The role of environmental geophysics in the investigation of an acid tar lagoon, Llwyneinion, North Wales, UK

Consultant John M. Reynolds¹ offers a case study of how environmental geophysics can provide the tools for effective survey and analysis of pollution hazards.

Introduction

During the last decade or so, environmental geophysics has really come of age. Two aspects have changed in particular: first, environmental geophysics is being used to investigate sites that 10 years ago would have been impossible or considered as ‘research’ sites. The technology for both acquiring and handling data, as well as increasingly sophisticated and easy to use software have enabled much more data (and with much finer spatial sampling) to be acquired with better quality and to be analysed more robustly. The downside of this case of use is that more unqualified and inexperienced people are entering the ‘industry’ (note I did not say ‘profession’) and there are more examples of bad surveys occurring. The second key factor is the regulatory and legislative climate that prevails; the UK is fast catching up with the USA in its increasing recourse to the law courts. Clients are not just looking for geological, environmental or engineering targets any more. Rather, there is a very rapidly developing use of environmental geophysics as a risk management tool. The kinds of risk for which environmental geophysics is being applied are listed in Table 1.

It can be seen from the range of risks now being managed that it is necessary for geophysicists to be much more aware of issues outside of, but relating to, our profession. The days of undertaking a geophysical survey and producing a few colour maps with anomalies marked on with a brief explanation are gone. However, I suspect it will take another decade for the message to finally get through.

The purpose of this article is to demonstrate, through the use of a recent case history, the way in which environmental geophysics was used for a variety of risk management purposes for perhaps one of the most contaminated sites in Wales at Llwyneinion, near Wrexham (Fig. 1). One government estimate put the potential cost of remediation of this site in excess of £100 million. In addition to achieving the technical objectives of the geophysical survey (detailed below), it was also required in order to reduce what was a very significant risk to health and safety, with regard to the people involved on the site as well as to local residents, both during the survey and afterwards. It was also needed to aid the design of further remediation investigations by providing key information about the site and by identifying potentially dangerous areas.

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² For a definition of environmental geophysics see Reynolds, 1997, p.2.
Table 1 Some types of risk for which environmental geophysics is being applied

<table>
<thead>
<tr>
<th>Types of risk</th>
<th>Description</th>
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<tbody>
<tr>
<td>Technical</td>
<td>Basic technical information about a site that, if wrong, would have a tangible impact on the future development of the site.</td>
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<tr>
<td>Economic</td>
<td>If the basic information about a site is wrong, undoubtedly further development will cost a great deal more than if an appropriate geophysical survey had been undertaken during the Site Investigation phase. Everyone can cite examples of cost overruns caused by 'unforeseen ground conditions'.</td>
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<tr>
<td>Health &amp; safety</td>
<td>Failure to identify the presence of potentially dangerous targets (i.e. buried metal drums containing chemicals that may be toxic and/or flammable or even explosive) would have serious implications for the health and safety of staff working at the site as well as for local residents. Where near surface cavities are concerned, identifying their presence (such as in shallow mine workings) may be a condition prior to allowing onto a site heavy plant that would itself be liable to collapse into voids. Some geophysical surveys (e.g. searches for unexploded ordnance) may be a requirement by insurance companies prior to intrusive investigations and may result in reduced insurance premiums.</td>
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<tr>
<td>Professional indemnity</td>
<td>Failure to undertake best practice, e.g. specifying the use of environmental geophysics for an investigation of a brown-field site (where it would be appropriate) may, according to one environmental lawyer in the UK, constitute technical negligence and would leave an engineering consultant at risk of a claim against his professional indemnity policy.</td>
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<tr>
<td>Warranty risks</td>
<td>Some environmental engineering consultants have warranty agreements whereby if they miss something important on a site, they are liable for the cost of treating it. For instance, for one company involved in cleaning up old gas holder sites, where underground tar pits are common, failure to find old pits could cost the consultant £0.5 million in remediation each time under his warranty agreement. Using geophysical surveys may help him find these and would therefore reduce his exposure under his warranty agreement.</td>
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of the site that should be avoided in the event of using intrusive methods (for reasons that should become obvious later). Finally, the survey was of significant use as far as the regulatory authority (Environment Agency) was concerned, as it provided key information for it to help 'manage' the site. Conversely, the same benefit was achieved as far as the owner of the site was concerned (Wrexham County Borough Council) as it was able to demonstrate to the Environment Agency that the methods being used were in accordance with the Agency's own guidelines for investigations on heavily contaminated sites, were generally environmentally benign, and that due regard had been paid to health and safety. For the same reasons, the local Health & Safety Executive (another UK regulatory body) was also satisfied. The survey helped the local authority to demonstrate that it was doing all that was possible and appropriate to fulfil its responsibilities in managing the site in full compliance with all the local regulatory authorities' conditions.

