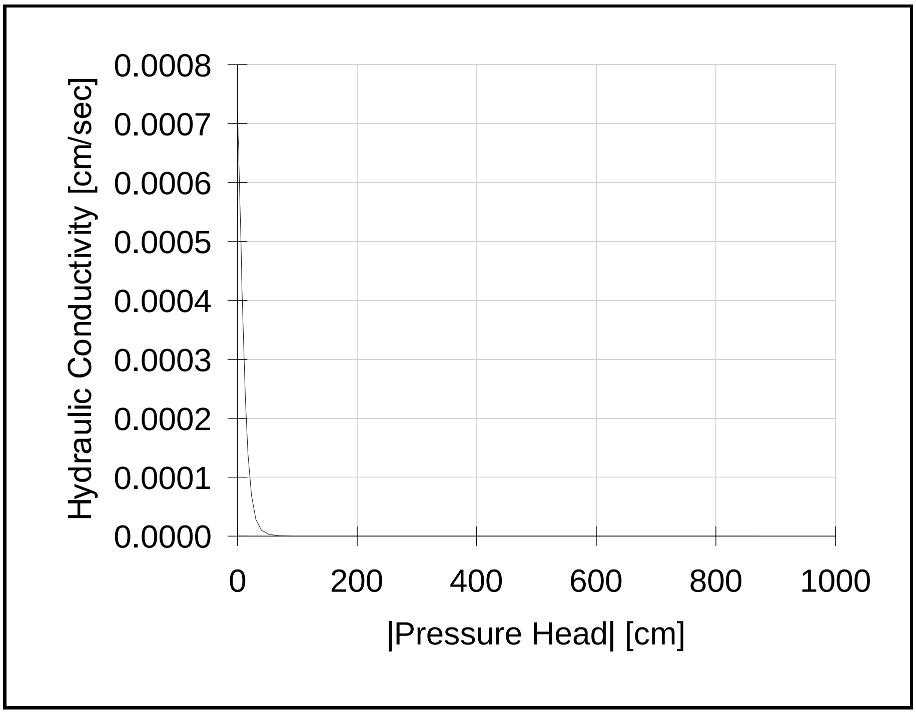


Position DD

Hydraulic Properties: Theta vs. h

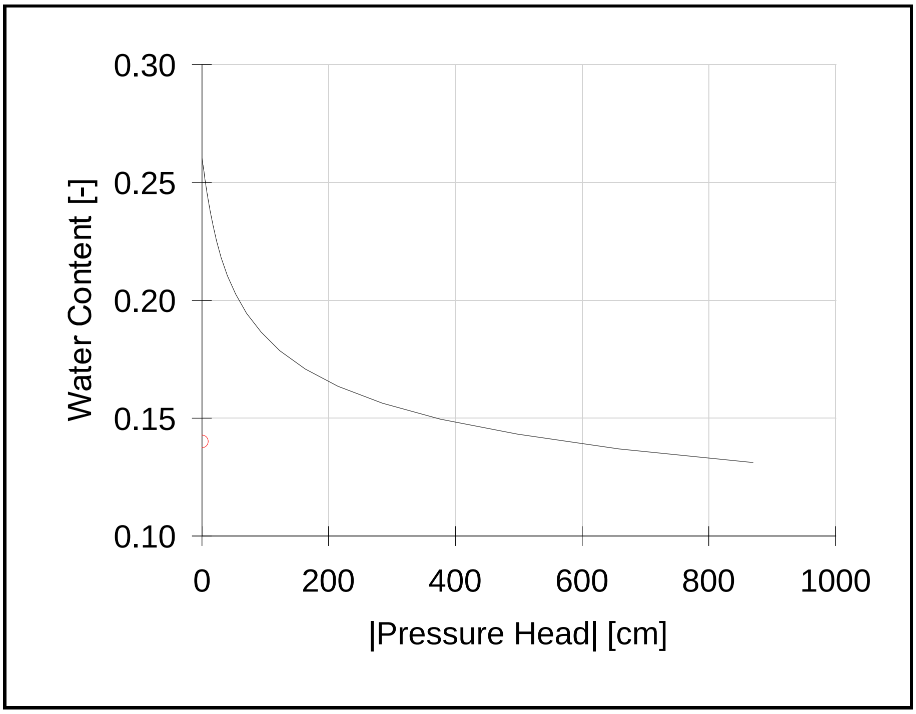


Hydraulic Properties: K vs. h

