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Use of peat as an engineering material: an engineering case study

L'utilisation de la tourbe comme un génie des matériaux: une étude de cas en génie

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ABSTRACT Part of a natural gas pipeline route constructed in Ireland passed through areas of ecologically sensitive and protected peat land habitats. To protect the sensitive habitats a number of construction and mitigation measures were employed using reworked peat as an engineering material to maintain the hydrological balance. Suitable low permeability peat derived from the works was used to provide acceptable hydraulic impedance barriers to isolate the works from the surrounding peat lands. Peat is generally not considered as an engineering material due to generally a lack of consensus on its behaviour, compressibility and low shear strength. Notwithstanding, peat (in the right circumstances) can be used as an engineering material with appropriate controls. The paper includes details of the use of peat in the works, together with the testing, analysis used to identify the appropriate low permeability peat to be used in the works.

RÉSUMÉ Une partie d'un réseau de pipelines de gaz naturel construit en Irlande a traversé des régions d'habitats de tourbières protégées et écologiquement sensibles. Afin de protéger les habitats sensibles un certain nombre de mesures de construction et d'atténuation ont été employées en utilisant principalement la tourbe retravaillée comme un matériau d'ingénierie, pour maintenir l'équilibre hydrologique. De la tourbe convenable de faible perméabilité, provenant des travaux, a été utilisée pour fournir des barrières d'impédance hydrauliques acceptables pour isoler les œuvres des tourbières environnantes. La tourbe n'est généralement pas considérée comme un matériau de construction en raison d'une absence de consensus sur son comportement, sa compression et sa faible résistance au cisaillement. Néanmoins, la tourbe (dans les circonstances adaptées) peut être utilisée comme un matériau de construction avec des contrôles appropriés. Le papier comprend des détails de l'utilisation de la tourbe dans les travaux, ainsi que les essais et analyses utilisés pour identifier la tourbe de faible perméabilité qui convient aux travaux.

1 CORRIB PROJECT & ONSHORE PIPELINE

The Corrib Project comprises the development of a natural gas field located approximately 83km off the coast of County Mayo, in northwest Ireland in 350m of water. The project involves the use of subsea gas production wells with processing of gas and control of subsea wells carried out from a gas terminal located onshore at Bellanaboy Bridge.

The pipeline from the field to the gas terminal is about 91km in length with about 83km of subsea pipeline and a further 8.3km of onshore pipeline (Figure 1). The project is being developed by Shell E & P Ireland Limited (SEPIL) with two partners, namely, Statoil Exploration (Ireland) Ltd and Vermilion Energy Ireland Limited.

The onshore section of the pipeline passes through and under a number of terrains. About 4.9km of the pipeline between the landfall at Glengad and Aughoose is within a tunnel that passes below Sruwaddacon Bay, which is an area of tidal mudflats that is a Special Protection Area. At Aughoose, the pipeline leaves the tunnel and the route passes through about 3km of peatland that comprises recovering eroded blanket peat and peatland planted with commercial forestry. The depth of peat ranges from 2m to locally up to 5m.

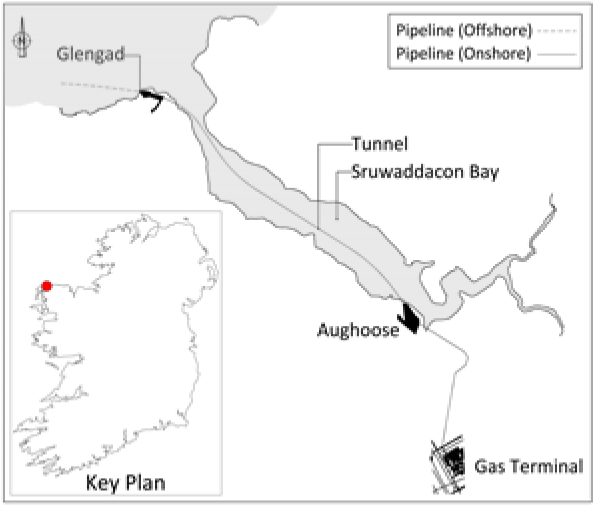

Figure 1. Location of onshore pipeline

Within the peatland the gas pipe is buried within a permanent stone road that comprised the removal of peat over a 12m wide corridor and replacement with stone fill (Figure 2). The use of a stone road within the peatland greatly reduces the risk of peat failure and provides a stable construction platform. Notwithstanding, the stone road introduces a significant body (over 100,000 m^3) of free-draining material into the peatland which could notably alter the hydrological balance. To protect the adjacent peatland a number of mitigation measures were employed, using essentially reworked peat as an engineering material, to maintain the hydrological balance of the adjacent peatland.

