CHARACTERISATION OF GRAVEL DEPOSITS IN THE PRE-GLACIAL CHANNEL, CENTRAL DUBLIN

STEPHEN KEALY, MICHAEL LONG, STEPHEN McCARRON, MARIE FLEMING and MILES FRIEDMAN

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Abstract

This paper reports on the production of an interactive 3-dimensional model over a key section of a pre-glacial channel feature in Dublin City. Significant infrastructural developments, most importantly the Dublin MetroLink project, are planned in the study area. The model presented here represents a complex depositional environment produced by several discrete phases of glaciation and deglaciation during the Quaternary and is consistent with previous published reports on the area. The geology in the study area typically consists of a Quaternary channel cut into the Carboniferous limestone bedrock, an intermittent lower glacial till, a large fluvio-glacial sand and gravel deposit and an intermittent upper glacial till.

The digital software used to manage and create a 3-dimensional ground model is described and is comprised of several commercially available modules. The digital 3-dimensional ground models are particularly useful as a single data repository which can easily be updated as new data becomes available. Interpretation of a large body of geotechnical tests confirmed the fluvio-glacial sand and gravel deposit is relatively non-homogenous but can be broadly characterised as a medium to very dense slightly sandy to sandy gravel. Simple index tests, such as particle size distribution analyses and standard penetration testing, are very useful for both material characterisation and interpretation of profiles, albeit the latter test results can be influenced by the presence of cobbles or boulders. Geophysical testing, especially shear wave velocity profiling, was shown to be a very useful characterisation tool in these deposits. The findings of this work are consistent with the overall understanding of the erosional features, pattern of glacial deposition and general geological history of the study area in Dublin.

Introduction

From a geotechnical engineer's perspective, Dublin City and environs are well known for their flooring in a thick competent glacial diamict, representing a sequence of lodgement tills (colloquially known as 'Dublin Boulder Clay'). Within these matrix-rich sediments, deep excavations are relatively easy to execute, little groundwater is encountered and ground movements associated with construction are modest (Farrell *et al.* 1995; Hanrahan 1977; Long *et al.* 2012a; Long and Menkiti 2007). Steep slopes can be excavated in the material and can stand open and unsupported for some time (Menkiti *et al.* 2004).

However, a significant geological feature underlying the city is a buried pre-glacial channel north of the River Liffey (Farrington 1929; Hoare 1976; Naylor 1965). This feature is thought to be up to 45m deep and is infilled mostly with water bearing fluvio-glacial gravels of variable consistency (O'Connor *et al.* 2020).

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Significant infrastructural developments are planned in the area overlying these deposits. Most importantly, the Dublin MetroLink project, which will connect the city centre to the airport, via underground railway lines, will likely encounter this pre-glacial channel specifically between and adjacent to the O'Connell and Mater stations. Other than the work mentioned above, some limited research into deep building basements constructed in the area (Long *et al.* 2012b) and a study of the abrasiveness of the fluvio-glacial deposits (O'Connor *et al.* 2020), little information has been published on the extent of the channel feature and the geotechnical properties of the associated deposits.

Research objectives

The purpose of this paper is to report on the generation of an interactive 3-dimensional model over a key section of the pre-glacial channel found in Central Dublin. The main objectives in creating the model are to:

- produce a database containing the geological and geotechnical aspects of the deposits found in the study area,
- constrain the shape and extent of the pre-glacial channel within the study area,
- determine the depth and extent of the fluvio-glacial deposits within the study area,
- determine the extent of the glacial till within the study area,
- characterise the engineering properties of the fluvio-glacial deposits, including the basic index properties and the strength and stiffness of the materials,
- compare the engineering parameters of the fluvio-glacial deposits to similar deposits in in a national context, and
- create a fully interactive 3-dimensional model based on the collated data.

Background Geology

Bedrock geology

The bedrock underlying the study area in Dublin City consists of the Lucan Formation, which is composed of interbedded dark argillaceous limestones and shales of Viséan (Mississippian) age (e.g. Sevastopulo and Wyse Jackson 2009). This unit has also been termed 'Calp Limestone' (e.g. Marchant and Sevastopulo 1980) and it represents a basinal carbonate facies developed in the Carboniferous Dublin Basin (e.g. Pickard *et al.* 1994). Extensive amounts of subglacial sediment were subsequently generated from the Lucan Formation during the Quaternary due to its soft, and highly erodable nature.

Pre-glacial channel

The pre-glacial channel infill underlying Dublin was first described by Farrington (1929), who proposed that it formed the original channel of the River Liffey (palaeo-Liffey), prior to glaciation taking place, and diverted from the present course of the Liffey near Heuston Station, Dublin (Fig. 1). Downstream of this diversion, the older channel loops northwards and flows under the northern part of the city before crossing the modern coastline, just south of Fairview Park at Annesley Bridge.

Naylor (1965) updated on Farrington's work in the vicinity of Dublin Bay and Dublin Port and broadly agreed with the original postulated reconstructed channel geometry. Several studies were subsequently published in the mid to late 1970s by the research group based at Trinity College Dublin and in the greater Dublin area, e.g. (Hoare 1975, 1976, 1977; Synge 1977; Culleton and Creighton 1979). The pre-glacial channel of the palaeo-Liffey is also included in the mapping of the Irish Sea Basin (ISB) deep channels of Whittington (1977) and included in the synthesis of ISB data used by Eyles and McCabe (1989) to support their glaciomarine hypothesis for last British–Irish Ice Sheet (BIIS) deglaciation of the ISB.

Recently Geological Survey Ireland (GSI) generated a 3-dimensional model of the bedrock topography under Dublin City, in addition to maps of rockhead level and depth to bedrock. A section of the latter map is shown on Figure 1 and shows the postulated pre-glacial channel of Farrington (1929). It is possible to trace this feature which turns south of the present River Liffey at Island Bridge and cuts a route to the Guinness Brewery at St. James Gate. It then moves north where it intersects the present Liffey channel and continues towards Smithfield before heading towards Grangegorman. The southern part of the channel cuts through O'Connell Street near Henry Street and the northern part cuts along the top of The Garden of Remembrance in Parnell Square. After passing through O' Connell Street the channel then veers towards North Circular Road and Eastwall. At Eastwall the channel runs diagonally across Alexandra Basin and Ringsend Peninsula.

Background Quaternary sedimentological history

A compilation of older evidence for glaciation in the Dublin region is summarised on Figure 2. Palaeoflow indicators in the area are provided by till fabrics, striae, roche moutonnee and eskers. Based on observations from various ground investigations, the

