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Characterisation of Calp Limestone in Dublin City Centre

Summary Report

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Abstract

Dublin City Centre is underlain by the Carboniferous Lucan Formation, known locally as the Calp Limestone. The Calp Limestone is a complex sequence of interbedded dark grey massive limestones, shaley limestones, mudstones, and cherts, deposited during the Dinantian Epoch of the Carboniferous Period. Due to the extensive overlying glacial deposits in Dublin City Centre which can extend up to 30 metres thick, bedrock exposures are limited, complicating direct observation of structural features such as faulting and folding.

The aim of this project was to create a geological and geotechnical model of the Calp Limestone within the Dublin City Centre study area. Along with the construction of a 3D ground model, this report presents a comprehensive engineering geological and geotechnical characterisation of the Calp Limestone based on ground investigation data collected through three large scale infrastructure projects, namely MetroLink, Metro North, and DART Underground. Supplementary ground investigation information from Geological Survey Ireland has also been incorporated.

Advanced modelling software has been employed to digitise and integrate the datasets arising from the various ground investigations. The resulting 3D geological and geotechnical model details the composition, weathering profiles, structural characteristics, and strength distribution of the Calp Limestone within the study area, providing valuable insight into the subsurface geology beneath Dublin City Centre.

Additionally, a virtual site survey and various site visits across the Dublin City region were undertaken to gain a better understanding of the Calp Limestone. By identifying geological features through visual observations on-site, the virtual survey and site inspections aimed to address some limitations of relying solely on borehole data available from ground investigations, providing valuable insights for the research project.

Key findings include the identification of weathered zones and fracture systems within the limestone, which have important implications for underground construction and the reuse of excavated material. The model also highlights the spatial variability in rock mass properties, influenced by both depositional history and post-depositional deformation.

Due to the requirements for intact rock strength laboratory measurements, samples tend to be selected from more intact pieces of core, namely the limestone. As such, there is very limited data available for the mudstone, with only seven UCS tests conducted on mudstone samples compared to 378 for limestone suggesting a sampling bias.

The Calp Limestone rock mass is dictated by the presence of three prevailing sets of discontinuities, namely bedding and two vertical to sub-vertical orthogonal joint sets. Within the borehole data used for this assessment, the quantity of bedding readings is notably higher than other discontinuities, enhancing confidence in identifying bedding orientation changes and suggesting potential large-scale folding trends.

These insights are critical for risk assessment and design optimisation in ongoing and future infrastructure developments in Dublin. By systematically compiling, assessing, and visualising the available data, this report contributes to a more detailed and practical understanding of the Calp Limestone, supporting safer and more efficient underground engineering in Dublin City Centre.

Recommendations for undertaking a ground investigation in the Calp Limestone are provided along with a suggestion for a more rigorous and standardised methodology for lithological descriptions of the Calp Limestone.

1. Introduction

The Carboniferous Lucan Formation, locally known as the Calp Limestone, dominates the bedrock geology of Dublin. The Calp Limestone was deposited during the Dinantian Epoch of the Carboniferous Period (approximately 325 to 363 million years ago). The Geological Survey Ireland (GSI) describes the Calp Limestone as an interbedded sequence of dark grey massive limestones, shaley limestones and massive mudstones and cherts. The Calp Limestone was deposited in a basinal and ramp environment in deeper water with limited fauna. The widespread bedding suggests that much of the limestone was deposited by turbidity currents (Marchant & Sevastopulo, 1980; Nolan, 1986).

Due to the thick cover of glacial till (up to 30m) overlying much of the bedrock in Dublin City Centre, very little information is available on faulting or folding within the Calp Limestone. Exposures in quarries around Dublin, such as Belgard Quarry in West Dublin, as indicated in **Figure 1**, show that faulting and folding within the rock mass can occur over short distances (< 1.0m) as well as on a macro scale of many tens of metres.

Figure 1 Exposure of Calp Limestone at Belgard Quarry, west Dublin.

This project represents a study examining the available geological and geotechnical ground investigation information for Dublin City Centre which has been collected through three large scale infrastructure projects, namely MetroLink, Metro North, and DART Underground. The ground investigation datasets provide an opportunity to consolidate, assess, and interpret available information, enabling the construction of a model of the Calp Limestone beneath a specific section of Dublin City Centre.

1.1 Aim and objectives of the Project

The aim of this project is to create a geological and geotechnical model of the Calp Limestone within the study area. This will be achieved through the analysis and digitisation of available ground investigation data, supplemented where possible with additional information such as GSI and in-house Arup ground investigation reports. The project utilised modern modelling software tools and benefited from guidance and review by experienced Ground Engineering experts working within the industry.

The resulting model includes information on the composition, depth of weathering, structure (both local and regional trends), and strength of the Calp Limestone. Special attention is given to identifying geological features such as deep weathering and fracture zones that could pose challenges to underground construction, or the potential reuse of excavated Calp Limestone. The analysed data is compiled and presented as a 3D model, allowing for a detailed examination of the composition, structure, and weathering characteristics of the Calp Limestone.

1.2 Sources of Information

A number of a previous ground investigation factual reports and associated AGS digital data were provided to Arup by Transport Infrastructure Ireland (TII) for interpretation and analysis. The ground investigation factual reports provided by TII used in this analysis include:

- DART Underground:
  - DART Underground Factual Report – Ground Investigation Report Volume 1 (IGSL, 2009)
- Dublin Light Railway
  - Dublin Light Railway Sandyford to Ballymun Line Tunnel Link between St. Stephen's Green and Broadstone – Factual Report on Ground Investigation, Volume 1 (Wimtec Environmental Ltd., 2000)
- Metro North:
  - Dublin Metro North Ground Investigation – RPA Contract M7081 – Factual Ground Investigation Report, Volume 1 (IGSL, 2007)
  - Report on a Ground Investigation at Dublin Metro North, Main Ground Investigation – Sections 6 & 7, Volume 11 (Norwest Hols Ltd., 2008)
  - Metro North Mater to Parnell – Geotechnical Site Investigation Report, Report No. 14806 (IGSL, 2010)
  - RPA7166_3 GGIW, Package 1 Metro North Enabling Works – O'Connell Street Substation, Report No. 09-0623A (Glover Site Investigations Ltd., 2010)
- MetroLink:
  - MetroLink Phase 1 Ground Investigation (Causeway Geotech Ltd. 2019)
  - MetroLink Phase 2 Ground Investigation (Causeway Geotech Ltd. 2020)
  - MetroLink Phase 3 Ground Investigation (Causeway Geotech Ltd. 2020)
  - MetroLink Phase 4 Ground Investigation (Causeway Geotech Ltd. 2020)
  - MetroLink Phase 5 Ground Investigation (Causeway Geotech Ltd. 2022)

Publicly available ground investigation reports and data sourced from the GSI within the study area were also compiled and analysed to supplement the ground investigation reports supplied by TII.

1.3 Report Layout

An introduction to this report is presented above, including a list of sources used for the development of the ground model.

Section 2 of this report presents an overview of the study area, including background, topographical setting, and historical development.

A literature review of available information relating to the Calp Limestone is presented in **Section 3**, including the geological setting and hydrogeological regime. **Section 4** describes the methodology undertaken during this study to analyse the available data, including generation of the ground model and the rock mass assessment. The results relating to the ground model output and analysis of the weathered bedrock are presented in **Section 5,** whilst **Section 6** presents the findings of the analysis of geotechnical rock testing and rock mass assessment.

Section 7 summarises the various site visits undertaken over the course of this study to a variety of Calp Limestone rock exposures across Dublin City. The engineering considerations of working within the Calp Limestone are detailed in **Section 8**, including excavatability, geo-hazards, and potential ground investigative techniques. **Section 9** of the report describes the findings of a gap analysis following the completion of this study. Finally, **Section 10** presents the recommendations for further study relating to the Calp Limestone with references provided in **Section 11**.

2. Study Area

2.1 Background and Setting

Dublin City Centre is a densely populated urban environment combining residential, commercial and industrial elements. The River Liffey flows west-east through the city centre. The project study area was influenced by data availability, data quality, and data density. To delineate and validate the study area, the locations of available borehole data from the MetroLink, DART Underground, and Metro North projects were initially plotted to determine data concentration and the optimal study area extents, as shown on **Figure 2.**

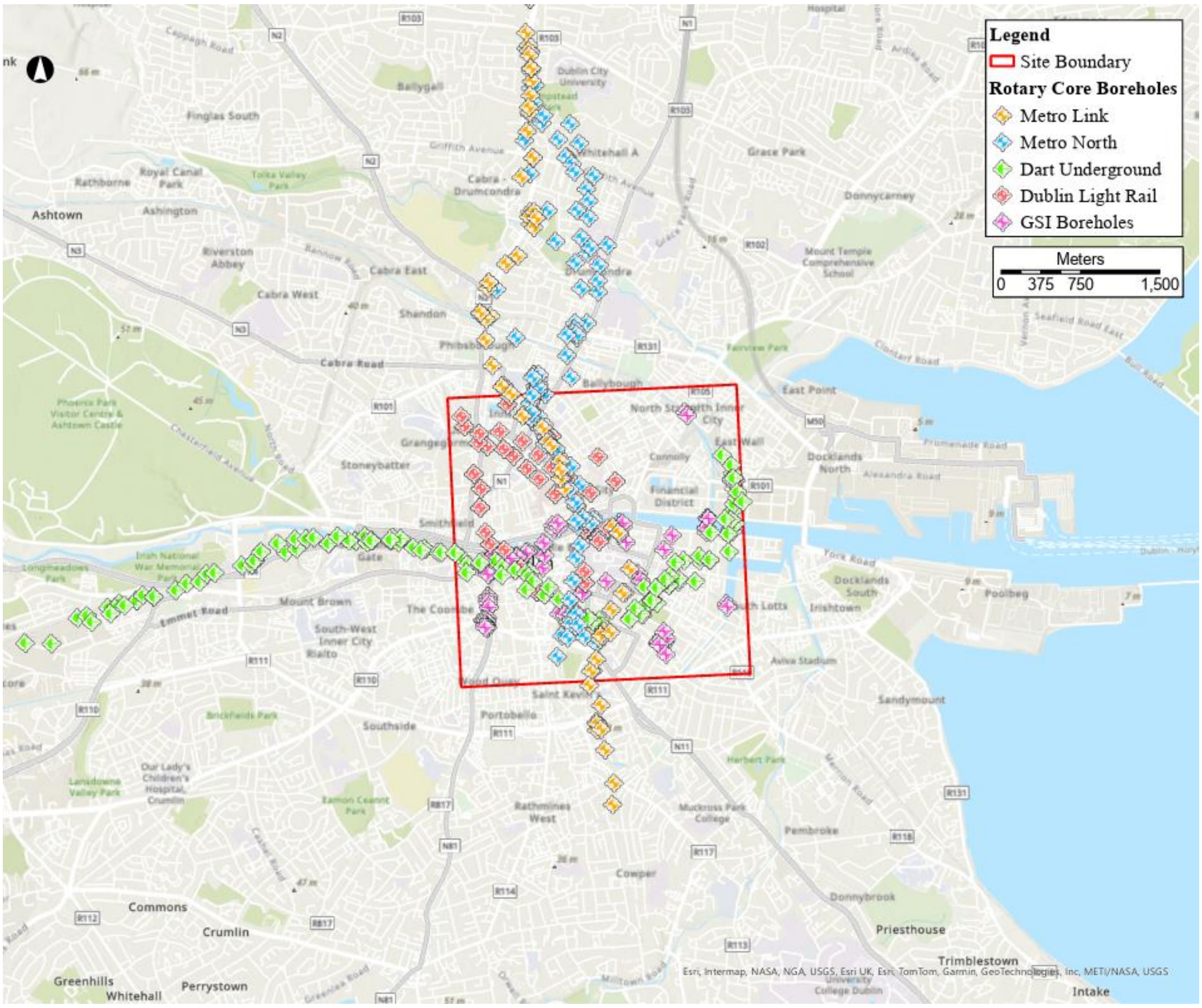


Figure 2 Project study area with exploratory locations provided by Transport Infrastructure Ireland at project outset.

The study area comprises approximately 7.5km^2 of the inner Dublin City Centre, as shown in **Figure 3**. The study area is bounded by the North Circular Road (R101) to the north, and by the Iveagh Gardens to the south. The study area extents to Fr. Matthew bridge in the west and to Grand Canal Dock in the east. The study area includes the historical centre of Dublin City including Trinity College Dublin, O'Connell Street and environs, and St. Stephen's Green.

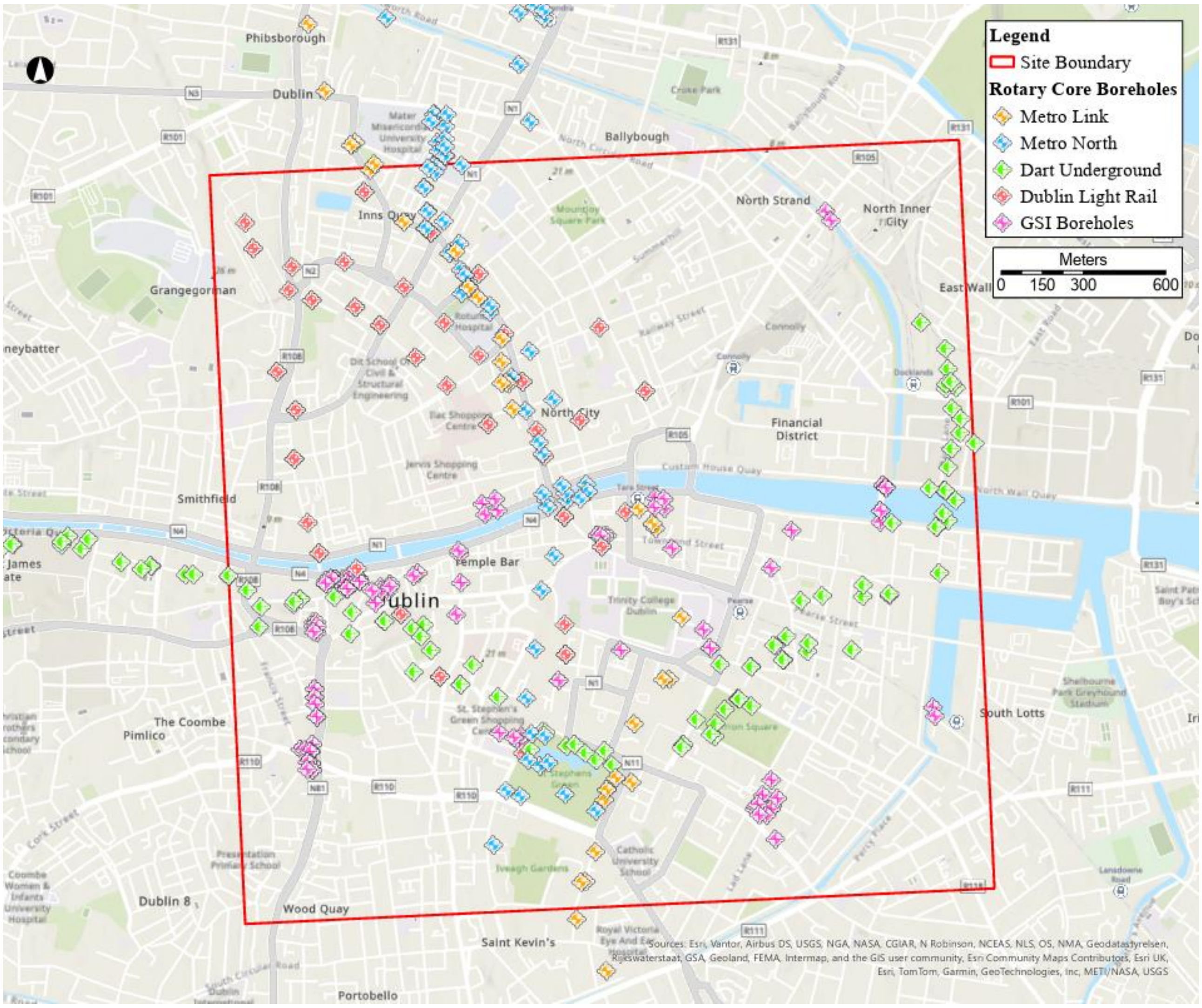


Figure 3 Exploratory Locations within the study area

2.2 Topography and Ground Elevation

Generally, the topography of Dublin City Centre, as shown in **Figure 4** below, has been influenced by the River Liffey which flows west to east through the centre of the study area. The highest elevations, approximately 25 metres Ordnance Datum (mOD), are encountered in the north-western portion of the study area and along the southern boundary, whereas the lowest elevations, approximately 1 mOD, are encountered along the River Liffey and the eastern boundary of the study area. The topography generally slopes in an eastward direction towards the Irish Sea.

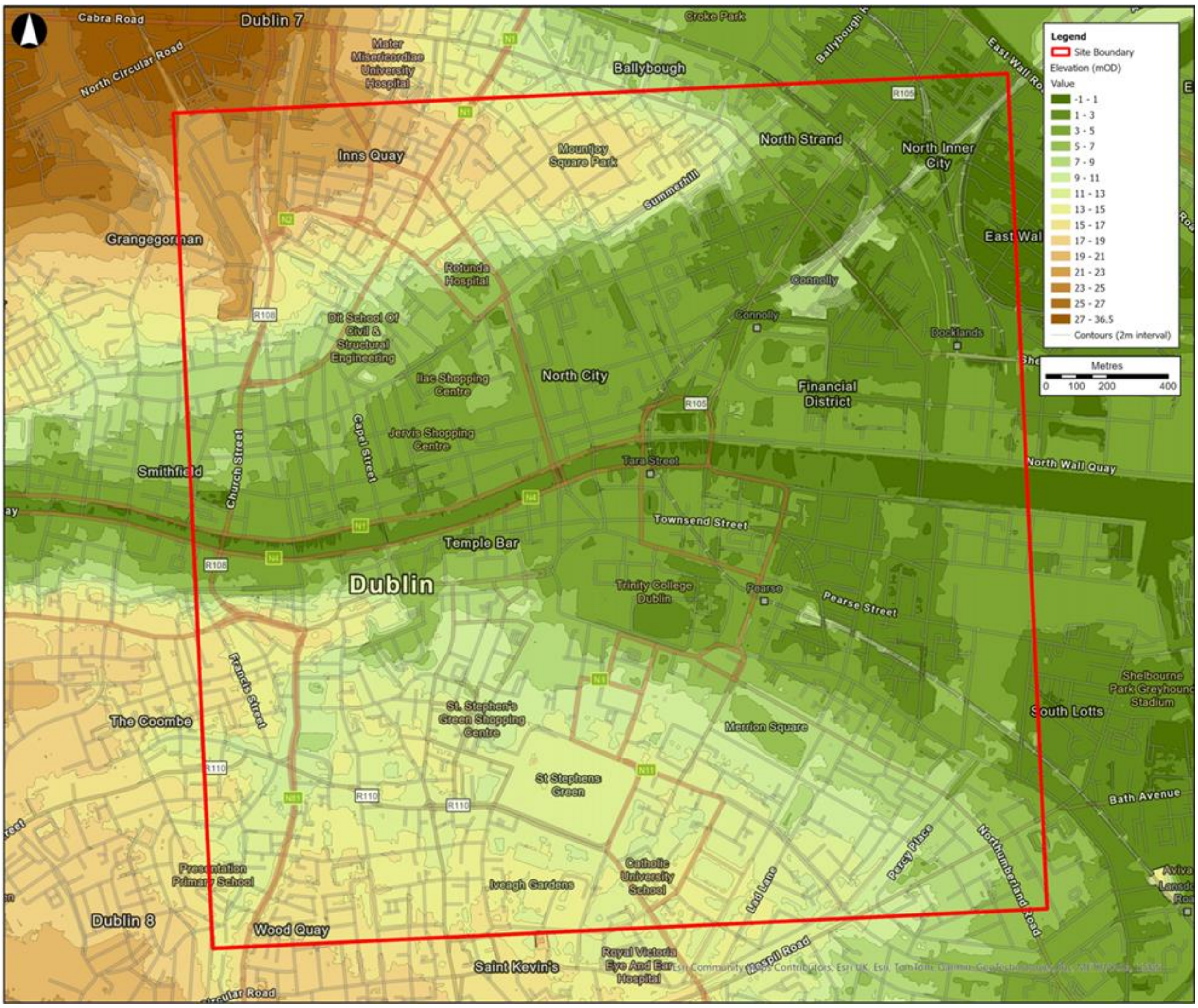


Figure 4 Topographical map of the study area using Open Topographic data (GSI).

2.3 Site History

In order to understand the historical development of the study area, a variety of Tailte Éireann (previously Ordnance Survey Ireland, OSI) historical maps were reviewed via the GeoHive spatial data hub (Tailte Éireann, 2026).

The OSI Historical 6-inch – First Edition map (1837–1842), as shown in **Figure 5**, depicts the urban environment of Dublin City Centre during the mid-19th century. The street layout of Dublin City Centre has remained relatively unchanged since the mid-19th century. Historical landmarks such as Trinity College (1), Saint Stephen's Green (2), and Dublin Castle (3) are included.

Eastern and northwestern portions of the study area were rural during the mid-19th century, being characterised by agricultural land. The peripheral zone in the northeast of the study area primarily encompasses docks (4), fortifications (5), and sparsely distributed small-scale industries (6).