2 STONE ROAD CONSTRUCTION

As part of the stone road design there was a requirement to maintain a 0.5m thick layer of insitu peat below the stone road to act as an aquiclude that would impede the downward movement of water. Due to the low permeability of peat compared to the underlying mineral soil the 0.5m thick layer of insitu peat effectively acts as an impedance layer and limits downward movement of water from the stone road into the underlying mineral soil. This was seen as particularly important in certain peatland areas where the project team had identified the potential for recovery of eroding blanket bog.

As part of construction, suitable stone fill was placed into the peat layer to from a peat stone matrix. This was then subjected to load testing to ensure that it was stable for construction traffic. It was not possible at all locations due to construction activity to maintain the 0.5m thick layer of insitu peat. As a substitute, it was proposed to place a layer of reworked peat into the stone road during backfilling.

To assess the effectiveness and required thickness of a reworked peat layer a test programme was set up to establish the permeability of reworked peat (disturbed peat). This allowed quantification of the likely downward movement (leakage) of water from the stone road and allowed a construction specification for identifying acceptable peat for re-use in the works to be compiled.

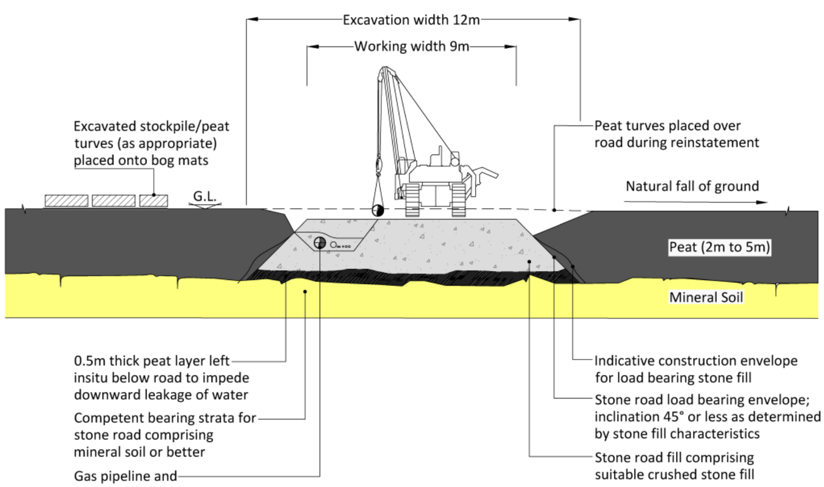

Figure 2. Typical stone road construction in peatland

3 PERMEABILITY OF REWORKED PEAT

3.1 Literature Review

Most technical papers reviewed addressed the permeability of intact (undisturbed) peat with only a limited number of papers covering the permeability of reworked (disturbed) peat. Notwithstanding, the principles that govern the permeability of intact peat can be applied to reworked peat to allow a reasonable assessment of its hydraulic behaviour.

The permeability of peat tends to be not only extremely variable spatially, but depends on the following:

- Amount of non-organic (mineral) matter,
- Extent of decomposition (humification), and
- Porosity of the peat (eg void ratio)

Mineral matter in peat is generally relatively low, particularly for Irish blanket peat which typically has an organic content in excess of 95%. Mineral matter that is present is typically due to airborne dust brought in by livestock, windblown coastal detritus, farm machinery or washed in by run-off/streams.

