Appendix 14.4

Geophysical Survey

Site at Ferrybank, Arklow

County Wicklow

Geophysical Survey

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Subsurface Geophysical Investigations

EXECUTIVE SUMMARY

1. Minerex Geophysics Ltd. (MGX) carried out a geophysical survey consisting of 2D-Resistivity, seismic refraction (p-wave) and MASW (s-wave) surveying for the preliminary ground investigation at a site at Ferrybank, Arklow, Co. Wicklow.

2. The site is a former wallboard factory and the site is currently for sale. The client is considering to purchase the site and to use parts of the construction of a waste water treatment plant.

3. The main objectives of the survey were to determine ground conditions, estimate the depth to rock and overburden thickness and to determine the strength of subsurface materials.

4. The survey was carried out along the two long sides of the existing long factory building.

5. The resistivity survey showed that the ground under the site has saline conditions and that the ground is therefore corrosive.

6. The shallow overburden is made up of topsoil, fill material and made ground consisting predominantly of blocks and gravel.

7. The deeper overburden (Layer 2 in the seismic interpretation) has a firm stiffness and is interpreted as sandy and gravelly overburden (marine sediments).

8. Layer 3 interpreted form the seismic refraction as weathered rock or very compact overburden has a high stiffness or compaction and seems suitable to carry piled foundations for structures with heavy loads. This layer occurs at a depth of approx. 10m at S1 and 15 to 20m on S2.

9. The MASW method determined shear moduli between 71 and 336 MPa for depths of 1.1 to 10.6 m bgl.

10. Future ground investigation should consist of trial pits for the overburden and of rotary coring (Geobore-S method) to investigate the layer 3.

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List of Tables, Maps and Figures:

1. INTRODUCTION

1.1 Background

Minerex Geophysics Ltd. (MGX) carried out a geophysical survey at the site of a disused wallboard factory at Ferrybank in Arklow, Co. Wicklow. The site is currently for sale and the client is considering to purchase the site and construct a waste water treatment plant. The survey consisted 2D-Resistivity, seismic refraction (p-wave) and MASW (s-wave) measurements. The survey was commissioned by Arup acting on behalf of Irish Water and Wicklow County Council.

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 generate an initial ground model that can be later improved by direct ground investigations.

1.2 Objectives

The main objectives of the geophysical survey were:

- To determine the ground conditions under the site
- To determine the depth to rock and overburden thickness
- To estimate the strength/stiffness/compaction of overburden materials and the quality of rock
- To detect lateral changes within the geological layers

1.3 Site Description

The site is located at Ferrybank in Arklow. The site is dominated by the long building of the disused factory. The site is close to a sea wall made from large blocks. The ground is generally very flat with elevations of 2.3 to 2.8 m OD. At the northern end of profile R1 the ground is uneven and large blocks of reinforced concrete are visible.

1.4 Geology

The shallow overburden geology consists of made ground and fill. Historical maps on the Ordnance Survey of Ireland webpage indicate that the Avoca River was meandering under the factory in historical times. The Avoca River is now flowing straight to the sea south of the site under investigation.

The deeper overburden is likely to consist of marine sediments like silt, sand and gravels.

The bedrock geological map of Carlow-Wexford (GSI, 1995) indicates that the southern survey area is underlain by the Maulin Formation described as dark blue-grey Slate, Phyllite and Schist. The northern part is underlain by the Kilmacrea formation described as dark grey slate and minor pale grey sandstone.

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 consisted of using 2D-Resistivity Profiles, Seismic Refraction and MASW profiles. The survey locations are indicated on Map 1.

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

2.2 2D-Resistivity

Two 2D-Resistivity profiles were surveyed with electrode spacing of 5m, up to 64 electrodes per set-up and a length of 315m for R1 and 205 m for R2. The readings were taken with a Tigre Resistivity Meter, Imager Cables, stainless steel electrodes, laptop and ImagerPro acquisition software. The survey was done along green strips of ground to avoid hardstanding surfaces.

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 materials.

2.3 Seismic Refraction

The seismic survey consisted of p-wave seismic refraction profiling at the locations shown on Map 1. Each of the profiles consisted of 24 geophones with 3 m spacing, resulting in lengths of 69m for S1 and 63m for S2. 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. Seven shot points per p-wave profile were used.

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.

In areas with thick concrete, tarmac or blocks a low velocity layer exists for the seismic waves below the solid surface layer. This makes it less certain or impossible to pick first breaks from geophones near the source and therefore no velocity determination for the shallow subsurface is possible. This results in larger deviations in the modelling and borehole results are required for a final calibration of the results.

2.4 MASW (Multichannel Analysis of Surface Waves)

The seismic shear wave velocity was determined by active MASW surveying. MASW (Multi-Channel Analysis of Surface Waves) determines the bulk seismic shear wave velocity versus depth. The velocities are used to determine the small strain shear modulus.

The MASW method was acquired along with the seismic refraction survey though the shots were done individually with a larger time window. 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. The shot points were located at the ends of the profiles.