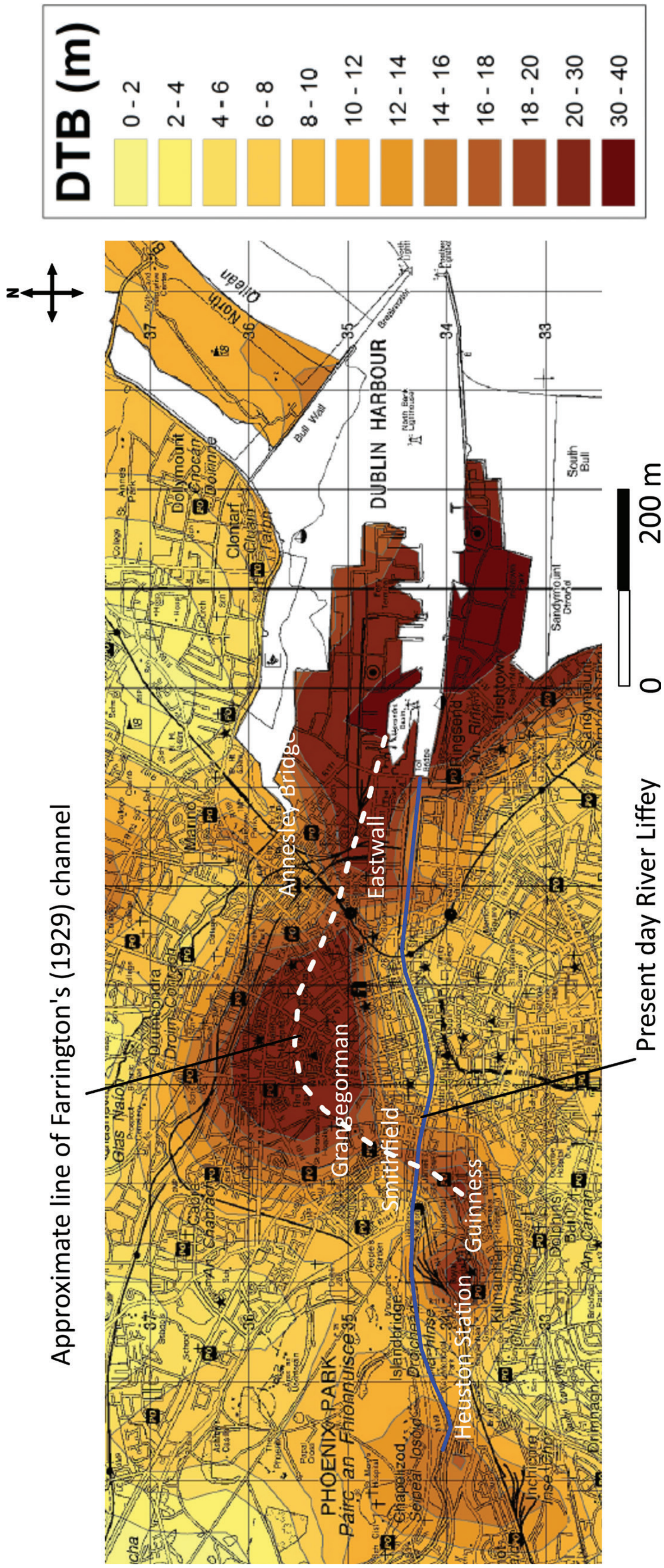

Fig. 1—Section of Geological Survey Ireland (GSI)'s Dublin Depth to Bedrock Map 2011, courtesy Beatriz Mozo, GSI. DTB = depth to bedrock.

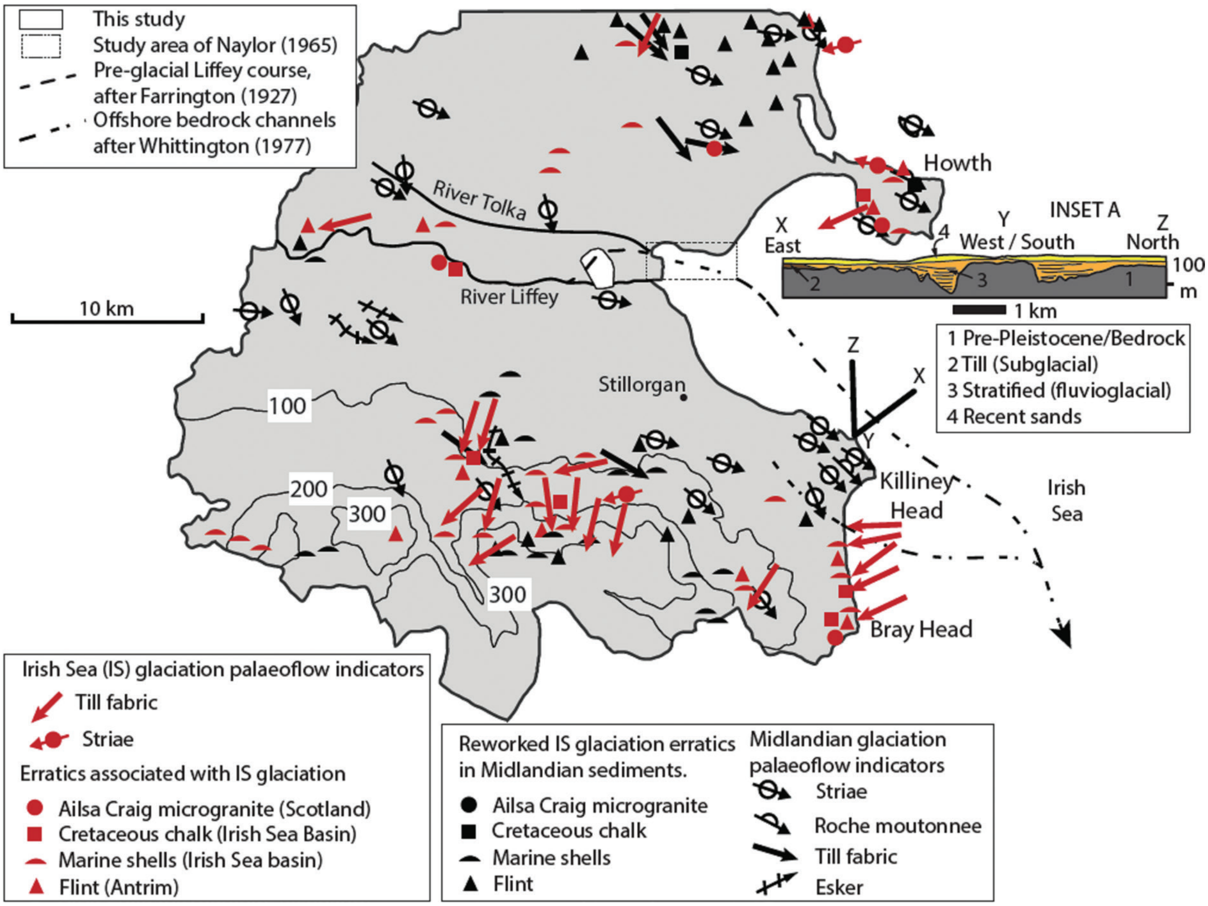

Fig. 2—Compilation of available glacial geological evidence in the Dublin County region (Farrington 1929; Naylor, 1965; Whittington 1977), including indicators, indicated separately, of glaciation from the direction of the Irish Sea Basin and subsequently from the central Midlands of Ireland (after Hoare 1975). Inset A is a cartoon representation of an offshore seismic section crossing a bedrock incised channel in southeast Dublin Bay (after Whittington 1977).

geology in the area typically consists of the pre-glacial channel, which is cut into the Carboniferous (Lucan Formation) limestone bedrock, an intermittent lower glacial till, a large fluvio-glacial sand and gravel deposit and an intermittent upper glacial till. Given the evidence presented in the research detailed above, in particular the work of Hoare (1975, 1976), this proposed four stage stratigraphic model accounts well for the glacial geology of the study area as summarised below and in Figure 3 (note that the same base map has been used in Figures 2 and 3 to aid comparison).

Lower glacial till

Following pre-glacial erosion (Event 1 in Fig. 3) in coastal regions of Leinster, the geological evidence clearly indicates that the last glacial was characterised by the interplay of ice from both northeasterly (ISB) and northwestern (Midlands, inland) sources. The most consistently applicable model is of a last ice flow from inland sources (upper inland tills and striae) with a preceding onshore (ISB) flow reworking marine muds and shell fragments (the well-known Irish Sea Till; e.g. Ó Cofaigh and Evans 2007).

Comparison of the evidence and interpretations of this previous work with the observations presented here, suggests that the simplest and most parsimonious model is that the lower glacial till of this study represents the onshore flows of ice in previous models (e.g. Hoare 1975; Event 2 in Fig. 3). These lower glacial till deposits beneath the gravels are interpreted to have been deposited as lodgement tills when the ice sheet overrode and eroded pre-existing substrates, including the underlying limestone bedrock and channel infill.

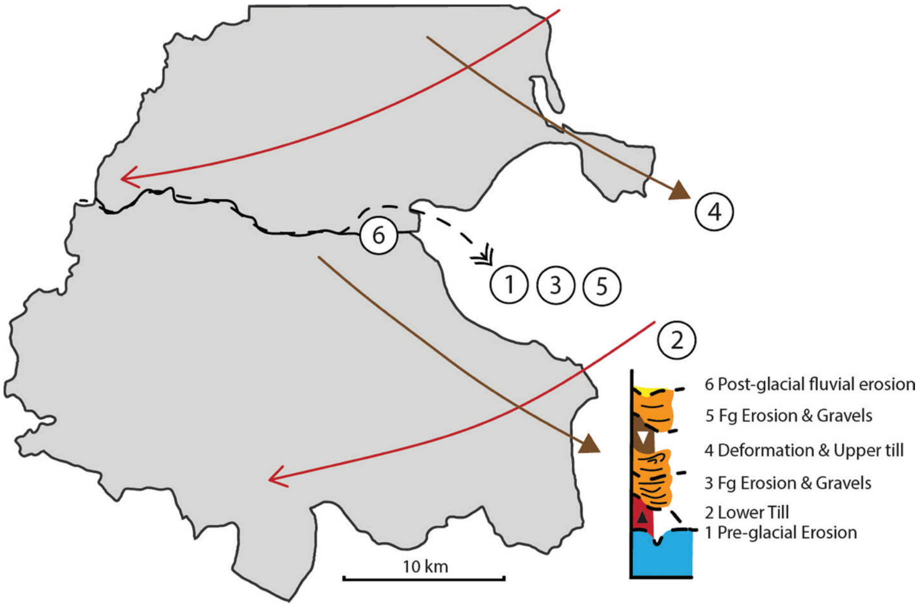

Fig. 3—A proposed event chronology for the development of the observed glacial sequence in the Liffey Valley (from oldest to youngest): 1. Incision into the pre-Quaternary cover and Carboniferous bedrock, defining a palaeo-Liffey river valley, extending offshore; 2. First phase of glaciation: Ice extending onshore from the direction of the Irish Sea Basin, depositing the 'lower glacial till'; 3. First phase of deglaciation: Partial fluvioglacial erosion of lower glacial till (2) and bedrock surface (1), followed by deposition of a complex proglacial fluvioglacial gravel sequence as ice withdraws to the northeast and eastward drainage along the Liffey valley is reinstated; 4. Second phase of glaciation: Subglacial deformation and compression of proglacial gravels (3) during ice advance from the Irish Midlands into the IS Basin and deposition of the 'upper glacial till'; 5. Second phase of deglaciation: Partial erosion of (4) and (3) by meltwater issuing from a westward retreating Irish Ice sheet margin, defining a post-glacial Liffey Valley followed by deposition of fluvioglacial gravels and their recent fluvial erosion (6).

