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Tailings storage at Lisheen Mine, Ireland

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Abstract

The Lisheen Mine, owned jointly by Anglo American and Iverna West, is located near Moyne, County Tipperary, Ireland. The mine produces lead and zinc concentrates derived from sulphide rich ore hosted in dolomitised limestone. Acid generating tailings from processing of the ore are deposited using the sub-aqueous technique in a fully composite lined tailings management facility (TMF), which is located on a peat bog. The TMF is the largest fully lined tailings storage facility in Europe and deposition of tailings is from a mechanised floating head capable of spreading the tailings evenly over the basin.

The facility has been constructed in two stages. Stage 1 of the TMF was constructed during 1998 to a maximum height of 12 m (elevation 130 m AOD) which included the removal of peat from the dam wall footprint, the installation of a composite LLDPE lining system, installation of rail tracks on the northern and southern embankment crests for the tailings distribution system and instrumentation. A micro-gravity survey was conducted to identify any paleokarstic structures within the underlying dolomitised limestone. Stage 2 works were constructed during 2002/2003, which included raising the dam walls by 4.5 m to a crest elevation of 134.5 m AOD, the extension of the composite lining, the installation of a central chimney drain and additional instrumentation.

This paper presents an overview of the methodology employed during the design of the facility as well as construction issues and the findings of the micro-gravity survey.

Keywords: Tailings; Sulphide ore; Tailings disposal; Environmental

1. Introduction

The Lisheen Mine is located near Moyne, County Tipperary, Ireland (Fig. 1). Activities consist of the underground mining of a lead/zinc orebody of approximately 17.7 million tonnes Mt. The mine life is estimated to be 14 years. Ore processing will generate some 13.5 Mt of tailings, of which approximately 50% is used as mine backfill. The remaining tailings, some 6.6 Mt will be disposed in the TMF, at a rate of some 260,000 m^3/annum. The ore is sulphide rich, which is acid generating when exposed to air.

The mine site comprises the processing plant and associated infrastructure and the TMF. Due to the cost of farmland in the area and ownership issues associated with purchasing land from a number of relatively small farm owners, the concept of constructing the TMF on the peat bog was developed. The original concept was to place the tailings directly on the peat and enclose them with a lined perimeter dam wall. This has been carried out in Canada although in Ireland, with some of the strictest environmental legislation already being practiced in the mining industry, this was not a feasible option. Based on the issues raised during the planning of a nearby lead/zinc mine a few years earlier, it was apparent that the TMF facility would not only have to be lined but composite lined.

The final design comprised a perimeter earth embankment founded on glacial till with the upstream face composite lined with linear low density polyethylene (LLDPE) and a geosynthetic clay liner (GCL). The basin area was lined with LLDPE and the compressed peat acted as the second lining.

Initially, consideration was given to remove the peat not only beneath the perimeter dam wall but also from the basin footprint within the impoundment area. This

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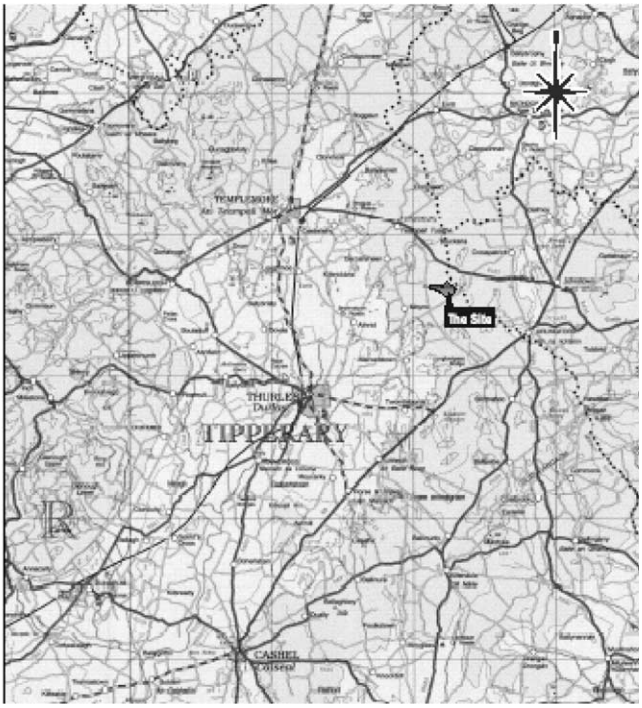