The decomposition (humification) of peat varies with depth. The upper layer of peat (acrotelm or vegetative layer) which is typically less than a metre deep contains living plant matter and is relatively undecomposed. The acrotelm layer has an open structure and its permeability is relatively high ranging from say 10^{-1} m/s at the peat surface decreasing to low values as decomposition increases at its base (say 10^{-6} m/s).

The catotelm layer, which underlies the acrotelm, contains essentially plant matter in varying degrees of decomposition (also referred to as humification). As may be expected, due to the much higher degree of humification and a greater degree of consolidation, the catotelm has notably lower permeability (less than 10^{-6} m/s).

There is a wide spread of peat permeability values (10^{-3} to 10^{-10}m/s) quoted in the literature from laboratory test results. It is difficult to relate the quoted permeability values to say degree of humification as in many cases the description of the tested peat is to general. Permeability results were typically determined on undisturbed (intact) peat samples; however a number of sources report permeability values for peats of varying types and states of humification (Figure 3).

Humification is the term given to describe the change of state from fresh plant matter to peat based on the von Post system (1922). Humification values range from H1 for intact young peat, to H10 for completely decomposed peat.

Permeability and humification values are given for various degrees of humification in Figure 3. From Crum (1992), fibric peat is mostly undecomposed and consists primarily of sphagnum moss. Hemic peat contains one to two thirds plant fibre. Sapric peat contains less than a third plant fibre.

As can be seen from Figure 3, there is a notable trend showing decreasing permeability with increasing degree of humification. A similar trend was reported by Bell (1991) from insitu measurement.

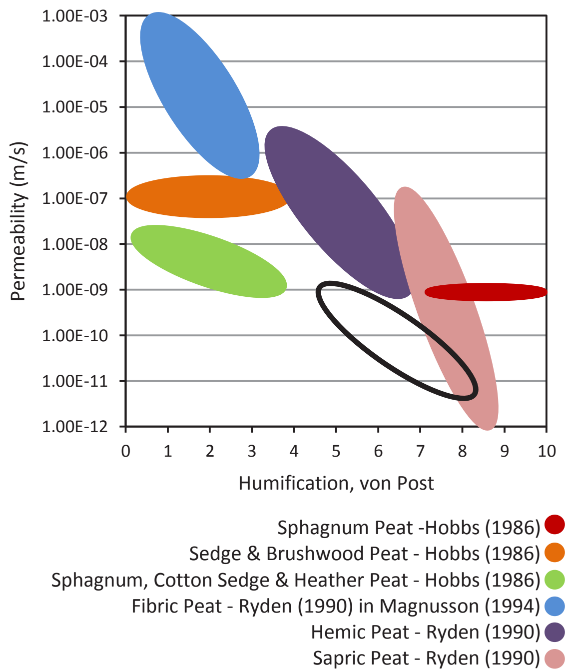

Figure 3. Relationship between humification and permeability (Peat from Corrib Project shown in black with no colour fill)

The permeability of all soils is determined by void ratio, size and shape of flow channels (Mesri and Ajlouni, 2007). Large void ratios, large pores, and straight flow channels result in high permeability, while small void ratios, small pores, and contorted flow channels result in low permeability. Hence it is not surprising that virgin fibrous peat has a very high permeability as it is characterised by a very porous

structure. Conversely, highly decomposed peat has reduced void ratio and water content and hence lower permeability.

An envelope of peat results from a number of sources showing permeability versus void ratio (O'Loughlin, 2007) clearly shows the reduction in permeability (k) with reduction in void ratio, which is described by the equation:

$$k = k_0 \left(\frac{e}{e_0} \right)^n \text{ .... (1)}$$

Where
e_o initial void ratio
e void ratio
k_o initial permeability
n constant

The best fit for equation (1) indicates k of 10^{-5} m/s at e = 22, reducing by 7 orders of magnitude to k = 10^{-10} m/s at e = 4.2. A void ratio of 2.5 is compatible with a moisture content of 300% (assuming G_s = 1.4 for peat: Skempton & Petley, 1970; Hobbs, 1986; Farrell, 1997; Nichol & Farmer, 1998).