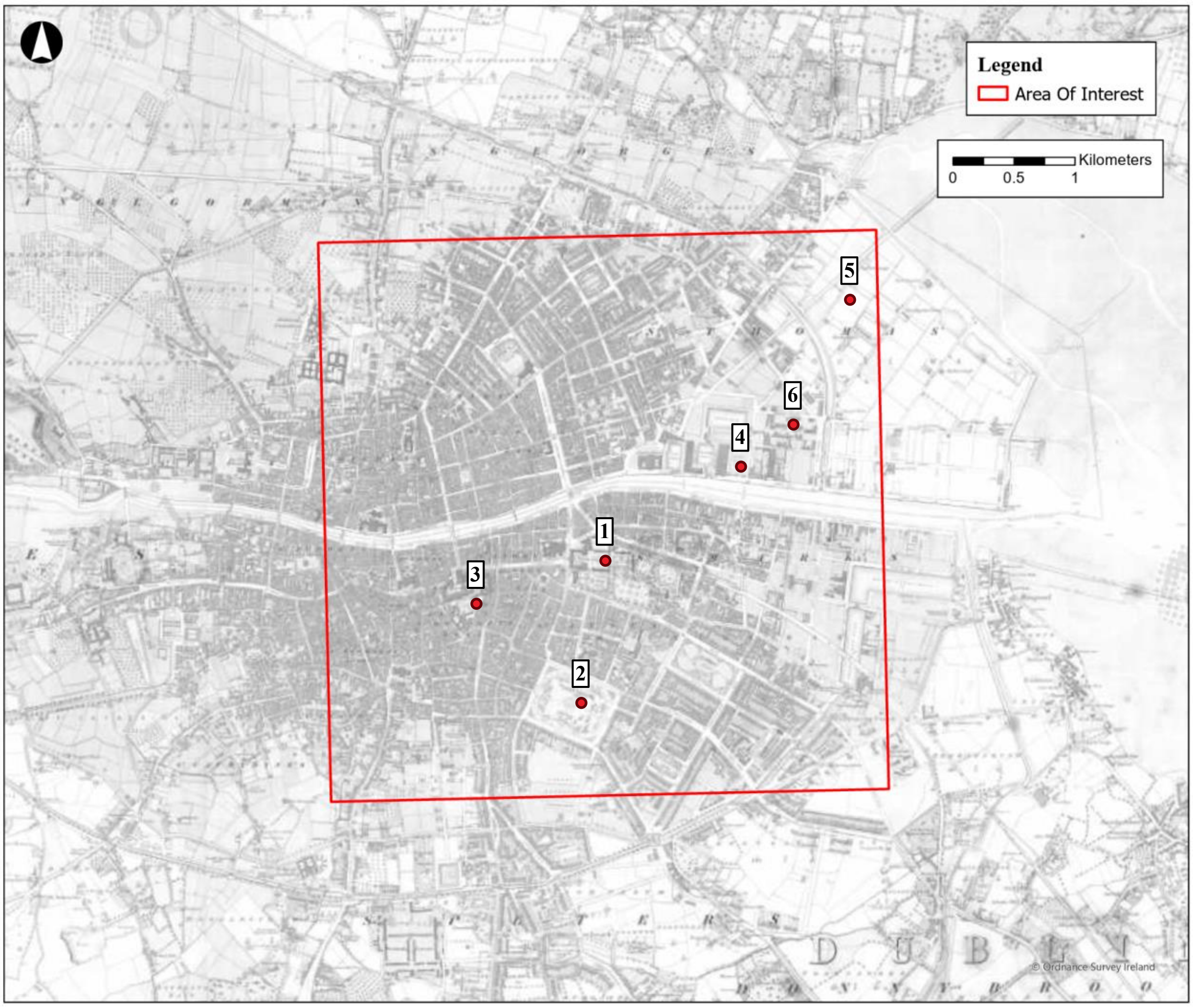


Figure 5 OSI Historic 6" Map (1837-1842), scale of produced map 1:50.000

By the 21st century, Dublin City Centre had undergone substantial development, as shown in **Figure 6**. Urban development, including residential, commercial, and industrial properties have expanded to cover the entire study area and its surrounding environs. The central portion of the study area has remained relatively unchanged since the mid-19th century, whereas widespread urban development is noted in the eastern portion of the study area.

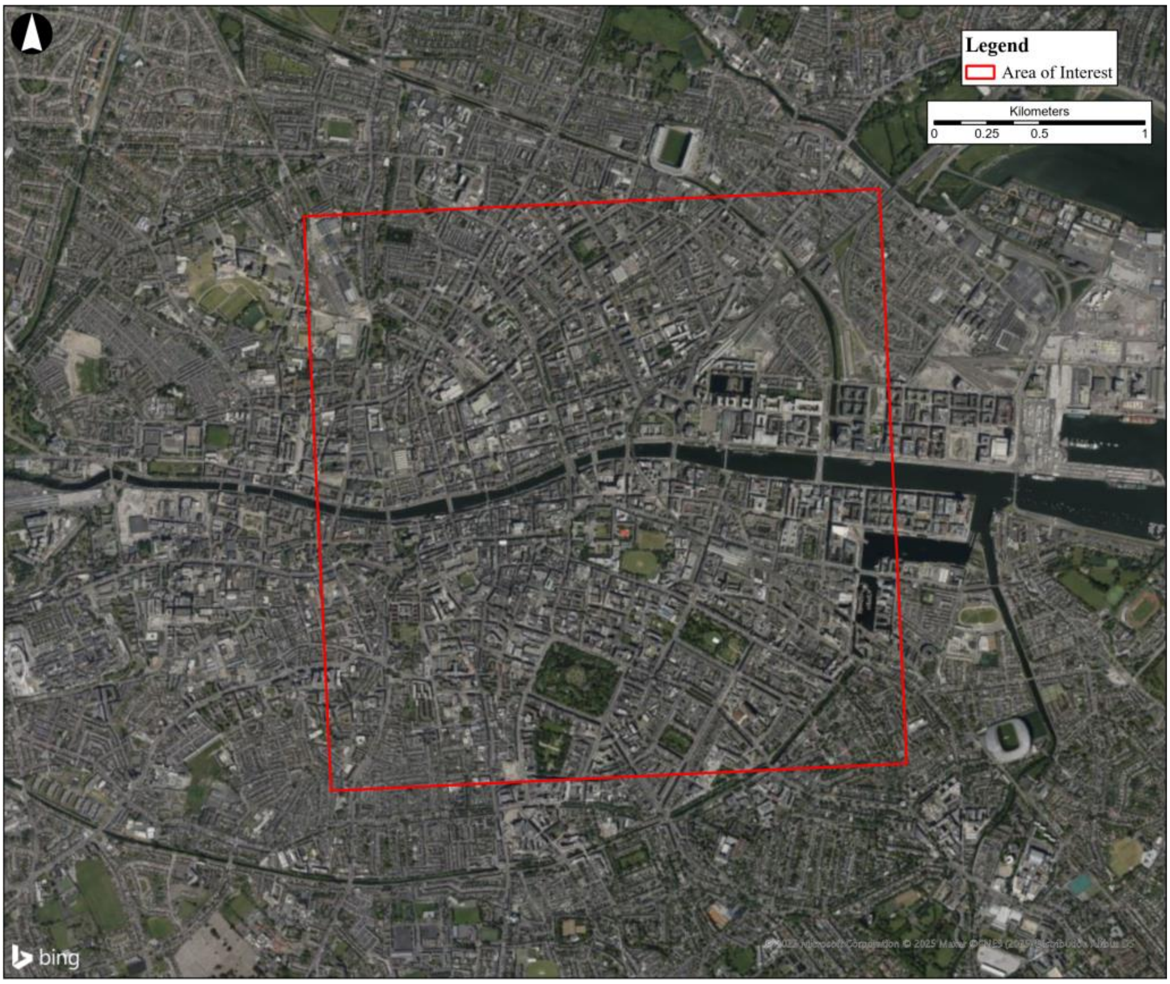


Figure 6 2025 aerial imagery of the study area indicating widespread urban development.

3. Literature Review

3.1 Geological Setting and History

3.1.1 Introduction

The geological environment is well understood in County Dublin and the surrounding area (Clarke *et al*., 2007; Gallagher *et al*., 2014; Parkes *et al*., 2014; Hennessy *et al*., 2014). Information pertaining to the geological formations in the periphery of County Dublin is widespread. However, the availability of valuable bedrock geological data decreases considerably when considering the more densely populated areas of Dublin City Centre. The bedrock geology of Dublin City Centre is also overlain by thick Quaternary deposits, up to 30 metres in places.

The GSI bedrock geological mapping (1:100k), as shown in **Figure 7** below, indicates faulting and folding within the limestone formations situated to the north of Dublin City, including the Tober Colleen Formation and the Malahide Formation. There are also folds exhibiting a northeast to southwest orientation, as well as faults displaying a north-northwest to south-southeast alignment, which conceivably could extend into the Calp limestone formation (Nolan, 1986). Highly folded and fractured zones have been noted in the limestone rock along with significant erosive activity prior to the Last Glacial Period, which eroded the ground at the "rockhead level" and created buried channels (Long and Murphy, 2003).

Furthermore, it is worth noting that the intrusive igneous rocks located to the south of Dublin City, bounded by an ENE-WSW strike fault, may have also contributed to the depositional environment of the Calp formation.

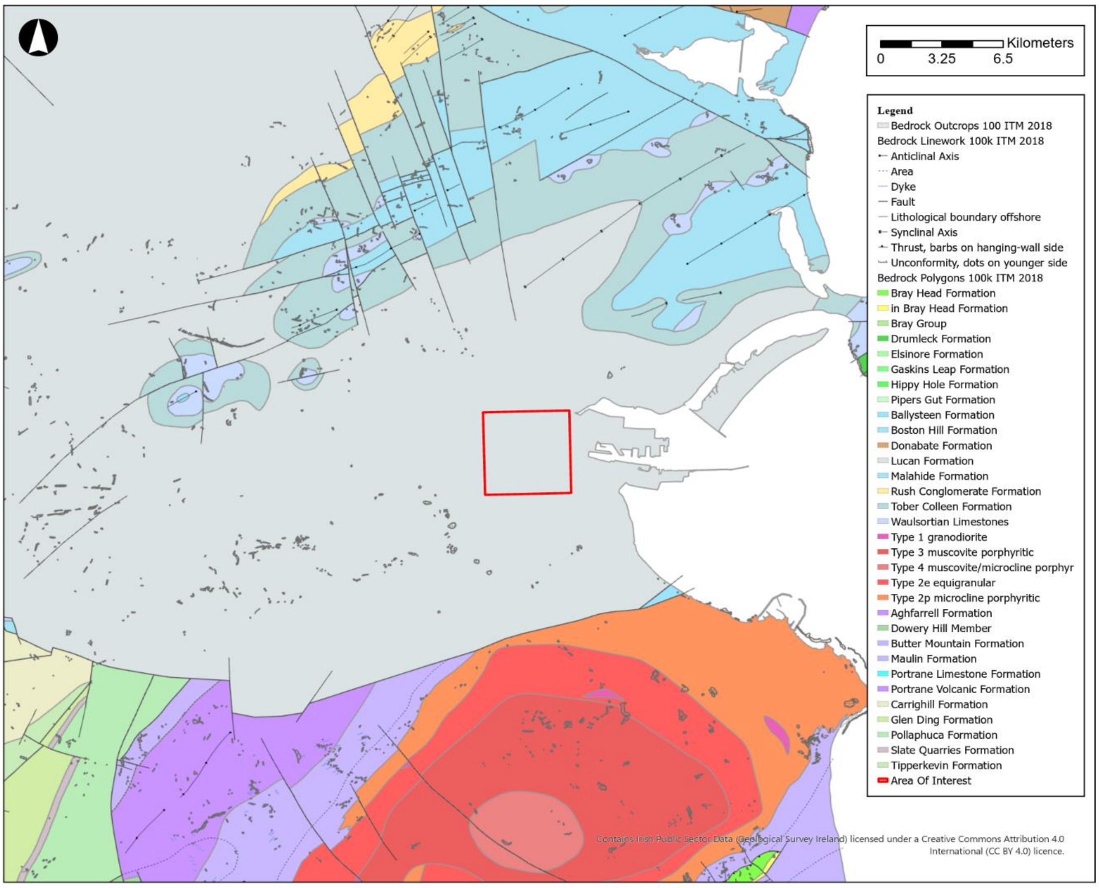


Figure 7 Geological map of Dublin City and the surrounding region, scale of 1:100k (GSI).

The presence of uncertainties regarding the extents of faults and folds, the thickness of glacial till and fluvio-glacial sediments, the presence of pre-glacial channels, along with the scarcity of outcrops collectively pose challenges in the understanding and determination of the geo-engineering conditions associated with the bedrock beneath the Dublin City.

3.1.2 Recent and Quaternary Geology

The majority of Dublin City Centre is underlain by made ground with areas of alluvial, estuarine, and marine deposits present that are associated with recent Quaternary water bodies, namely the River Liffey and its tributaries (many of which have been modified and/or culverted within Dublin City Centre). These in turn overlie significant thicknesses of Quaternary deposits, primarily glacial till.

During the Pleistocene epoch of the Quaternary (approximately 2.58 million years ago to 11,700 years ago), two glaciations covered County Dublin which gave rise to the deposition of glacial till. Typically, during glacial advance, boulder clays were deposited sub-glacially as lodgement till over the eroded bedrock surface, whilst granular moraine deposits were laid down at the glacial margins.

Subsequently, with the progressive retreat of the ice sheets from the region following the end of the Last Glacial Period (approximately 11,700 years ago), granular fluvio-glacial deposits were laid down by melt waters discharging from the front of the glacier which are generally encountered as sand and gravel lenses within the glacial till deposits. As the glacial deposits were deposited in a dynamic environment with glacial and fluvio-glacial influences, the material can exhibit significant lateral and vertical variations in grain size distributions over short distances.

Glacial till is the predominant subsoil across the Dublin region, being typically described as till derived from limestones. The subsoils of the region may also be comprised of made ground where major development has occurred.

As discussed in Kealy *et al*. (2021), and presented in **Figure 8**, the Quaternary geology in the area is characterised by a sequence that includes the pre-glacial Liffey channel, incised into the Carboniferous limestone bedrock (specifically, the Calp Limestone), and subsequent infilling with intermittent layers of lower glacial till. Above this, there is a substantial deposit of fluvio-glacial sand and gravel, and, in turn, a layer of upper glacial till.

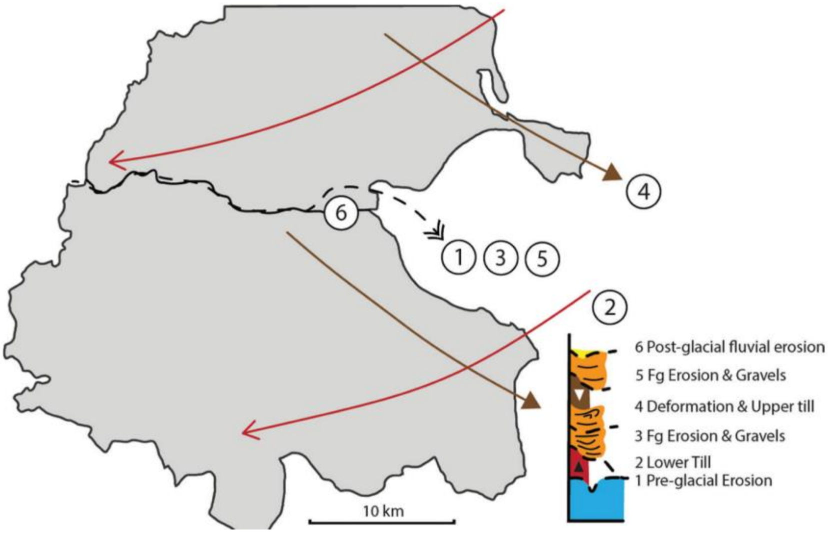


Figure 8 Glacial sequence in the Liffey Valley (Kealy *et al*., 2021)

3.1.2.1 Lower glacial till

The lower glacial till deposits at the base of the Quaternary depositional sequence are interpreted to have been deposited as lodgement tills where the advancing ice sheet was in contact or coupled with the underlying bedrock. Lodgement tills are understood to form sub-glacially under pressure melting conditions.

When the ice sheet is in contact with the underlying bedrock, frictional heating will take place. The debris that was encased in the ice sheet is deposited into the contact zone of the ice sheet and the underlying bedrock (Menzies & Shilts, 2002; Kealy *et al*., 2021). Pressure applied from the overlying ice, which reached up to 3km thick in places, resulted in the formation of a very stiff to hard lodgement till.

3.1.2.2 Fluvio-glacial gravels

Prior to ice sheet advance over the Dublin City region, fluvio-glacial sand and gravel deposits were preferentially laid down along pre-exiting river channels and depressions in the bedrock as a result of meltwater discharge from the advancing ice sheet, as shown in **Figure 9**. Following ice sheet advance over the Dublin City region and deposition of the lower glacial till, widespread fluvio-glacial deposits were laid down across the region during a period of glacial retreat as a result of a negative mass balance, as shown in **Figure 10** (Kealy *et al*., 2021).

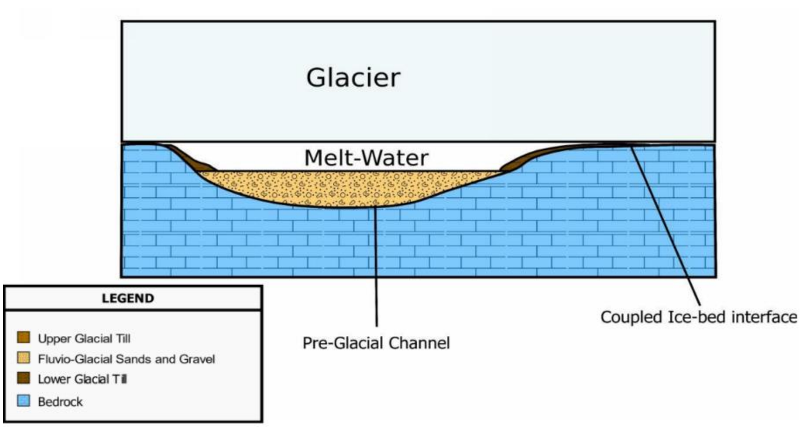


Figure 9 Initial deposition of fluvio-glacial sands and gavels and Lower glacial till (Kealy *et al*., 2021)

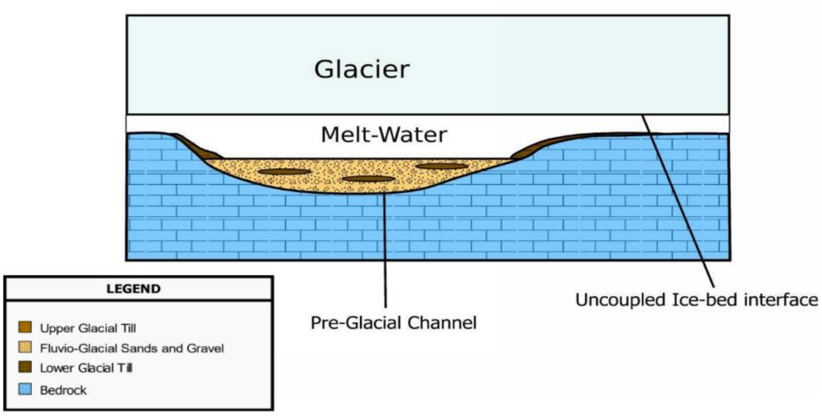


Figure 10 Uncoupling due to negative mass balance within in the glacial system and deposition of fluvio-glacial sands and gravels during a period of glacial retreat (Kealy *et al.*, 2021)

3.1.2.3 Upper glacial till

During the final phase of glacial advancement across the region, the mass balance within the ice sheet was positive and the production of meltwater was at a minimum. In these conditions, the ice sheet can become coupled with the underlying stratum, as shown in **Figure 11**. The underlying sands and gravels were over consolidated due to the overlying pressure of the ice sheet. A younger, upper lodgement till was then deposited on top of the sands and gravels (Kealy *et al*., 2021).

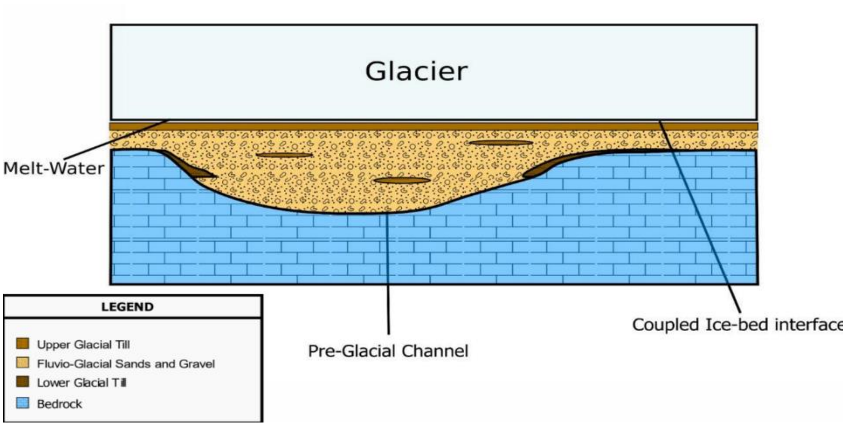


Figure 11 Coupling and deposition of upper till (Kealy *et al.*, 2021)

3.1.2.4 Post-glacial geological episodes

During final deglaciation, further widespread glacio-fluvial sands and gravels were deposited.

Post-glacial transport of these final glacio-fluvial sands and gravels was accompanied by the incision of the upper glacial till. 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 fluvio-glacial gravels and their recent fluvial erosion (Kealy *et al*., 2021).

3.1.2.5 GSI Quaternary Mapping

According to the GSI Quaternary 1:50,000 map (**Figure 12**), the predominant Quaternary deposits within the study area consist of anthropogenic urban sediments. These urban sediments are closely associated with the residential and industrial areas of Dublin City.

Glacial till deposits derived from limestones are widespread in the northwest and southern portions of the study area. It is likely that the urban sediments associated with Dublin City Centre are underlain by these glacial till deposits. In addition, there are alluvial deposits distributed in areas adjacent to the River Liffey.

The GSI Quaternary mapping also indicates a small portion of the marine sediments in the eastern section of the study area, particularly in the Grand Canal Dock area.