Fig. 1. Location plan.

was assessed as being prohibitively expensive. An engineering solution was therefore needed to,

- manage an even tailings deposition on the LLDPE in order to prevent excessive differential settlement in the peat and prevent slumping of the tailings;
- to ensure the safe biaxial strain envelope of the LLDPE liner was not exceeded;
- to remove water expelled from the peat during consolidation; and
- to remove gas from the peat trapped beneath the lining during peat consolidation.

A secondary issue was the management of the tailings to minimise the potential for oxidisation and hence acid generation. This required special attention as the underlying bedrock comprises dolomitised limestone, which would be susceptible to acid attack.

This paper presents an overview of the key design and construction issues.

2. TMF design

2.1. Site investigations and laboratory testing

2.1.1. Site investigations

Site investigations at the site were carried out in 1993 and 1995 during feasibility studies by others. Site investigations were carried out to address:

- competency of the bedrock;
- classification and suitability of the glacial material beneath the embankment footprint and in the borrow areas; and
- physical properties and suitability of the peat as a lining material.

Field investigations comprised geotechnical drilling using rotary air blast and coring methods, supplemented with cone penetration testing (CPT). Field tests included standard penetration tests (SPT) and falling head permeability tests.

The field studies identified the typical ground conditions underlying the TMF as:

- peat bog—up to 5.5 m thick;
- glacial till—varying in thickness from 0.5 to 3.1 m beneath the perimeter dam wall;
- bedrock—comprising Waulsortian limestone (30–80 m thick) with the upper section dolomitised, overlying argillaceous bioclastic limestone of the Ballysteen limestone formation.

2.1.2. Peat properties

The peat thickness varies across the site from <1 m to approximately 5.5 m (with some isolated areas of up to 9.0 m identified during construction of stage 1). The physical properties of the peat are generally:

- a typically high moisture content which ranges 800–1200%;
- non-plastic;
- bulk densities between 1.01 and 1.05 t/m^3;
- specific gravity between 1.49 and 1.64;
- an undrained shear strength of 5–10 kPa.

The engineering properties of the peat were identified through extensive laboratory and field testing. Studies were carried out to identify its suitability as a secondary liner for the base of the impoundment and also to identify its consolidation properties. As expected, the two properties were found to be interlinked.

The permeability of the peat in situ was determined by conducting falling head tests in piezometers installed during investigation. The in situ permeability was found to range 1.6×10^{-8}–8.3×10^{-8} m/s.

Laboratory permeability testing, comprising constant rate of strain (CRS) and permeameter methods on undisturbed samples and in a Rowe cell on slightly disturbed and completely remoulded samples with preload. The resultant permeabilities from the laboratory tests were approximately 1.0×10^{-8}–5.0×10^{-11} m/s at effective stresses of 40 kPa for the slightly disturbed and remoulded samples, decreasing to 1.0×10^{-9}–3.0×10^{-11} m/s at 160 kPa.

The consolidation of the peat during the various stages of the permeability testing was monitored. Volumetric strains of 70–80% were recorded for maximum loading expected from the tailings, indicating the peat (as expected) to be highly compressible.

Consolidation modelling was undertaken using data from the permeability tests, and predicts 90% primary consolidation after 10 years, although pore pressure dissipation could continue for another 20 years.