Using equation (1), it is reasonable to suggest that the permeability of reworked peat, which will have a lower moisture content than intact peat, is likely to approach limiting values in the range, k = 10^{-10} to 10^{-12} m/s. As this is typical of the permeability of clays used as liners/capping for landfills (less than 10^{-9} m/s), it is reasonable to suggest that the peat will act in a similar (impedance) manner to a clay liner.

At the Lisheen mine site, research on reworked peat showed a decrease in permeability with reworking (Dillon et al. 2004). Typical insitu measurements of intact peat permeability were of the order of 10^{-8} m/s. Following reworking of peat samples and preloading in consolidation tests permeability values reduced to 10^{-11} m/s. The decrease in permeability was likely attributable to the destruction of any existing structure within the peat and the addition of consolidation from loading.

4 TEST PROGRAMME

The test programme to determine the permeability of reworked peat comprised field testing and laboratory testing of peat samples.

4.1 Field Testing

Fieldwork was undertaken at three peat locations at the gas terminal site at Bellanaboy and at a nearby peat deposition site at Srahmore near Bangor Erris, County Mayo. The fieldwork comprised initially ground investigation to establish and characterise the ground profile at all locations. Following the ground investigation insitu large scale permeability tests and insitu piezometer permeability testing was carried out in both intact and reworked peat.

Where appropriate the fieldwork was carried out in line with BS5930:1999 (British Standards Institution, 1999). The following testing was carried out:

- Intact peat: Water level recovery data recorded in piezometers following their installation was analysed to determine an approximate permeability value for intact peat. This was to assess the baseline peat permeability conditions.
- Reworked peat: Rising head permeability tests carried out in piezometers installed in gouge core holes/boreholes within placed reworked peat at gas terminal site.
- Reworked peat: Rising head permeability tests carried out in piezometers installed in gouge core holes within reworked peat at the Srahmore site. This placed peat was transported to Srahmore in 2007 and originated from the gas terminal site.
- Reworked peat: Large scale permeability tests using large diameter water-filled pipes embedded in reworked peat.

Determination of permeability of peat from field testing was carried out using the variable head technique outlined in Section 25.4 of BS5930: 1999. The results are summarised below:

- Permeability tests for peat carried out in piezometers showed that reworked peat has a permeability of about 10-9 to 10-10 m/s, which was slightly lower than the permeability of intact peat which had a permeability of about 10-9 m/s. This corresponds with the results of the literature review.
- Peat permeability results determined from large scale field tests ranged from 3.5 x 10-8 to 4.1 x10-9 m/s. These results are higher than those results obtained from permeability tests carried out in piezometers, and it was suspected that there was possible preferential leakage of water from the water-filled pipes in the large-scale tests.

4.2 *Laboratory Testing*

Disturbed (reworked) and undisturbed peat samples were obtained during the investigation for testing. Testing was undertaken on the peat to classify and determine engineering properties in particular permeability properties of peat. Laboratory measurement of peat permeability was carried out following BS1377:1990 Part 6 using a triaxial cell.

To simulate construction conditions, some disturbed peat samples were mixed with 30% gravel (10mm size) by volume to determine the effect of stone inclusions. A number of the peat samples were also tested with a geofabric (Terram 4000) placed at the base of the test sample. The results of the laboratory permeability tests are summarised below:

- The results showed peat permeability range of 8 x 10^{-10} to 4.1 x 10^{-11} m/s, which is slightly lower than insitu results.
- The reworked peat permeability results showed a lower permeability than undisturbed results, which would be as expected.
- The inclusion of gravel within reworked peat showed no notable reduction in permeability; this is considered due to the very low permeability of the reworked peat matrix.
- The inclusion of the geofabric into the base of peat samples showed no appreciable difference in the results compared to samples without geofabric. Given the short duration of the testing any reduction in permeability due to say clogging of the geofabric would not be evident.
- For peat samples a comparison of permeability and humification (determined using von Post 'H' value) was carried out. This showed no appreciable difference in permeability between H5 to H8 humified peat. Peat with a humification of H5 or greater generally had a permeability of about 10^{-9} m/s or less. Reworked and more highly humified peat had a lower permeability.