An additional reason for this case history is that very few surveys of the type described below have been undertaken and the results published. While resistivity imaging and electromagnetic methods have been used over buried oil- and tar-contaminated waste deposits (Chambers et al., 1999), the use of magnetic gradiometry and seismic methods to survey over an acid tar lagoon has not been described previously.

The nature of the problem

The site of the current Llwyneddion lagoon has an industrial legacy dating back over 250 years. Coal mining and iron smelting are believed to have taken place from c. 1750 to 1860, followed by quarrying associated with brick making from c. 1820 to 1964 (Nichol, 1997). The site has also been mined for coal, and three uncapped mineshafts were thought to exist beneath the quarry, with a further three capped mineshafts known around the perimeter of the quarry. During the late 1950s to early 1960s the quarried clay resource became depleted and tipping of industrial waste products commenced, comprising acid sludges and drums of unknown chemicals (Fig. 2). Up until March 1972, c. 94 000 tonnes of sulphuric acid mixed with tar-like hydrocarbons, and 7500 tonnes of spent bentonite containing absorbed heavy oil were deposited, together with perhaps more than 1000 metal 55-gallon drums of uncertain contents. The acid tar waste originated predominantly from benzene refining at Burmah-Castrol Company, Ellesmere Port. In 1980 the Local Authority purchased the site for £1 from the estate of the family that had operated the quarry, due to concerns over the state of the site. Since then, simple clean-up work and security fencing have been undertaken and various remediation options considered, but as yet the site remains untreated (Fig. 3).

In August 1980, the site comprised a 75 mm layer of volatile hydrocarbon floating on about 0.5 m of water (with a pH of <2.5) over the tar waste, which was thought to be up to about 10 m thick. One of the steel drums may have contained a sodium product so that, when the drum corroded, water contacted the sodium and ignited. The ensuing fire, the largest ever seen in North Wales, burnt off the volatile hydrocarbon (solving one problem!), the heat evaporated the acid water

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and ignited the acid tar beneath. The acid smoke plume could be seen in Ellesmere Port some 32 km to the north (Fig. 1). The entire town of Rhosllanerchrugog had to be evacuated until the fire was extinguished. Since then, there has generally been about 0.5 m of acid water covering the tar waste except during unusually dry hot weather (rare for Wales!) when the water cover occasionally evaporated off, allowing hydrocarbon fumes to be produced, causing both another major fire risk and an odour nuisance as well as a health risk to local residents.

**Operational details**

The brief given to my company by the local authority was to design and manage a geophysical investigation to locate the metal drums, and map the thickness of tar waste in the lagoon, taking into account the onerous conditions placed on the operation by both the Environment Agency and the local Health & Safety Executive. A full decontamination unit and rescue facilities had to be on site at all times during the survey, in case anyone should be unlucky enough to fall into the lagoon. Protective clothing had to be worn by field staff to avoid acid burns and the toxic effects of the tar, and no staff were permitted to work over the lagoon unless absolutely necessary and unavoidable. So how does one access 1.3 ha of lagoon with an adequate spatial sampling to achieve the technical objectives of the survey, without anyone working over the lagoon?