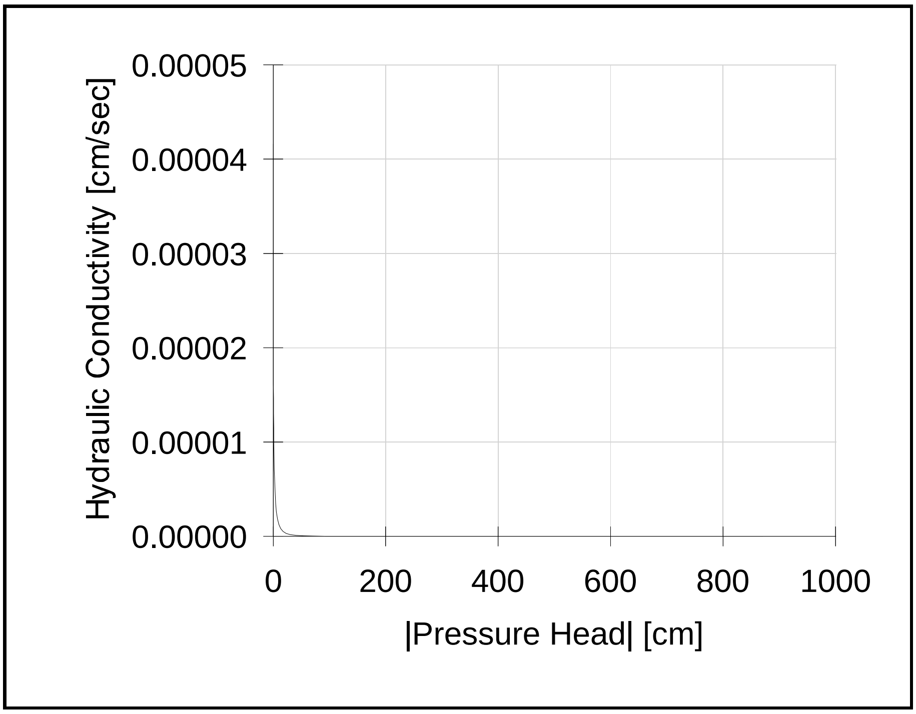


Position EE

Hydraulic Properties: Theta vs. h

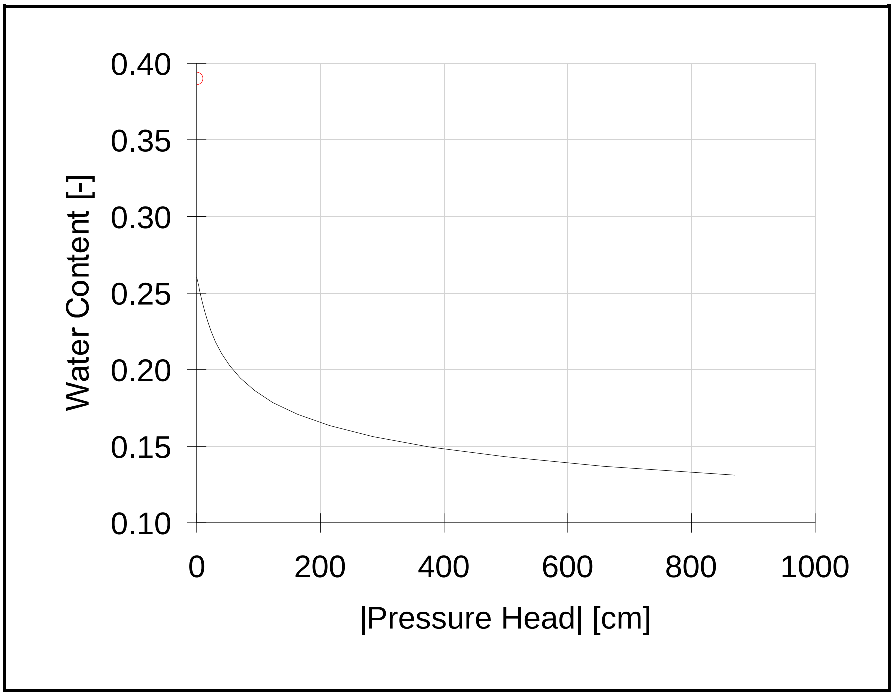


Hydraulic Properties: K vs. h

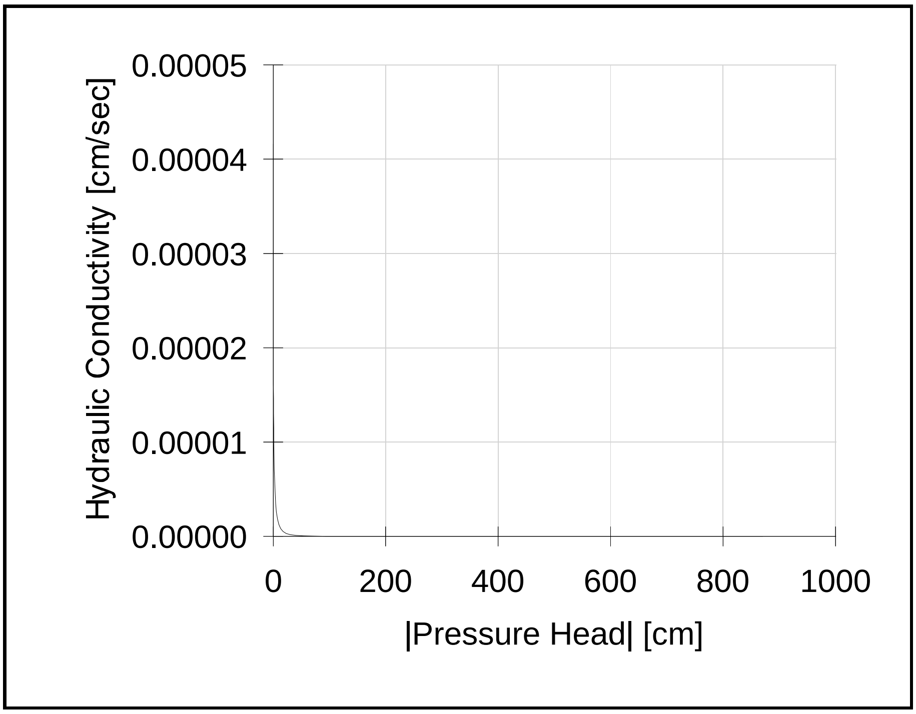