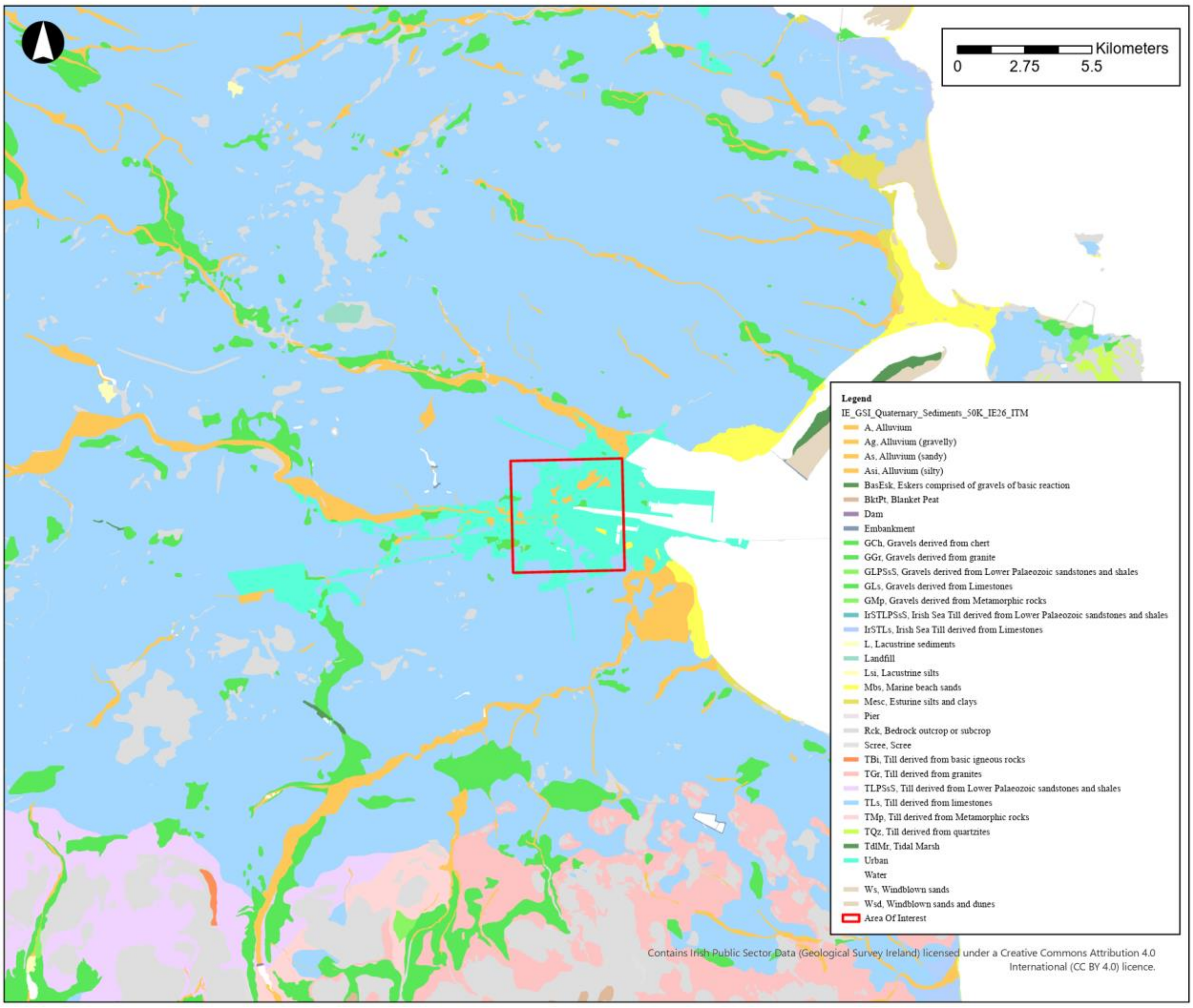


Figure 12 GSI Quaternary geology map in a scale 1:50,000 (Geological Survey Ireland)

3.1.3 Bedrock Geology

The Calp Limestone underlies most of the Greater Dublin Area including all of Dublin City Centre, as shown in **Figure 7**. Most projects in the Dublin City region requiring rock-structure interaction are located within the Calp Limestone. The Calp Limestone is fault-bounded by older intrusions of Caledonian granites (Leinster Granite) to the south and by the Tober Colleen formation to the north (Johnson, 2022).

There is a system of joints, faults, and folds recorded in the Carboniferous Limestone formations underlying the surrounding area of Dublin City.

Joints, defined as fractures in the rock along which there is no transverse displacement, are the most common type of geological feature (Jaeger *et al*., 2007). Joints appear in sets that are parallel and spaced relatively evenly, with sets forming in different orientations so that the rock mass is divided into a "blocky structure". Joints are important to rock mechanics as they divide the rock into separate units, facilitating sliding along the planar surfaces and preferential pathways for groundwater flow (Jaeger *et al*., 2007).

Faults are fracture surfaces on which transverse displacement to the nominal plane has occurred. Joints and faults are likely to have a common origin due to rock stress, and it is common for joints to increase in frequency near a fault (Jaeger *et al*., 2007). Highly stressed zones and fractures associated with folds in the bedrock have been identified within the Calp Limestone (Long and Murphy, 2003).

Due to the thick overlying glacial deposits, evidence of folding and faulting in the Calp Limestone underlying the study area is sparse (Long and Murphy, 2003). There is a system of faults shown to the northwest of Dublin City trending north-northwest to south-southeast (**Figure 7**). These faults are located where the Malahide Formation, Waulsortian Limestone, and Tober Colleen Formation meet. There are likely to be many more faults and folds present within the Calp Limestone beneath Dublin City than those identified to date, due to the thick cover of overburden.

3.1.3.1 Calp Limestone

According to Marchant and Sevastopulo (1980), the term “Calp” was introduced by Richard Kirwan’s second edition of Elements of Mineralogy (1794), to describe the dark, argillaceous, fine-grained Carboniferous limestones of the Dublin district. A literature survey reveals that the typical locality for the Calp Limestone is the Lucan and Palmerstown area of west County Dublin (Marchant & Sevastopulo, 1980).

The Calp Limestone has previously been mapped at areas of bedrock outcrop exposure (Marchant & Sevastopulo, 1980) in order to describe the bedrock lithology. Exposures of the Calp Limestone in the Dublin City region were identified from an inventory of quarries near Palmerstown and Lucan in west County Dublin. The most important exposures studied by Marchant and Sevastopulo are described below, with the locations shown in **Figure 13**. The quarries mapped by Marchant and Sevastopulo are located approximately 6 km to the west of the Dublin City Centre study area.

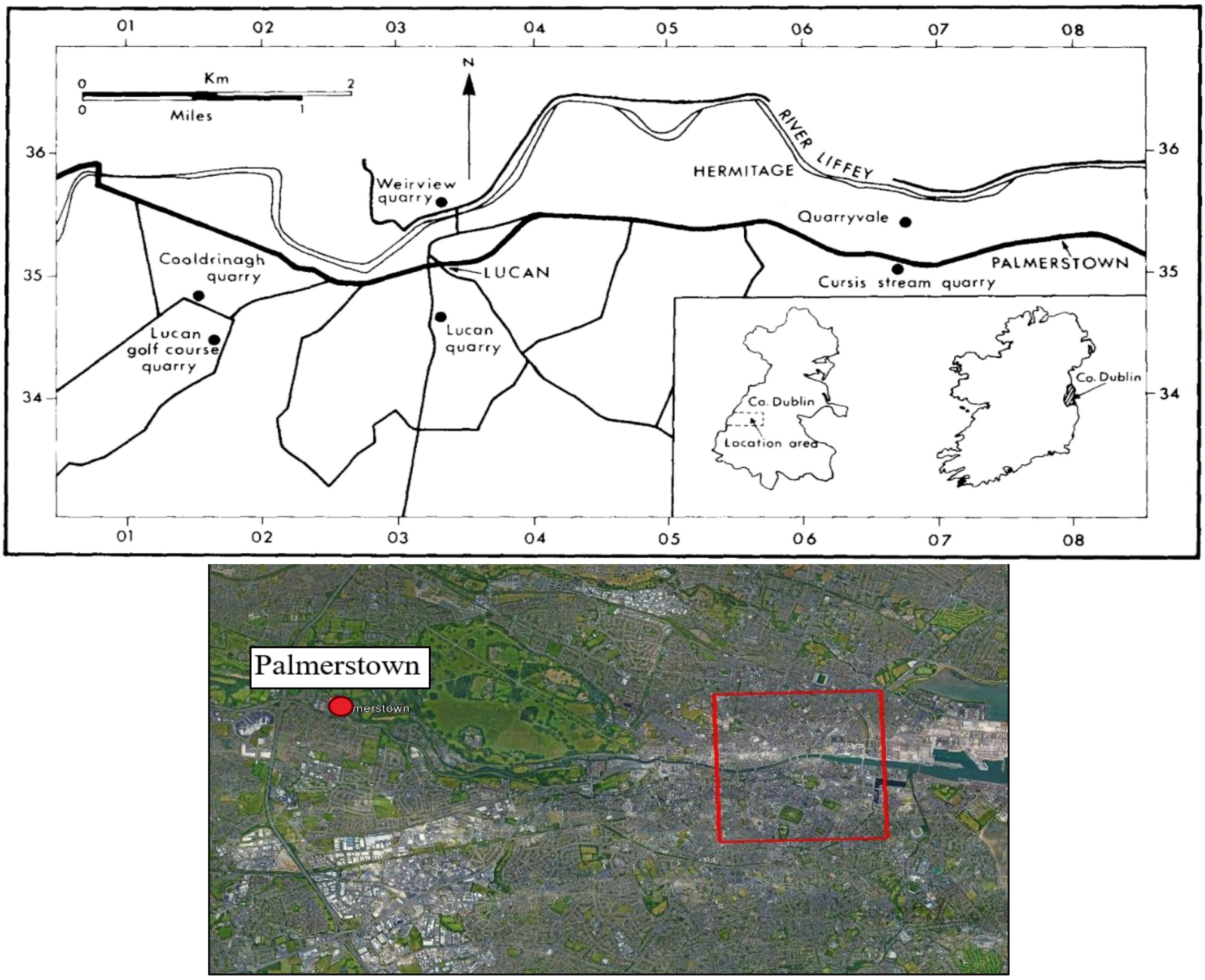


Figure 13 Map of the quarries that Marchant and Sevastopulo (1980) used to describe the Calp limestone

Description of Calp Limestone

The most significant sections of Calp Limestone mapped by Marchant and Sevastopulo from Lucan and Weirview quarries are shown in **Figure 14** to illustrate the nature of the strata of the Calp Limestone. The other quarries mapped provided only a few metres of sections.

Based on observations, three different rock types within the formation have been identified (Marchant & Sevastopulo, 1980):

1. Fine grained, occasionally cherty, limestones that are dark grey to black when fresh, and weathered paler, usually to light grey,
2. Rare dark coarser grained limestones,

3. Dark, calcareous, variably fissile mudstones, that show the same range of colours as the limestones.

More than 85% of the limestone beds are less than 0.4 m thick, typically 0.2 m or less. Bedding is generally crudely tabular with sharply defined upper and lower bedding planes, however, several individual beds vary in thickness along their length. In most cases of beds with variable thickness, it is the upper bedding plane which is uneven and hummocky. The uneven upper bedding plane can be shown to be original as the profiles of the hummocks are congruent with undulating laminations (Marchant & Sevastopulo, 1980).

Details of the internal structures of the limestone bedding were difficult to map, except on the clean weathered faces found in part of Weirview quarry. The most characteristic structure is lamination, usually seen as a difference in relief reflecting the different textures of adjacent laminae, but in some cases defined by colour banding (Marchant & Sevastopulo, 1980).

For the most part the laminations are horizontal, but low angle inclined laminations occur at the base of some beds. Steeper small-scale cross lamination also occurs in the upper parts of some of the beds of Quarryvale, Lucan, and Weirview quarries. Examples of disturbed and folded lamination also occur, for example in Lucan quarry. The grains are usually coarser at the lamination bases and grade upwards into finer grained limestones (Marchant & Sevastopulo, 1980).

The mudstones range from blocky to fissile and a steep cleavage is developed in many strata. The carbonate content of mudstone strata varies and some transition gradationally into fine grained limestones. Macrofossils can only be found in coarser limestones (Marchant & Sevastopulo, 1980).

Depositional environment and age of the Calp Limestone

Limestones similar to the Calp Limestone formation have been deposited in various late Palaeozoic basins (Marchant & Sevastopulo, 1980). An interesting resemblance to the Calp Limestone can be seen in the Lower Carboniferous Rancheria Formation in New Mexico, where both dark, spicular fine-grained limestones and coarser limestones from shallow-water environments have been found. It is likely that much of this sediment which forms the Calp Limestone was deposited by turbidity flows, but more data needs to be examined from different sections in the Dublin area to confirm this idea (Marchant & Sevastopulo, 1980).

The foraminifera and algae present in the Calp Limestone, especially archaediscids, indicate that it likely formed during the Arundian age (Marchant & Sevastopulo, 1980).

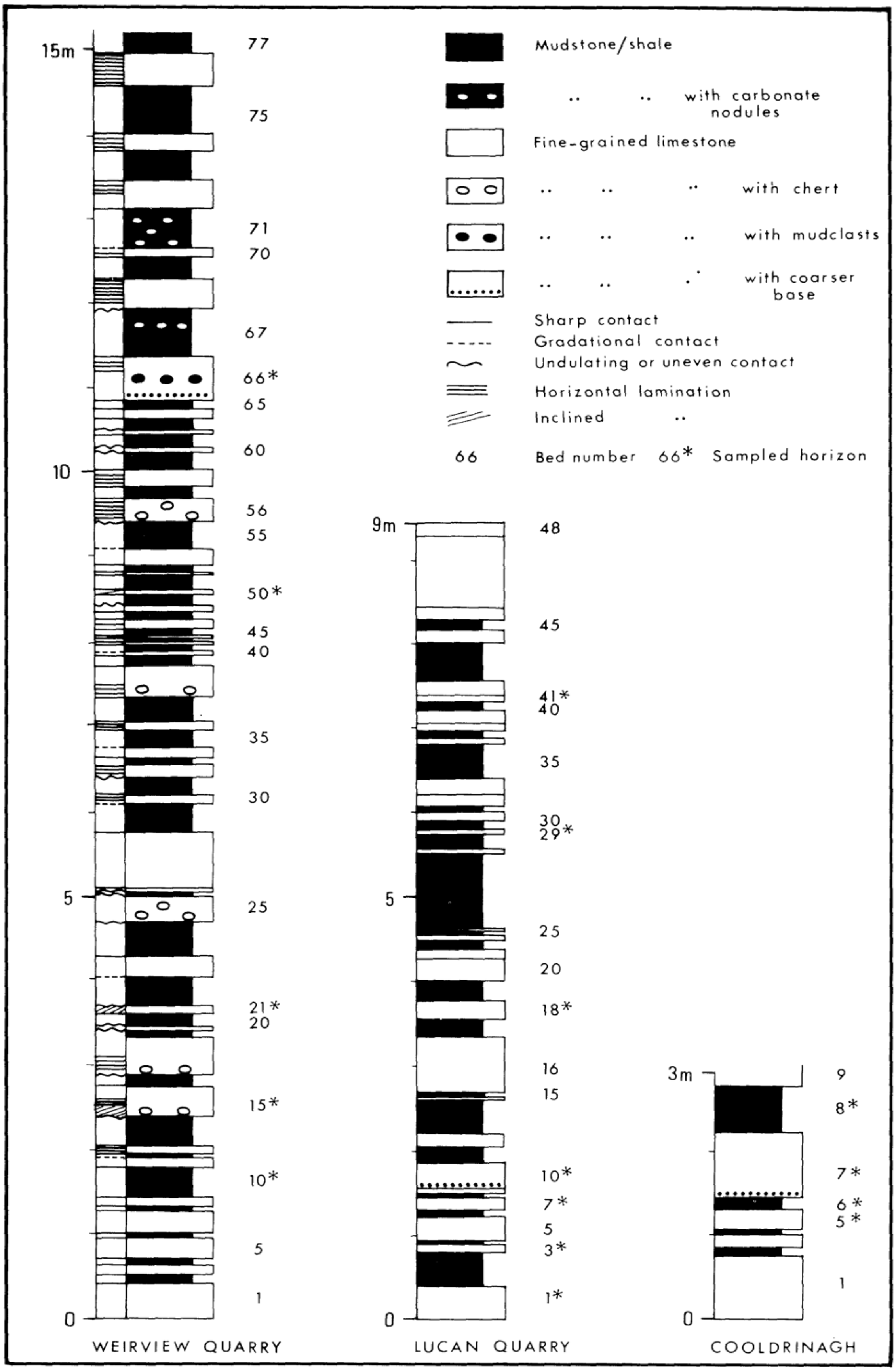


Figure 14 Sections for Weirview, Lucan and Cooldrinagh quarry based on Marchant and Sevastopulo (1980) observations

3.1.3.2 *Depth to bedrock*

Defining the depth of the bedrock poses significant challenges, primarily due to the following reasons:

1. Ground investigation data originates from various separate projects, leading to potential variations in drilling methods and the descriptions provided in the logs.
2. Given that the overlying formation consists of very stiff to hard glacial till deposits (also known as Boulder Clay), it is expected that instances of refusal during drilling may have been inaccurately described as encounters with bedrock, introducing the possibility of "false positives" into the model.
3. Dublin's subsurface geology is quite intricate, due to various depositional environments that have shaped it over time. As a result, the underground conditions in Dublin can vary significantly from one location to another.

The GSI depth to bedrock mapping for Dublin City indicates, for the majority of the study area and north of the Liffey River, the depth to bedrock is anticipated to range from 25 to 30 metres, as shown in **Figure 15**. This likely relates to the erosive activity of the preglacial palaeo-Liffey. Conversely, to the south of the Liffey, the bedrock is expected to be much closer to the surface, with depths ranging from 5 to 10 metres.

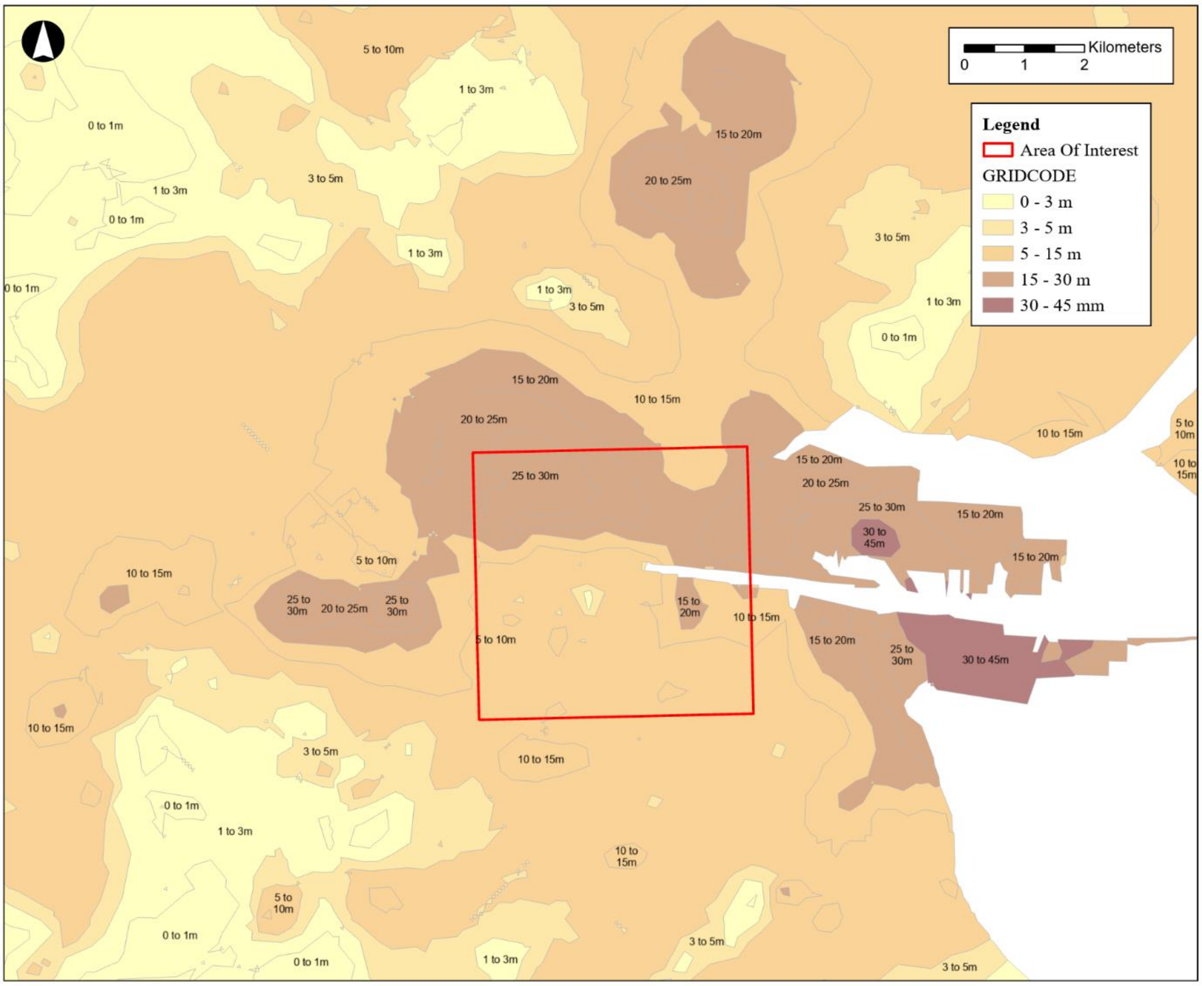


Figure 15 GSI Depth to bedrock map

It is important to note that the GSI's depth to bedrock mapping model is intended to provide a general impression of the depth to bedrock and is not entirely reliable on its own. A more comprehensive geological and geotechnical model of the Calp Limestone is developed as part of this study.

3.1.3.3 *Structural geology*

The most significant tectonic events that have shaped the geology of the central Dublin area are the Dinantian and Hercynian tectonic events (Nolan, 1986). The Dinantian tectonism is characterised as a syn-sedimentary tectonic activity.

Detailed basin analysis indicates that major phases of Dinantian tectonism coincide with periods of basin expansion and differentiation. The local extension direction was approximately oriented in a north-south direction. This estimation is not highly accurate as the area has subsequently experienced later tectonic rotation.