From the test results it was concluded that the peat would be an excellent low permeability liner, either as an in situ material or placed as fill where absent beneath the basin of the facility. There was also no discernable change in either compressibility or permeability characteristics with depth.

Peat is also a significant absorbent of ions, particularly metals and a significant amount of work was carried out by others in the early stages of the project when it was considered that the tailings could be placed directly on the peat.

2.1.3. Glacial till

The glacial till varies in thickness beneath the TMF from 0.5 to 3.1 m. It is variable in composition and typical of ablation tills found in the Tipperary region of Ireland. In general, the material is gravely sandy clayey silt, but varies from a sandy gravel to a gravely sandy silty clay. The plasticity index of the till is generally <6% to non-plastic, indicating the clay fraction is of low plasticity. The strength of the material is very sensitive to changes in moisture content.

In situ falling head tests were carried out in the glacial till which gave results of 2.8×10^{-7}–8.9×10^{-9} m/s. Laboratory permeability tests were also carried out, giving low permeability's ranging from 2.1×10^{-9} to 4.2×10^{-11} m/s. For the purpose of seepage analyses, the field permeability's were used as they represent a worst case scenario.

Consolidation undrained triaxial tests were also conducted. These tests returned effective friction angles of 35–36° with 0 kPa friction.

Field strength tests, comprising SPT and CPT tests indicated N values in the range 10–46 with an average of 20.

Based on the results of field and laboratory studies, it was concluded that the glacial till would be a suitable foundation material for the embankments. It was expected that isolated zones of soft material would be encountered during excavation of the peat. These zones would need to be removed and replaced with granular material.

2.1.4. Bedrock

The limestone was found to generally have an unconfined compressive strength of 100–200 MPa, with a spread of 40–240 MPa.

The main concern with siting the TMF on the Waulsortian limestone was the potential for voided paleokarsts. Drilling records from site investigations indicated the presence of paleokarsts. However, where intersected by core drilling, these were found to be infilled with sands and gravel size fragments of limestone. A micro-gravity survey was to be carried out once peat has been removed from the embankment footprint in order to investigate the potential of any paleokarsts in the Waulsortian limestone. This method was used on a nearby mine with considerable success.

2.1.5. Embankment fill

Material for construction of the embankments would be sourced from local borrow pits, developed specifically for TMF construction. The local materials are glacial tills, generally sandy silty gravels. These are relatively permeable compared to the peat. It was identified that the facility would need to be fully lined to minimise the impact of seepage water from the facility.

2.2. Design and analyses

2.2.1. Design criteria

The design of the TMF had to meet the following criteria:

- storage of tailings using a sub-aqueous manner to minimise the potential for acid generation from the pyrite rich ore;
- provide sufficient storage for a minimum of 4 years/stage, at a rate of rise of <1 m/year;
- meet strict EPA requirements in regards to the release of environmentally harmful substances.

2.2.2. Design concept

The TMF embankment was constructed in two stages, 130 m AOD and 134.5 m AOD. The upstream wall slope of stage 1 was 3H:1V and for stage 2, 2H:1V. The downstream slope is at 2H:1V. A central chimney drain was included in stage 2 to control the long-term phreatic surface in the downstream sector of the dam wall. A plan and cross-section through the embankment is presented in Figs. 2 and 3.

The storage volume for each of the two stages, based on the crest elevations above are 1.5 and 3.6 Mm^3, respectively.

The embankments are to be constructed from glacial type material. A platform of granular material (graded limestone rock fill and mine waste) was assumed to be placed on the exposed glacial till after the removal of the peat.