5 ANALYSIS OF WATER LEAKAGE

5.1 *Theoretical Background and Baseline*

A simple 1-dimensional analytical seepage model was constructed of the stone road, peat and subsoil profile to allow determination of vertical water leakage from the stone road. The model was based on Darcy's law for groundwater flow. The purpose of the model was to use the permeability results to determine the potential for downward water leakage through the stone road and reworked peat layer.

In order to minimise the hydrological impact along the stone road the proposed reworked peat layer, in combination with other mitigation measures, would be required to maintain similar leakage rates as the baseline condition, that is the natural leakage of water through the peat into the sub-soil beneath.

The determined baseline leakage was estimated at 80mm/year per unit area, which is considered to be consistent with current knowledge with respect to the water balance in blanket peat.

5.2 *Results of Water Leakage Analysis*

An analysis was carried out to determine the thickness of a reworked (disturbed) peat layer required to satisfy the baseline condition of leakage rate of 80mm/year per unit area or less.

Table 1 shows the thickness of reworked peat layers and the corresponding calculated leakage rate for a range of permeability. The results show that:

- A permeability value of 5 x 10-10 m/s or less is required to achieve the baseline leakage condition for a 0.5m thickness of reworked peat.
- A permeability value of 1 x 10-9 m/s or less is required to achieve the baseline leakage condition for a 1m thickness of reworked peat.

Table 1. Thickness of reworked peat layer to satisfy baseline leakage conditions (80mm/year per unit area or less – shaded cells)

Thickness of Reworked Peat Layer	Peat Permeability (m/s) and Leakage (mm/year)					
	5×10^{-9}	1×10^{-9}	5×10^{-10}	1×10^{-10}	5×10^{-11}	1×10^{-11}
0.50m	741	148	74	15	7	1
0.75m	494	99	49	10	5	1
1.00m	371	74	37	7	4	1

6 CONCLUSIONS

(1) For the Corrib Project a section of the onshore pipeline was constructed within a permanent stone road through about 3km of sensitive peatland (Figures 1 and 2). The stone road introduced a significant body of free-draining material into the peatland.

(2) To maintain the hydrological balance within the peatland a 0.5m thick layer of insitu peat was required to be left below the stone road to act as an aquiclude to impede downward leakage of water from the stone road.

(3) Where it was not possible to maintain the 0.5m thick layer of insitu peat below the stone road as a substitute, it was proposed to place a layer of reworked peat into the stone road during backfilling.

(4) To assess the effectiveness/thickness of a reworked peat layer a test programme was carried out to establish the permeability of reworked peat and to determine the potential downward leakage of water from the stone road for various thicknesses of reworked peat (Table 1).

(5) The findings of the test programme resulted in the adoption of a 1m thick impedance layer of reworked peat being used in the stone road with a required permeability of 1 x 10^{-9} m/s or less. Based on the above, construction specifications were established for the use of reworked peat (Table 2).

(6) The key controlling parameter for determining peat permeability was humification. A H5 humified peat or greater was shown in this study to have a permeability of the order of 10^{-9} m/s or less.

Table 2. Specification for use of reworked peat within the works

Sample Location	Test Type	Test Standard	Test Frequency	Acceptable Limits
Placement	Moisture content	BS1377 1990, Part 2	1/50 linear m	For comparative purposes
Placement	Laboratory permeability	BS1377 1990, Part 6	1/50 linear m	Less than 10^{-9} m/s
Placement	Visual homogeneity	Material should be free of tree roots, debris, clods of vegetation and unacceptable materials	Continual visual inspection	No unacceptable material present
Placement	Geotechnical engineering description	BS 5930:1999 and von Post humification classification	1/50 linear m	von Post H5 or greater
Placement	Layer thickness	Layer thickness measured using suitable scaled pole/measure	1/10 linear m	Min 1000mm
Storage	Moisture content	BS1377 1990, Part 2	1/125m^3 per month	For comparative purposes
Storage	Laboratory permeability	BS1377 1990, Part 6	1/125m^3 after 2 weeks of storage	Less than 10^{-9} m/s

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