FEHILY TIMONEY
30 YEARS

CONSULTANTS IN ENGINEERING, ENVIRONMENTAL SCIENCE & PLANNING

APPENDIX 4

Minerex Geoservices Geophysical Survey Report

Tuam Historic Landfill

Tuam Co. Galway

Geophysical Survey

Report Status: Draft

MGX Project Number: 6499

MGX File Ref: 6499d_Tuam-005.doc

25th May 2020

Confidential Report To:

Fehily Timoney & Co.
J5 Plaza
North Park Business Park
North Road
Dublin 11

Report submitted by:
Minerex Geophysics Limited

Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare, W23X7Y5
Ireland
Tel.: 01-6510030
Email: info@mgx.ie

Issued by:

Author: John Connaughton (Geophysicist)

Reviewer: Hartmut Krahn (Senior Geophysicist)

Subsurface Geophysical Investigations

EXECUTIVE SUMMARY

1. Minerex Geophysics Ltd. (MGX) carried out a geophysical survey consisting of EM31 ground conductivity, 2D-Resistivity and seismic refraction (p-wave) surveying for the ground investigation of the Tuam Historic landfill, County Galway.
2. The main objectives of this survey were to identify the extent and depth of the former landfill site, quantify the volume of the waste, provide information on nature of the waste body, waste type and composition, look for evidence of leachate migration from the site and provide information on the underlying subsoil and bedrock.
3. The online geological map of Ireland (GSI, 2019) indicates the bedrock under the site is Visean Limestones, described as undifferentiated limestone. Visean Limestone is karstifiable.
4. The EM31 Ground Conductivity survey shows high conductivities throughout the site which indicates mainly domestic and industrial waste material. The conductivities decrease towards the periphery of the site which indicates a reduction in the thickness of waste material. The extent of the waste material on the site covers an area of 27,700 m^2.
5. The depth of the waste layer extends to the level of the surrounding land which is around 35 – 39 mOD. The total average depth of waste material is approx. 8 m.
6. Total volume of waste material is calculated as 221,600 m^3.
7. The layer below the landfill may consist of clay or peat overburden or overburden with leachate.
8. Fresh rock below this layer minimises migration of leachate but there may be possible leachate migration into the rock near the west of the site.

CONTENTS

List of Tables, Maps and Figures:

1. INTRODUCTION

1.1 Background

Minerex Geophysics Ltd. (MGX) carried out a geophysical survey at an historic landfill in Tuam, Co. Galway. The survey consisted of EM31 ground conductivity, 2D-Resistivity and seismic refraction (p-wave) measurements. The survey was commissioned by Fehily Timoney & Co.

The survey employed various geophysical methods that complement each other and improve the interpretation. The role of geophysics as a non-destructive fast method is to allow later targeted direct investigations. Those results can be used to improve the initial results and interpretation.

A geophysical survey is a fast and effective way to investigate the waste size, extent and possible leachate from the landfill in a non-invasive manner. The geological background is also investigated a part of the survey. This survey is part of the Tier 2 site investigation and test report.

1.2 Objectives

The main objectives of the geophysical survey were:

- Identify the extent and depth of the former landfill
- Quantify the volume of the waste
- Provide information on the nature of the waste body, waste type and composition
- Look for evidence of leachate migration from the site
- Provide information on the underlying subsoil and bedrock

1.3 Site Description

The site is located off the R347 south of the town of Tuam. The Barna Waste Recycling Centre is located in the SE corner of the site. The site has a dome shaped topography with the highest elevations in the middle of the site and steep drops in elevations around the edges. The survey area consists of a capped historic landfill, grassed across its extents, surrounded by a wire fence. The site is accessed via the adjoining recycling centre/civic amenity site.

1.4 Geology

The online bedrock geological map of Ireland (GSI, 2019) describes the quaternary sediments as cut over raised peat. The survey area is underlain mostly by Visean Limestone, described as undifferentiated limestone.

Visean Limestone is karstifiable but the nearest karst features are over 1.7 km NE of the site.

1.5 Report

This report includes the results and interpretation of the geophysical survey. Maps, figures and tables are included to illustrate the results of the survey. More detailed descriptions of geophysical methods and measurements can be found in GSEG (2002), Milsom (1989) and Reynolds (1997).

The client provided maps of the site and the digital version was used as the background map in this report. Elevations were surveyed on site and are used in the vertical sections.

The interpretative nature and the non-invasive survey methods must be taken into account when considering the results of this survey and Minerex Geophysics Limited, while using appropriate practice to execute, interpret and present the data, give no guarantees in relation to the existing subsurface.

2. GEOPHYSICAL SURVEY

2.1 Methodology

The methodology is outlined in the tender documents and consisted of EM31 Ground Conductivity measurements across the site to map and determine targets for additional geophysical methods including 2D-Resistivity and Seismic Refraction Profiling. These profiles were carried out in different directions through the middle of the waste body as identified through the EM31 ground conductivity survey.

The survey locations are indicated on Map 1. The profiles and parameters are tabulated in Table 1 below.

All geophysical surveys are acquired, processed and reported in accordance with British Standards BS 5930:1999 +A2:2010 'Code of Practice for Site Investigations'.

Table 1: Geophysical Survey Locations and Acquisition Parameters

Profile Name	**Electrode/Geophone Spacing/m**	**Number of Electrodes/Geophones**	**Profile Length/m**
R1	3	54	159
R2	3	72	213
SUM			**372**
S1	3	54	159
S2	3	72	213
SUM			**372**

2.2 EM31 Ground Conductivity

The EM31 ground conductivity survey was carried out over the area indicated in Map 1 on lines nominally 10 m apart. Along each line a reading of ground conductivity was taken every second while walking along, thereby resulting in a survey grid of nominally 10 x 2 m. The locations were measured with a sub-meter accuracy SERES DGPS system attached to the EM31 and all data was jointly stored in a data logger. The conductivity meter was a GEONICS EM31 with Allegro data logger and NAV31 data acquisition software. The instrument was checked at a base station, the readings were stable and no drift occurred.