Fluvio-glacial gravels

The fluvio-glacial deposits of this study are stratigraphically enclosed within the intermittent lower and upper glacial tills (which represent two discrete ice advances). These sand and gravel deposits most likely accumulated possibly initially under, and then in front of, a northeastwardly receding ice front (Event 3 in Fig. 3).

Subsequently these sediments may have been incised and influenced by a resumption of glaciofluvial drainage (from the Irish/inland ice sheet) along the eastward draining palaeo-Liffey Valley. If so, this process may have been quite catastrophic initially, given the likely ponding of water in the upper reaches of this drainage system between two ice sheet sectors. The resulting glaciofluvial body would be a complex one, having been derived from multiple sources over a period of time which witnessed considerable palaeoenvironmental change.

Upper glacial till

The final glacial movement in the area (Event 4 in Fig. 3) would have been from an inland source, considered as a readvance by Synge (1977; his Blessington Readvance). This Late Midlandian-aged southeast directed flow across the Leinster region is well observed in lithological composition of the clasts in the sediments associated all over the Leister region (e.g. Culleton and Creighton 1979) and striae data (Hoare 1975). The clast lithological data of this upper till was the focus of previous work on the engineering properties of the lodgement till material (Skipper *et al.* 2005; Long and Menkiti 2007) and it was considered a glacial deposit by Naylor (1965). It is likely that the cover of the younger till is not complete over the study area due to initial variability in distribution and post-depositional partial erosion by meltwater and subsequent fluvial activity.

Compaction of 'interstadial' gravels

This latter glacial flow offshore from the Irish Midlands would have occurred over a proglacial landscape containing what would have then been interstadial pro-glacial outwash gravels infilling the topographic low of the palaeo-Liffey drainage system under present day Dublin. This glacial overriding caused compaction, consistent with the high stiffness and density of the deposits detailed below.

Later geological episodes

Incision of the upper till during deglaciation, and further glaciofluvial supply along the Liffey system, would have accompanied final deglaciation. This was likely caused by meltwater issuing from a westward retreating Irish Ice Sheet margin, defining a post-glacial Liffey Valley, followed by partial infilling of fluvioglacial gravels and their recent fluvial erosion (Events 5 and 6 in Fig. 3). This occurred probably around 19 ka BP, based on available geochronological control (see for example Small *et al.* 2018, whose dating programme included some key sites in the Dublin hinterland for example Bray and Howth heads). These later deposits are not dealt with in this paper.

Methods

Defining the study area

The chosen study area (Fig. 4) is broadly rectangular in shape, measuring approximately 1.6km in the north-south direction and 1.1km east-west. It is bounded to the south by Burgh Quay and Wellington Quay, to the east by Capel Street up to Constitution Hill, to the north by Blessington Street Basin and the Mater Hospital and to the West by Gardiner Street. The study area was delineated based on the known extent of the pre-glacial channel, with a focus on the area of most importance historically and economically.

Data gathering

A full description of the process of data gathering, borehole selection and data synthesis is given by Kealy (2017) and is summarised as follows:

Most of the borehole data used was taken from prior site investigations related to the MetroLink (formerly known as the Metro North), the Luas and Dublin Light Rail, as provided by Transport Infrastructure Ireland (TII). The remainder of the borehole data was taken from GSI's geotechnical data viewer: (https://www.gsi.ie/en-ie/data-and-maps/Pages/Geotechnical.aspx).

A multi-stage process was adopted when building the model with additional boreholes being gradually added to the model to improve accuracy. Many of

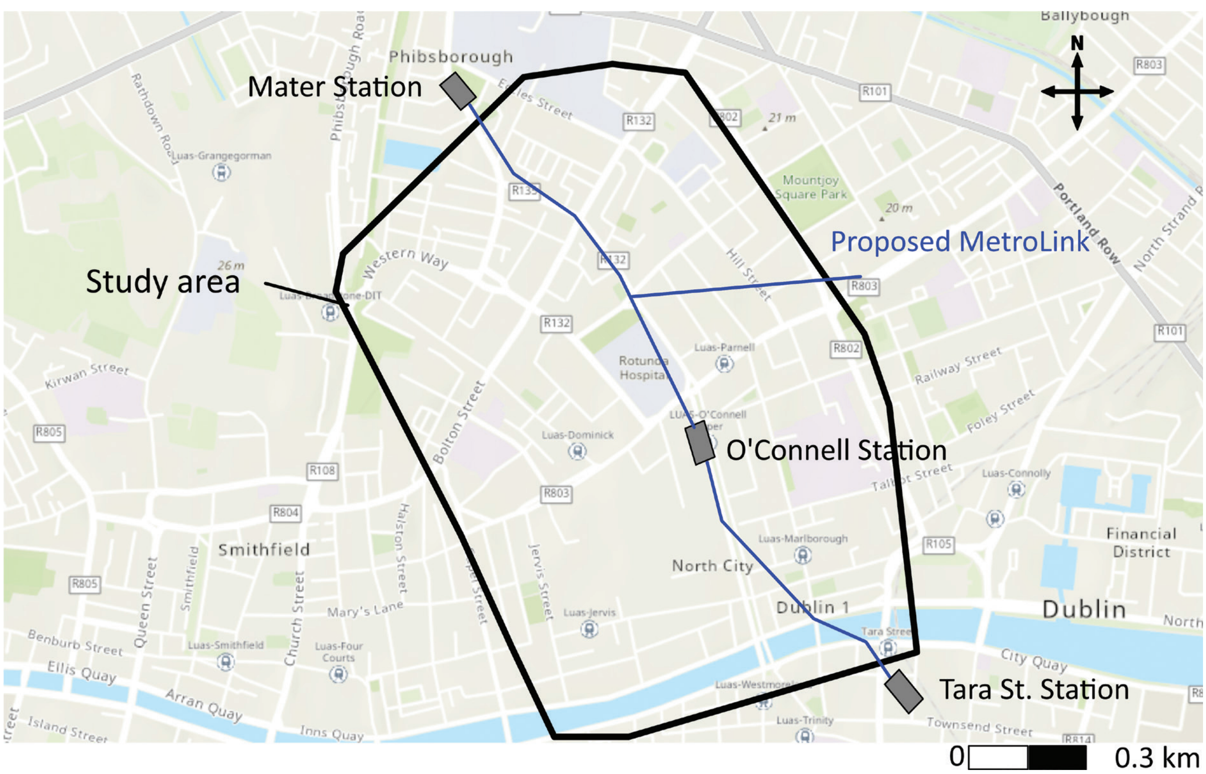

Fig. 4—Geographic limits of study area in Dublin City and proposed route of Dublin MetroLink. Base map: Ordnance Survey Ireland, ITM/basemap_premium [map online], Scale 1:10,000, [Phoenix Park Dublin], Available: OSI MapGenie Service, UCD licence [Accessed 02 July 2021].

the boreholes were made using cable percussive (shell and auger) techniques and other data included those from open hole rotary percussive drilling (wagon drilling), open hole rotary techniques and Geobore S boring.

The cable percussion logs were used for studying the overburden and were considered the most complete logs for this material. Rotary coring, open holing and Geobore S logs were used to determine the top of rock and its profile. The GeoBore S logs were also used to profile the overburden deposits where core was recovered. These different drilling techniques presented various challenges. In particular the cable percussion holes often met shallow refusal and the logs associated with the open hole techniques are extremely subjective and were eliminated from the study if not clear.