Finger drains were included in the design, positioned at regular intervals, from inside to outside of the embankment during the stage 1 construction. These

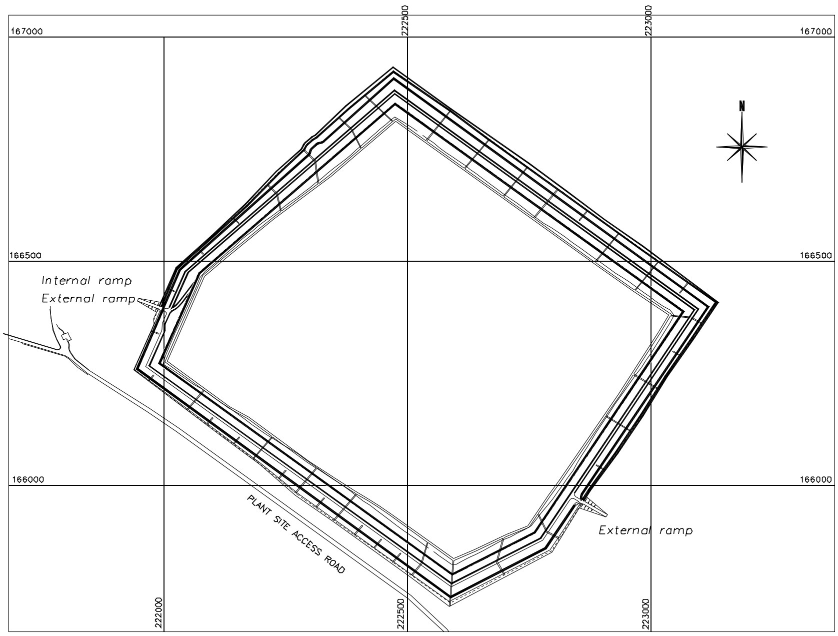

Fig. 2. Plan of TMF.

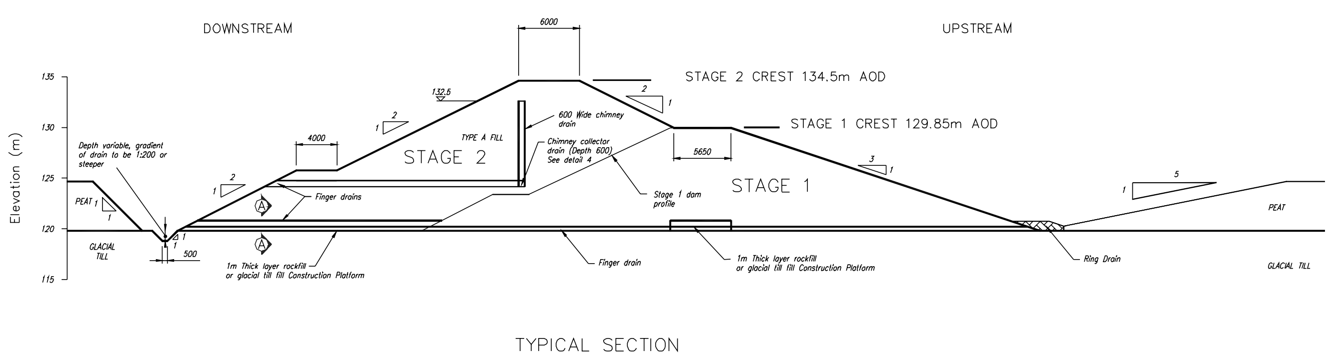

Fig. 3. Typical section through TMF wall.

drains would collect seepage water from consolidation of the peat and allow pore pressures within the peat near the dam wall to dissipate.

A chimney drain, constructed during stage 2 works will be connected to a series of upper finger drains, at 100 m centres to manage long term phreatic conditions within the downstream zone of the embankment. These finger drains will be positioned so that the invert of the outlet is level with, or slightly higher than the adjacent peat level.

2.2.3. Rate of rise

The TMF has a surface area of 78 ha, sufficient to limit the rate of rise of tailings to less than 1 m/annum. The estimation of rate of rise for the facility was quite complex since the rate of consolidation increases with increasing load, as well as long term consolidation effects.

2.2.4. Hydrology

The site is located in the Suir river catchment, between the Rossesstown river and Drish river. Both rivers flow into the Suir river.