EM31 ground conductivity determines the bulk conductivity of the subsurface over a typical depth between 0 and 6 m below ground level (bgl). and over a radius of approx. 5 m around the instrument.

2.3 2D-Resistivity

2D-Resistivity profiles were surveyed with electrode spacing of 3 m, up to 64 electrodes per set-up and a maximum length of 189 m per profile. The readings were taken with a Tigre Resistivity Meter, Imager Cables, stainless steel electrodes, laptop and ImagerPro acquisition software. Profile R2 was acquired in roll-along mode to achieve continuous depth across the profile.

During 2D-Resistivity surveying data is acquired in the form of linear profiles using a suite of metal electrodes. A current is injected into the ground via a pair of electrodes while a potential difference is measured across a second pair of electrodes. This allows for the recording of the apparent resistivity in a two-dimensional arrangement below the profile. The data is inverted after the survey to obtain a model of subsurface resistivities. The generated model resistivity values and their spatial distribution can then be related to typical values for different geological and manmade materials.

The penetration depth of a resistivity profile increases towards the centre where it reaches an approx. value of $1/6^{th}$ of the layout length.

2.4 Seismic Refraction

Seismic refraction profiles were surveyed with geophone spacing of 3 m and 24 geophones per set-up resulting in a 69 m length per set-up. The recording equipment consisted of a 24 Channel GEOMETRICS ES-3000 engineering seismograph with 4.5 Hz vertical geophones. The seismic energy source consisted of a hammer and plate. A zero-delay trigger was used to start the recording. Normally 7 shot points per p-wave profile were used.

Set-ups were acquired in longer continuous profiles using common shot points between set-ups and concatenating into longer profiles at the processing stage.

In the seismic refraction survey method, a p-wave is generated by a source at the surface resulting in energy travelling through surface layers directly and along boundaries between layers of differing seismic wave velocities. Processing of the seismic data allows geological layer thicknesses and boundaries to be established.

Seismic Refraction generally determines the depth to horizontal or near horizontal layers where the compaction/strength/rock quality changes with an accuracy of 10 – 20% of depth to that layer. Where low velocity layers or shadow zones are present (e.g. below solid ground surface) or where layers dip with more than 20 degrees angle the accuracy becomes much less.

2.5 Site Work

The data acquisition was carried out on the 21st May and 9th of June 2020. The weather conditions were variable throughout the acquisition period. Health and safety standards were adhered to at all times. The locations and elevations were surveyed with a Carlson NR3 RTK-GPS to accuracy < 0.05 m.

3. RESULTS AND INTERPRETATION

The interpretation of geophysical data was carried out utilising the known response of geophysical measurements, typical physical parameters for subsurface features that may underlay the site, and the experience of the authors.

3.1 EM31 Ground Conductivity

The EM31 ground conductivity values were merged into one data file for the survey area and contoured and gridded with the SURFER contouring package. The contours are created by gridding and interpolation and care must be taken when using the data. The contour map is overlaid over the location and base map (Map 2) and the values in milliSiemens/metre (mS/m) are indicated on the colour scale bar.

Within the top 6 m bgl, the conductivities are characteristic for certain overburden and rock types. If there is a high content of clay minerals (which are electrically conductive) then the overburden conductivity will be higher than as if there is a high content of clastic grains like sand or gravel. The purer the clay and the lower the sand/gravel content the higher the conductivity. The water content in the overburden also influences the conductivity but generally the clay content has a larger effect.

Non-natural material like waste or leachate will generally have a high conductivity or increase the conductivity of the natural geological material. Many waste materials decompose or dissolve in the ground and enrich the ground and water with ions, which increase the conductivity and decrease the resistivity. Waste material from domestic and industrial (D/I) sources generally contain more decomposable or dissolvable material than waste from construction or demolition (C&D). Therefore D/I Waste will have lower resistivities and higher conductivities than C&D waste.

The scale used on this site represents the very high conductivity results surveyed throughout the site. The highest conductivities are found in the centre of the site where conductivities are typically above 60 mS/m. Very high conductivities indicate deep D/I waste material. Around the edge of the site the conductivities begin to decrease. Conductivities between 20 – 30 mS/m would indicate some waste material, while conductivities of less than 20 mS/m which are only found on the periphery of the site would usually indicate soil and rock fill, natural material or C&D waste.

3.2 2D-Resistivity

The 2D-Resistivity data was positioned and inverted with the RES2DINV inversion package. The programme uses a smoothness constrained least-squares inversion method to produce a 2D model of the subsurface model resistivities from the recorded apparent resistivity values. Three variations of the least squares method are available and for this project the Jacobian Matrix was recalculated for the first three iterations, then a Quasi-Newton approximation was used for subsequent iterations. Each dataset was inverted using seven iterations resulting in a typical RMS error of <3.0%. The resulting models were colour contoured with the same resistivity scale for all profiles and they are displayed as cross sections (Figure 1). A vertical exaggeration of 4 is used for the sections.

The resistivities are the inverse value of the conductivities therefore remarks made above for the conductivity are also valid for the resistivity. It has to be considered that the conductivity is determined as a single bulk value for a depth range from 0 - 6 m bgl while the 2D-Resistivity method determines the values based on depth levels.

Both profiles show a rapid change with depth from low resistivities to high resistivities at approx. 30 mOD. Low resistivities (<62.5 Ohm) indicate mainly D/I waste material or leachate but may also indicate clay-rich or peat overburden. High resistivities (>500 Ohmm) at depth indicate fresh limestone. Both profiles are laterally consistent which indicates D/I waste throughout the site.

Profile R1 has low – medium conductivities at depth. This may indicate a karst feature or leachate penetrating into the rock layer. It may also be an artificial effect of the very low resistivities above it and sharp topography along the surface.