Initially boreholes were selected which penetrated the deepest into bedrock to create a profile for the top of bedrock. Subsequently boreholes close to the buried channel were considered, with the ones in, or closest to, the channel used first. Following this, boreholes were then selected by reliability and depth. Emphasis was placed on data from site investigations with known quality control procedures (e.g. the MetroLink, the Luas and Dublin Light Rail).

Ultimately 290 borehole records were used (Fig. 5), fourteen cross-sections were manually produced and the study area was broadly sub-divided into seven sectors where the ground conditions were similar.

The modelled subsurface in the study area represents a complicated fluvio-glacial palaeoenvironment, resulting in a complex stratigraphy (on a local level) comprising sands, gravels, slightly clayey gravelly sands, clayey sandy gravels and glacial till. In the initial stages of generating the model the intention was to represent with accuracy all the major and minor stratigraphic units found in the borehole logs. In particular, it had been hoped to sub-divide the fluvio-glacial sand and gravel deposits into different units, but the dataset was not robust enough to make this division with confidence. Ultimately it was decided to simplify the ground model into four separate units namely: the bedrock, the lower glacial till, the fluvio-glacial (FLGL) deposit and the upper glacial till (in ascending stratigraphic order).

Data synthesis

Analysis and synthesis of the data followed workflows previously developed in-house by ARUP for the construction of digital 3-dimensional ground models (Chung 2007). All of the ground investigation data were imported into the gINT geotechnical subsurface data management software (Bentley 2015). In gINT the geotechnical data were organised in tables, and ultimately transferred to GIS, where data were compiled, managed, visualised and analysed on a geographical basis. The borehole logs contain all relevant data such as strata type, standard penetration tests N values (SPT ‘N’), water strikes, samples taken, coordinates and elevation.

The data was inputted into gINT using two different methods:

1. The first approach used the Association of Geotechnical and Geoenvironmental Specialists (AGS 2015) data from the previous Metro North Site Investigations, which was provided by TII. The AGS data format allows for easy sharing between different software packages used within the geotechnical/geoenvironmental industry. Of the final 290 boreholes used approximately 50 boreholes were imported in this fashion.
2. The remaining 240 boreholes from the study area were manually re-keyed from the original paper records, including sample and SPT records.

All the data were then exported to Microsoft EXCEL, with point data associated with each borehole and details of the geology associated with each borehole by depth, kept on two separate sheets. All boreholes were given an X and Y (geographical) coordinate. A Z coordinate was assigned for both the top and bottom each identified stratigraphic unit within the boreholes. The results were then filtered by geology code. This procedure made it possible to create separate spreadsheets for each unit. These spreadsheets then become the data sets that were used for contouring the units across the study area.

The Surfer 8 contour and mapping programme (Golden-Software 2002) was used to produce contours from the borehole data. The base of each stratum was used for contouring, except for the Carboniferous bedrock, where the top of the bedrock was used. Using the borehole input data, the software then creates a grid of data. Both the Kriging and the Natural Neighbour gridding methods were trialled (Golden-Software 2002) but it was found that a combination of both of these methods, where the two grid files are merged mathematically, was the most reliable. When the contour map was created it was then exported as a Drawing Interchange Format (DXF) file, which was then viewed and further edited in ArcMap.

ArcMap (ArcGIS 2015) was then used to geospatially reference all data to the Irish Grid (ITM) Coordinate system, create a database of all referenced data to view graphically in ArcMap, produce

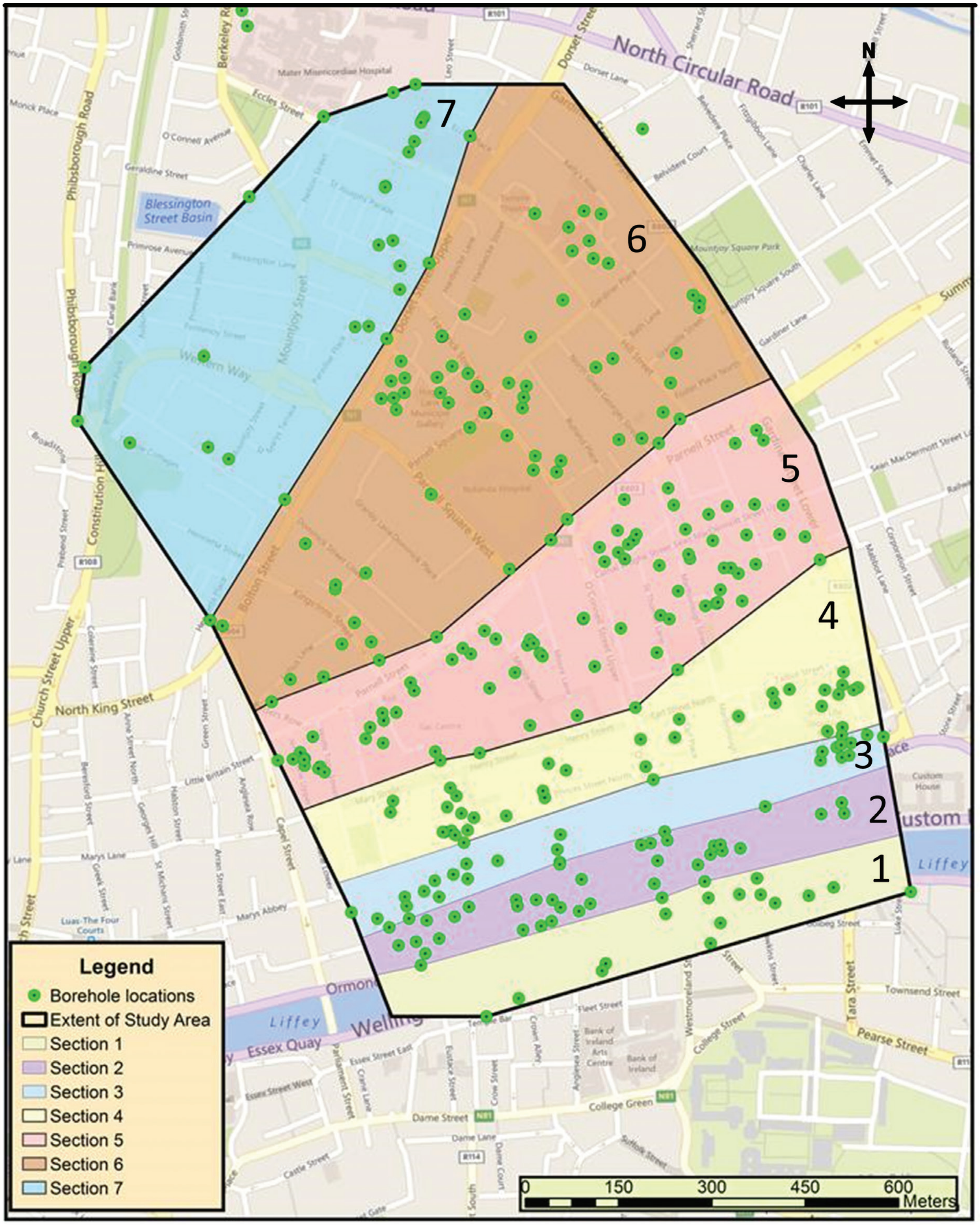

Fig. 5—Location of boreholes used in the study in Dublin City and division of the study area into seven sectors. Base map: Ordnance Survey Ireland, ITM/basemap_premium [map online], Scale 1:10,000, [Phoenix Park Dublin], Available: OSI MapGenie Service, UCD licence [Accessed 02 July 2021].

TIN (triangulated irregular network) files from the DXF files produced in gINT and Surfer and carry out post-map editing. A TIN file is a vector-based representation of the physical surface being created and in this case these surfaces represent the bases of the geological units (apart from the bedrock) found in the study area. TIN files are made up of irregularly distributed nodes and lines with three-dimensional coordinates (X, Y and Z) that are arranged in a network of non-overlapping triangles.

With all the TIN files created it was then possible to view them in ArcScene. ArcScene is a visualisation application that is used to view GIS data in three dimensions (ArcGIS 2015). All boreholes were projected in Irish Grid using the Arup Geotool (Chung 2007). This software then creates 3-dimensional borehole sticks. A colour scheme was applied to geology codes produced in gINT so that the borehole sticks were coloured in accordance with their strata.

All the images generated by the process described above were then reviewed using the manually produced 2-dimensional profiles.

Index testing of gravels

The basic index properties of the FLGL deposits were characterised by the results of particle size distribution (PSD) tests, carried out to BSI (1990a). From the PSD curve it was then possible to determine the effective size (D_{10} – which is the maximum size of the particles in the smallest 10% of the sample), the D_{60} and coefficient of uniformity ($C_U = D_{60}/D_{10}$) values.