Many constrains exist for the MASW method and the main factors on this site that affect the methods are strong vertical velocity gradients and changing velocity structure and layer thicknesses along the profiles.

2.5 Site Work

The data acquisition was carried out on the 10th of March 2016. The weather conditions were fair throughout the acquisition period. Health and safety standards were adhered to at all times.

The locations and elevations were surveyed with a TRIMBLE RTK-GPS to accuracy < 0.05m.

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 2D-Resistivity Models

The 2D-Resistivity data was positioned and inverted with the RES2DINV inversion package. Overlapping and roll-along profiles were concatenated for a joint inversion. 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. The resulting models were colour contoured with the same resistivity scale for all profiles and they are displayed as cross sections (Figure 1).

The resistivities cover a large range typical for materials from dry made ground and rock or gravel fill to saline ground conditions.

Very low resistivity values (<20 Ohmm (orange to red colours) indicate saline ground conditions that are caused by saline sea water intruding under the site. These intrusions were expected before the survey. The resistivity proved these saline conditions to be true and therefore the ground under the site has to be treated as corrosive. This means that future possible structures, foundations and underground pipes/cables have to be rated to withstand corrosive conditions. This can be a cost factor for a proposed development.

The shallow ground to a few meters of depth in characterised by high resistivities (> 80 Ohmm) indicating fill and made ground made mainly from rock or gravel fill. There does not seem to be a large amount of clay in the fill material.

The saline ground conditions do not make it possible to interpret the data further other than to state that the ground in intruded by saline water. Therefore the ground must be permeable for water and it could be made up from weathered rock or sandy gravelly overburden. The purpose of the resistivity survey was to establish the amount of saline ground and to check if the ground is corrosive.

3.2 Seismic Refraction Models

The seismic refraction data was positioned and processed with the SEISIMAGER software package to give a layered model of the subsurface. The numbers of layers has been determined by analysing the seismic traces and four layers were used in the models. All seismic profiles were subject to a standardised processing sequence which consisted of a topographic correction which was based on integrated elevation data, first break picking, tomographic inversion, travel-time computation via ray-tracing and velocity modelling. Residual deviations of < 2 msec RMS have been obtained for each profile. Following each processing stage QC procedures were adhered to. The resulting layer boundaries are shown as thick lines overlaid on the 2D-Resistivity cross sections (Figure 1). The average seismic velocities obtained within the layers are annotated on the sections as bold black numbers.

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 some subsurface materials the higher the seismic velocity. Similarly for the other parameters it is generally valid that a stronger material will have a higher seismic velocity. For rock the seismic velocity is higher when the rock is stronger and less weathered. If the rock is more weathered broken fractured or fissured then the seismic velocity will be reduced compared to that of intact fresh rock.

Because of the above relation the seismic refraction method and seismic velocities are suitable to investigate ground where the layers get denser, more compacted and stronger with depth. A disadvantage is that some materials have the same seismic velocity: A very stiff or very dense highly consolidated overburden and a weathered rock can have the same seismic velocity range (as is the case in the layer 3 below).

Layer 1a has a thickness of 1 – 2 m and seismic velocities of 270 - 300 m/s. This overburden is interpreted as topsoil and soil with a soft or loose stiffness or compaction.

Layer 1b was modelled with a velocity range of 600 – 1100 m/s and a thickness of 6 – 9 m. The velocity and the hard ground on site indicate fill material and made ground.

Layer 2 velocities of 1500 – 1700 m/s indicate predominantly overburden which is saturated by water.

Layer 3 velocities of 2800 – 2900 m/s indicate a weathered rock or very compact overburden. The elevation of the top of this layer varies between – 5 to – 7 mOD on S1 and around -15 mOD on S2.

3.3 Interpretation of Seismic Refraction

Table 1 summarises the interpretation. The stiffness/compaction and the rock strength/quality have been estimated from the seismic velocity. Interpreted cross sections are shown in Figure 2. The interpretation has been made from and for the seismic refraction profiles only.

Table 1: Summary of Results and Interpretation

Layer	**General Seismic Velocity Range (m/sec)**	**Stiffness/ Compaction or Rock Strength/ Quality**	**Interpretation**
1a	270 – 300	Soft or loose	Topsoil
1b	600 - 1100	Dense	Fill Material/Made Ground
2	1500 - 1700	Firm or dense	Overburden
3	2800 - 2900	Fair Rock or very dense Overburden	Weathered Rock or very compact Overburden

3.4 Results for MASW Survey

The MASW profiles were positioned, processed, analysed and modelled with the SEISIMAGER/SW software package. The objective is to obtain a profile of shear wave velocity versus depth and to calculate the small strain shear modulus Gmax from the shear wave velocities. Two opposed shot points from each profile set-up were acquired and were analysed. One end shot for each profile showed a good dispersion curve while the other did not show a useful curve. This can happen on build up sites and has been observed before on other sites. The good shots were used for further processing:

Following processing steps are done to achieve this:

1. Edit the shot point geometry and display the shot points for each profile
2. Edit traces and/or apply filters to improve the shot record for the next step
3. A dispersion curve (phase velocity versus frequency plot or dispersion image) is computed
4. For each shot the maximum amplitude at each frequency of the dispersion image is selected and then the picks for the dispersion curve are truncated (frequency gate), smoothed and brought forward into the modelling process
5. An initial model of shear-wave velocity versus depth V_s is computed
6. An inversion is carried out to create the final V_s curve (Shear wave versus depth). The valid depth range is noted and the data saved in a file
7. For stable repeatable results the shear wave velocity versus depth is extracted and the depth range covered by the real survey data is then listed in Table 2.
8. The small strain shear modulus (also named Gmax) for each shot point and depth is computed by using a density of 2000kg/m^3 typical for consolidated overburden (Eq. 1)

   (Eq. 1) $G = V_s^2 * \rho * 10^{-6}$

   where G = Shear Modulus (MPa)

   V_s = Seismic Shear Wave Velocity (m/s)

   ρ = Density (kg/m^3)

The results are tabulated in Table 2 and the models of the shear wave velocity versus depth are shown on Figure 3.

Shear modules between 71 and 336 MPa have been derived for depths of 1.1 to 10.6m.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made:

- The geophysical survey carried out at the Ferrybank site showed the following results:
- The resistivity survey showed that the ground under the site has saline conditions and that the ground is therefore corrosive. This will have an impact in the design of future structures, foundations and underground pipes/cables.
- The shallow overburden is made up of topsoil, fill material and made ground. Historical maps indicate that the ground has been filled over a previous river bed of the Avoca River. When grounding electrodes is was noted that the ground is very rocky and stony along the factory building. The seismic velocities on profile S1 at the south-eastern end of the site indicate solid fill layers that could be made up from blocks and gravel.
- The deeper overburden (Layer 2 in the seismic interpretation) has a firm stiffness as derived from the MASW results. It is likely sandy and gravelly overburden that are marine sediments and they are saturated as indicated by the p-wave velocity.
- Layer 3 interpreted form the seismic refraction as weathered rock or very compact overburden has a high stiffness or compaction and seems suitable to carry piled foundations for structures with heavy loads. This layer occurs at a depth of approx. 10m at S1 and 15 to 20m on S2. This depth does not seem too bad for a coastal site where the marine sediments can reach thicknesses of several 10 m.
- The MASW method determined shear moduli between 71 and 336 MPa for depths of 1.1 to 10.6 m bgl.
- The seismic p-wave velocities for layer 3 allow a rough estimate of shear moduli of 2000 – 4500 MPa for this layer.
- Future ground investigation should consist of trial pits for the overburden and of rotary coring (Geobore-S method) to investigate the layer 3. Cable percussive borehole would be likely to refuse at a shallow depth.
- The recommendations above should not preclude any other site investigation that may be carried out based on geological, geotechnical or engineering considerations.

5. REFERENCES

1. **GSEG 2002.** Geophysics in Engineering Investigations. Geological Society Engineering Geology Special Publication 19, London, 2002.