The development of the Dublin basin is attributed to its role as an extensional structure during the Dinantian epoch (approximately 359 to 326 million years ago). The positioning of the basin was influenced by pre-existing faults and crustal heterogeneities, which were created as a result of the intrusion of Devonian granites.

Moreover, the Carboniferous rocks of the Dublin have undergone an anomalously high degree of Hercynian compressional deformation (Sevastopulo, 1981). This compression has caused the development of a heterogeneous distribution of Hercynian strain with a clockwise rotation of the Dublin area by up to 30 degrees, as well as re-activation of pre-existing faults. There have been previous attempts to depict the structural geology beneath Dublin City and the surrounding area (Nolan, 1986), as shown in **Figure 16** below.

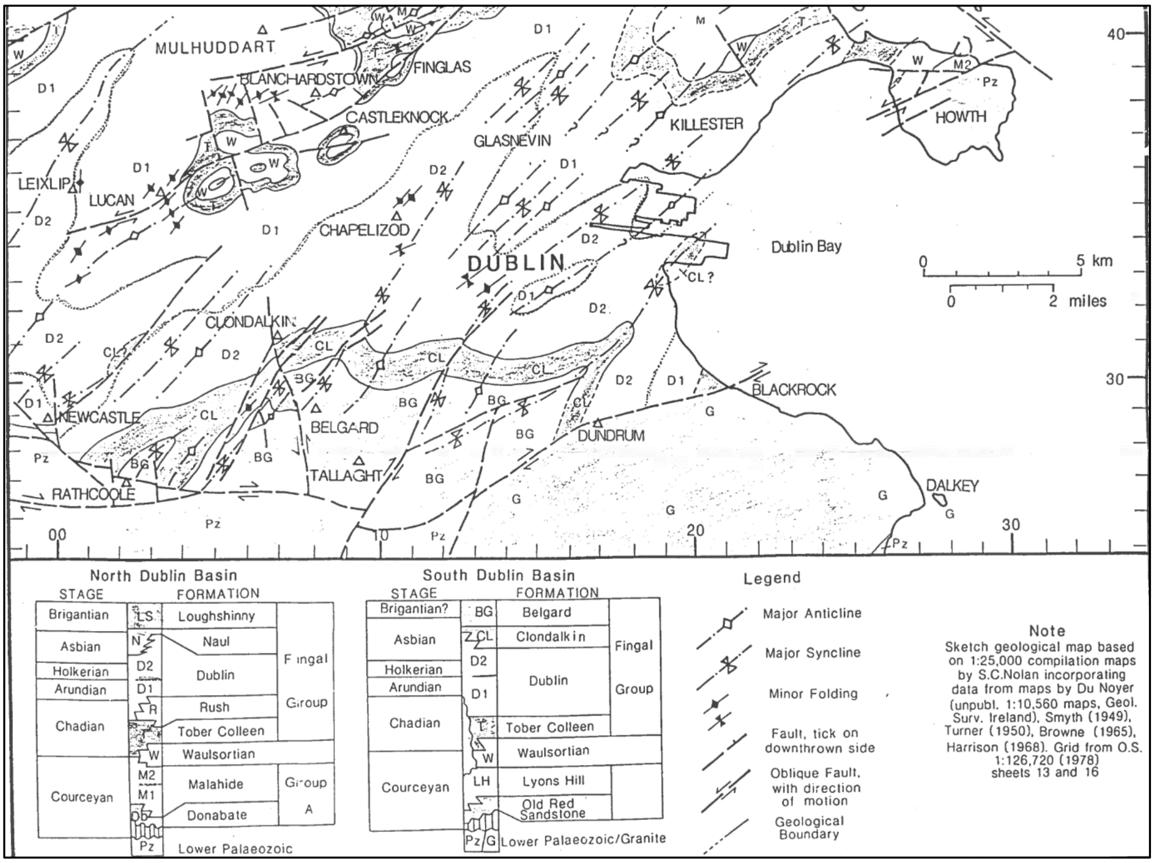


Figure 16 The Carboniferous Geology of the Dublin Area (Nolan, 1986)

3.1.3.4 Bedrock geology summary

Dublin City Centre's bedrock geological information is very limited in densely populated areas with thick till covers (**Figure 7**). However, large scale trends and large exposures of bedrock in the neighbouring areas allow for an initial interpolation of the ground conditions beneath Dublin City.

- A representative description of the Calp Limestone would be that it consists of fine grained, occasionally cherty, limestones that are dark grey to black when fresh, with interbedded dark, calcareous, variably fissile mudstones, that show the same range of colours as the limestones.

- In terms of structural geology, the GSI publicly available information indicates regional faulting in a northwestern to southeastern orientation and folding in a northeastern to southwestern orientation, for the limestone formations in north County Dublin. The intrusive igneous rocks south of Dublin, namely the Leinster Granites, may also have had an impact on the depositional environment of the Calp limestone.

- The impact of Quaternary events also needs to be considered. Two distinct glacial events eroded the bedrock surface and created variable depositional environments, hence there is high uncertainty regarding the depth of the bedrock across the site. These events are responsible for the deposition of the lower and upper glacial till when the ice sheet was in contact with the underlying bedrock sub-glacially under pressure melting conditions, as well as the deposition of fluvio-glacial deposits during a period a glacial retreat.

The expected generalised ground conditions, along with estimated depths and thicknesses are presented in **Table 1** below.

Table 1 Summary of the Ground Conditions

Main geological formation	Subcategory	Description	Expected depth to stratum (m)	Estimated stratum thickness (m)
MADE GROUND	Made Ground	Made ground consists of human-made artificial materials, which may encompass construction debris, waste materials, various substances, etc. It differs from natural soil or geological formations and can exhibit diverse engineering properties.	0-3	0-3
BOULDER CLAY	Upper glacial till	Stiff to very stiff, yellowish brown, slightly sandy slightly gravelly SILT/CLAY with some cobbles	3-10	≈7
	Fluvio-glacial deposits	Dense to very dense with zones of medium dense sand and gravel deposits.	10-20	≈ 10
	Lower glacial till	Very stiff, dark brown, slightly sandy to sandy, slightly gravelly SILT or CLAY/SILT with a relatively high proportion of gravel to cobble and rarely boulder-size exotic clasts	20-25	≈ 5
WEATHERED BEDROCK	Calp Limestone	Weak to medium strong limestone and mudstone, heavily fractured and weathered.	25-30	≈ 5
BEDROCK		Strong to very strong limestone with interbedded mudstone.	>30	Unknown

3.2 Hydrogeological Regime

Groundwater can be defined as water that is stored in, or moves through, pores and cracks in subsoils and bedrock. Aquifers are subsoil deposits or bedrock that contain sufficient porosity (voids), and which are permeable enough to allow water to flow through them in significant quantities. The potential of the aquifer to store and transport water is governed by permeability, which is a measure of the connection between voids, and of which there are two types:

- Intergranular permeability found in sediments, sands, gravels and clays, where water moves between sediment grains.
- Fissure permeability found in fractured bedrock, where water moves through cracks, faults and joints.

The groundwater regime is a complex system influenced by various factors, including the underlying geology, the fractures in the bedrock, the availability of water and rainfall for recharge, and the nature of the overlying Quaternary deposits.

As detailed in **Section 3.1.3**, the bedrock geology of this area is mostly limestone bedrock and covers the entirety of the site and the surrounding area. Permeability in these strata is typically a function of the lithology, the extent of dolomitization, faulting or fracturing, and degree of karstification. The geology of this area is highly variable, but it is usually dominated by low permeability, fine grained and argillaceous limestones and shales. The importance of the aquifers in the region is shown in **Figure 17**.

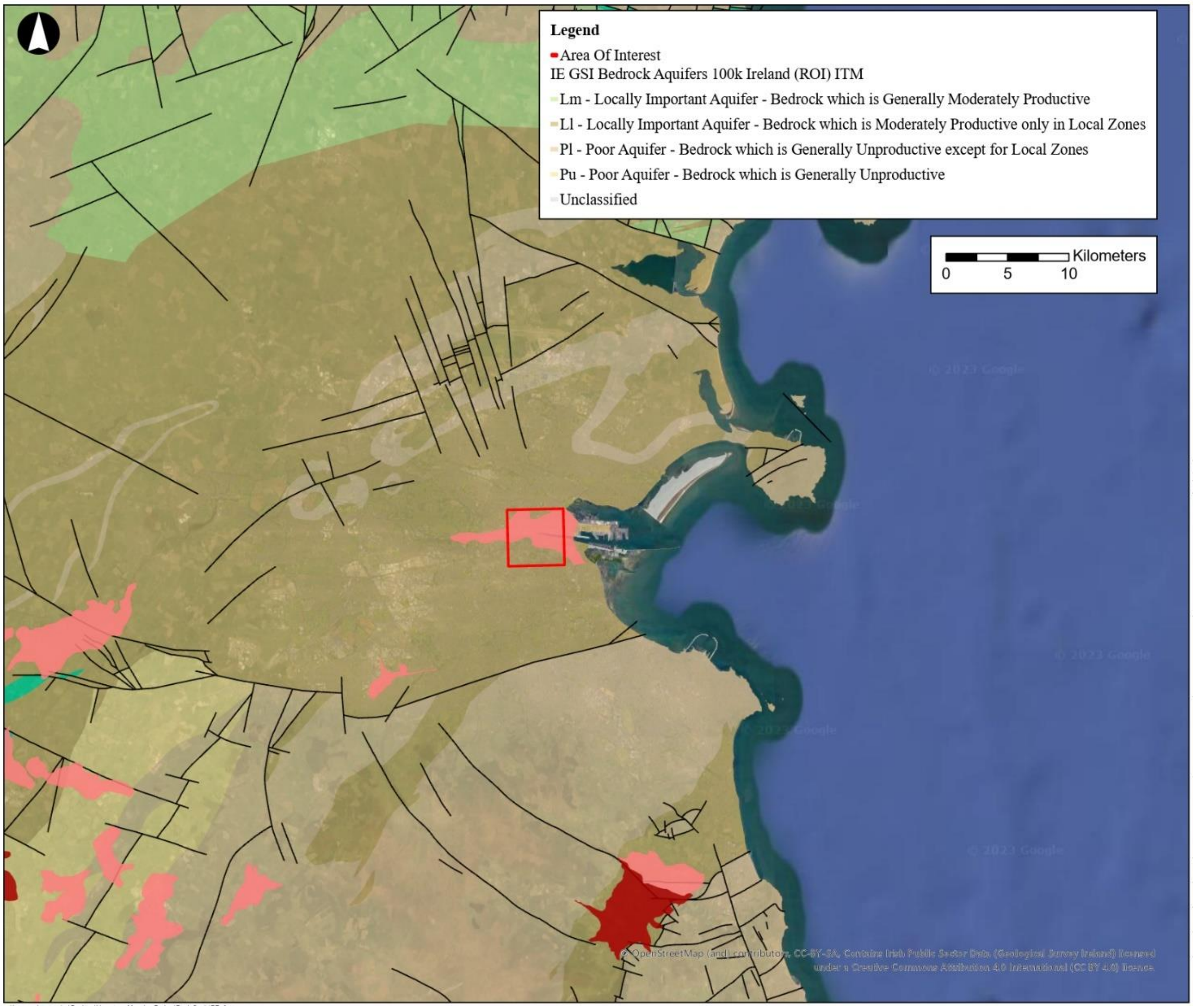


Figure 17 GSI Bedrock aquifers map 1:100.000

3.2.1 Groundwater Resources and Wells and Springs

The GSI Wells and Springs mapping, as shown in **Figure 18** below, indicates that the majority of Dublin City and the surrounding region bedrock is categorised as a Locally Important Aquifer. The Calp Limestone bedrock is generally considered to be moderately productive only in local zones.

However, within the study area of Dublin City Centre, a significant portion is categorised as a locally important gravel aquifer due to the prevalence of widespread Quaternary sand and gravel fluvio-glacial deposits. This aligns well with the placement of wells and springs, which may preferentially target the gravel aquifer.

However, it is important to highlight that there are many well boreholes with depths exceeding 100 metres, where bedrock is encountered at depths less than 10 metres. In such cases, it is expected that despite the presence of the gravel aquifer, water is likely being extracted from the fractured bedrock.

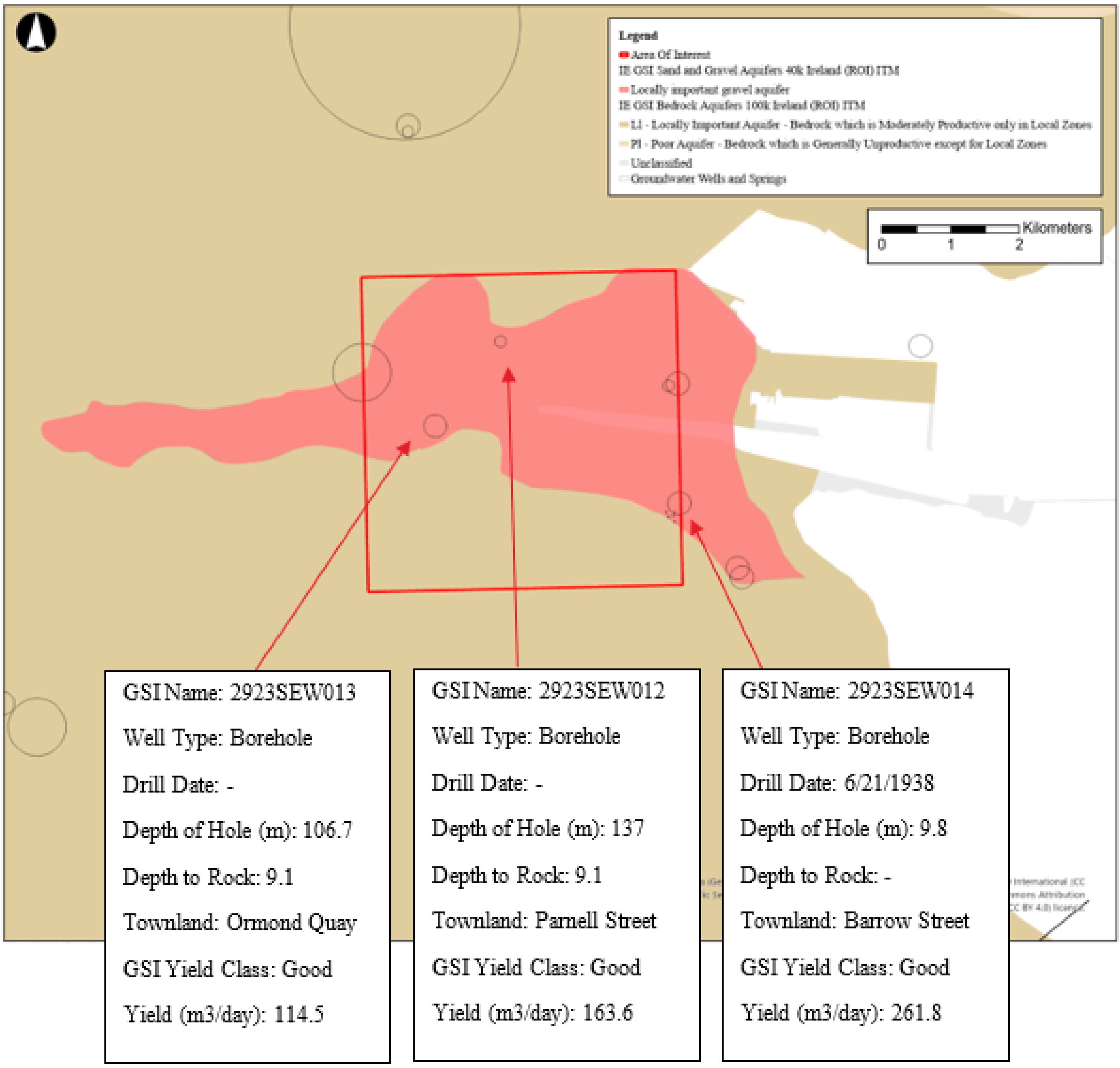


Figure 18 GSI sand and gravel aquifers, bedrock aquifers and groundwater wells and springs map.

3.2.2 Groundwater Vulnerability

The GSI Groundwater Vulnerability map (**Figure 19**) highlights a noticeable contrast between the northern and southern areas of the study area. North of the River Liffey, groundwater vulnerability is categorised as low. However, in the southern portion of the study area, there is increased variability in groundwater vulnerability. To the south of the River Liffey, the majority of the study area, is classified as a moderate risk of groundwater vulnerability. Nevertheless, there are small zones, such as near Leinster House, where groundwater vulnerability is significant, ranging from high to extreme, which implies that bedrock may be close to the surface. This correlates with the GSI depth to bedrock mapping presented in **Figure 15**.

Figure 19 GSI groundwater vulnerability 1:40.000 map.

3.3 Technical Limitations

Several challenges facing this project have been identified, the majority of which relate to the quality and nature of the datasets that form the basis of this study. The following potential gaps and limitations were identified at the outset of this project:

- The central ground investigation data analysed in this study has been compiled from three separate projects with multiple different contractors. This could lead to differences in the reporting style, drilling methods, testing methods, and the descriptions included in the logs.
- The different ground investigations were undertaken with differing objectives specific to each of the three separate projects. Each ground investigation had a different focus and therefore the information recovered may not be directly aligned with the aims of this project or focused on the characterisation of the Calp Limestone.
- The three investigations which form the basis of the dataset for this project were carried out over a substantial period (approximately 15 years). The standards for testing and reporting are likely to have changed in that period, along with the file formats and packages used to handle the data related to the ground investigations. The files themselves may be corrupted or unreadable and therefore not suitable for inclusion in the model.
- Given the age of the cores and the nature of the Calp Limestone, there is the possibility that some of these cores may have deteriorated over time. Furthermore, there is the possibility that the cores may have been lost in the intervening years.

- There is the possibility that, due to limitations in the drilling methods, refusal during drilling may be described as encountering bedrock. This may not be the case, and care should be taken to ensure such "false positives" are not entered into the model.
- There are no major outcrops of Calp Limestone in Dublin City Centre. The Calp Limestone cannot be viewed at a large scale within the city. Any exposed outcrops were only temporarily exposed during construction, quickly covered back up once the basements for which the excavations were carried out were completed.
- Both the regional and project scale structural geology will be difficult to determine through rock core analysis alone. This is coupled with a scarcity of outcropping rock in the urban setting along with a current lack of knowledge on the overall availability and geographical spread of orientated rock core data (from downhole geophysics).
- The study extent is relatively limited, extending from the southern extent of St. Stephen's Green to the Rotunda Hospital in the north inner city. The limited study area may be of insufficient size to identify regional trends.

3.3.1 Addressing the Technical Limitations

The gaps and limitations highlighted above have been addressed during this project as follows:

- All data collected was catalogued in a central database and underwent a data assurance and quality control review to check the integrity of the files. Where relevant historical data was available in PDF format only, the data was digitised to a suitable format for import into the relevant software packages. The format of specialist data, such as downhole televiewer data, was assessed and, where applicable, consultation with the original geophysical contractor was sought to determine its suitability and interoperability.
- A desk study and literature review of publicly available data was carried out on the study area, as presented in **Section 3**, to determine the expected parameters for the model. These parameters were used to assess the datasets for accuracy and consistency. Parameters falling outside of the expected ranges were not disregarded but checked in more detail to determine if there was a valid reason as to why they differ. Factors such as which dataset the parameters originate from, along with the drilling method, were considered when interpreting the findings.
- The geotechnical testing, both in-situ and laboratory testing was catalogued and checked to ensure that all tests followed standardised testing methods, which then allowed for a comparison of the results between ground investigations and locations.
- Site visits were organised to a number of Calp Limestone exposures to establish a benchmark for the Calp Limestone as it appears in outcrop, as discussed further in **Section 7**. The findings of the visual inspections to Calp Limestone exposure were compared to what was visible in the cores.
- A rock mass assessment was carried out to evaluate how the Calp Limestone behaves in situ. The rock mass assessment helped with visualisation when extrapolating the nature of the Calp Limestone from the available limited core samples to the larger study are scale.
- Where televiewer data or down hole data was available, these logs were used as benchmarks to help determine the dip and dip direction of the discontinuities and the internal structure of the Calp Limestone, along with any structural features such as faults and folds. By utilising the skills gained through research and techniques used and developed in UCD, along with those developed through experience and practice, it was possible to develop a robust ground model for the study area with information on the depth to bedrock, thickness of weathered zone, strength, and other geotechnical and structural details.

4. Methodology

This section details the methodology used to generate the 3D model which is the main output of this study. A methodology for the rock mass assessment, including the analysis of weathered bedrock and various rock testing parameters are also presented.

4.1 3D model generation

The initial task for 3D model generation involved an examination of the data received in both PDF and AGS format. A catalogue of the various file types was prepared in Microsoft Excel® (Microsoft, 2023). The AGS file format facilitates the direct loading of data into Bentley's gINT® software program to start the process of creating the ground model (Bentley Systems, 2023). Initially, gINT® was used to extract the coordinates of the boreholes.

ESRI's ArcGIS® (ESRI, 2023) was employed to produce maps from the coordinates extracted from gINT®, pinpointing the borehole locations. An iterative process of cleaning and reassessing the data was carried out and eventually the final site boundary was selected. This involved reviewing the available data and identifying those locations where bedrock was encountered.

The next step required the transfer of data, in the form of Excel® tables extracted from gINT®, into Seequent's Leapfrog® software program (Seequent, 2024). Leapfrog® plays a crucial role in generating both the ground model and the overburden-bedrock surface. The preference for Leapfrog® over alternatives like Surfer® or other ground engineering software arises from its efficiency in modelling complex geological conditions.

This is essential considering the expected geological complexity of the structure of the Calp Limestone beneath Dublin City. The initial data was reviewed in Leapfrog®, and the model was iterated a number of times using different modelling settings, considering factors such as existing topography and data points available. The iterative process workflow of model creation and refinement is shown in **Figure 20** below.