Characterisation of the FLGL deposit is limited by the fact that not all of the boreholes penetrated the entire FLGL stratum and that regular laboratory and *in situ* testing was not always carried out. The available laboratory and *in situ* tests were limited to approximately 40% of the original borehole records used. However, this dataset does allow for a reasonable overview of the engineering properties of the sands and gravels as a mass deposit.

There is also a possibility of fine material being washed out during the shell and auger drilling and sampling processes. Long *et al.* (2012b) examined this possibility by recovering samples from the bulk excavation at the Smithfield site (some 500m east of the study area) and comparing the PSD curves to those carried out on samples recovered from regular drilling. These authors found that the representative sand content in the bulk samples was about 25%, compared to some 15% to 20% reported in the borehole samples.

A further limiting factor is the unknown quantity of large cobbles and boulders in the stratum. This is due to limitations of recovering larger clasts based on the diameter of the borehole (typically 20cm in diameter) and the removal of the larger cobbles and boulders (usually those greater than 5cm–7.5cm) prior to testing.

Stiffness and strength testing of gravels

The strength and stiffness characteristics of the FLGL are obtained mostly from SPT test results (BSI 1990c), which involves counting the number of blows required to drive a standard tool by 300mm into the stratum under study. The results are often influenced by the tool encountering a large cobble or boulder. Typically the test is stopped and deemed a 'refusal' at a count of 50 blows.

Some large shear box testing, involving specimens some 300mm x 300mm and 180mm high were also carried out (BSI 1990b).

Geophysical testing

A comprehensive series of *in situ* and laboratory geophysical tests were carried out at the Mater Hospital site in 2010, when the site was under investigation as the location of the new Children's Hospital of Ireland. This site is located at the northern end of the study area. These tests included cross hole and downhole tests (ASTM 2014a,b) in two rotary cored boreholes located some 40m from one another and some surface wave tests using the multichannel analysis of surface wave method (Park *et al.* 1999). These tests yielded profiles of shear wave velocity (V_s) versus depth. Some further MASW test results are available for the O'Connell St. area from the MetroLink and Metro North site investigations. As well as being useful in material characterisation studies V_s values can be used to determine the small strain stiffness of the materials from:

$$G_{max} = \rho V_s^2 \qquad (1)$$

where: G_{max} is in Pa, V_s = (m/s), ρ = density (kg/m^3)

Results

Borehole data analysis and 3-dimensional model

The resulting 3-dimensional image of the top of the Carboniferous bedrock (Fig. 6), together with the top of bedrock contour map generated from the data (Fig. 7) indicates that ground level across the study area falls from north to south towards the River Liffey from about 17.5mOD at the Mater Hospital

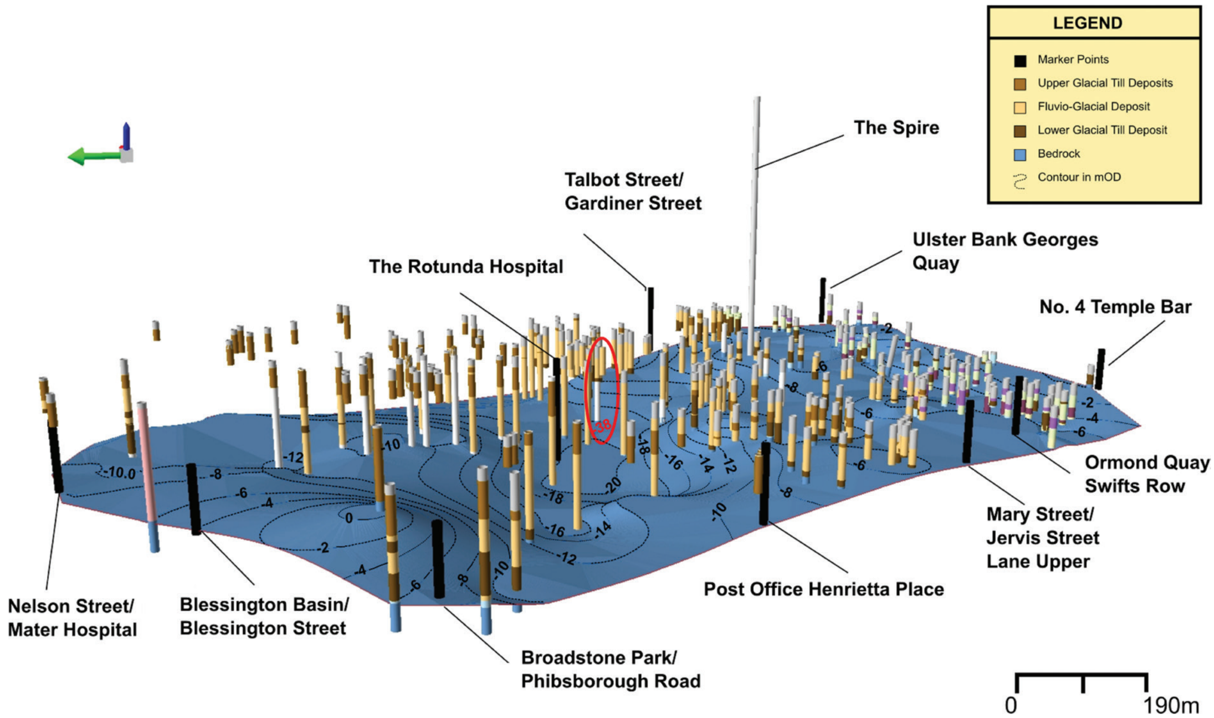

Fig. 6—3-dimensional model of the study area in Dublin City highlighting the top of the Carboniferous limestone bedrock. The model is viewed looking towards the southeast and the green arrow points northwards.

to some 4mOD at the southern end of O'Connell St. At the southern end of the study area top of bedrock is reasonably uniform at an elevation of – 6mOD to -8mOD and then falls sharply to the base of the channel at some -24mOD near the Rotunda Hospital before rising again steeply to the north-west. It should be noted that one isolated borehole near to the Rotunda Hospital shows very deep bedrock at about -38mOD. Towards the east and the north-east the bedrock level remains low at some -10mOD to -12mOD before falling away to some -30mOD at the north-eastern section of the study area.

The location of the base of the lower glacial till deposit and the top of bedrock, along with the outline of the pre-glacial channel (as inferred from the model), is shown on Figure 8. The lower glacial till can be found along the flanks of the channel and is generally absent from the central part of the channel. The base of the lower glacial till mirrors the top of bedrock at the southern and northern ends of the study area.

The 3-dimensional model of the contours of the base of the lower glacial till, the FLGL deposits and the upper glacial till is shown on Figure 9. The upper glacial till is generally absent at the southern end of the study area, adjacent to the River Liffey. It is typically at about +10mOD towards the northern end of the study area and falls to the south to a lowest level of about –5mOD near the Rotunda Hospital, where the top of bedrock is also at its lowest elevation in the subsurface.

Basic index testing of the FLGL deposit

A full discussion on the properties of the FLGL deposit is given by Kealy (2017) based on the sub-division of the area into seven sectors (Fig. 5). Here the focus is placed on conditions in Sector 5, which spans the central and deepest area of the pre-glacial channel feature and represents an area of commercial and historical importance in Dublin City. Furthermore the proposed O'Connell Street Metrolink station is located in this sector (Fig. 4).

A large number of particle size distribution tests is available for Sector 5 (see Fig. 10 for a representative sample). Data was obtained from 14 boreholes for a depth range between 2.5m to 26m. The material is relatively un-homogenous, but all the samples can be described as a sandy gravel. The sand content ranges between 0 and 40%, with an average of 14%. The gravel content ranges from 28% to 98%, with an average of 80%. The percentage of sand and gravel remains approximately constant with depth despite some scatter in the data (Fig. 11). These data do not