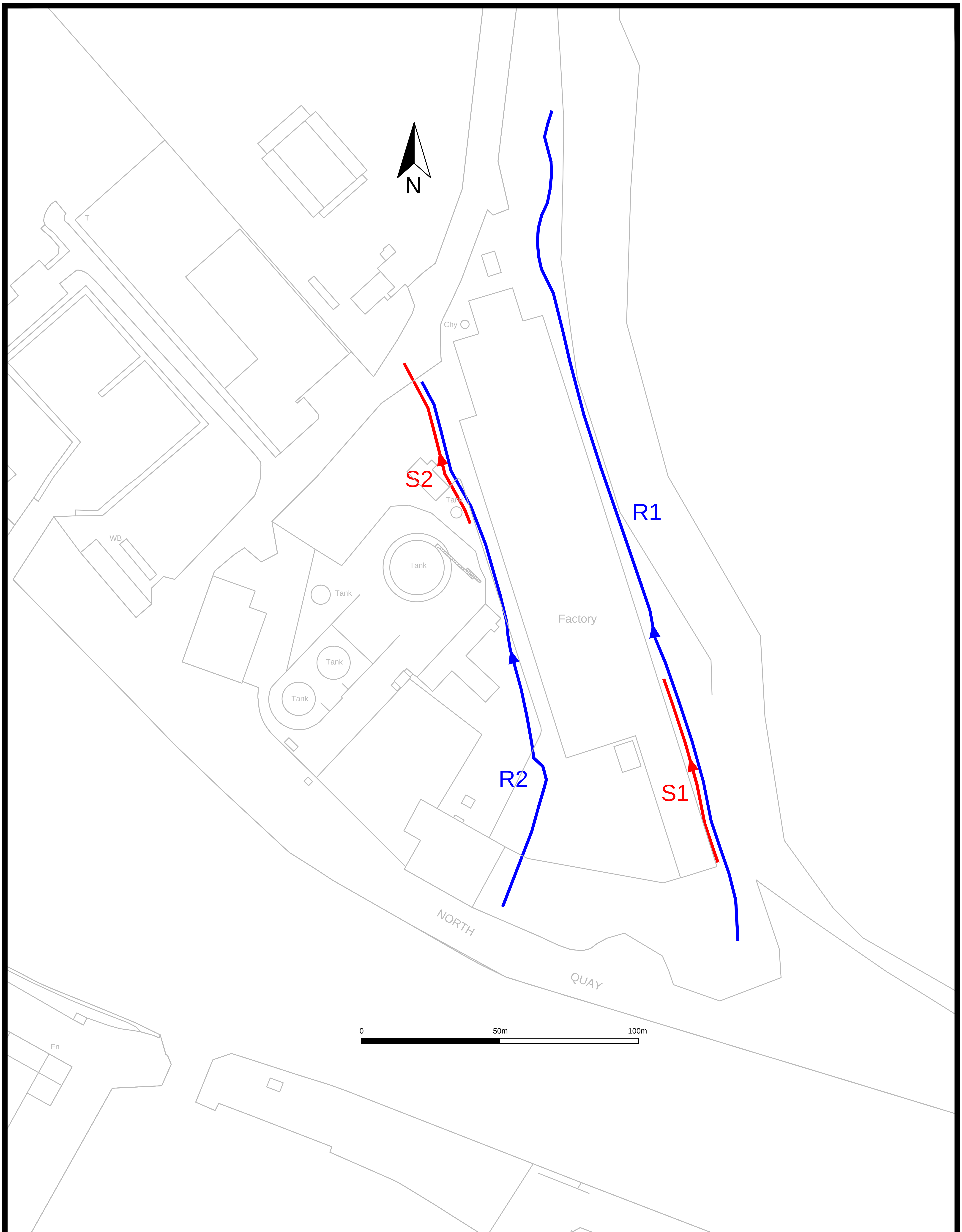
2. **GSI, 1995.** Geology of Carlow-Wexford. Geological Survey of Ireland 1995.

3. **Milsom, 1989.** Field Geophysics. John Wiley and Sons.

4. **Reynolds, 1997.** An Introduction to Applied and Environmental Geophysics. John Wiley and Son.

Table 2: MASW S-Wave Velocity and Shear Modulus

MASW Profile	Interpretation/Comment (Note: The density used for computing the Shear Modulus is 2000 kg/m^3)	Depth (m)	S-Wave Velocity (m/s)	Gmax - Shear Modulus in MPa
S1	The dispersion image shows a well defined curve for the depth range 2.3 to 10.6 m bgl.	2.3	222.0	98
		3.0	236.5	111
		3.8	243.8	118
		4.6	271.7	147
		5.5	302.1	182
		6.4	306.3	187
		7.4	340.3	231
		8.4	348.1	242
		9.5	356.6	254
		10.6	410.1	336
S2	The dispersion image shows a well defined curve for the depth range 1.7 to 10.6 m bgl.	1.1	188.9	71
		1.7	201.2	80
		2.3	220.0	96
		3.0	236.3	111
		3.8	246.3	121
		4.6	263.1	138
		5.5	263.4	138
		6.4	281.1	158
		7.4	292.2	170
		8.4	295.1	174
		9.5	309.7	191
		10.6	313.4	196