Geophysically, the obvious method for mapping the metal drums was magnetic gradiometry, and to determine the depth of tar, seismic methods were considered to provide the most useful information. Electrical methods, as used by Chambers et al. (1999), for example, were thought to provide insufficient relevant detail and could not be used to indicate unambiguously whether the tar waste in the lagoon had set or not, whereas P-waves probably could. The remaining question was how to deploy these methods whilst still complying with the conditions set by the Health & Safety Executive and the Environmental Agency. The answer was to use a Geometrics ‘MagCat’ (Fig. 4), which was modified to suit each of the two geophysical methods.

**Magnetic gradiometry**

The MagCat was set up with the magnetic gradiometer sensors (Geometrics G858) on the front of the platform with the measuring instrument housed in a waterproof plastic container at the rear. The measured data were telemetered to the shore via a radio modem. Accurate positioning was achieved by placing an active prism at the rear of the MagCat, which was tracked continuously from the shore by a robotic geodimeter. To mobilise and control the MagCat over the lagoon, the platform was attached front and rear to polyethylene ropes (acid resistant) connected to shore-based...
Figure 4 Detail of the Geometrics MagCat platform used for the magnetic survey. (a) Magnetic survey offset diagram; (b) the equipment in use.

The MagCat could be hauled along each traverse by controlling the speed of the manual winches, providing sampling at a spatial interval of < 0.2 m along each profile. The whole winch assemblies were moved along each opposite shore to provide a line interval of 2.5 m.

Measurements for total field intensity at each sensor were captured (e.g. Fig. 5) and the resulting vertical gradient obtained. Maps of the magnetic parameters provided a spatial perspective across the lagoon from which it was possible to identify the locations of drum graves and, in many cases, individual drums, as well as, importantly, areas without any drums present. Each magnetic profile was modelled using commercially available software (Mag2DC) in order to locate the position of the magnetic target along each transect and its depth below the lagoon surface. The resulting output was a map (Fig. 6) showing the target locations and exclusion zones around them in which there was a risk of encountering a drum (or drums) in the case of any intrusive work. Such information thus helps to define areas where no drums are likely to be found, as well as areas where drums are known to exist. This helps to direct those involved in subsequent intrusive work to locate test areas safe to work in without the risk of encountering a metal drum (and its contents!).

Seismic surveys

The seismic refraction survey was undertaken using the MagCat as a floating platform from which the seismic source (sleeve gun) was deployed (Fig. 7). The location of the platform was determined using the same system as that for the magnetic gradiometry survey. Deployed separately was a marine hydrophone streamer (Exploration Electronics Ultra-high Resolution 24-channel hydrophone array) with 2 m group intervals. The array was laid out across a 46 m long section of the lagoon at a time, and left to sit in the soft tar surface during acquisition of data over that spread length. The MagCat with the seismic source was pulled across the lagoon and the sleeve gun fired at 2 m intervals over the hydrophone spread and slightly beyond, in order to obtain ground coverage. Once the first spread was completed, the MagCat was held stationary while the hydrophone cable was dragged on to cover the next 46 m length of profile. The MagCat was reversed and several off-end shots acquired before moving to the next...
length of the hydrophone spread. The hydrophone was moved as many times as necessary in order to cover the required length of the lagoon. Seismic lines were obtained at 10 m line intervals across the lagoon with two oblique transverse lines; orthogonal lines were not possible due to the restricted access along parts of the shoreline.

As a shot record was obtained at each shot location into 24 channels (Fig. 8), data quality could be assessed at each geophone/shot location. Time–distance graphs were obtained for each profile and a combination of reciprocal 'delay time', Hagedoorn's 'Plus/Minus', and basic intercept times methods of analysis were used to determine basic 2D models along each seismic profile. In addition, the refraction data were also processed using SvsOrr@2D (Optim, USA) to produce 2D P-wave velocity panels for each section. Note that on the shot record (Fig. 8) reflections can also be identified.