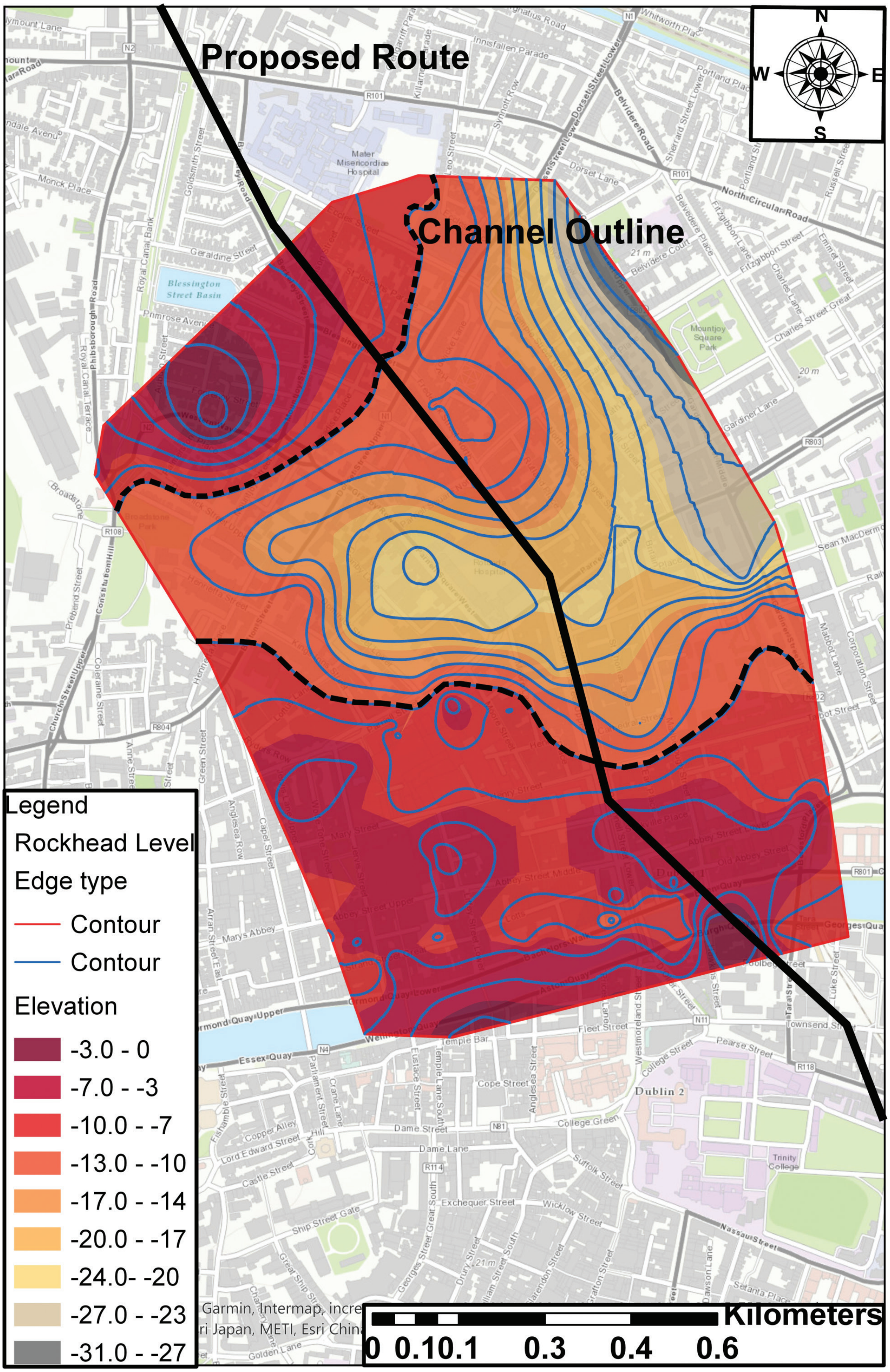

Fig. 7—2-dimensional (plan) view of the study area highlighting depth in the subsurface to the top of the Carboniferous limestone bedrock.

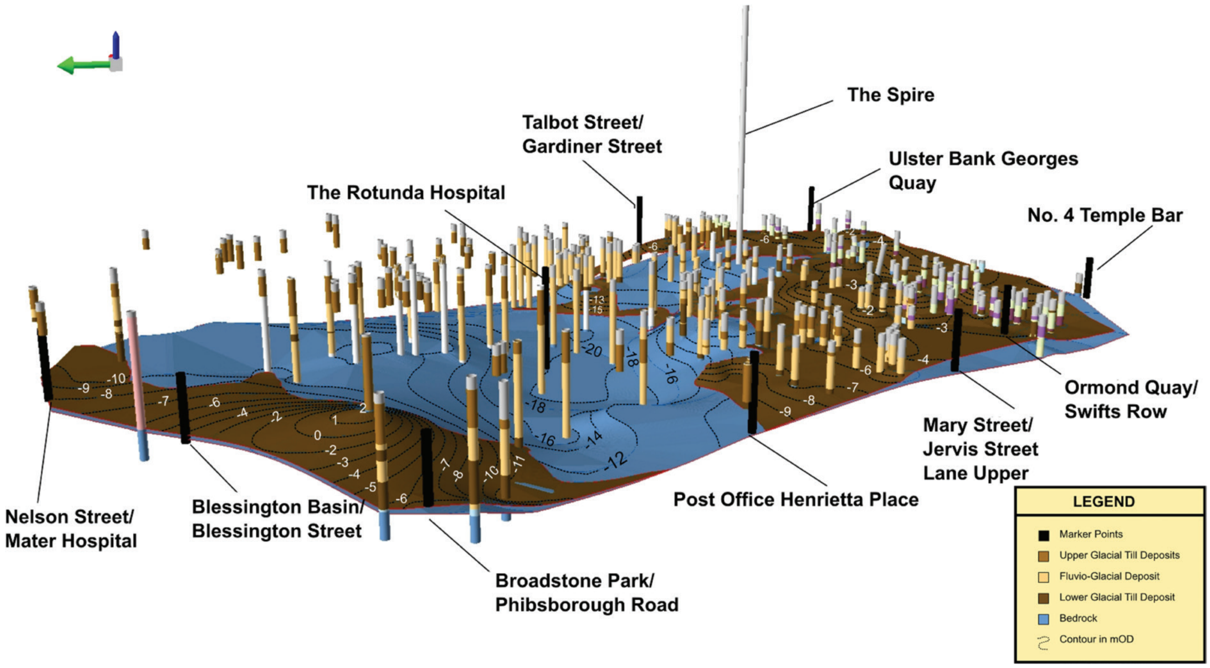

Fig. 8—3-dimensional model of the study area in Dublin City highlighting the base of lower glacial till deposit and the underlying bedrock. The model is viewed looking towards the southeast and the green arrow points northwards.

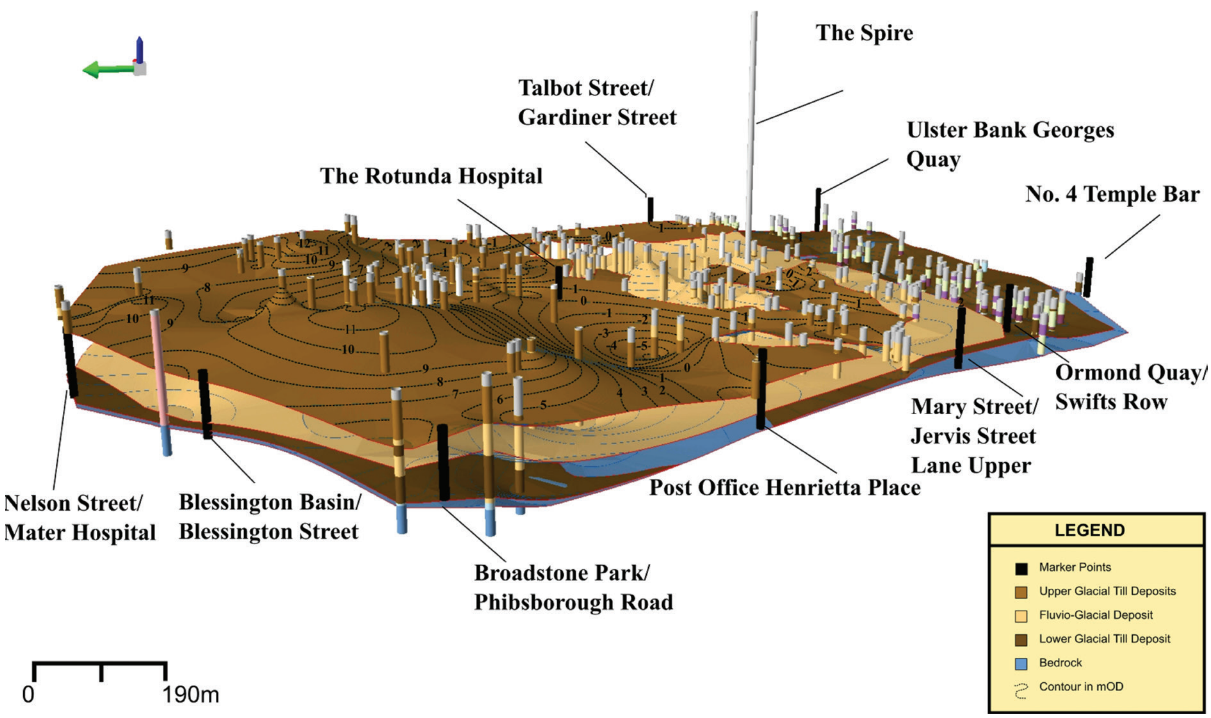

Fig. 9—3-dimensional model of the study area in Dublin City highlighting the base of the upper glacial till, fluvio-glacial deposits, lower glacial till and Carboniferous bedrock. The model is viewed looking towards the southeast and the green arrow points northwards.