The average annual rainfall at the site is 840–900 mm with average annual evaporation at approximately 450 mm. There is a net water gain in the area. This was addressed by the pumping regime developed for the mine by others.

The TMF will be operated with a minimum depth of 1 m of water over the top of the tailings level to minimise the potential for oxidisation of the pyrite rich tailings and a freeboard of 1 m to allow for design flood events.

2.2.5. Groundwater

Groundwater conditions in the area of the TMF site were generally within a metre from the top of peat at the time of the field investigations.

The effects of dewatering of the orebody have been assessed by others. The predicted long term draw down in the area of the TMF is in the order of 5–10 m, with the zone of influence extending some 5 km from the mine workings.

The installation of monitoring wells has been carried out taking into account the projected drawdown around the facility. Monitoring to date has shown a general downwards trend in groundwater levels around the TMF. Following completion of the mine, groundwater levels will recharge to within 1 m of the ground surface.

The TMF was therefore designed to have a wet toe.

2.2.6. Seepage modelling

Seepage from the TMF will be controlled by the low permeability composite lining system, and the tailings level within the basin. Based on experience from previous projects, it was assumed that leaks of generally less than 10 mm^2 in size occur at a rate of 2–5 leaks/ha.

Results of the seepage analysis indicate that seepage rates through the base of the facility, due to defects would range from 20 to 200 m^3/day after completion of stage 2 works. The volume of seepage laterally through the embankments via the GCL/LLDPE would be in the range of 5–50 m^3/day at the final dam elevation. After 30–300 years, some deterioration of the geomembrane can be expected and seepage through the embankments could increase to the order of 100–500 m^3/day for the total area of the TMF.

The peat thickness was also modelled to identify the minimum thickness required to act as a low permeability contact to the underside of the geomembrane on the base of the facility. Modelling identified that a minimum thickness of 1.5 m of peat would be required to provide a minimum 1 m thick layer after consolidation with a sufficiently low permeability of 1×10^{-9} m/s.

In order to assist in the removal of the water from the consolidation of the peat, a perimeter ring drain was included in the design around the upstream toe of the embankments. Finger drains were connected to the ring drain that passed through the foundation of the embankment to the outside toe. Consolidation water therefore had a free path to escape.

2.2.7. Stability analysis

A detailed stability analysis was carried out using parameters gathered from the field and laboratory studies. The analyses indicate a factor of safety under pseudo-static conditions corresponding to a 0.16 g acceleration, of 1.5 assuming an effective angle of friction of 35° for the glacial tills used for embankment construction and foundation soils. The analyses indicated that if the friction angle were reduced to 32°, the factor of safety would reduce to 1.3, which is satisfactory for the earthquake condition.

2.2.8. Liner system

The composite lining system consists of a 2.0 mm linear low density polyethylene (LLDPE) geomembrane over a 4.5 kg/m^2 geosynthetic clay liner (GCL) on the embankments and LLDPE over peat on the floor of the facility. Maximum predicted consolidation of the peat will be in the order of 3.2 m. This magnitude of settlement is relatively small compared to settlements associated with capped landfill sites that are readily accommodated by the flexible LLDPE.

Stresses on the LLDPE, as a result of peat consolidation were assessed at 20% (best case) and 80% (worst case) of the biaxial strain at yield for the LLDPE. Therefore consolidation of the peat could be accommodated.

2.2.9. Instrumentation and monitoring

2.2.9.1. Peat thickness. To measure peat consolidation beneath the lining during the operation of the facility, resistivity monitoring is carried out on a six monthly basis and the data compared to the design predictions. Electrodes were installed in a series of arrays at six locations under the liner, three along the northern side of the facility and three along the southern side.

2.2.9.2. Groundwater and phreatic conditions. Monitoring wells are located at intervals of approximately 100 m around the perimeter of the facility. Piezometers have been installed to monitor the phreatic conditions at specific sections in the embankments.