The seismic refraction analysis revealed a four-layer structure, with three layers existing within the tar itself. A thin uppermost layer has a P-wave velocity range of 200–800 m/s; within the main tar body itself, the next two layers were found to have P-wave velocities of 1560 ± 20 m/s and 1715 ± 65 m/s, respectively, with velocity increasing with depth. This was thought to suggest that the tar was more viscous with depth. The surface low velocity layer within the tar was found to vary across the site, with the lowest velocities being recorded in association with the softest parts of the tar surface and where gas bubbles and hydrocarbons were observed to emerge at the surface. This was seen most easily during part of

Figure 6 Plot of zones of influence arising from metal drums and drum graves determined from the interpretation of magnetometry data.

Figure 7 Detail of the Geometrics MagCat platform as set up for the seismic survey. (a) Seismic survey offset diagram; (b) the equipment in use during firing of the sleeve gun seismic source.

Figure 8 Example shot record.
the survey (during December 1999–January 2000) when the lagoon froze over. Where the gas and volatile hydrocarbon seeped out they were trapped beneath the ice that then melted, producing obvious spots visible from above (Fig. 9). These areas also correlated with zones identified on a dual frequency transponder survey (for water depth, tar surface bathymetry) where penetration into the tar was greater with the lower frequency transponder than with the higher frequency source. The P-wave velocity range for the bedrock underlying the tar was found to be in the range 2150–3600 m/s.

The analysis of the reflection components of the shot records provided further information about the depths of the tar. Furthermore, along one cross-line, a diffraction event was found that coincided with the reported location of an unceded mineshaft. At the location of another mineshaft, no event was found, suggesting that, in accordance with anecdotal historical information, this had been mined out at the base of the quarry prior to the pouring of the acid waste.

**Discussion**

Where both magnetic gradiometry and seismic data were obtained over the same transects, it was possible to integrate the analysis. From this it was possible to identify the locations of metal drums and to see where within the tar they may be located. One such integrated profile is shown in Fig. 10. It was noted that no isolated drums appeared to occur at depths below about 2 m, just above the point where it was found that the P-wave velocity increased, suggesting a more viscous tar. This information is important when considering potential remedial methods. However, some drum graves were found to lie at the base of the tar, suggesting that the drums had probably been dumped before the main tipping of the tar.

The seismic survey resulted in depths to the base of the tar being determined over 80% of the area of the quarry floor.

This contrasts with an intrusive survey conducted in November 1980 where only three piston sampling sites out of 10 actually reached the base of the tar.

**General conclusions**

The integrated geophysical survey conducted at Llwyneiniein demonstrated its effectiveness in meeting the technical objectives for the survey, plus satisfying the stringent conditions imposed by the regulatory authorities. This has enabled the site owner to demonstrate compliance with both environmental and safety conditions. The geophysical survey provided more information than most of the previous intrusive investigations undertaken over the previous 22 years. This was especially true in relation to the spatial resolution, where the depths to the base of the tar were determined over 80% of the quarry area, in contrast to only three out of 17 intrusive probes having reached the base of the tar in a survey in 1980.

The magnetic gradiometer survey also identified areas of drum graves, as well as identifying the locations of isolated metal drums and areas where no drums were located at all. This information, coupled with modelled depths to the drums, is crucial both for the design of subsequent remediation work and for any further intrusive testing, so as to avoid hitting any buried drums.
The geophysical survey, together with desk studies have provided details of the distribution of buried metal drums and also the characteristics and thicknesses of the tar over most of the lagoon. The geophysical survey, the first of its kind for such a site, demonstrated the benefits of using these techniques on such a complex and environmentally difficult site. It has also provided the client with the means of reducing the total risk of ownership of the site due to significantly increased knowledge and understanding of it. This case history serves as a useful demonstration of the role of environmental geophysics as a risk management tool, as well as a sophisticated means of providing robust technical information about a given site.

Acknowledgements

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References


About the author

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In the Environmental geoscience special topic article ‘The role of environmental geophysics in the investigation of an acid tar lagoon, Llwynniinion, North Wales, UK’ by John M. Reynolds, on page 634, First Break October 2002, the wrong Fig. 6 was shown. The correct Figure is reproduced below:

In First Break November 2002, p. 716, Figure 3 was incorrectly labelled as Figure 2.

Figure 6 Plot of zones of influence arising from metal drums and drum graves determined from the interpretation of magnetometry data.