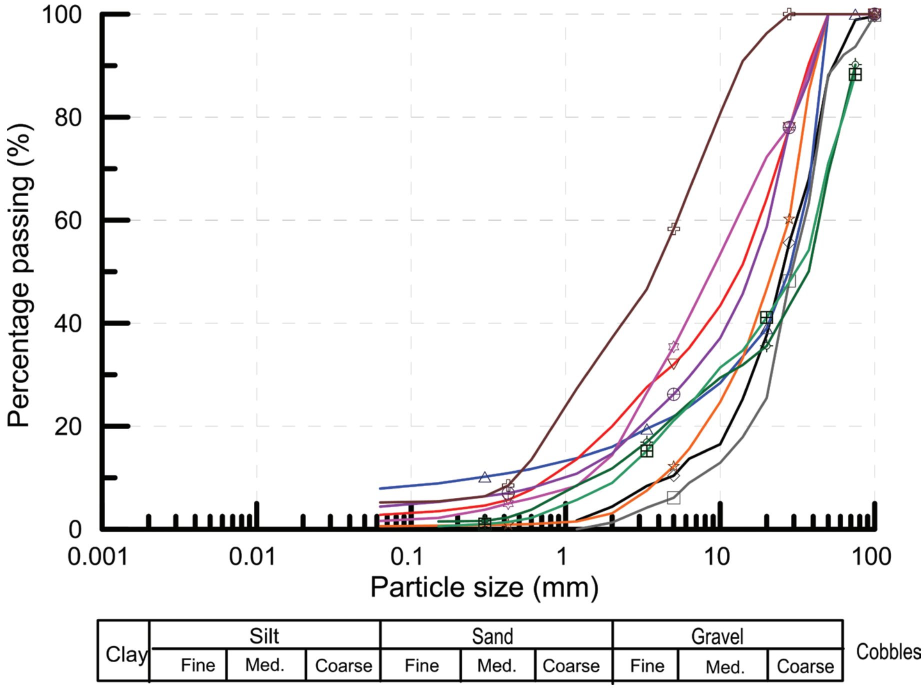

Fig. 10—Sample particle size distribution plot for Sector 5 in the study area in Dublin City (see Fig. 5 for reference).

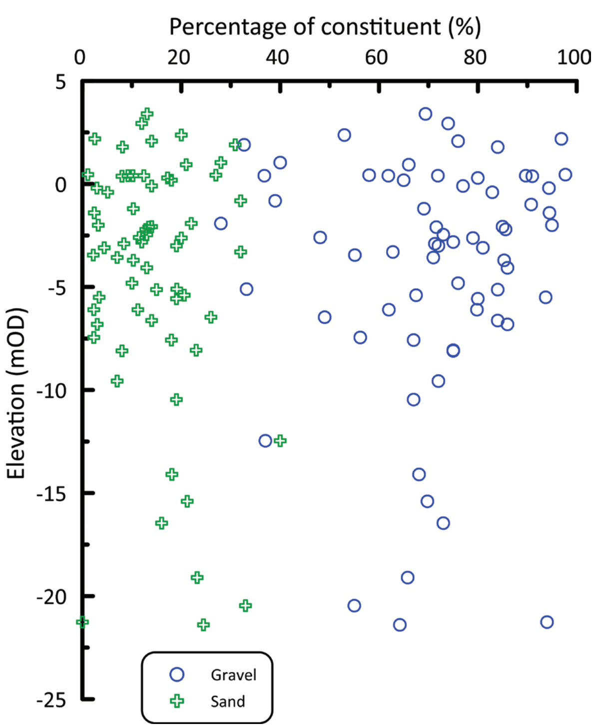

Fig. 11—Percentage of sand and of gravel with depth for Sector 5 in the study area in Dublin City (see Fig. 5 for reference).

account for some possible loss in sand content due to the sampling process as described above.

The material has an average effective size (D_{10}) of about 2.7mm and a D_{60} value of 22.4mm. The resulting uniformity coefficient (C_U) is on average 26 (range 2 to 225) which corresponds with a medium- to well-graded material (Craig 2004).

Strength of the FLGL deposit

The strength of the FLGL deposit can be characterised largely by the results of SPT tests (Fig. 12) but also from the results of some large shear box tests (Fig. 13). SPT N values show considerable scatter in the data and there are many refusals (denoted by N = 50). The presence of cobbles and boulders in the FLGL material would have contributed to these refusals. According to ENISO (2005) the material can be classified as medium dense to dense with very dense zones. There seems to be a tendency for slight increase with depth, especially to about -8mOD.

A large shear box test was carried out on a sample of gravel obtained from the Mater Hospital site at about 13.2m depth. The sample was compacted to a density of 2Mg/m^3 and subjected to a consolidation stress of 150kPa, which is approximately equal to the

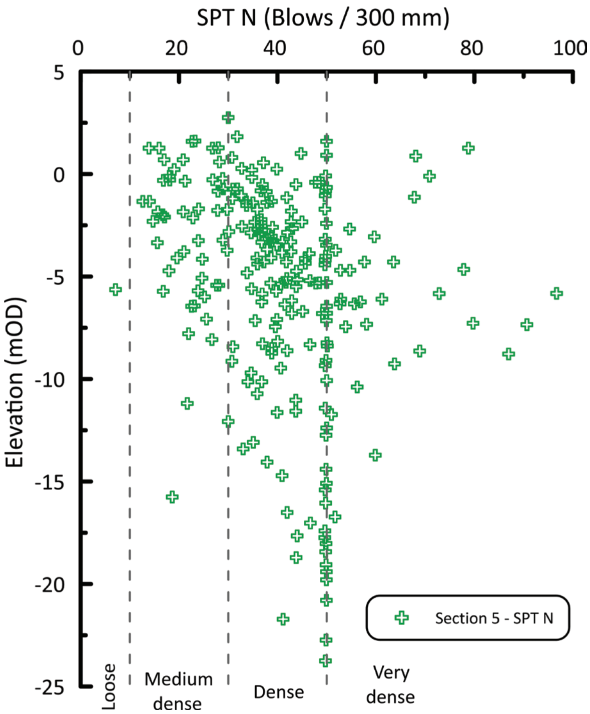

Fig. 12—SPT ‘N’ values for the fluvio-glacial deposit in Sector 5 in the study area in Dublin City (see Fig. 5 for reference).

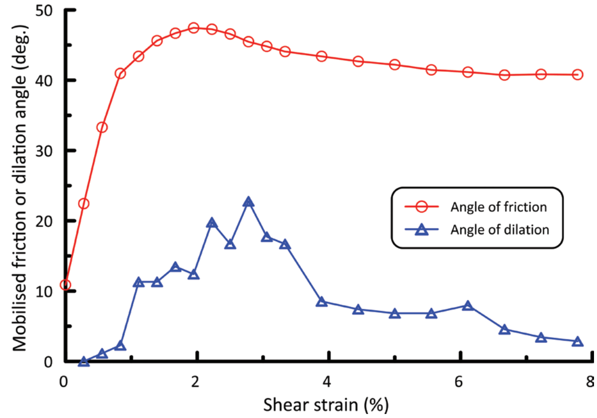

Fig. 13—Results of shear box test on fluvioglacial material.

in situ effective stress of the sample. The results show that the FLGL has a peak friction angle (ϕ') = 47.4°, a residual friction angle (ϕ_{cv}') of 40° and a maximum angle of dilation (ψ') of some 22° (Fig. 13). These very high values are consistent with the dense nature of the material as suggested by the SPT tests.

Stiffness of the FLGL deposit

All of the shear wave velocity data for the Mater Hospital site are shown on Figure 14. Ground conditions at this site are characteristic of those in the pre-glacial channel, with a 8.6m layer of made ground and an interval of upper glacial till overlying 10.2m of FLGL, which in turn overlies the lower glacial till. The data includes profiles of $V_{s\text{-}vv}$, $V_{s\text{-}vh}$ and $V_{s\text{-}hh}$ from the borehole tests and MASW profiles for two locations on the Mater site. In the designation of the V_s values, vh for example means vertically orientated and horizontally polarised waves. All of the profiles are similar with V_s values ranging between about 450m/s and 850m/s. These values correspond to the material being very dense (NIBS 2003) with its density increasing with depth. They are again consistent with the very high stiffness values suggested by the SPT tests. The material exhibits very little anisotropy of stiffness with on average $V_{s\text{-}vh}$ / $V_{s\text{-}hv}$ = 0.9 for the FLGL material.