3.3 Seismic Refraction

The p-wave seismic velocity is closely linked to the density of subsurface materials and to parameters like compaction, stiffness, strength and rock quality. The higher the density of the subsurface materials the higher the seismic velocity. Similarly, for the other parameters it is generally valid that a more compacted, stiffer and stronger material will have a higher seismic velocity. For rock, the seismic velocity is higher when the rock is stronger, less weathered and has a higher quality. If the rock is more weathered, broken, fractured, fissured or karstified then the seismic velocity will be reduced compared to that of intact fresh rock.

The seismic refraction data was positioned and processed with the SEISIMAGER software package. The data shows very low seismic velocities near the surface but did not identify any higher velocity layers within the parameters of the survey. This occurs typically when the waste material is generally greater than 5 m thick. Velocities were determined for the ground below the surface and these are annotated on the sections on Figure 1.

3.4 Interpretation of Resistivity and Seismic Refraction

The seismic refraction and 2D-Resistivity provide information on two physical parameters of the waste material, however as discussed above the waste material may share some of these physical parameters with other material. Therefore, by using both methods together a clearer picture of the waste body is obtained.

Waste material generally consists of low velocity, low resistivity material. The 2D-Resistivity data and the seismic refraction data shows low velocities and resistivities near the surface across the survey area.

Historic maps do not show any development on the site previous to it being a landfill and it is assumed the waste was dumped on the surface rather than in an excavation. The surrounding elevations are around 35 – 39 mOD which is the assumed depth of the landfill. This gives a waste layer which is up to 10 m thick near the middle of the site but becomes very thin near the edges where the topography drops off.

Where low resistivities continue below this, it is an indication of leachate in the natural ground below the landfill. The low resistivities below the landfill may also be due to clay-rich or peat overburden.

High resistivities beginning at between 25 and 30 mOD along both profiles give an indication of rock depth as the seismic refraction model do not penetrate to this depth. The high resistivities are interpreted as good limestone with no leachate.

Along Profile R1, low – medium resistivities at depth may indicate leachate in the rock layer, karstified rock or it may be an artificial effect from the strong topographical gradient on the surface and the fact that the profile does not reach the natural ground around the landfill.

Table 2 summarises the interpretation. Interpreted cross sections are shown in Figure 2. The interpretation has been made from all available information. The resistivity models have been used to delineate between waste and natural material and the depth to rock. Resistivity data is better suited to show rock types and features within the rock while seismic refraction velocities are indicating the change of compaction, stiffness or rock quality with depth.

Table 2: Summary of Interpretation

Layer	General Seismic Velocity Range (m/sec)	General Resistivity Range (Ohmm)	Interpretation
1	200	<62.5	Waste (Mainly Domestic & Industrial)
2	700	>62.5	Overburden with Leachate
3a	N/A	>500 (At Depth)	Fresh Limestone
3b	N/A	<500 (At Depth)	Karstified Limestone, Leachate within Limestone or Artificial Effect

4. CONCLUSIONS AND RECOMMENDATIONS

Geological Background

The geophysical survey indicates the landfill is underlain by overburden over fresh limestone. The overburden material below the waste material is approx. 9 m thick and could contain any material like peat, clay or sand and gravel. The fresh limestone should restrict the movement of leachate below the waste and overburden however low resistivities along profile R1 may indicate leachate penetration towards the west of the site.

Lateral extent of waste and landfill boundary

The area outlined in orange on Map 3 shows the interpreted extent of the landfill using all the information available. The interpreted landfill extent covers an area of approx. 27,700 m^2.

Vertical extent (depth) of waste

The thickness/depth has been estimated from the seismic refraction and 2D-Resistivity data. Considering the thickness of the interpreted Layer 1, an average thickness of 8 m has been calculated for the waste material. This estimate includes any capping or natural fill material on top of the main waste body.

Including the layer of overburden below the landfill containing leachate (Layer 2), the total depth of waste and leachate reaches an average of 17 m bgl.

Volume of waste

Considering the areas and average thickness above, the volume of the waste body is estimated at 221,600 m^3.

Nature of waste

Low resistivities and seismic velocities measured are consistent with industrial and domestic waste throughout of the landfill.

Capping layer

There is no engineered capping layer over the landfill and the geophysics survey does not show any significant natural material over the landfill.