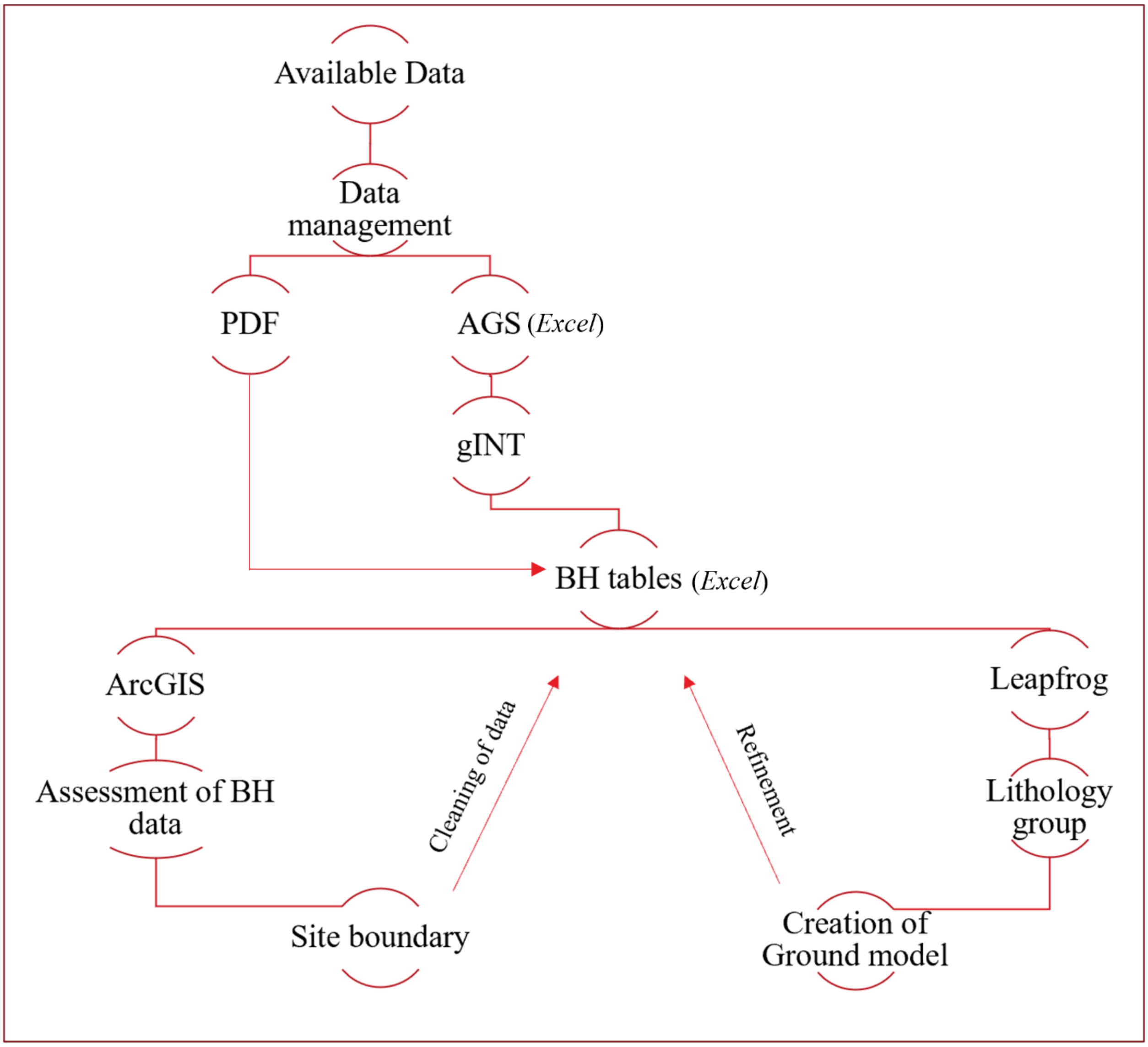


Figure 20 3D model creation methodology flow chart.

4.2 Analysis of Weathered Bedrock Surface

A systematic approach was developed as part of this study to analyse the weathered bedrock surface across the study area. This systematic approach was applied to the DART Underground rotary core boreholes provided as an example of the methodology. Results of this methodology are presented in **Section 5.3**.

4.2.1 Methodology

In order to identify the weathered bedrock an examination of the core photographs and correlated borehole logs was conducted. A list of cores to be removed from storage and visually inspected to confirm our findings has been compiled as part of this analysis.

An Excel® spreadsheet was created, noting the driller's description of the bedrock at the contact with the overburden to identify whether it had been described as weathered bedrock. In most cases, there was a general description of the rock and its weathering state, but it was only logged as a section of weathered rock in cases where it was almost completely destructed.

Core photographs were analysed for any signs of colour change, weathering products, change in fracture state, or strength variations to distinguish weathered bedrock from fresh or faulted rock. Additionally, core recovery information from the logs were recorded to support visual interpretations.

There were some limitations to this method: for example, some rock was not recovered during drilling but described as fresh or weathered rock. In these cases, no photos were available to confirm the descriptions.

Furthermore, some photos were blurry or of poor quality, making it difficult to accurately assess the weathering state and depths due to unreadable measuring tapes.

After making detailed notes on the strength and structure of the rock, each core was classified in accordance with Figure 9 of the British Standard (BS) 5930:2015 Description and Classification of weathered rock for engineering purposes, reproduced below in **Figure 21**.

APPROACH 4: CLASSIFICATION INCORPORATING MATERIAL AND MASS FEATURES		
Class	Classifier	Typical characteristics
A	Unweathered	Original strength, colour, fracture spacing
B	Partially weathered	Slightly reduced strength, slightly closer fracture spacing, weathering penetrating in from fractures, brown oxidation
C	Distinctly weathered	Further weakened, much closer fracture spacing grey reduction
D	Destructured	Greatly weakened, mottled, ordered lithographic in matrix becoming weakened and disordered bedding disturbed
E	Residual or reworked	Matrix with occasional altered random or 'apparent' lithorelics, bedding destroyed. Classed as reworked when foreign inclusions are present as a result of transportation

Figure 21 Description and classification of weathered rock for engineering purposes British Standard (BS) 5930:2015 classification of weathered rock for engineering purposes.

4.3 Rock Mass Assessment

Engineering rock mechanics is concerned with the behaviour of rock as an engineering material and all resultant impact on structures that are built in or on top of the rock. It is distinct from structural rock mechanics, which is the study of natural geological structures in rock.

Rock mass behaviour is dependent on the density, nature, and extent of the discontinuities within the rock along with the intact rock strength, mineralogy and lithology, weathering, and groundwater conditions, Rock mass behaviours can also be influenced by any historical anthropogenic interventions.

4.3.1 Point Load testing (PLT)

Point Load testing (PLT) is an accepted rock mechanics method used to determine a rock strength index. It can be performed both in the laboratory and in the field. The simplicity and speed of the test allows an appreciable volume of testing to be conducted, making it a valuable tool for efficiently characterising rock material (**Figure 22**).

Figure 22 Diametrical PLT (https://www.geotech.hr/en/point-load-test-plt/).

Point Load testing, as described in Casey and Fleming (2014), is performed by subjecting a rock specimen to an increasingly concentrated load until failure occurs by splitting the specimen. The concentrated load is applied through coaxial, truncated conical platens. The failure load is used to calculate the point load strength index (Is). As the point load test can be carried out on irregular rock cores or core samples of varying dimensions, the result must be corrected to the standard equivalent diameter of 50mm. This number is referred to as the corrected Point Load Strength Index Is_{50} (Casey and Fleming, 2014).

Initially, the relevant PLT information for each project was exported from AGS to create a project-specific database in Microsoft Excel®. The spreadsheet included information such as Borehole ID, Sample Depth (mOD, mBGL), Is and Is_{50}, as well as loading direction and stratum lithology, if applicable.

The point load data for each project was initially plotted on a scatter graph against depth to identify any clear relationship between compressive strength and depth. The next step, before separating the data by geological type, was to plot scatter graphs for each loading direction to compare the results. Following this, the data was divided into mudstone and limestone categories, and a series of graphs was generated to facilitate comparisons between similar test types across the different lithologies.

4.3.2 Rock Testing

As part of this project, rock testing and in-situ testing data from the Metro North, DART Underground, and MetroLink projects were examined. Relevant geotechnical and rock testing data were compiled, digitized where necessary, and quality-checked for assessment. This project primarily focused on intact rock tests, such as Point Load testing (PLT) and Uniaxial Compressive Strength (UCS) testing, which were evaluated to generate graphs revealing how these parameters vary under certain conditions. Rock mass properties, such as information relevant to discontinuity sets, can only be obtained in situ through visual observations and their application in engineering heavily relies on the nature and scale of the project under consideration. The various types of rock testing carried out in each of the provided ground investigation reports are detailed in below.

Project Name	Name of AGS or report file	Rock Testing										
		UCS	Stiffness	PLT	Tensile strength	Direct shear	Packer / Lugeon	Porosity	TCR/SCR/RQD	Petrographics	TRL 447 Suite	TBM suite
Metro North	14806 051010 REPORT	16	-	60	-	-	✓	-	✓	-	-	✓
	F15404P2_ExportTable	18	-	76	-	-	-	-	✓	-	-	-
	11826ags_20_7_07	97	-	160	-	-	✓	-	✓	-	-	✓
	F14824P4(2)	67	-	598	-	✓	✓	✓	✓	-	-	✓
	O'Connell Street Report	5	-	4	-	-	-	-	✓	-	-	-
	Metro North Sum	203	-	898	-	-						
Metro Link	MetroLink Phase 1 GI AGS 13.11.2019	20	✓	X	10	✓	✓	✓	✓	✓	✓	✓
	MetroLink Phase 2 AGS 02.04.20	9	✓	1	8	✓	-	✓	✓	✓	✓	✓
	MetroLink Phase 5 AGS 27.04.22	17	-	36	-	-	-	✓	✓	-	-	✓
	Metro Link	46	-	37	18	-						
Dart Underground	CompleteJob 201109 AGS	98	4	798	25	✓	✓	-	✓	✓	-	✓
	Interconnector	35	-	554	-	-			✓	-		
	Dart Underground Sum	133	4	1352	25	-						
Total		382	4	2287	43	-						

Figure 23 Rock testing table.

Most rock laboratory testing includes compressive strength tests for intact rock, with strain being recorded in only a few cases during shearing tests.

While there is an abundance of point load tests due to their low cost, the lack of accurate descriptions of the exact testing processes often made the analysis of results challenging and sometimes unreliable for scientific comparisons.

After the quality assessment and statistical analysis described in this section, the results, including the compressive strength of intact rock, were incorporated into the Leapfrog® model.

4.3.2.1 Uniaxial Compressive Strength (UCS)

The Uniaxial Compression Test is a laboratory procedure used to determine UCS of a rock specimen. UCS represents the maximum axial compressive stress a sample can withstand under zero confining pressure. While both rock mass and intact rock specimens can be tested under the UCS setting in geotechnical design, it is widely used for intact rock compressive strength as at a larger scale, rock mass behaviour is influenced by factors such as discontinuities, faults, and weathering.

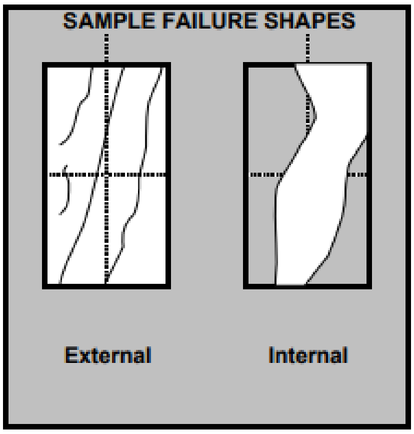
Initially, the relevant UCS rock testing information for each project was exported from AGS to create a project-specific database in Microsoft Excel®. The database included information such as Borehole ID, Sample Depth (mOD, mBGL), and Compressive Strength test results.

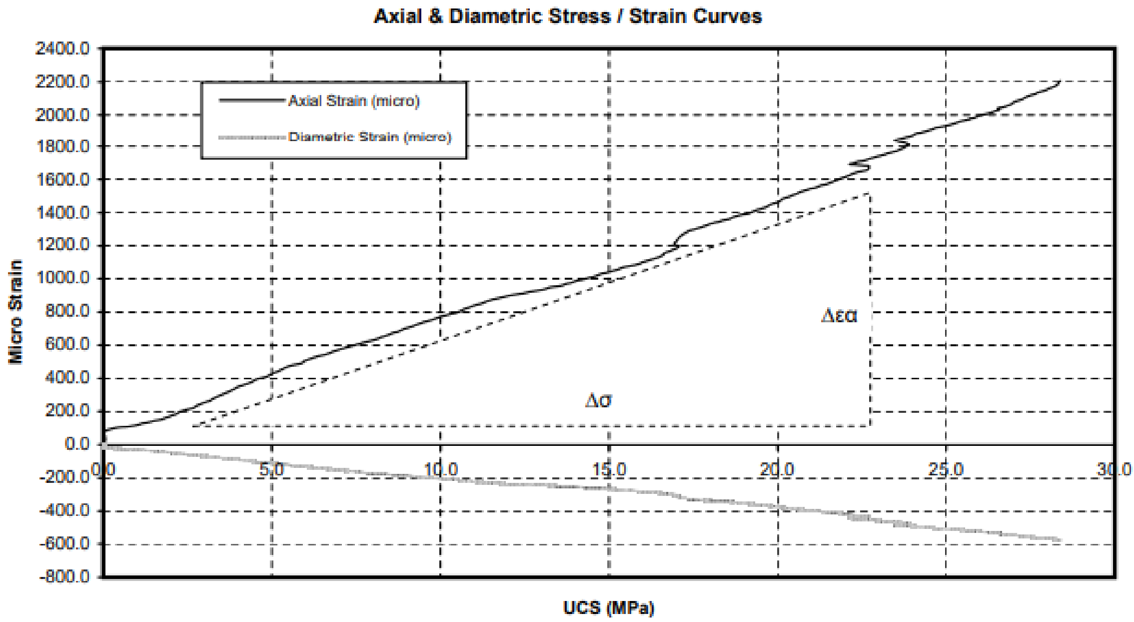
The UCS data for each project was first plotted against depth to identify any clear relationships between compressive strength and depth. Subsequently, the data from all projects were combined for statistical analysis, including data visualisation through pie charts with the limits of each segment corresponding to standardised strength categories in accordance with Table 25 in BS 5930:2015. Box-and-whisker plots were generated to provide a statistical representation of the results allowing to attribute mean, median and characteristic values after filtering out any outliers.

The UCS database was updated to include for lithological information with each UCS test result assigned a classification of limestone or mudstone based on the corresponding stratigraphic logs. The statistical analysis process, including data visualisation, was repeated for each project and each geological formation (limestone or mudstone). Composite plots displaying all project data in single plots were also produced. This approach enabled statistical analysis of the data for each lithology, helping to determine characteristic values.

An example of a UCS test result included in the analysis undertaken during this project is included in below.

BOREHOLE		NBH212
SAMPLE		C
DEPTH	m	19.20-19.70
SAMPLE DIAMETER	mm	101.09
SAMPLE HEIGHT	mm	200.20
TEST CONDITION		Saturated
RATE OF LOADING	kN/s	0.9
TEST DURATION	mm.sec	4.24
DATE OF TESTING		19/12/2019
LOAD FRAME USED		2000kN
LOAD DIRECTION WITH RESPECT TO LITHOLOGY		Unknown
FAILURE LOAD	kN	227.9
YOUNG'S MODULUS *E* (AVERAGE)	GPa	13.76
POISSON'S RATIO *v*		0.25
UNCONFINED COMPRESSIVE STRENGTH	MPa	28.4
WATER CONTENT (ISRM Suggested Methods)	%	0.9
BULK DENSITY (ISRM Suggested Methods)	Mg/m^3	2.65
DRY DENSITY (ISRM Suggested Methods)	Mg/m^3	2.63





Test Notes:
Method of Young's modulus determination - Average Modulus of Linear Portion of Axial Stress-Strain Curve
Method of Poisson's ratio determination - slope of axial curve / slope of lateral curve
Young's modulus and poisson's ratio calculated between stress levels of 2.4MPa and 22.7MPa

Figure 24 Extract from MetroLink NBH212 reporting UCS test results, including both axial and radial strain measurements, showing the specimen's compressive strength, Young's modulus (E), and Poisson's ratio.

Sampling bias tends to occur when selecting core for UCS testing, with the optimal samples in terms of size and testing suitability selected, which may not be reflective of the strength of the rock mass as a whole. Mudstone should be targeted in zones where it is relatively thick and at greater depths, for example at Belgard Quarry in west Dublin, where better material conditions can be encountered due to higher confinement stresses. Using high quality sampling techniques suitable for weak rocks (Geobore-S) can improve recovery of intact specimens, increasing the reliability of UCS results and enhancing confidence in the subsequent geotechnical design.

4.3.3 Discontinuity Orientation (Downhole Geophysics)

The downhole geophysics data provided by TII was supplied in PDF and .txt file formats. To facilitate analysis, the dip and dip direction data were compiled into a database with Microsoft Excel®, ensuring the dataset could be easily transferred to the relevant software. Where feasible, data was imported from the .txt files to increase efficiency and minimise human error. However, manual entry was required for the data contained in the PDF files.

Upon compiling all available borehole data from the study area, Rocscience Dips® software was employed to plot and analyse the data on digital stereonets (Rocscience, 2026). Initially, the data was represented in a stereonet where the poles of the discontinuity readings were plotted. Subsequently, these poles were used to form a stereonet with contours based on the density of the data points to highlight areas of consistent readings. These areas were then used to produce planes that represent the identified trends.

This process was repeated for each individual borehole, after which the data from each project was compiled into one stereonet to assess the consistency of the results across the study area. Finally, all of the readings across the three projects were compiled to produce a final stereonet of the overall structure of the Calp Limestone in the study area.

5. Calp Limestone Ground Model

5.1 Introduction

A 3D ground model of the study area has been created in Seequent's Leapfrog® geological modelling software, as detailed in **Section 4.1**. A preliminary ground model was produced following data import of the available ground investigation data. The preliminary ground model was refined through continued analysis and interpretation. The 3D ground model produced allows users to navigate across the study area, identify zones with similar characteristics, or isolate and study smaller portions of the study area. This section presents the findings of the iterative process and production of the refined ground model of the study area.

5.2 Refined Model

5.2.1 Model generation

Topography defines the upper boundary of the ground model and is a key factor in ensuring the accuracy of the model outputs. For this project, topographic data was generated by combining four 2 m-resolution LiDAR-derived DTM maps (OPW3206, OPW3233, OPW3207, and OPW3234), produced by Fugro in 2011 and publicly available via the Open Topographic data viewer on the GSI portal, as shown in **Figure 25**.

This dataset includes Irish Public Sector Data from Geological Survey Ireland and the Office of Public Works, licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

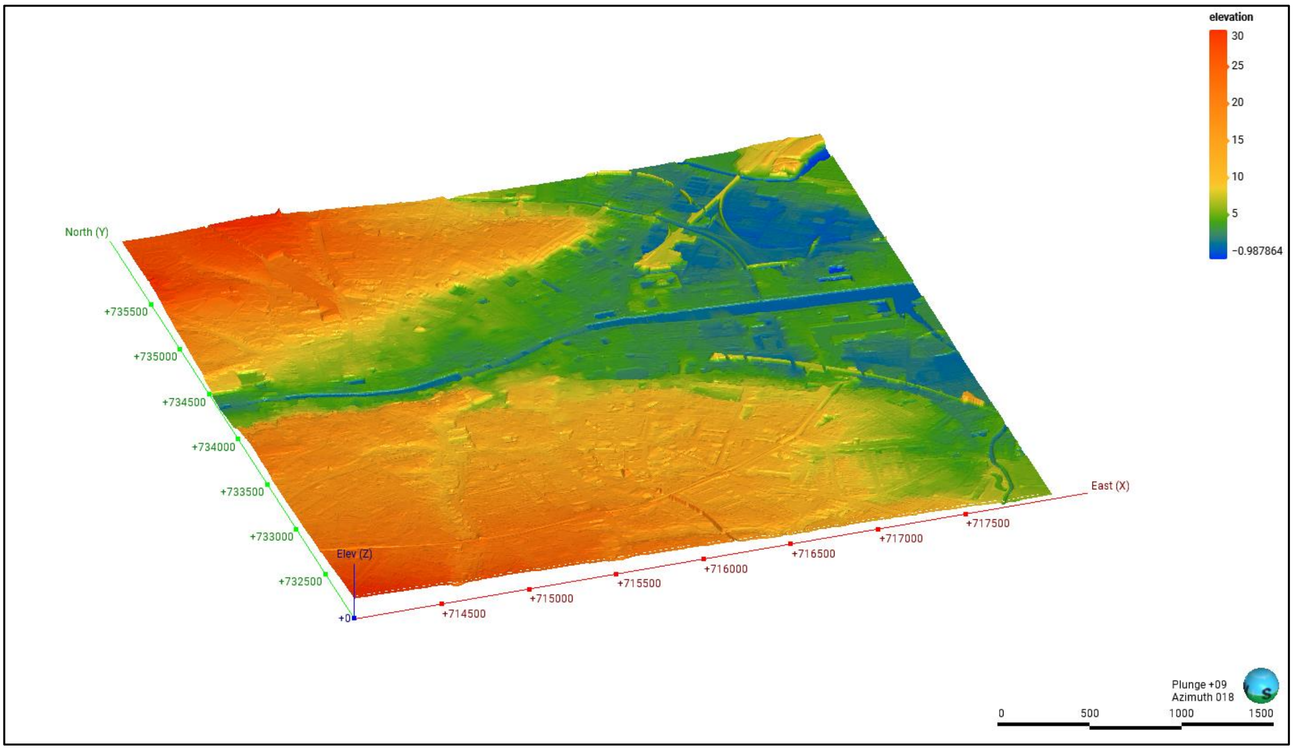


Figure 25 LiDAR-derived topography used for Leapfrog model.

A total of 397 no. rotary core boreholes were used in the development of the ground model. This includes 209 no. boreholes from the dataset provided by TII, 167 no. from the publicly available GSI database, and 21 no. boreholes from Arup in-house projects. The GSI boreholes were used solely to fill data gaps and to provide information on the depth to bedrock, as no additional lithological data accompanies the publicly available package. **Figure 26** shows the locations of all boreholes used in the model.