Monitoring and analysis of groundwater is carried out at the frequencies contained in the EPA licence for the facility.

2.2.9.3. Embankment crest monitoring. Movement of the embankments are monitored at regular intervals from fixed survey locations around the facility. No significant movements have been recorded to date.

3. Construction

3.1. General

Construction activities were carried out in 1998 and 2002/2003. Construction volumes for stages 1 and 2 are presented in Table 1.

During the course of peat excavation, groundwater was found to be slightly artesian in places in the embankment footprint and the majority of the area was below the ground water level. A rock platform was constructed over the majority of the footprint area rather than a central 'core' as described in the design.

Two main borrow areas were used for the construction. Carrick hill borrow area was developed during

Table 1
Construction quantities

Stage	Peat excavation (m^3)	Fill placement (m^3)	LLDPE (m^2)
1	539,000	3,200,000	633,900
2	280,000	850,000	62,000

stage 1 works, the Derryville borrow area, augmented by Carrick hill was utilised during stage 2 works.

3.2. Micro-gravity survey

The TMF and surrounding area is underlain by Waulsortian limestone, a dolomitic limestone, which is known, from drilling undertaken in 1998, to contain paleokarstic structures (Golder Associates, 1998). The purpose of the micro-gravity survey was to investigate sub-surface mass deficiencies in the bedrock which could either be open or infilled.

Micro-gravity surveys were carried during both stages of construction using a Scintrex CG-3M Automated Micro-gravity meter. The 1998 survey identified a number of significant anomalies. Fig. 4 represents the results of the survey undertaken in 1998 covering the area of the TMF footprint and is a residual Bouguer gravity map.

These data are presented with a scale in micro-gals and are contoured in dark grey (negative values) through to light grey (positive values). Anomalies are shaded in dark grey. Based on these results it was recommended that a representative number of the more significant negative anomalies and a positive feature should be targeted for core drilling. Five boreholes were subsequently drilled. The results of drilling in anomalous areas indicated paleokarstic features, infilled with sand and limestone fragments. The results of drilling on gravity highs indicated generally competent ground with very few anomalous conditions, although minor core loss was encountered.

It was concluded that the anomalies were a good indicator of the presence of zones of possible enhanced solution that are probably controlled by faults and/or fracture systems.

The results of the 2002 survey (Golder Associates, 2002) generally indicated extensions to the anomalous ground encountered during the 1998 survey. Fig. 5 represents the results of the survey undertaken in 2002 covering the area of the wall raise footprint and is a residual Bouguer gravity map. (The same grey scale as that used in Fig. 4 has been used in the production of this map.)

The data shown in Fig. 5 indicate a number of significant anomalous areas, these are generally shaded in blues. By analogy with the results from the 1998 survey and subsequent borehole investigation programme (2003), these anomalies were found to be underlain by infilled paleokarstic structures depicting probably fault or fracture systems.