Leachate

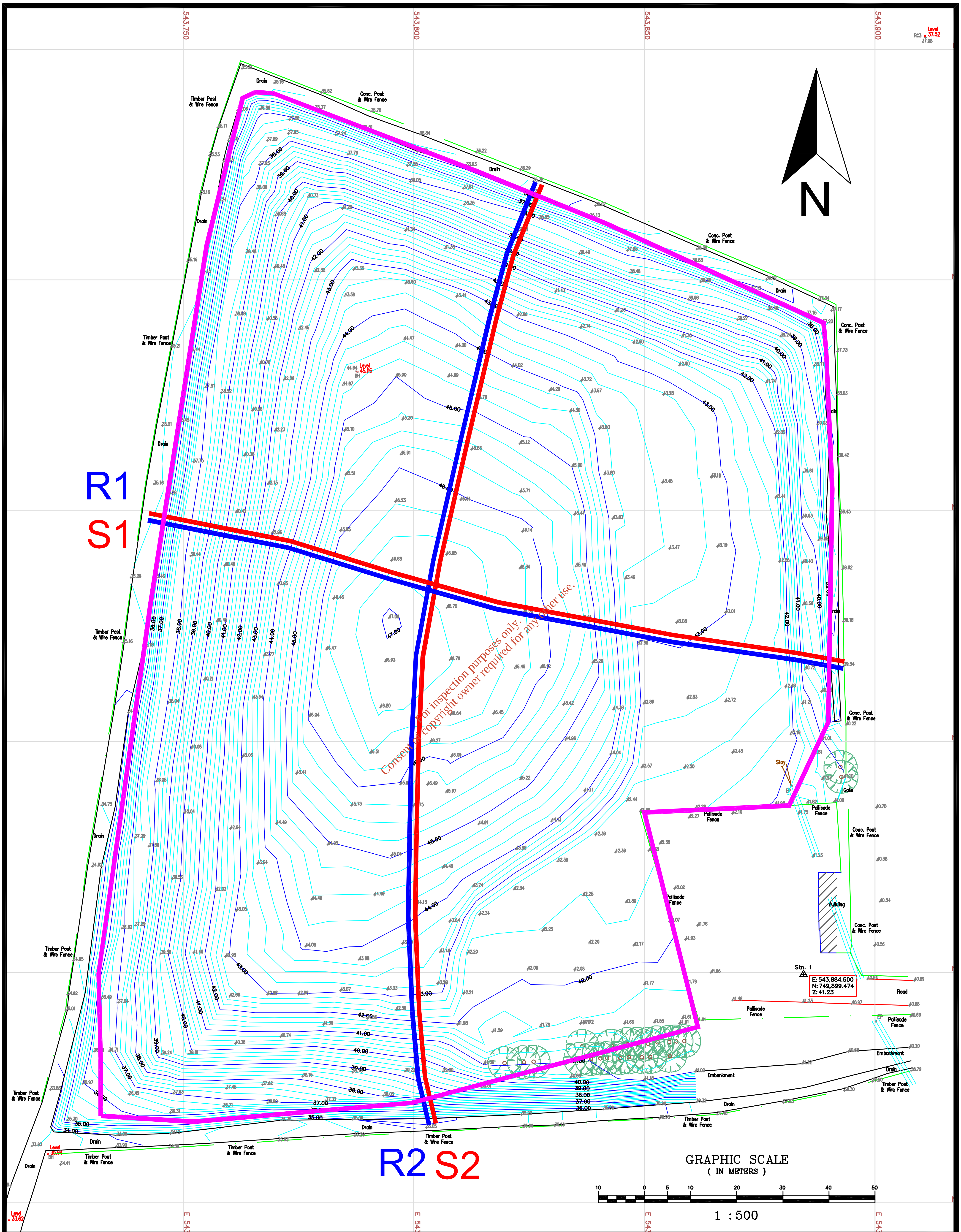
Low resistivities below the waste body is interpreted as likely leachate. The fresh limestone below this layer should generally restrict the leachate movement but there may be leachate penetration into the rock along profile R1.

Recommendations

It is recommended to carry out a borehole where the profiles cross (543803, 749983). This will determine if the low resistivities are due to leachate. It will also determine the overburden below the landfill and identify leachate within this layer.

5. REFERENCES

1. **GSEG 2002.** Geophysics in Engineering Investigations. Geological Society Engineering Geology Special Publication 19, London, 2002.
2. **GSI, 2019.** Online Bedrock Geological Map of Ireland. Geological Survey of Ireland 2019.
3. **Milsom, 1989.** Field Geophysics. John Wiley and Sons.
4. **Reynolds, 1997.** An Introduction to Applied and Environmental Geophysics. John Wiley and Son.



Minerex Geophysics Limited

Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare
Tel. (01) 6510030
Email: info@mgx.ie
Web: www.mgx.ie

CLIENT FTCO

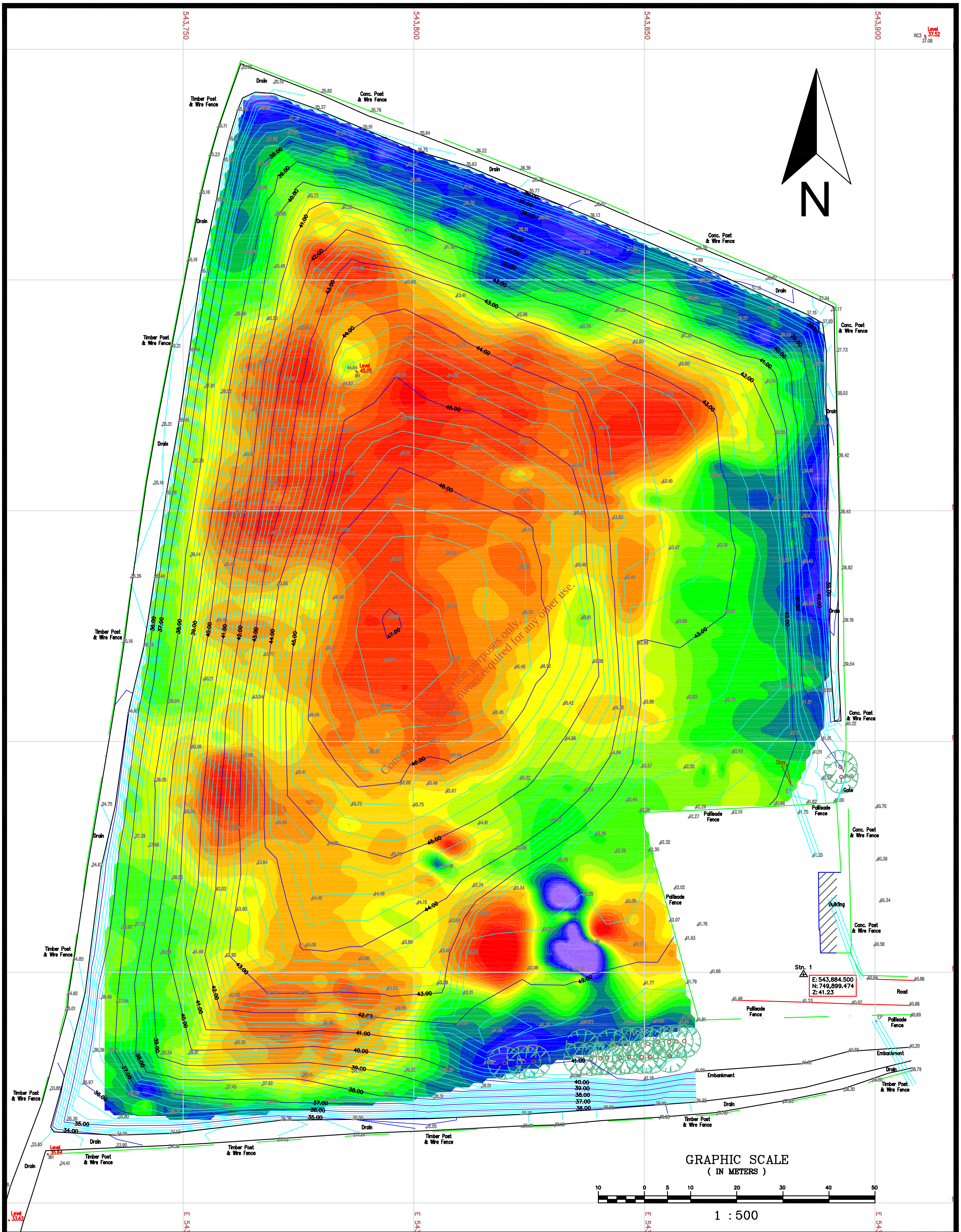
PROJECT Tuam Historic Landfill Geophysical Survey