The geological grouping shown is a simplified representation of the original logs, intended to focus on the identification and extent of the Calp Limestone bedrock. The geological stratigraphy used in the model includes:

- The overburden, which includes all soils and subsoils overlying the Calp Limestone bedrock, such as topsoil, made ground, glacial till (Boulder Clay), and fluvio-glacial sands and gravels.
- The weathered Calp Limestone. This classification is based entirely on the borehole logs and AGS files. No additional interpretation was applied by Arup.
- The fresh, unweathered Calp Limestone bedrock. It was not possible to differentiate between the mudstone and limestone members of the formation, as this would require reliable lateral correlation between boreholes, which were often spaced more than 1 km apart.

The model benefits from a high density of borehole data in key areas such as St. Stephen's Green, O'Connell Bridge, Christ Church Cathedral, and along the planned routes of major infrastructure projects like the DART Underground, MetroLink, and Metro North. In these zones, borehole spacing typically ranges from 20 to 50 metres, providing a strong foundation for interpolation.

While data coverage is less dense in parts of the northeastern, southeastern, and southwestern corners, and west-central portion of the study area, where borehole spacing can extend up to a kilometre, the available boreholes still offer valuable control points. In these portions of the study area, the model relies on broader interpolation, which, while less constrained, still provides a useful representation of the subsurface and helps to highlight areas where further investigation could enhance model accuracy.

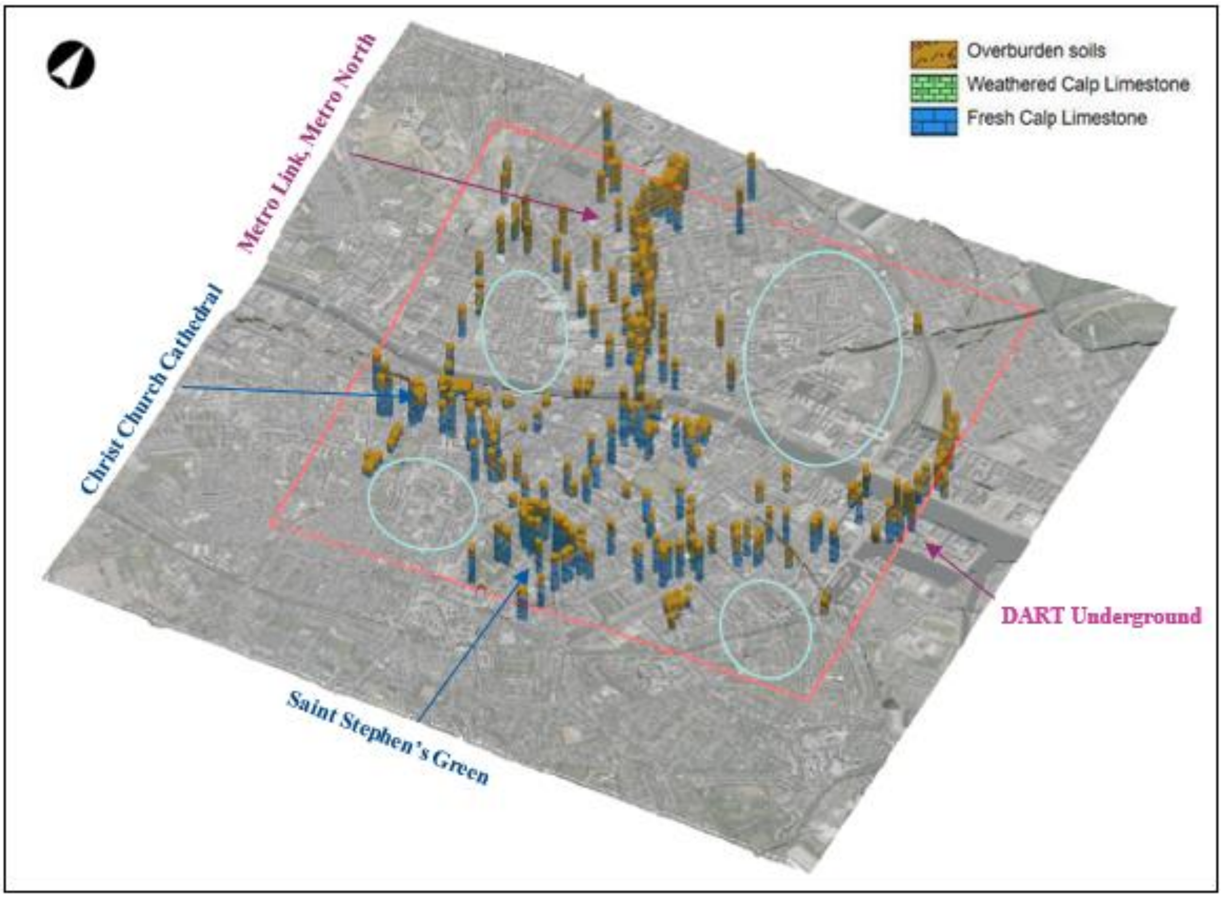


Figure 26 Location of Boreholes Used in the Leapfrog Model, Displayed over Bing Aerial Imagery

Based on the lithological grouping described above, a 3D geological model was generated comprising three distinct layers, as illustrated in **Figure 27**. Leapfrog® geological modelling software was used to create the model, relying on borehole data, specifically, the contact points between different lithological units, to interpolate surfaces between these locations.

The topographic surface defines the model's upper boundary, while a depth of -50 mOD was selected as the lower boundary for presentation purposes only. This elevation level does not represent the actual base of the Calp Limestone formation, as this cannot be determined within the scope of this study.

A 1 km deep borehole drilled by GSI in Grangegorman (TU Dublin)[3] in 2021 encountered the Calp Limestone to a depth of 665 m.

The model covers the entire study area with a spatial resolution of five metres. Lithological boundaries were defined by connecting the contact points between formations identified in borehole logs, generating continuous surfaces. The volumes between two successive surfaces represent the corresponding lithological units.

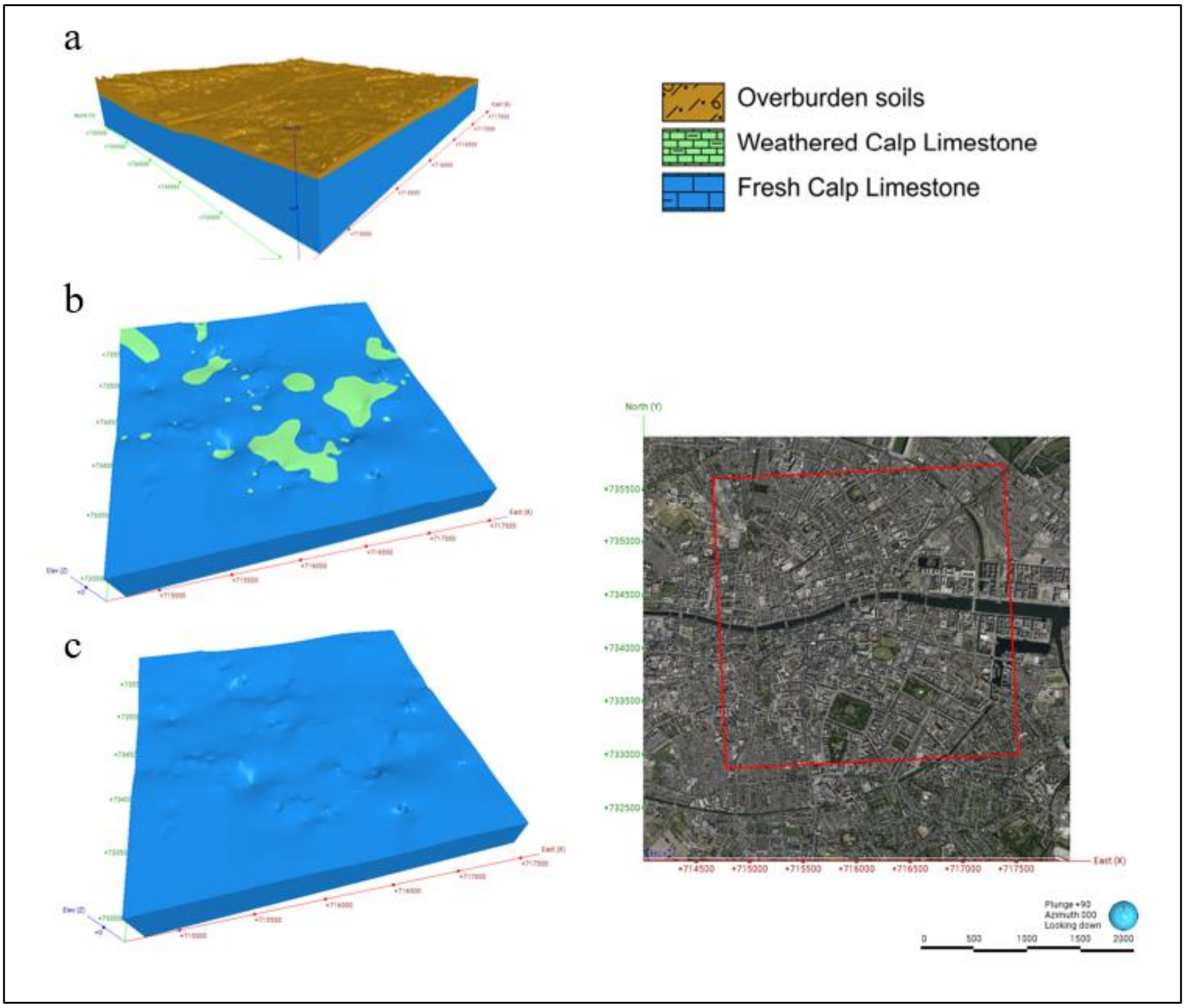


Figure 27 Perspective Projections of the Final Leapfrog Model a) All geological layers visible) Weathered and fresh Calp Limestone only, c) Fresh Calp Limestone only

UCS results were also incorporated into the model, as shown in **Figure 28** below. These results were categorised based on the strength classification ranges defined in accordance with Table 25 of BS 5930:2015). The values represent the raw compressive strength results from the UCS tests, with no correlation factors applied.

[3] Borehole Number/Name: GSI-21-004, Grangegorman (G'Gorman)

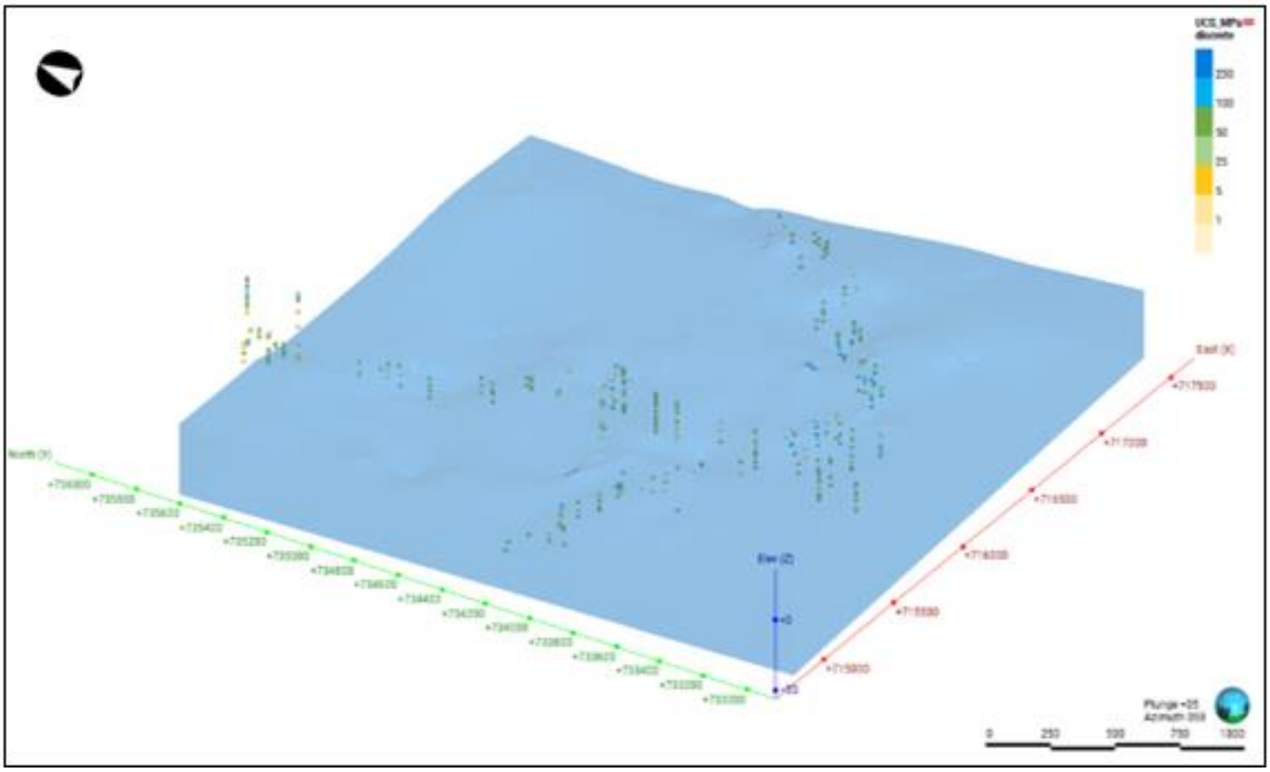


Figure 28 The fresh Calp Limestone layer with the UCS results shown as point information in Leapfrog.

Geological cross sections can be generated from the 3D model. For example, **Figure 29** is a geological cross section through the refined geological model trending northwest-southeast through the centre of the study area. It illustrates the variability in topography and change in lithology across the study area. In turn, **Figure 30** demonstrates a geological cross section through the refined geological model trending east to west through the southern portion of the study area. The thickness of overburden is much more consistent in this location.

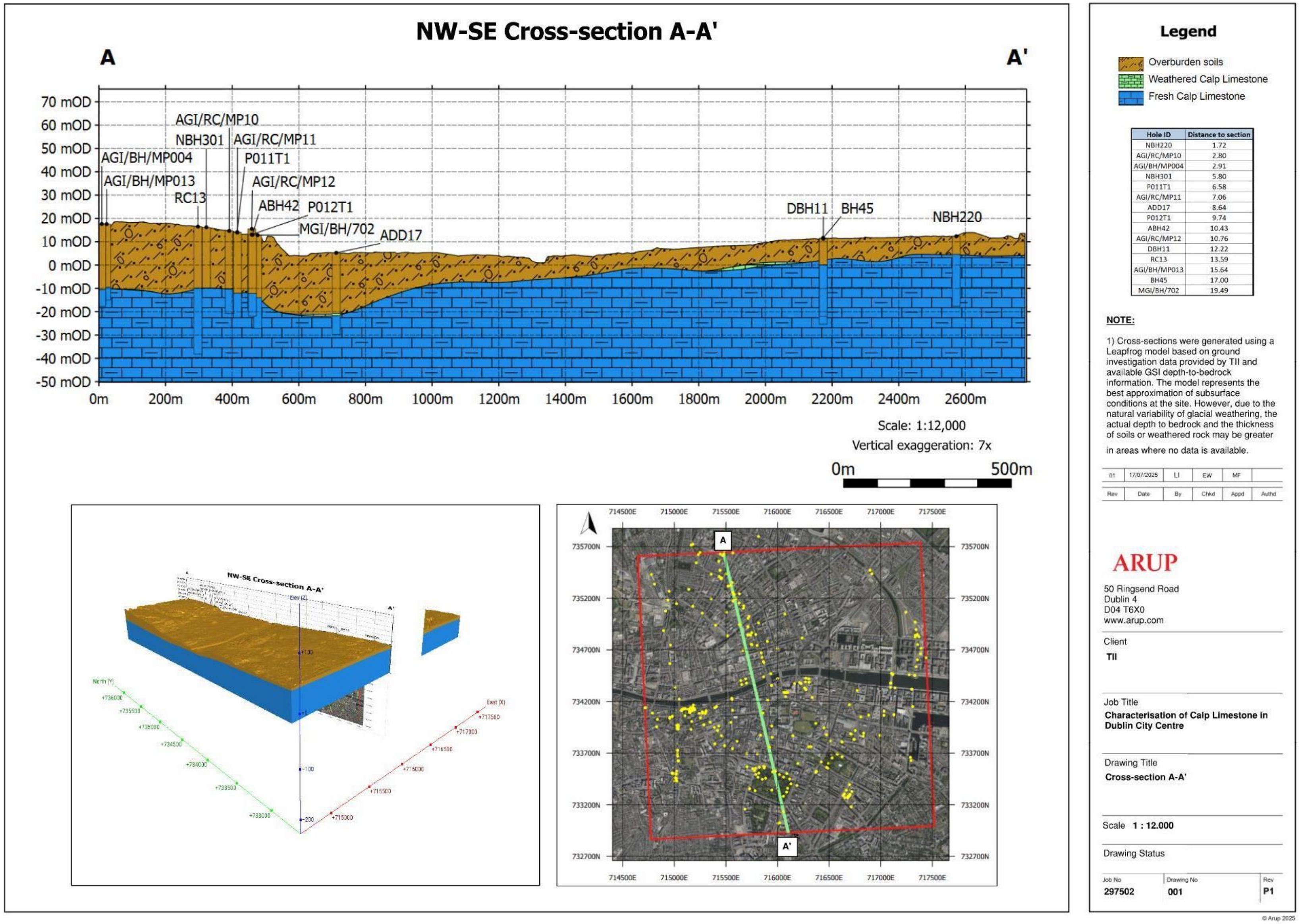
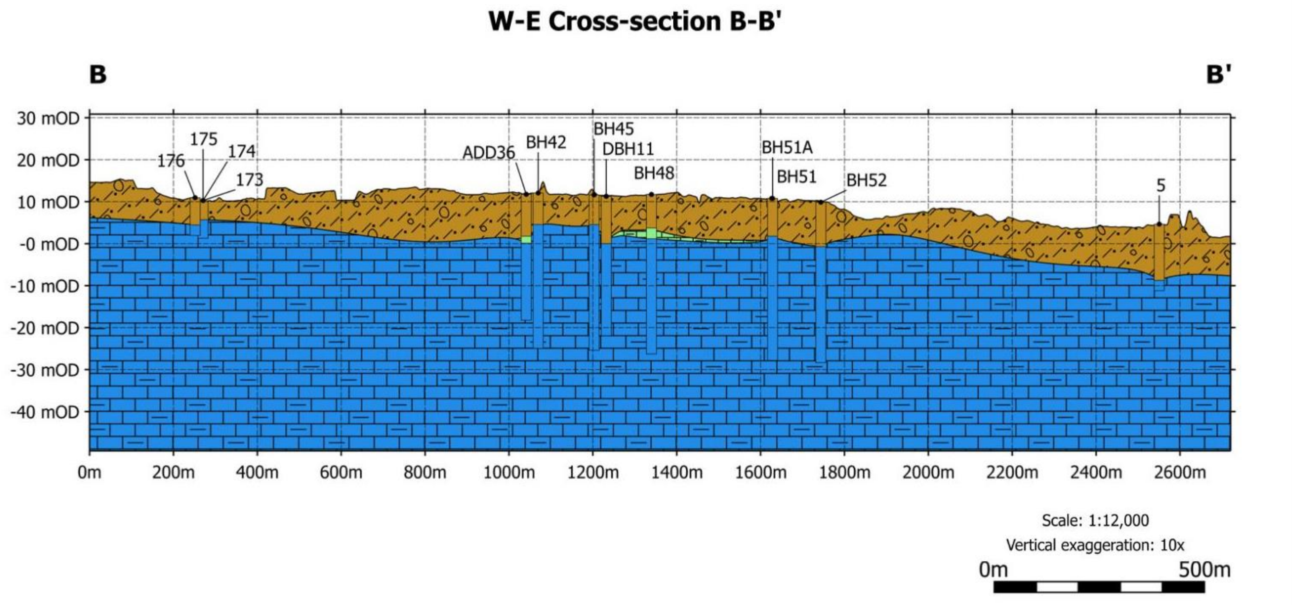
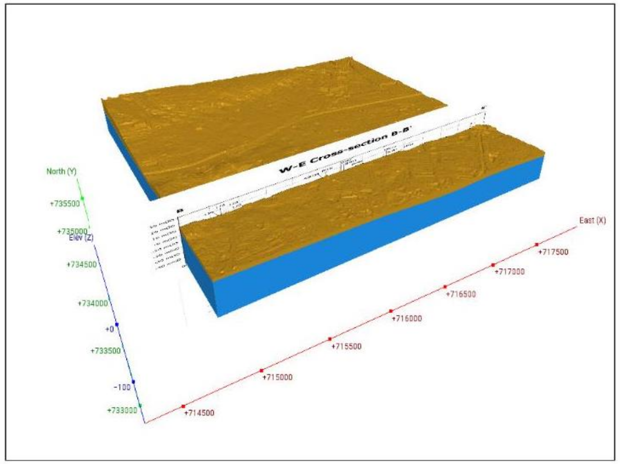
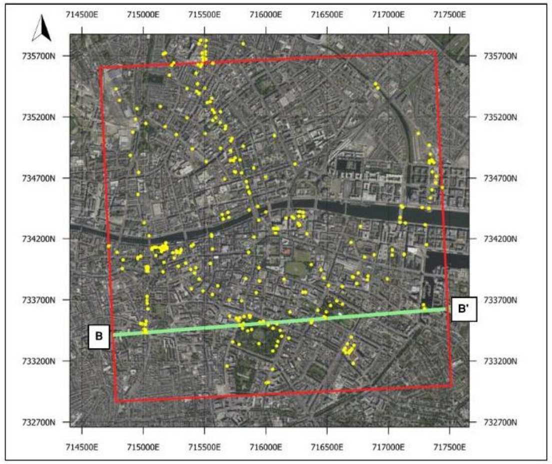


Figure 29 Geological cross section through the refined geological model trending northwest-southeast through the centre of the study area







Legend

Overburden soils
Weathered Calp Limestone
Fresh Calp Limestone

Hole ID	Distance to section
ADD36	0.621389993
BH52	6.013675798
BH42	11.18209238
BH45	13.12737316
BH51A	13.85793041
BH48	14.20685306
BH51	15.94462398
DBH11	17.06166163
173	1.549945061
174	1.549945061
175	1.549945061
176	1.929550193
5	17.19722861

NOTE:

1) Cross-sections were generated using a Leapfrog model based on ground investigation data provided by TII and available GSI depth-to-bedrock information. The model represents the best approximation of subsurface conditions at the site. However, due to the natural variability of glacial weathering, the actual depth to bedrock and the thickness of soils or weathered rock may be greater in areas where no data is available.