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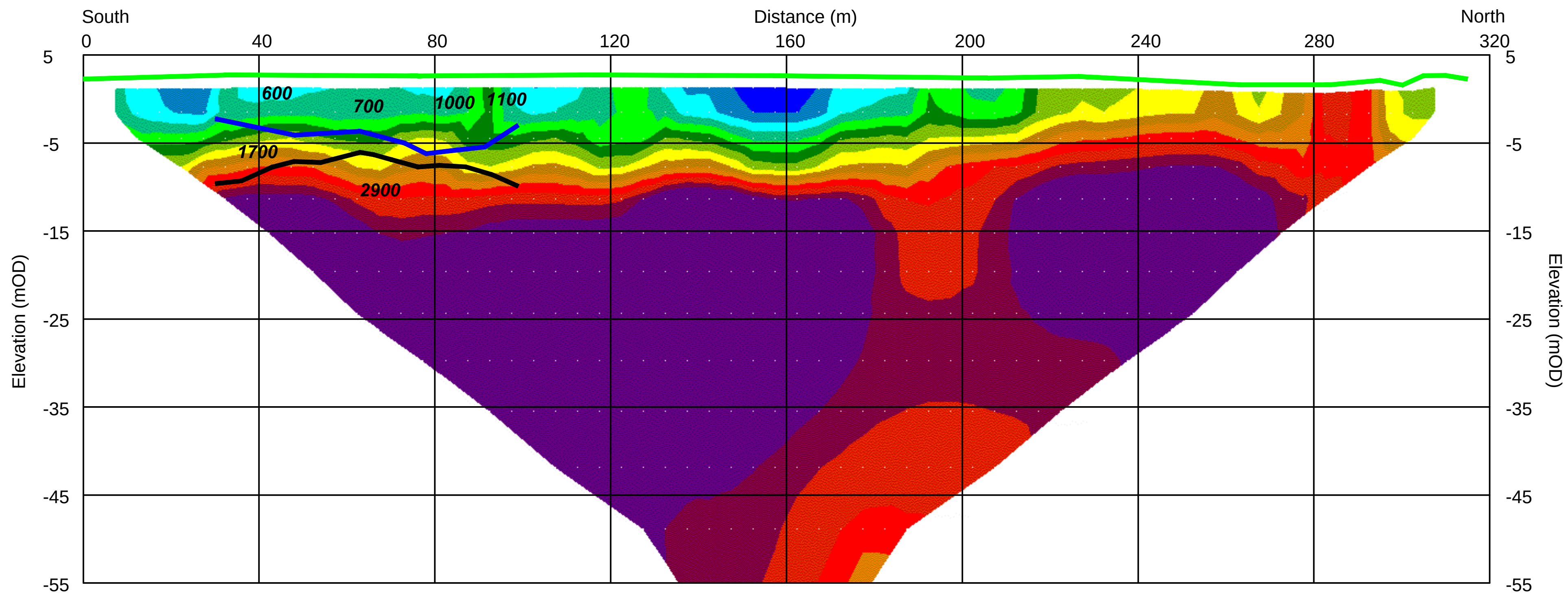
CLIENT	Irish Water Arup
PROJECT	Site at Ferrybank, Arklow Geophysical Survey
TITLE	Map 1: Geophysical Survey Location Map

SCALE:	1:1250 @ A3
PROJECT:	6049
DRAWN:	HK
DATE:	14/03/2016
MGX FILE:	6049d_MapsFigs.dwg
STATUS:	Draft

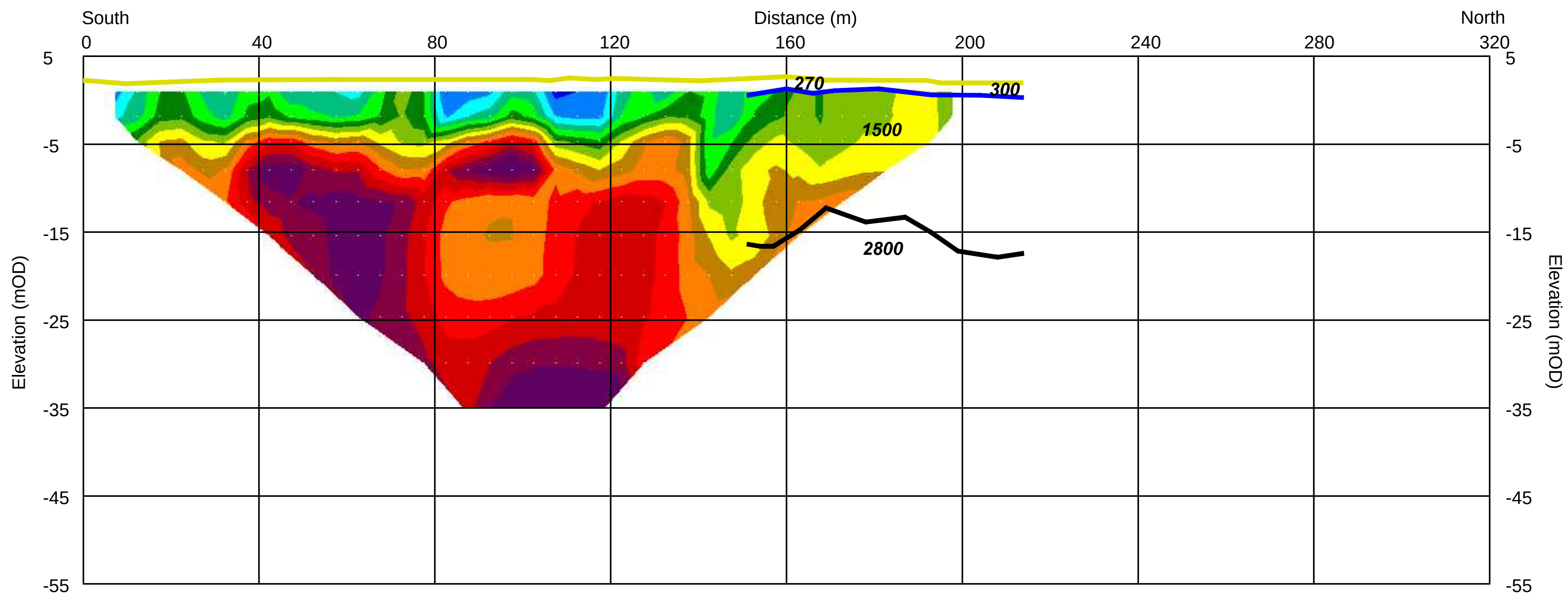
LEGEND: Geophysical Survey Locations:

R2	2D-Resistivity Profile
S1	Seismic Refraction/MASW Profile

2D-Resistivity Profile R1 and Seismic Refraction Profile S1 Model



2D-Resistivity Profile R2 and Seismic Refraction Profile S2 Model



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CLIENT	Irish Water Arup
PROJECT	Site at Ferrybank, Arklow Geophysical Survey
TITLE	Figure 1: Models of Geophysical Survey

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LEGEND:

Layers from Seismic Refraction Model:

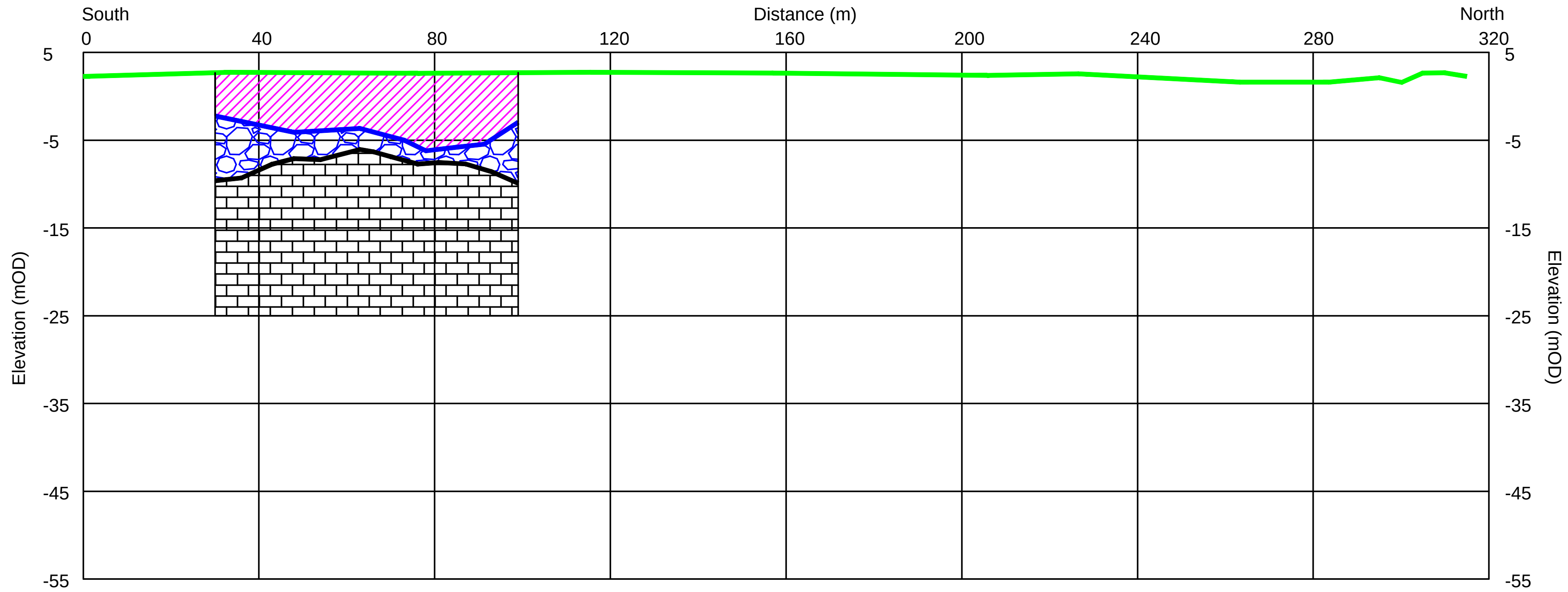
- Ground Surface/Top of Layer 1a (270 - 300 m/s)
- Ground Surface/Top of Layer 1b (600 - 1100 m/s)
- Top of Layer 3 (1500 - 1700 m/s)
- Top of Layer 3 (2800 - 2900 m/s)