TITLE Map 1: Geophysical Survey Location Map

SCALE:	1:750 @ A3
PROJECT:	6499
DRAWN:	JC
DATE:	22/05/2020
MGX FILE:	6499d_Tuam_MapsFigs.dwg
STATUS:	Draft

LEGEND: Geophysical Survey Locations:

R2	2D-Resistivity Profile
S1	Seismic Refraction Profile
	EM31 Survey Area



Minerex
Geophysics Limited

Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare
Tel. (01) 6510030
Email: info@mgx.ie
Web: www.mgx.ie

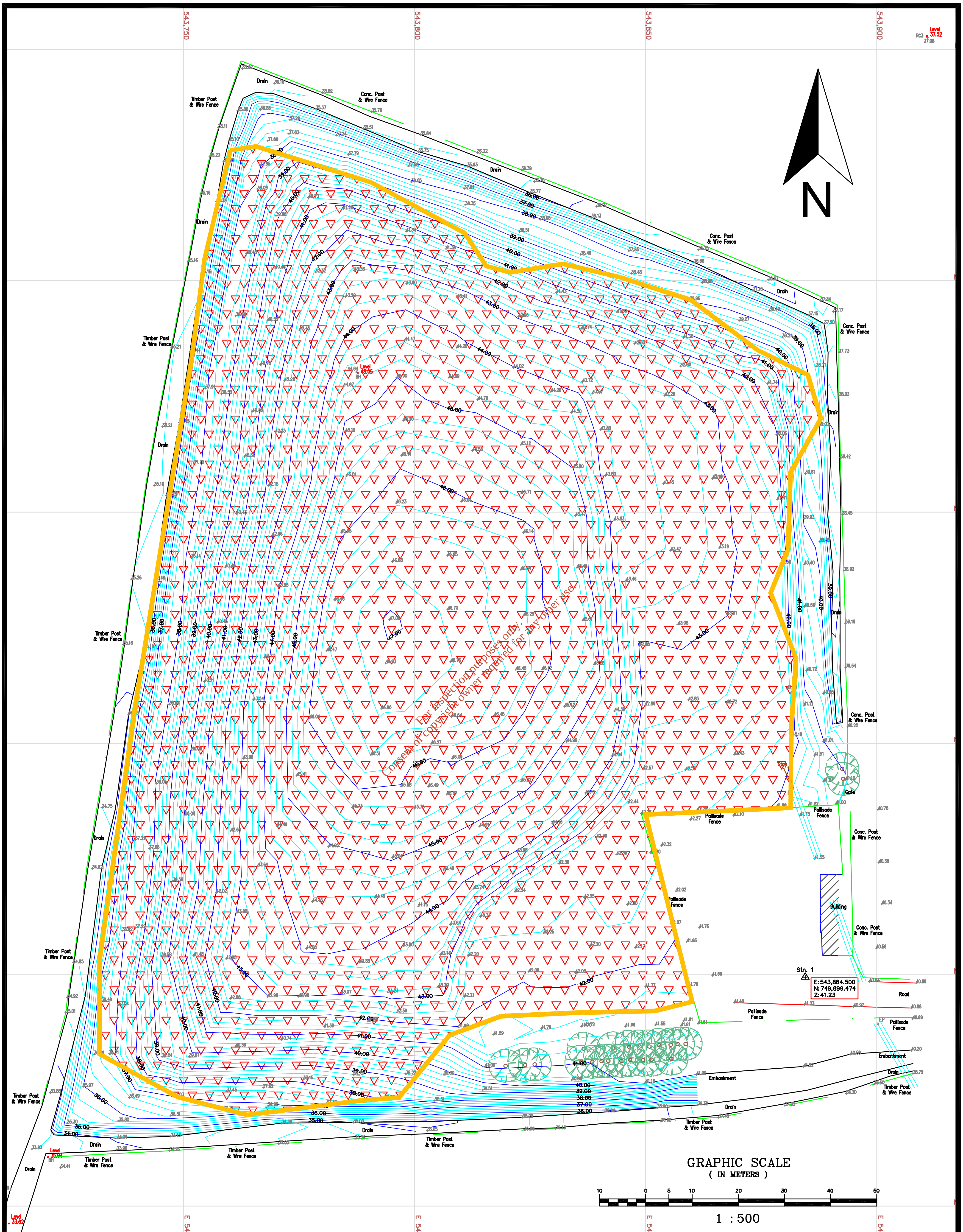
CLIENT	FTCO
PROJECT	Tuam Historic Landfill Geophysical Survey
TITLE	Map 2: EM31 Ground Conductivity Contour Map

SCALE:	1:750 @ A3
PROJECT:	6499
DRAWN:	JC
DATE:	22/05/2020
MGX FILE:	6499d_Tuam_MapsFigs.dwg
STATUS:	Draft

LEGEND: EM31 Ground Conductivity Values:

0 10 20 30 40 50 60 70 80 90 100

The map shows the EM31 ground conductivity contours mS/m. The low (blue) conductivities indicate the no waste material. The middle range (green) values indicates some waste material. The high (red) values indicates the deepest waste area.