01	17/07/2025	LI	EW	MF	
Rev	Date	By	Chkd	Appd	Authd

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Client
TII

Job Title
Characterisation of Calp Limestone in Dublin City Centre

Drawing Title
Cross-section B-B'

Scale **1 : 12.000**

Drawing Status

Job No	Drawing No	Rev
297502	002	P1

Figure 30 Geological cross section through the refined geological model trending east to west through the southern portion of the study area

5.2.2 Heatmaps

Leapfrog® enables the creation of thickness grids such as the depth-to-bedrock (DTB) map shown in **Figure 31** below. This map was produced by combining the surfaces of weathered and fresh bedrock into a unified top-of-rock surface. The DTB values were then calculated by subtracting the elevation of this surface from the digital terrain model, representing the ground surface elevation.

The results reveal pronounced variability in bedrock depth across Dublin City Centre. These variations are likely the result of a combination of glacial erosion on the underlying Calp Limestone and potential structural controls such as faulting and folding. The map offers a higher-resolution alternative to the publicly available GSI depth-to-rock dataset, as shown in **Figure 15**, and aligns well with its broader trends, suggesting good correlation despite differences in resolution and data density.

Figure 31 below clearly shows that the deepest bedrock occurs north of the River Liffey, with depths reaching up to 30 to 35 mBGL, particularly in areas such as Phibsborough and Drumcondra. In contrast, bedrock is generally much shallower south of the River Liffey. Around Trinity College, depths range from 1 to 10 mBGL, while areas near St. Stephen’s Green exhibit depths between 6 and 15 mBGL. Further west, around Christ Church Cathedral, depths again range from approximately 1 to 10 mBGL. This spatial pattern may reflect the influence of glacial scouring in the northern part of the city and a relatively more elevated and resistant bedrock profile to the south.

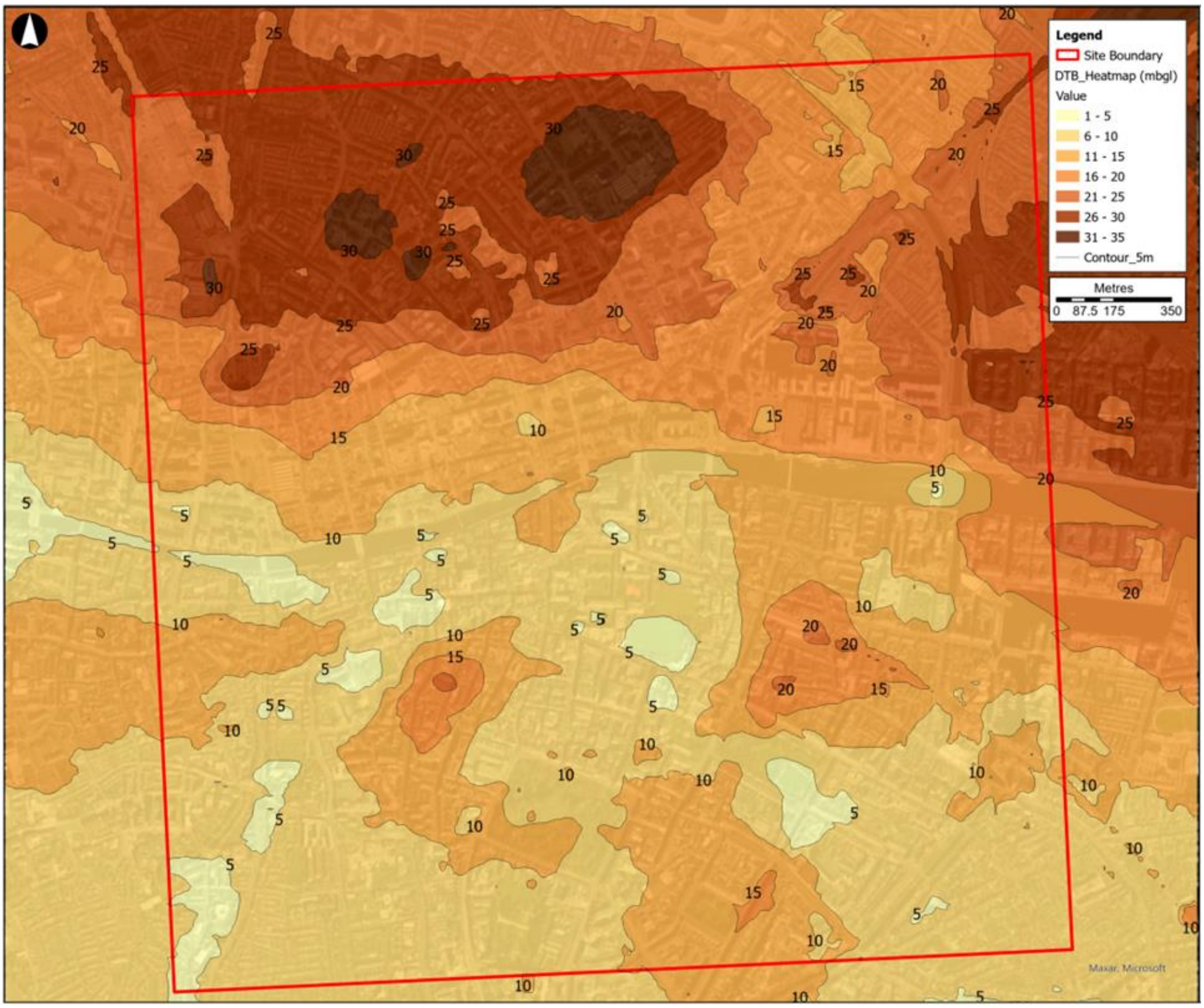


Figure 31 Depth to rock map generated in Leapfrog geological modelling software following an analysis of the stratigraphical logs available as part of this study.

Leapfrog® geological modelling software also allows for the creation of meshes that represent the thickness of specific lithological units, for example, weathered bedrock. The weathered bedrock was encountered in 65 boreholes out of 397 boreholes used for the model and, as illustrated in **Figure 32** below, the modelled thickness of ranges from 0 to 2.1 metres. The distribution appears irregular and does not exhibit a clear spatial trend across the study area. Instead, the weathered bedrock is concentrated in discrete clusters, primarily aligned with the footprints of major linear infrastructure projects. This pattern reflects a spatial bias in the input data, which is densest around proposed linear infrastructure works such as DART Underground, MetroLink, and Metro North. According to the heatmap, the areas where this layer is thickest are around St. Stephen's Green and the zone between Grand Canal Dock and Trinity College Dublin.

Figure 32 Thickness of weathered bedrock generated in Leapfrog geological modelling software.

5.3 Analysis of the Weathered Bedrock Surface

5.3.1 Introduction

The identification and classification of weathered bedrock is critical in understanding the subsurface conditions of the Calp Limestone or the 'top of rock' as it is often described. The impact of glaciation along with the thickness and stiffness of the overlying Quaternary sediments (comprised predominantly of loose rock plucked, transported and redeposited during glaciation) often impacts the determination of the thickness and extents of weathered rock in the study area. This in turn can lead to a misinterpretation of the top of rock during both non-intrusive and intrusive ground investigations as follows:

- Non-intrusive geophysical surveys may not be able to distinguish between the overconsolidated overlying glacial till (Boulder Clay) and weathered Calp Limestone due to similar strength and density properties.

- Ground investigation data originating from various projects and sources may lead to potential variations in drilling methods and the weathered rock descriptions; and
- Given that the overlying formation consists of glacial till (Boulder Clay), it is expected that instances of refusal where core was not recovered during drilling, particularly cable percussive drilling, may have been inaccurately described as encountering the top of bedrock.

Using rotary borehole information from the DART Underground project, a systematic approach was adopted to interrogate and apply a classification system to the weathering profile of the Calp Limestone across 65 boreholes within the study area. This process involved examining core photographs and correlated borehole logs to identify weathered bedrock, without direct access to the cores themselves. The analysis relied on the driller's descriptions, visual assessments of core photographs for signs of weathering, and supporting data such as Rock Quality Designation (RQD), Solid Core Recovery (SCR), and fracture spacing. Despite some limitations, such as incomplete recovery and varying photo quality, this method allowed for a consistent classification of weathered rock in accordance with Figure 9 of BS 5930:2015, as presented in **Figure 21**.

5.3.2 Results

Each of the 65 boreholes from the DART Underground ground investigation was classified using the method described in **Section 4** and the results can be seen in **Table 2** and **Figure 33** below.

Table 2 Distribution of weathering classifications encountered during the DART Underground ground investigation.

Weathering State Based on BS5930	Weathering classification	No. of Boreholes
A	Unweathered	3
B	Partially weathered	41
C	Distinctly weathered	11
D	De-structured	0
E	Residual or Reworked	0
-	Bedrock not encountered	10

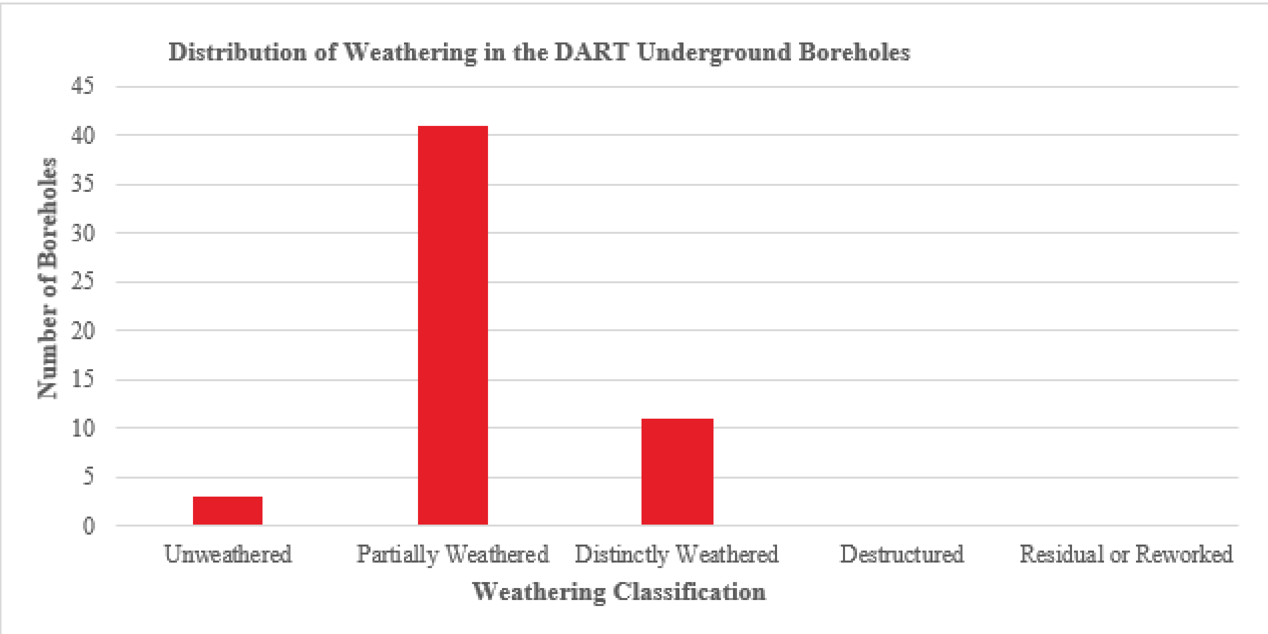


Figure 33 Distribution of Weathering Extent in the DART Underground Cores.

Ten of the 65 boreholes were immediately removed from classification as they did not meet bedrock, and the extent of weathering could not be classified.

From the other 55 boreholes that could be classified, only three were classified as unweathered. The majority of the boreholes, approximately 75%, were identified as partially weathered, with only 11 boreholes described as distinctly weathered. None of the boreholes exhibited signs of de-structured, residual, or reworked bedrock. However, in some cases, descriptions of 'highly weathered rock' were noted with no recovery, for example in BH48 of the DART Underground final factual report. Typical core photographs and associated borehole logs used for this analysis, for example BH49, are presented in **Figure 34** and **Figure 35** respectively.

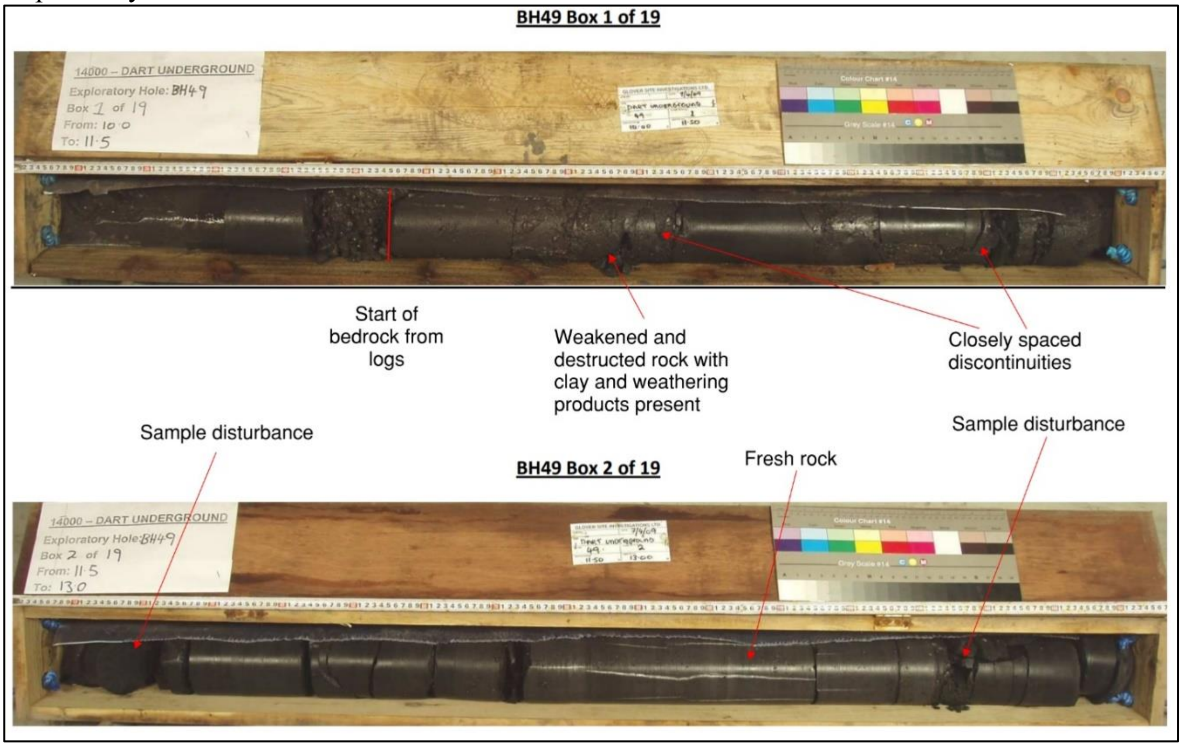


Figure 34 Annotated core photograph from BH49 (DART Underground).

IGSL | **GLOVER SITE INVESTIGATIONS LIMITED**

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 14000

CONTRACT	DART Underground	**DRILLHOLE NO**	**BH49**
		SHEET	Sheet 2 of 4
CO-ORDINATES	316,191.42 E 233,422.88 N	**DATE STARTED**	06/04/2009
GROUND LEVEL (mOD)	11.84	**DATE COMPLETED**	09/04/2009
CLIENT	Iarnród Éireann	**DRILLED BY**	G. Torrens
ENGINEER	Arup Halcrow JV	**LOGGED BY**	R. Noonan

RIG TYPE	Comacchio 450
FLUSH	Polymer Gel
INCLINATION (deg)	-90
ORIENTATION	-
CORE DIAMETER (mm)	102

Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%
10.00–11.50	87	45	33
11.50–13.00	100	94	57
13.00–14.50	100	91	54
14.50–16.00	100	97	83
16.00–17.50	100	100	89
17.50–19.00	100	95	52
19.00–	100	93	63

Fracture Zones (m)	Fracture Spacing Min / Avg / Max (mm)
10.48–12.65	NI / 103 / 410
12.65–13.66	NI / 45 / 140
13.66–17.45	NI / 113 / 600
17.45–18.37	30 / 66 / 140

Description	Depth (m)	Elevation (mOD)
Black sandy gravelly clay. No recovery, driller's description. *(continuation)*	10.48	1.36
Strong to very strong, thinly to medium bedded, black, fine grained ARGILLACEOUS LIMESTONE, fresh to slightly weathered. Sub-unit 1 - Strong to very strong, thickly to thinly bedded, pale grey, fine-grained, sandy LIMESTONE, fresh to slightly weathered. Sub-unit 2 - Moderately strong to weak, thinly laminated to thinly bedded, black, MUDSTONE/SHALE, slightly to moderately weathered. Discontinuity Set 1: medium to locally very closely spaced, sub horizontal, planar, smooth to rough, open, clean to locally clay smeared, locally stained brown Discontinuity Set 2: medium to widely spaced, sub vertical, planar, smooth to rough, open, clean, locally calcite lined <1mm infill.	12.08	-0.24
Sub Unit 1 - sandy Limestone - see main description 12.11-12.64m - 4 no. Sub vertical calcite veins 1-5mm thick	12.65	-0.81
ARGILLACEOUS LIMESTONE - see main description 12.65-12.71m - Sub Unit 2 - Mudstone /Shale 13.52-13.94m - Sub Unit 1 - sandy Limestone 13.66-13.68m - Sub Unit 2 - Mudstone /Shale 13.94-13.95m - pyrite band 10mm thick 14.9-15.42m - 1 no. Sub vertical calcite vein 10-15mm thick	14.95	-3.11
Sub Unit 1 - sandy Limestone - see main description	15.48	-3.64
ARGILLACEOUS LIMESTONE - see main description 16.42m - pyrite band 2mm thick 19.66m - pyrite on fracture surface		

REMARKS

Inspection Pit Dug to 1.20m. For detailed discontinuity information see discontinuity sheet. Borehole grouted upon completion.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
					No water strike

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments
07-04-09	19.00	19.00	not recorded	End of shift
08-04-09	19.00	19.00	8.50	Start of shift

INSTALLATION DETAILS

Date	SP Depth	RZ Top	RZ Base	Type
14-04-09	**38.20**	**19.00**	**38.00**	**50mm SP**

DART UNDERGROUND RC 14000 RC.GPJ IGSL.GDT 8/10/09

Figure 35 Geotechnical logs from BH49 (DART Underground).

Discrepancies were noted in a number of factual borehole logs when the stratigraphic log was compared to the core photographs, as shown above in **Figure 34** and **Figure 35**. For example, at BH49 of the DART Underground project, interpretation of the core photographs performed during this study concluded that the upper portions of the bedrock were distinctly weathered due to the destruction of rock with weathering products and clay present, and closely spaced discontinuities, as shown in **Figure 34**. Weathered bedrock was not described within the factual borehole log, with the rock only described as 'fresh to slightly weathered'. It is this general and vague description of the bedrock in the borehole log which made the further classification of weathered bedrock identified during this study more valuable.

5.3.3 Conclusions

The classification of the weathering state of the rock encountered in the boreholes of the DART Underground drilling programme underscores the prevalent weathering across the study area. There is a discrepancy between the rock described in the borehole logs and the rock that has now been classed as weathered bedrock according to the criteria outlined in **Figure 21**. This highlights the importance of undertaking a detailed assessment of the weathering profile in the recovered core to ensure the accuracy of a project ground model.

Despite the challenges encountered, this method proved effective in providing a clear understanding of the weathering states of the bedrock across the study area. It is possible that no weathered rock was classified as de-structured/ residual or reworked due to the difficulties in recovery of cobbles and highly weakened rock as a result of the drilling method. However, in the boreholes where the overburden was recovered, cobbles were often seen in the glacial till (Boulder Clay) which were not related to the weathered bedrock.

This approach also allowed for identification of cores with possible evidence of faulting or deep weathering so they can be pulled from storage and examined in greater detail if required.

6. Rock mass assessment

6.1 Introduction

The assessment of rock mass conditions is a fundamental aspect of geotechnical investigations, providing critical insights into the structural integrity and engineering properties of subsurface materials. This section presents an overview of the methodologies and findings related to the evaluation of rock mass quality within the project study area.

Rock mass behaviour is dependent on the density, nature and extent of the discontinuities within the rock mass along with the intact rock strength, mineralogy and lithology, weathering and groundwater conditions (and any historical manmade interventions etc). The properties of intact rock and discontinuities are typically upscaled and combined to predict the engineering behaviour of a rock mass as a whole.

By integrating detailed logging, core photography, and advanced classification techniques, the study seeks to enhance the understanding of weathering processes and their implications for ground behaviour, thereby supporting the development of a robust 3D ground model for future engineering works.

This section details the rock mass assessment undertaken as part of this project. Firstly, **Section 6.2** outlines the intact rock testing results from the Metro North, DART Underground and MetroLink ground investigations that were examined as part of this study. Secondly, **Section 6.3** provides an overview of the methodologies and findings related to the assessment of rock mass conditions within the project study area, focusing on the factors influencing rock mass behaviour. Finally, **Section 6.4** provides an overview of the methodologies and findings related to the evaluation of rock mass quality, emphasizing the integration of detailed logging, core photography, and advanced classification techniques to enhance the understanding of rock mass behaviour and support the development of a robust 3D ground model for engineering purposes.

6.2 Intact Rock Testing

6.2.1 Uniaxial Compressive Strength (UCS)

A total of 382 tests were conducted within the site boundary, enabling the identification of characteristic compressive strength values that can serve as a reference for any planning phase of a project involving Calp Limestone. The potential risks to the reliability of these values arise from the presence of outliers in the dataset. However, the analysis aims to minimise the impact of these outliers by employing both statistical and scientific methods.