Position FF

Hydraulic Properties: Theta vs. h

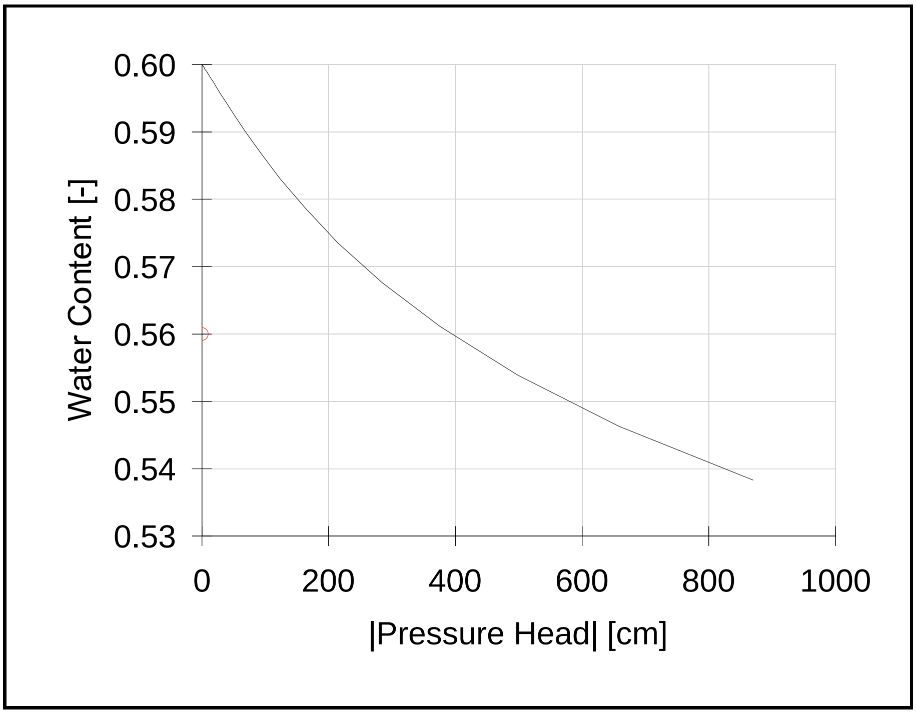


Hydraulic Properties: K vs. h

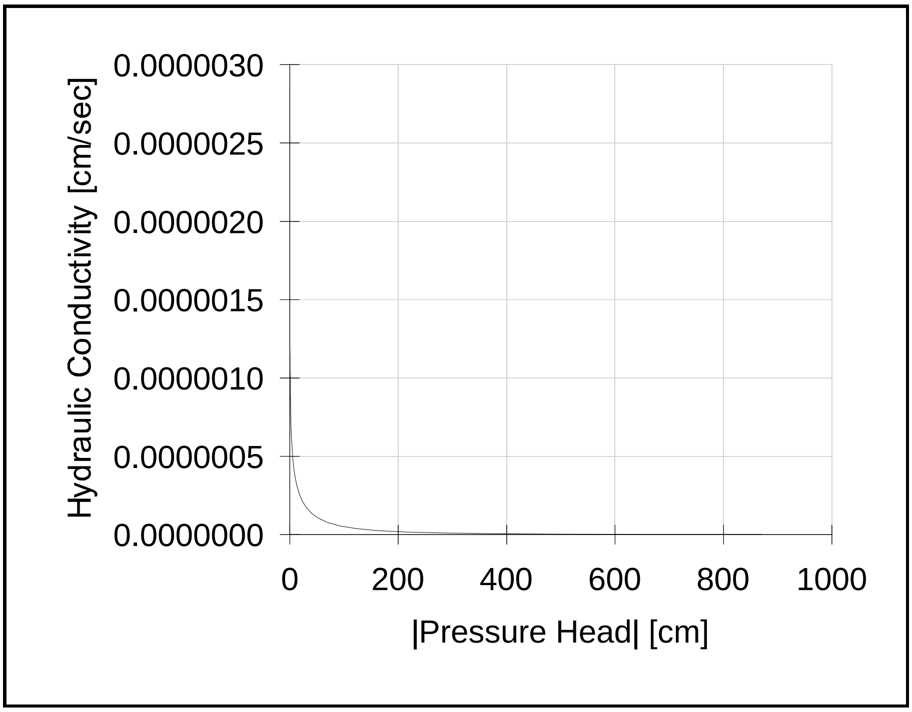


Position GG