1800 Seismic Velocity in m/s

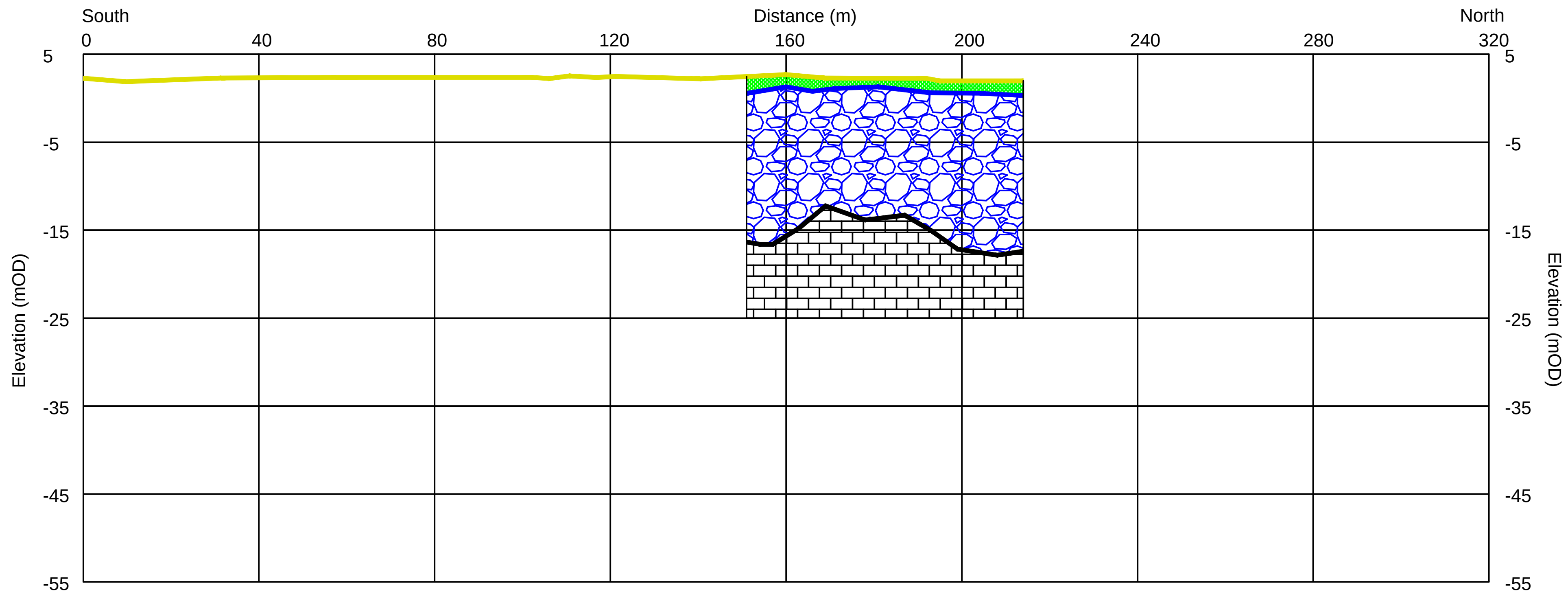
Resistivities (Ohmm) for 2D-Resistivity Model

5.00 10.0 20.0 40.0 80.0 160 320 640

2D-Resistivity Profile R1 and Seismic Refraction Profile S1 Interpretation



2D-Resistivity Profile R2 and Seismic Refraction Profile S2 Interpretation



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CLIENT	Irish Water Arup
PROJECT	Site at Ferrybank, Arklow Geophysical Survey
TITLE	Figure 2: Interpretation of Geophysical Survey

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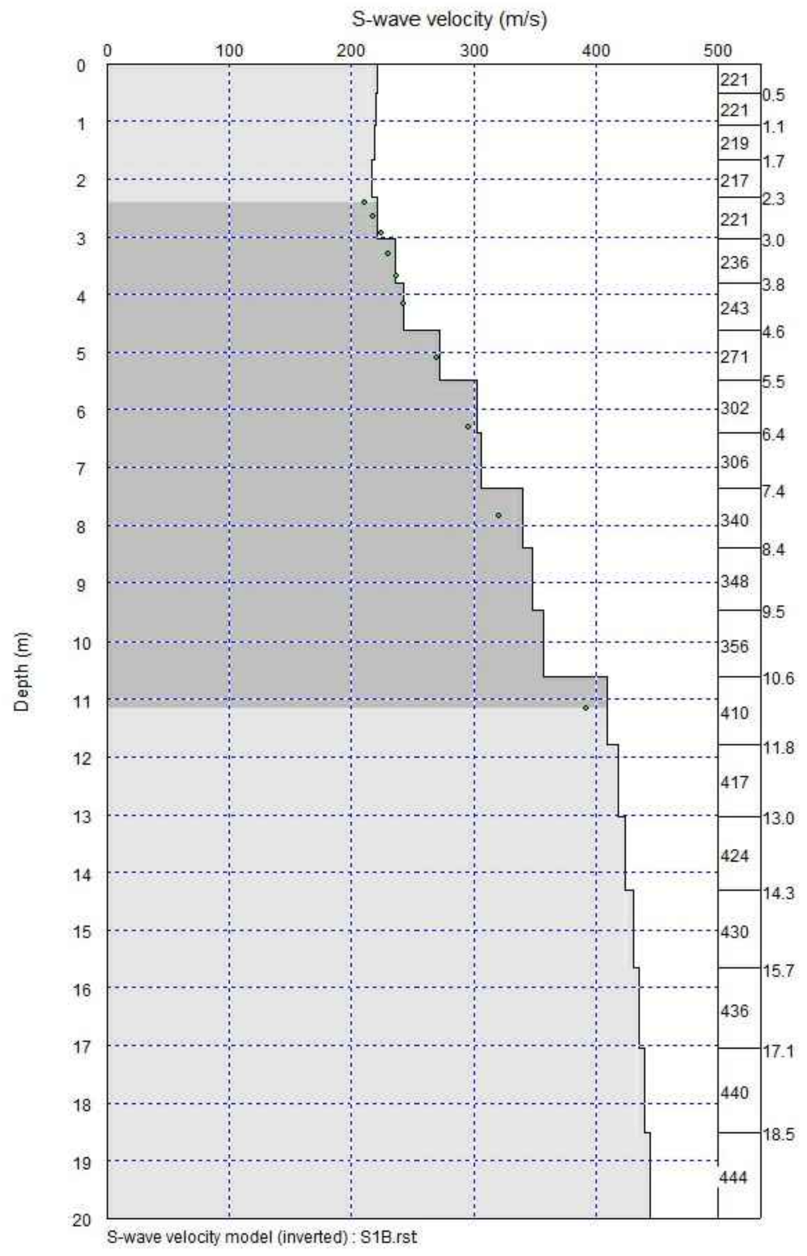
LEGEND:

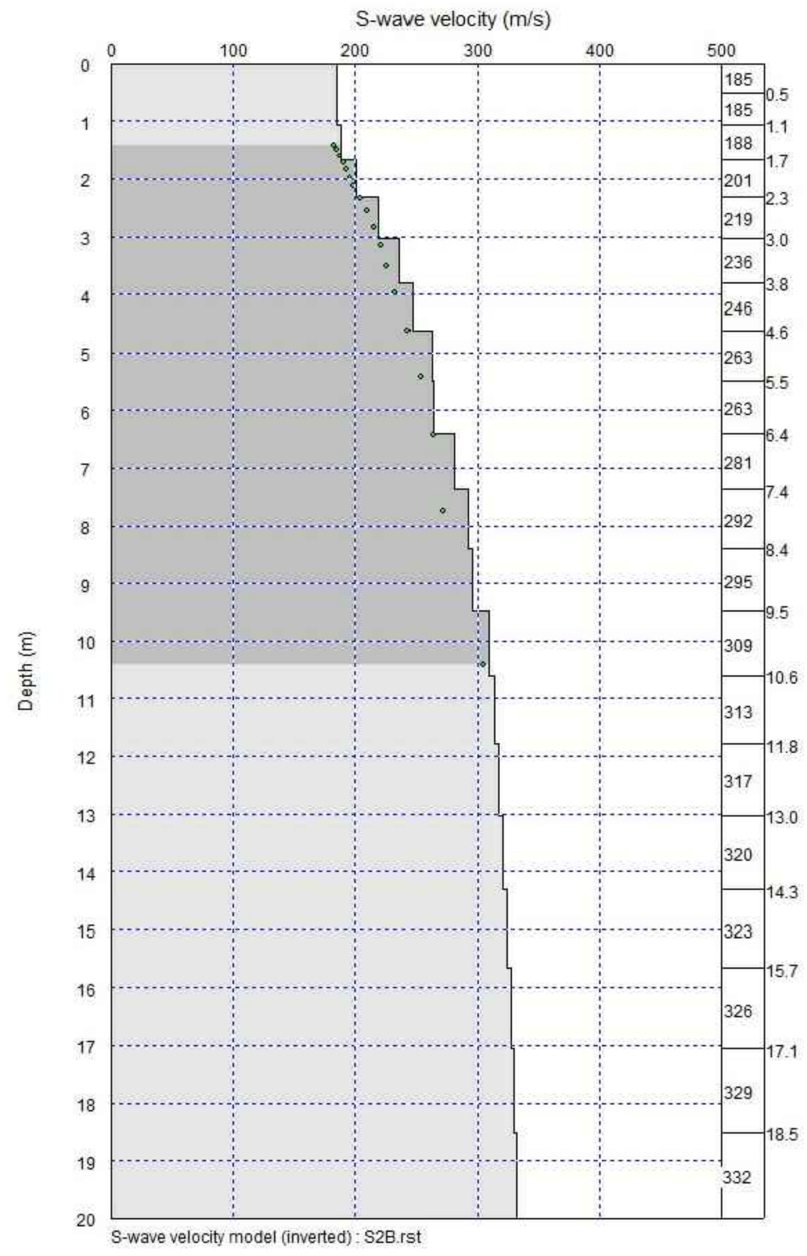
Interpretation of Seismic Refraction:

- 1a Soft or loose Topsoil
- 1b Fill Material/Made Ground
- 2 Firm or dense Overburden
- 3 Weathered Rock or very compact Overburden

Shear Wave Velocity (m/s) versus Depth (m) for S1



Shear Wave Velocity (m/s) versus Depth (m) for S2



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CLIENT	Irish Water Arup
PROJECT	Site at Ferrybank, Arklow Geophysical Survey
TITLE	Figure 3: MASW Results

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LEGEND:

The graphs show the shear wave velocity versus depth determined by the MASW method. The green dots show the picks from the dispersion curve and the dark grey shaded area indicates the depth range represented by measured data