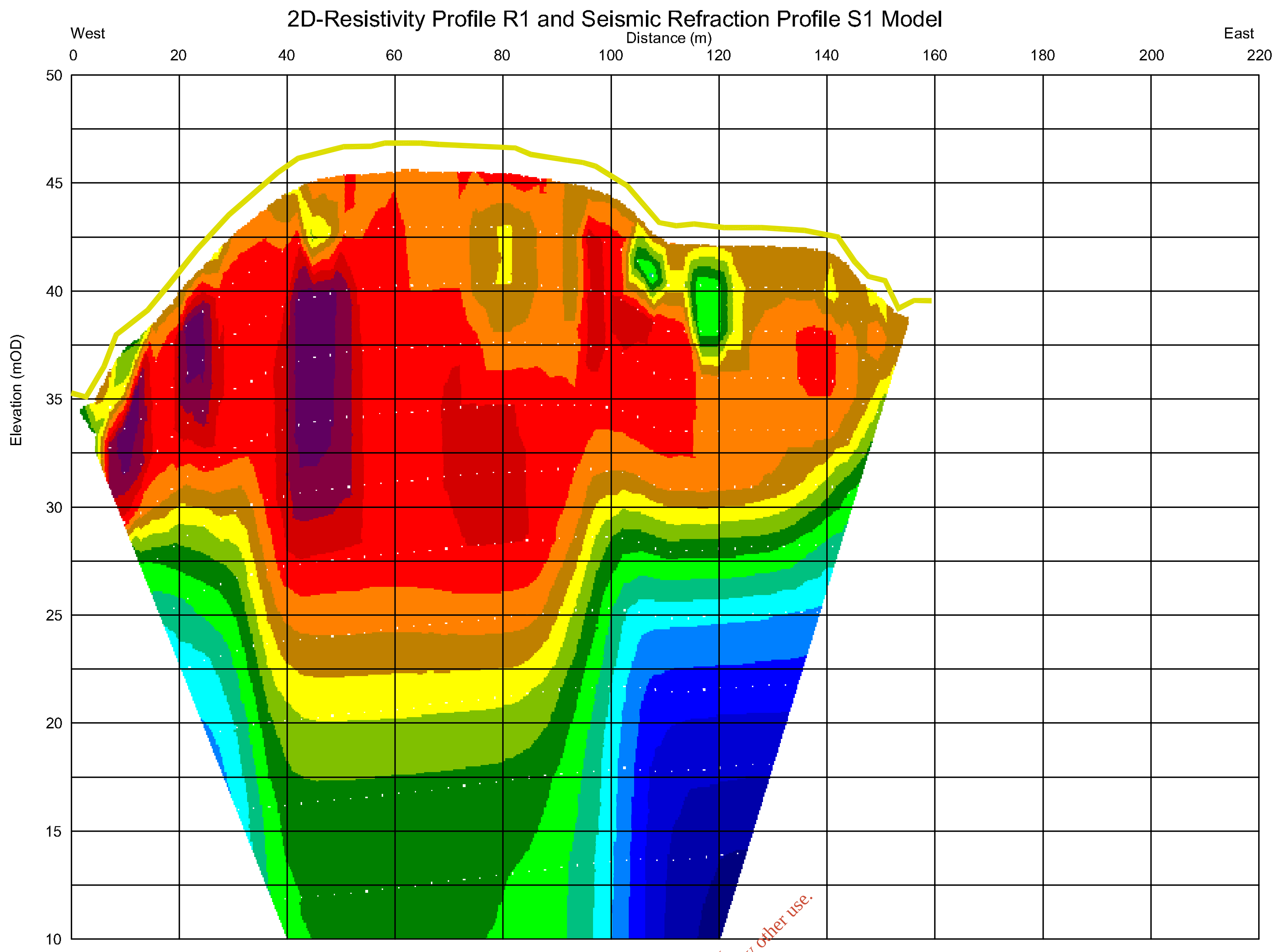
Minerex Geophysics Limited

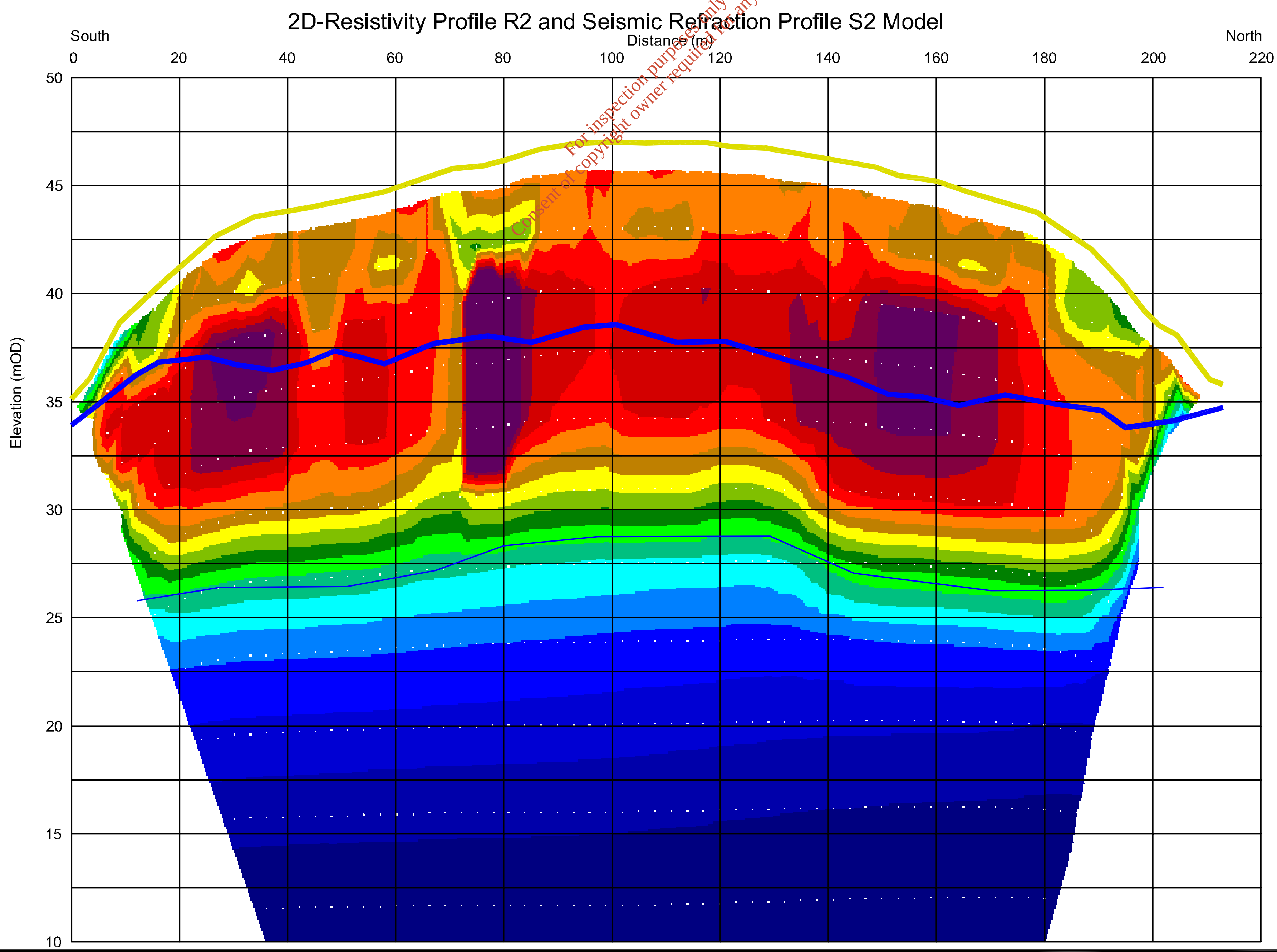
Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare
Tel. (01) 6510030
Email: info@mgx.ie
Web: www.mgx.ie

CLIENT	FTCO
PROJECT	Tuam Historic Landfill Geophysical Survey
TITLE	Map 3: Geophysical Survey Interpretation Map
SCALE:	1:750 @ A3
PROJECT:	6499
DRAWN:	JC
DATE:	22/05/2020
MGX FILE:	6499d_Tuam_MapsFigs.dwg
STATUS:	Draft