Hydraulic Properties: Theta vs. h

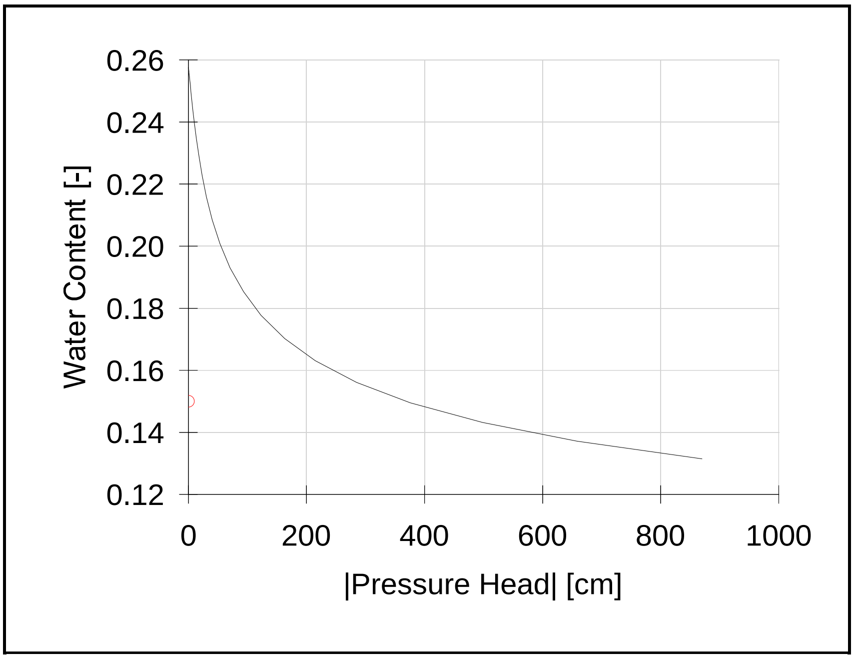


Hydraulic Properties: K vs. h



Position HH

Hydraulic Properties: Theta vs. h



Hydraulic Properties: K vs. h