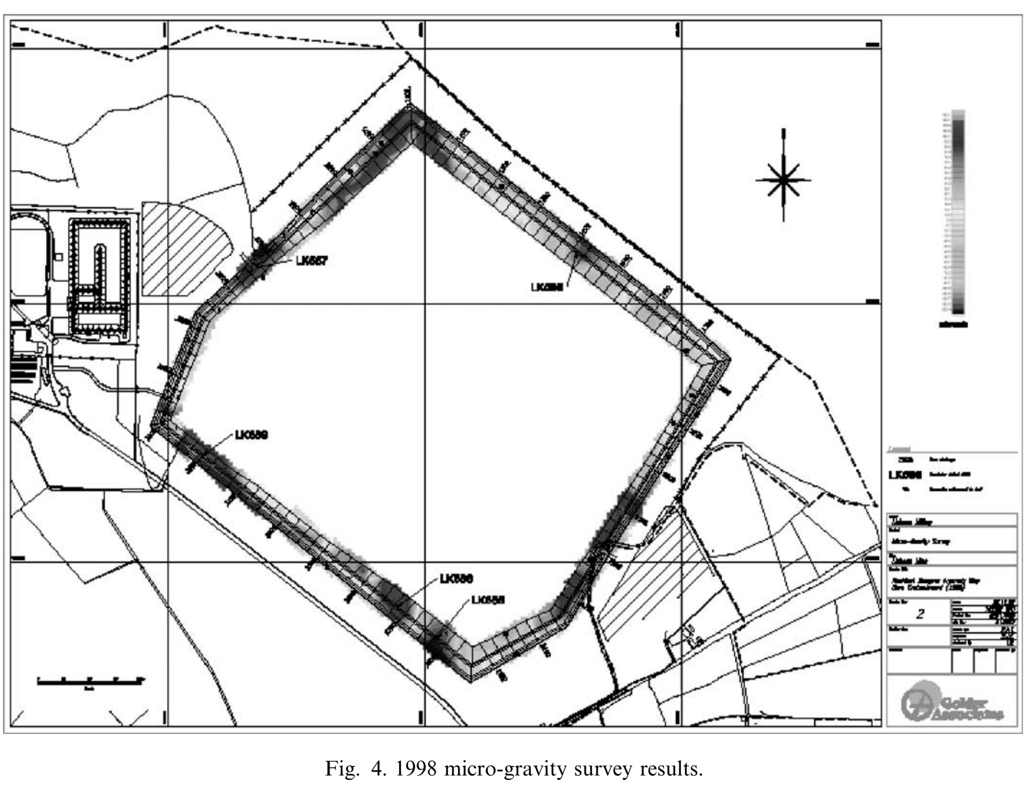

Fig. 4. 1998 micro-gravity survey results.

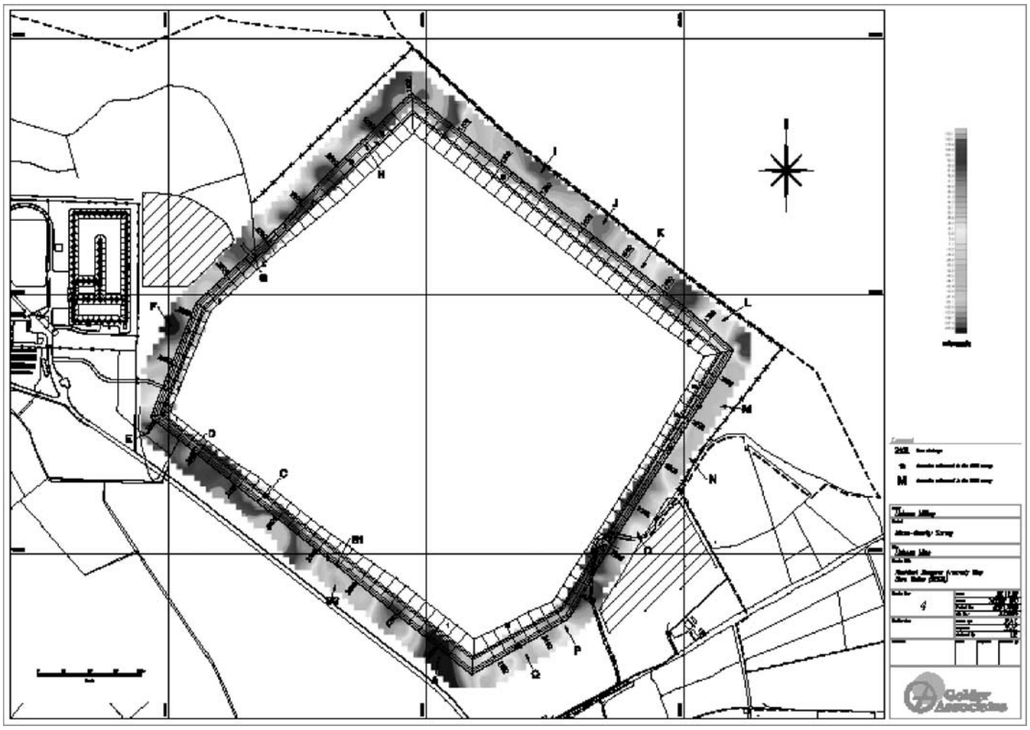

Fig. 5. 2002 micro-gravity survey results.