LEGEND:

Extent of D/I Waste





Minerex Geophysics Limited

Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare
Tel. (01) 6510030
Email: info@mgx.ie
Web: www.mgx.ie

CLIENT	FTCO
PROJECT	Tuam Historic Landfill Geophysical Survey
TITLE	Figure 1: Models of Geophysical Survey

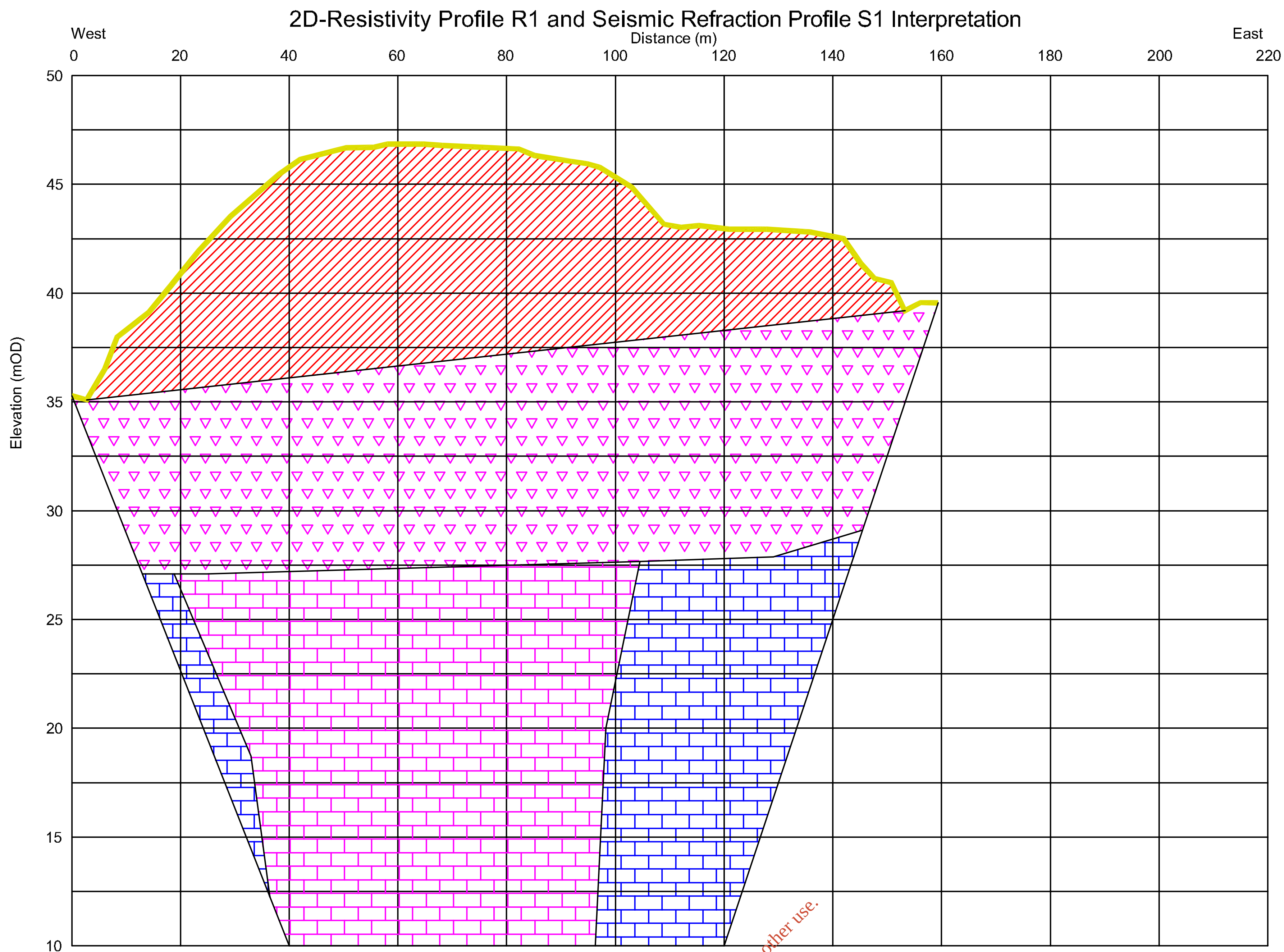
SCALE:	1:1000 @ A3
PROJECT:	6499
DRAWN:	JC
DATE:	22/06/2020
MGX FILE:	6499d_Tuam_MapsFigs.dwg
STATUS:	Draft