Discussion and Analysis of Data

Comparison with gravels elsewhere in Ireland

Kealy (2017) presented a detailed comparison between the FLGL deposit in the Dublin pre-glacial channel and fluvio-glacial deposits found in the Curragh, County Kildare, and also in Cork City. The Curragh contains a large deposit of fluvio-glacial gravels known locally as the ‘Curragh Aquifer’. These gravels were deposited in a shallow trough in the underlying Carboniferous limestone, which is orientated north-east to south-west. They are associated with a glacial outwash depositional environment from the last glaciation in Ireland and can reach up to 70m depth (Glanville 1997; Wright 1988). Work carried out by Coppinger and Farrell (2003) during the construction of the Kildare Bypass encountered the gravels to a depth of 35m. Available test results for the Curragh suggest that two distinct strata exist: a sand layer and a gravel layer. However, the particle size distribution tests for these materials also fall within the distribution boundaries observed for the Dublin pre-glacial channel (Fig. 10). SPT tests for the Curragh gravels show average N values of close to 50 blows/300mm, indicating the material is dense to very dense, similar to the Dublin City deposits.

Long *et al.* (2015) present a detailed characterisation of the fluvio-glacial gravels in Cork City and their particle size distribution data, again, show the material is very similar to that found in Dublin City. However, SPT ‘N’ values for Cork are much more variable, with frequently loose or loose to medium dense layers being encountered. It is possible that the fluvio-glacial sands and gravels found in Cork

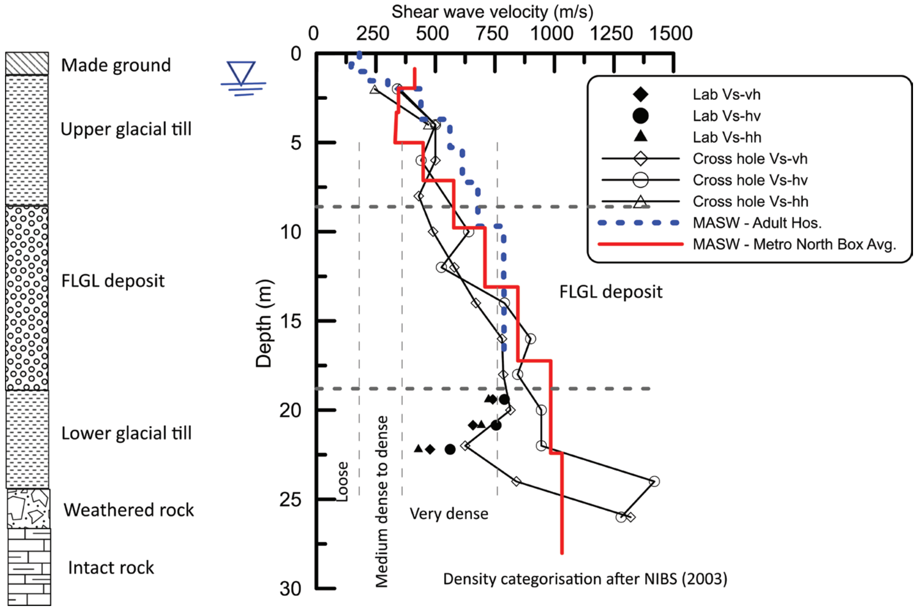

Fig. 14—Summary stratigraphy (far left) and shear wave velocity data (right) from the Mater Hospital site in Dublin City.

are associated with the end of glaciation and did not undergo post depositional consolidation during a period of glacial advancement. In contrast, the deposits found in Dublin and the Curragh may have been compacted (increasing effective density), post deposition, due to being overridden by a glacier readvance.

The ground model at several sites within the pre-glacial channel but outside the study area in Dublin City are described by (Long *et al.* 2012b). Similarly (Higgins and Mason 1989, 1991) discuss the geology, ground conditions and foundation construction at the Custom House Docks site. In all cases the fluvio-glacial deposits are very similar to those described here.

Relationship between FLGL deposit parameters and depositional environment

Fluvio-glacial sediments by definition are created as a result of the complex sediment production and transport mechanisms and processes associated with melting ice masses, as outlined above. They are often vertically and laterally variable in terms of grain size and texture, and this is also the case for the Dublin City deposits.

The material has C_U values greater than 5, suggesting that it is non-uniform. The SPT and V_s results confirm that the material is medium dense to very dense, suggesting that some post depositional compaction has taken place (possibly due to subsequent glacial re-advance). The deposit can be characterised on the whole as a medium dense to very dense slightly sandy to sandy gravel.

Summary and Conclusions

The main objectives of this project were to produce a fully interactive 3-dimensional sub-surface geological and geotechnical model of Quaternary strata, including a postulated pre-glacial channel feature, beneath the centre of Dublin City, an area of considerable commercial and historic importance. Some conclusions from the work are as follows:

- Digital 3-dimensional ground models are particularly useful as a single data repository by creating a user-friendly geotechnical database to allow for the data management of the various formats of ground investigation information which can easily be updated as more data becomes available.
- Ground investigation information can be scattered, not easily accessible or interoperable from hardcopy boreholes, requiring manual digitisation to varying digital formats, and often lacks the spatial connection needed to visualise it properly within the study area.

- The digital software used to manage and create 3-dimensionsal ground models (Figs. 6, 8, 9) does not detract from the need for the data to be properly scrutinised and analysed to allow for a robust interpretation of the ground conditions within a given study area.
- The model presented here of the pre-glacial channel in Dublin City represents a complex depositional environment postulated based on four phases/glacial episodes and is consistent with other published accounts of the Quaternary geological history of the area.
- This work has delineated the position of the pre-glacial channel in the study area. At the location of the proposed MetroLink, for example, the channel is about 1km wide and approximately 45m deep.
- The fluvio-glacial deposit within the channel can be characterised on the whole as a medium dense to very dense slightly sandy to sandy gravel.
- The work highlights the usefulness of relatively simple and inexpensive tests such as particle size distribution analyses (PSD) and standard penetration testing (SPT) to aid in characterising the material. However SPT tests can be misleading due to refusal on cobbles and boulders.
- The study also supports geophysical shear wave velocity measurements for stiffness characterisation.
- The deposits are similar to those found elsewhere in Ireland, e.g. at the Curragh in Kildare and in Central Cork. This work has helped to explain why, for example, the deposits are denser and stronger than those in Cork due to the post-depositional processes which took place.

Recommendations for further research

Consideration should be made for further use of geophysical methods. The most common geophysical approach for distinguishing gravel deposits is using resistivity measurements (e.g. O'Connor *et al.* 2016). Unfortunately, the effectiveness of resistivity investigations in urban environments may be severely limited because of interference from electrical noise and underground services and the difficulties in planting electrodes into the ground. Recently developed continuous capacitive resistivity (CCR) systems may be more suited for urban resistivity investigations as electrodes do not need to be planted and can instead be towed along the ground.

Measurements of seismic velocities may also be indirectly used to indicate the presence of gravels, due to their dependence of density and small strain elastic stiffness. P-wave seismic refraction testing has generally been used in the past as an indicator for gravel density. As P waves can travel through water, this approach also has the advantage of being able to distinguish between saturated and unsaturated gravels and thereby provide an indication of the depth to the water table.

In very dense, saturated gravels the V_s and V_p contrast between fluvio-glacial gravels and glacial till can be unclear, as can be seen for example on Figure 13. It is therefore recommended, wherever possible, to perform all three techniques in order to assist interpretation. (Long *et al*. 2012b) demonstrate the usefulness of such geophysical investigations at two greenfield sites within the pre-glacial channel, but outside the study area. These authors also present typical ranges of resistivity and seismic measurements for materials commonly found in central Dublin.

It would of course be very useful to regularly update the model with additional ground investigation data and from observations during construction of the MetroLink.

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STEPHEN KEALY
Ground Investigations Ireland Ltd.,
Dublin, Ireland

MICHAEL LONG (corresponding author)
School of Civil Engineering,
Newstead Building,
University College Dublin
Belfield, Dublin 4, Ireland
e-mail: Mike.Long@ucd.ie

STEPHEN McCARRON
Department of Geography,
Maynooth University,
Ireland

MARIE FLEMING
ARUP Consulting Engineers,
Dublin, Ireland

MILES FRIEDMAN
Transport Infrastructure Ireland,
Dublin, Ireland