4. Tailings deposition strategy

The conventional method for discharging tailings is sub-aerially from single or multiple spigots on a ring main. The tailings slurry travels across the tailings beach, depositing the coarser fraction closest to the discharge point with the finer fraction being deposited at the edge of a centrally located pool of supernatant water. Conventional methods could not used for Lisheen because the tailings are acid generating and need to be deposited below water using the sub-aqueous method. This is normally carried out from floating discharge points which are moved periodically. Underwater, the tailings slope formed could be in excess of 10% and resulting peaks of tailings would result in significant differential settlement and possibly slumping.

Extensive laboratory testing of the peat was carried out to identify its engineering properties, as discussed in the preceding sections. The tailings discharge arrangement was therefore designed to deposit tailings in an even manner over the entire floor of the facility. An innovative method was developed which comprised a mechanised floating pipe that could traverse the surface of the TMF and deposit tailings evenly over the floor of the facility. The floating pipe, or head, is controlled by ballasted rail cars on the northern and southern embankment crests. The rail cars travel up and down the rail track for deposition on a east to west or west to east direction. The floating head is connected to the rail cars by cables that are wound in or out to deposit tailings in a north to south or south to north direction. To date the deposition has been quite successful, although as part of stage 2 works, the rail cars were modified by Lisheen Mine to make the deposition process more autonomous.

It was anticipated that any gas build up beneath the lining would migrate to low pressure areas, i.e., areas not covered by tailings and water. The water rise in the facility was extremely rapid due to the amount of water being discharged from the underground development. Gas was being trapped in a number of random locations

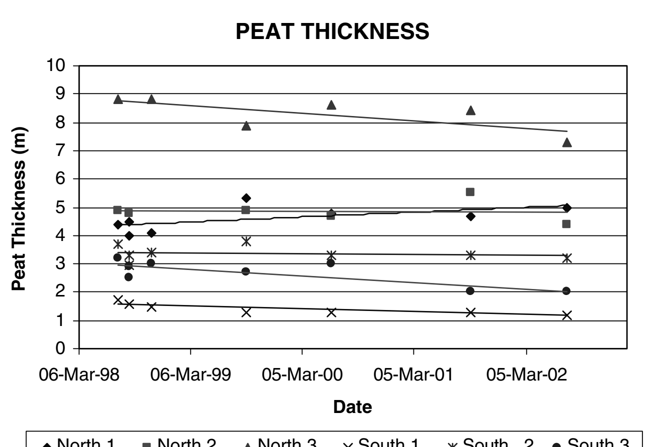

Fig. 6. Plot showing monitored peat thickness.

forming bubbles which protruded above the water level. Valves were inserted into the lining at the location of the bubbles to bleed of the gas.

Resistivity monitoring has been carried out on a six monthly basis to measure consolidation of the peat. Results to date have shown some reduction in the thickness of peat, especially in the northern (deepest) part of the TMF. The results are presented in Fig. 6. There is a general trend in reduction of peat thickness for each of the monitoring points, except for monitoring point 'North 1', which is exhibiting a slight increase in thickness. The maximum change in thickness is approximately 1.5 m.

References

Golder Associates, 1998. Micro-gravity survey TMF embankment the Lisheen Mine Ireland. Report No. 98512349.

Golder Associates, 2002. Micro-gravity survey TMF embankment raise, The Lisheen Mine Ireland. Report No. 02517365.