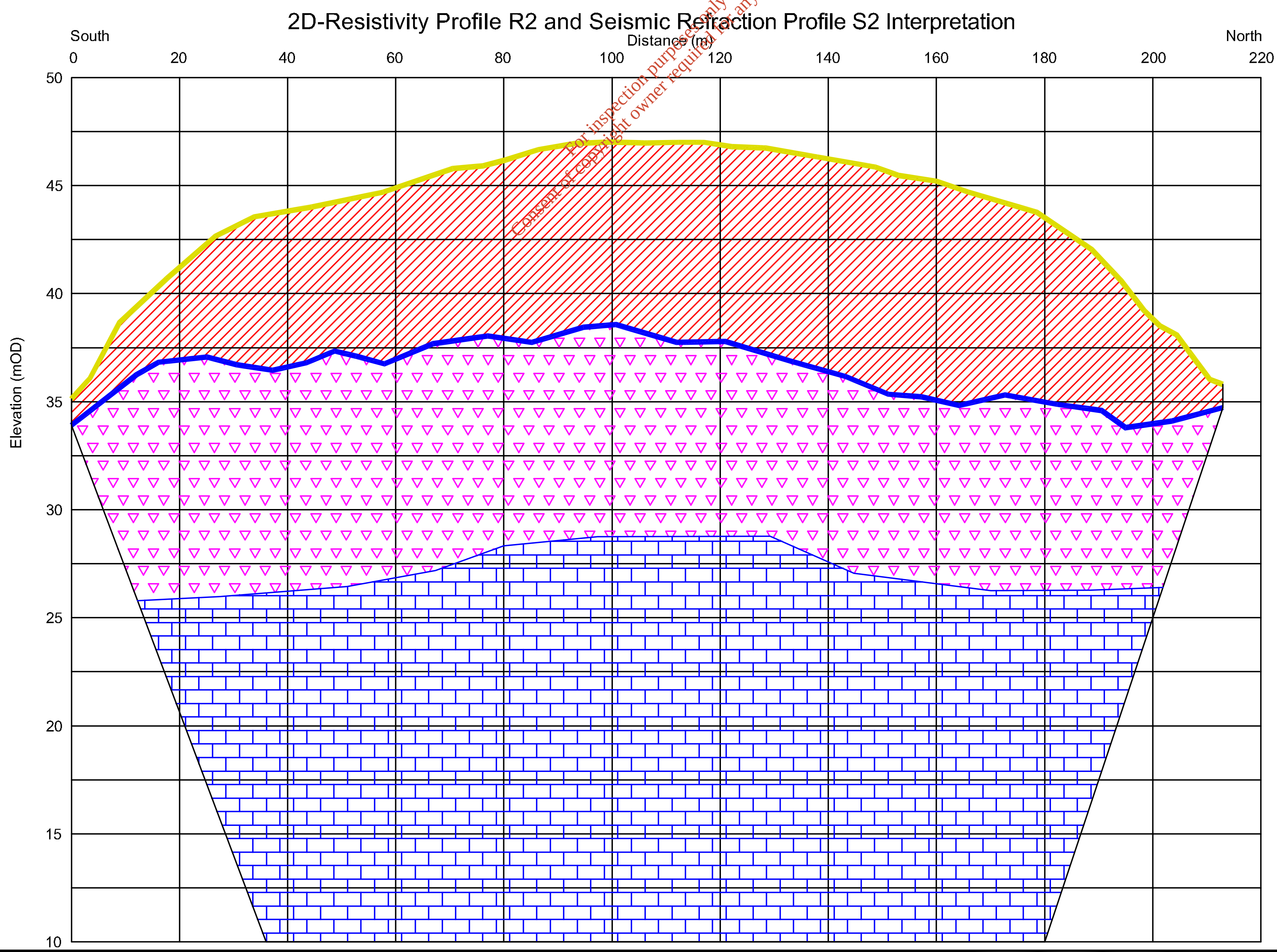
LEGEND: Layers from Seismic Refraction Model:

- Ground Surface/Top of Layer 1 (200 m/s)
- Top of Layer 2 (700 m/s)

2D-Resistivity Model Values:

7.82 15.6 31.3 62.5 125 250 500 1000





Minerex
Geophysics Limited

Unit F4, Maynooth Business Campus
Maynooth, Co. Kildare
Tel. (01) 6510030
Email: info@mgx.ie
Web: www.mgx.ie

CLIENT: FTCO

PROJECT: Tuam Historic Landfill Geophysical Survey

TITLE: Figure 2: Interpretation of Geophysical Survey

SCALE: 1:1000 @ A3

PROJECT: 6499

DRAWN: JC

DATE: 22/06/2020

MGX FILE: 6499d_Tuam_MapsFigs.dwg

STATUS: Draft

LEGEND:
Interpretation:
- 1 Waste (Mainly D/I)
- 2 Overburden with Leachate
- 3a Fresh Limestone
- 3b Karstified Limestone, Leachate within Limestone or Artificial Effect