6.2.1.1 Limitations and mitigation:

A number of limitations and associated mitigation measures were considered for this project:

- Very high values of UCS (e.g., locally massive, very thickly bedded, fresh, extremely strong limestone) or very low values of UCS (e.g., locally distinctly weathered with mineralisation alteration of limestone) have minimal impact on such a large dataset. Additionally, values found to be overestimating or underestimating the compressive strength were filtered out through statistical analysis.
- Different lithologies yield different ranges of compressive strength; therefore, the lithology was split between limestone and mudstone.
- A lack of accurate descriptions in AGS or reports for the lithology of a small number of samples tested was noted. Where lithology was not described, the compressive strength value was assigned to the lithology that best fit the observed value. Additionally, in certain projects, the lithology was obvious due to clear testing aims. For example, in the DART Underground and MetroLink projects, mudstone was not tested for UCS, possibly due to the difficulty in preparing adequate core samples, given the very thin bedding and weak nature of the material.
- Conducting a UCS test is straightforward if standards are followed, leaving little room for doubt, especially compared to tests like the point load test, where the loading axis relative to the discontinuity orientation was rarely properly described. However, even in UCS testing, the discontinuity orientation in relation to the axial loading was not described. This means that if these two were parallel or perpendicular, outliers could be incorporated into the dataset. Nonetheless, the proposed characteristic value within a range of compressive strength limits the risk of considerable errors.
- Other factors like human-induced errors, such as incorrect core dimensions, improper saturation levels, or sample disturbance, cannot always be directly known or mitigated against. The Contractor is responsible for the correct execution of the testing by experienced professionals, limiting the risk of this type of error being induced in the dataset.

The proposed ranges are only indicative of the lithologies and should not be used for detailed design but for reasonable estimation of the intact rock compressive strength in preliminary phases.

6.2.1.2 Results

Before Lithological Separation:

The UCS testing results indicate a widespread scatter across the three projects analysed, as shown in **Figure 36** and **Figure 37** below. It is typical for the compressive strength of sedimentary rocks to increase with depth. However, based on the findings of the three projects analysed, compressive strength does not increase with depth. A large range of compressive strength values are recorded across all depths within the stratigraphic profile of the projects analysed. Widespread scatter across the results may have stemmed from the sample selection process during each of the projects analysed, as well as poor stratigraphic logging, weathering, and fault zones, as discussed further below. A trendline along this data had a very low R^2 achieved and so was considered statistically irrelevant and removed.

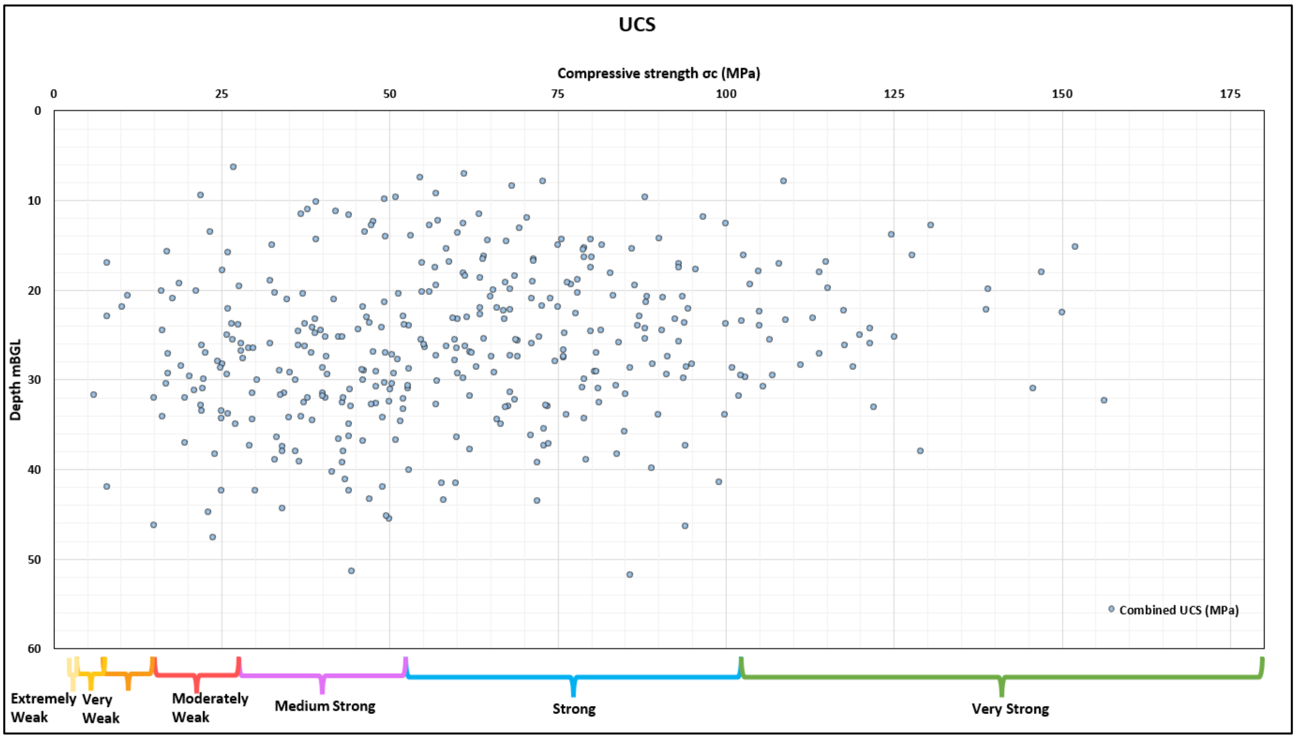


Figure 36 UCS Compressive strength over depth (mBGL).

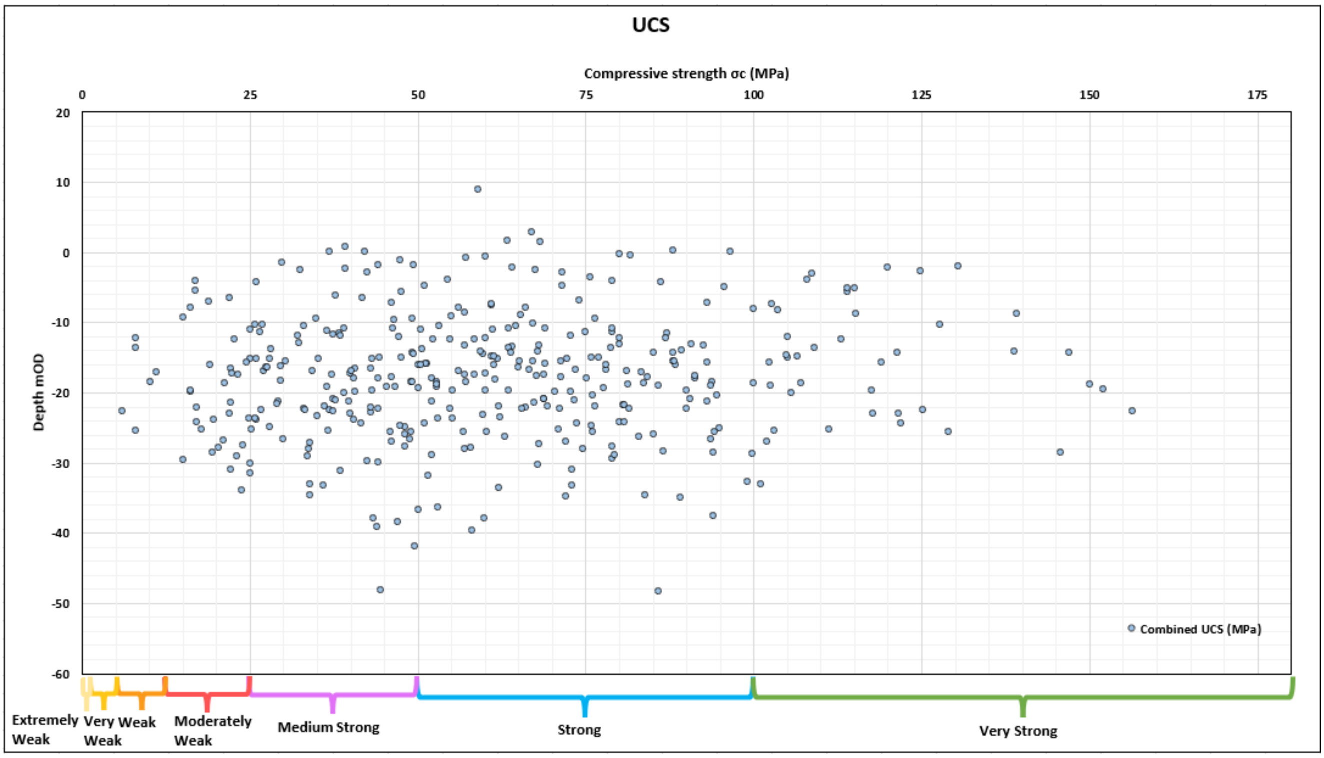


Figure 37 UCS Compressive strength over depth (mOD).

A large proportion of rock core samples tested (49%) have compressive strengths ranging from 50 to 100 MPa, corresponding to the "Strong" category in accordance with Table 5 of BS EN ISO 14689-1:2003, as seen in **Figure 38**. Additionally, 29% of the samples fall within the 25 to 50 MPa range, classifying them as "Medium Strong." Another 11% of the samples exhibit compressive strengths between 100 and 250 MPa, placing them in the "Very Strong" category. Finally, 11% of the samples have compressive strengths ranging from 5 to 25 MPa. Notably, no samples were recorded with compressive strengths below 5 MPa.

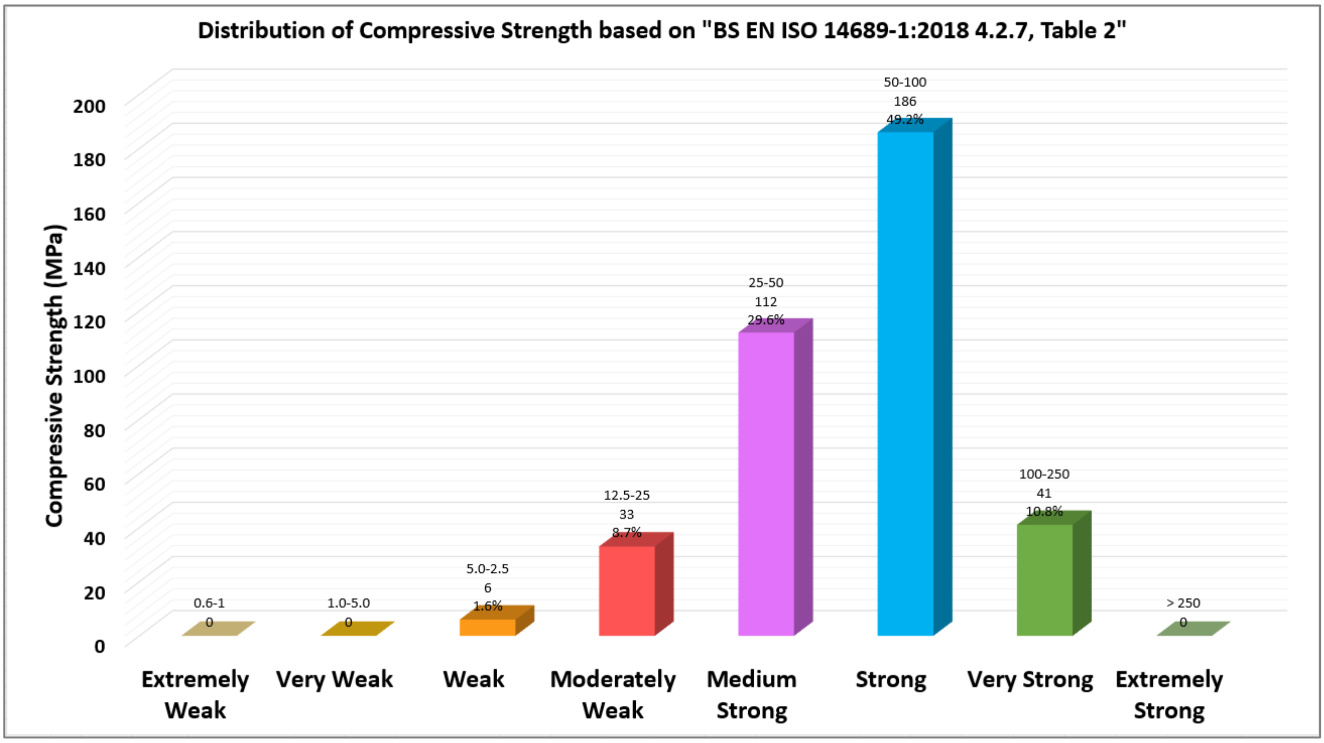


Figure 38 Distribution of UCS values.

<u>After Lithological Separation:</u>

Figure 39 shows the UCS compressive strength over depth (mBGL) after lithological separation.

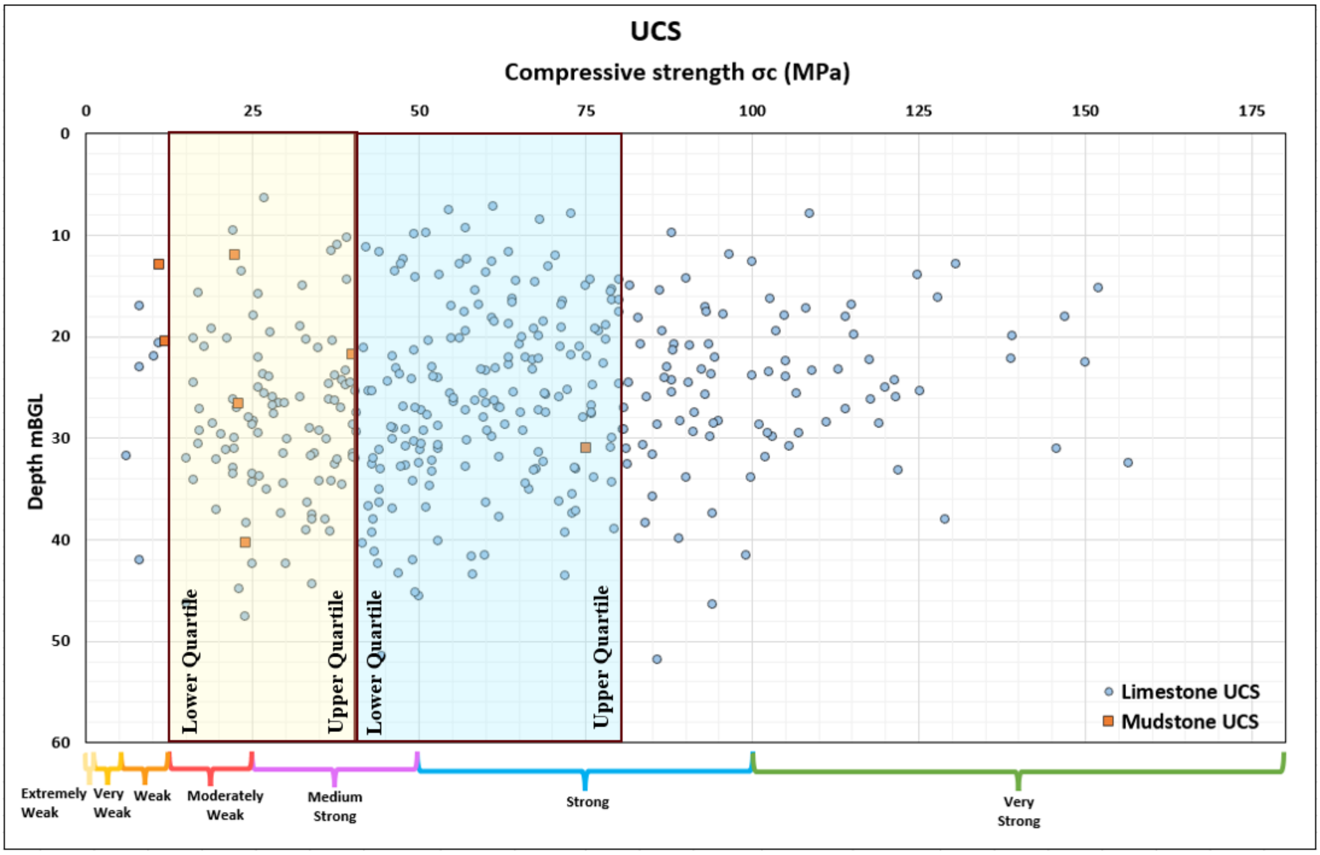
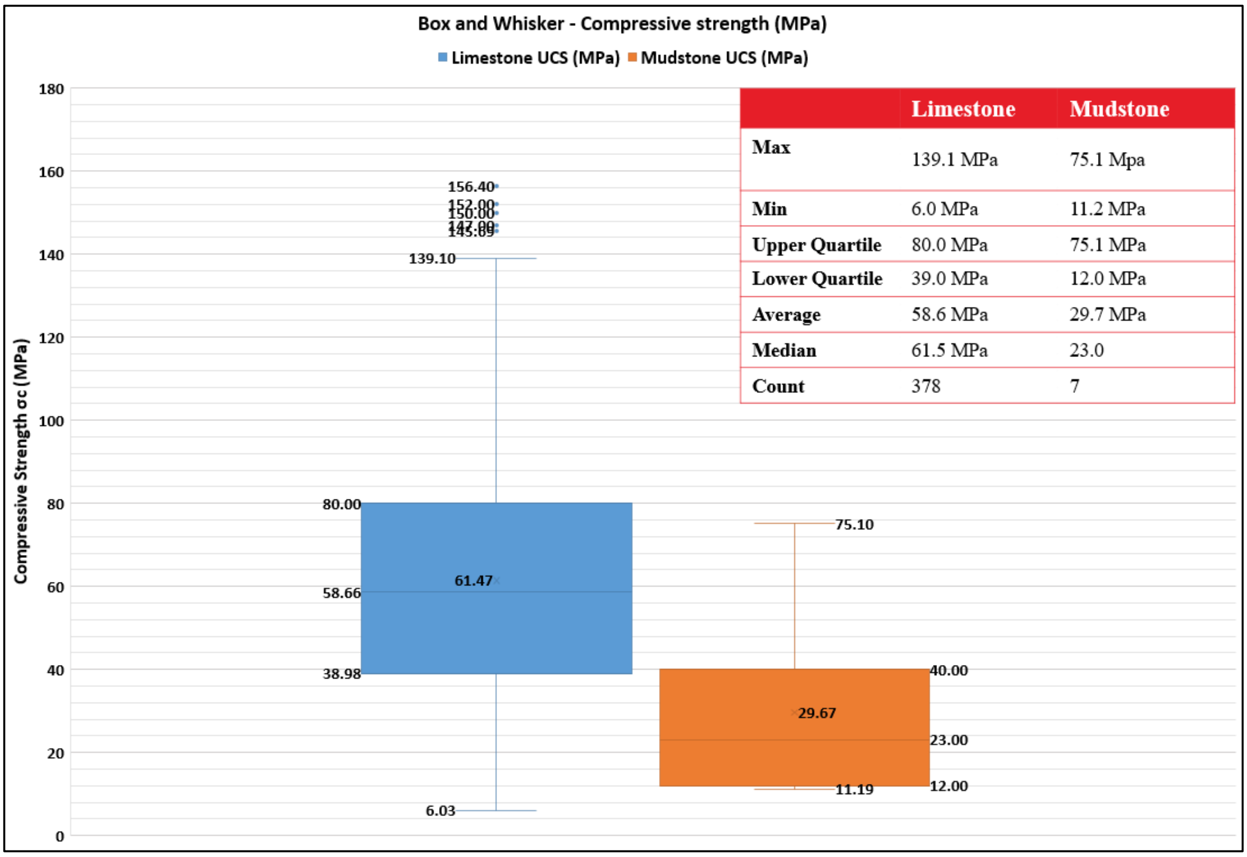


Figure 39 UCS compressive strength over depth (mBGL) after lithological separation.

There is very limited data available for the mudstone, with only 7 UCS tests conducted on mudstone samples compared to 378 for limestone as shown on **Figure 40** along with a summary of the UCS range. While defining the lithology of the sample log descriptions, AGS descriptions and rock core photographs have been employed.

However, due to inconsistency and subjectivity of the descriptions along the three projects, the presence of outliers in the two populations is evident in the datasets; inducing the risk of the mudstone being logged incorrectly as limestone; especially in instances with low compressive strength (σ_c).

Near the surface, this material may resemble black Boulder Clay in texture and mechanical properties, as observed during the site visit to Harcourt Square, making sample preparation extremely challenging. However, during our visit to Belgard, as discussed in **Section 7.1.5** below, the mudstone observed at greater depths appeared stronger and potentially suitable for obtaining adequate UCS samples.



	Limestone	Mudstone
Max	139.1 MPa	75.1 Mpa
Min	6.0 MPa	11.2 MPa
Upper Quartile	80.0 MPa	75.1 MPa
Lower Quartile	39.0 MPa	12.0 MPa
Average	58.6 MPa	29.7 MPa
Median	61.5 MPa	23.0
Count	378	7

Figure 40 Box and Whisker – UCS ranges for each lithology.

A better understanding of the mudstone members in the formation is essential, as they are expected to play a critical role in controlling failure, particularly in areas where mudstone is predominant and rock-to-rock contact between limestone blocks may be limited. Currently, the mudstone is much less understood compared to the limestone. If UCS testing of the mudstone layers proves difficult, point load tests should be considered. However, determining a reliable correlation factor for the mudstone is nearly impossible given that only seven tests have been conducted within the study area.

6.2.1.3 Conclusion

A large scatter in UCS results has been observed across the three projects analysed. The compressive strength of sedimentary rocks typically increases with depth due to the greater confining pressure from the overlying material. However, such a trend has not been observed in the project dataset. Also, it has been noted that a wide range of compressive strength values were recorded across all depths within the stratigraphic profile. It is believed that due to the complex geological setting in Dublin City Centre and the heterogeneous nature of the Calp Limestone, the compressive strength is influenced by several complex factors, including:

- Presence of mudstone members:
  - Mudstone potentially creates zones of lower strength, as have been verified from the UCS dataset. A representative intact rock compressive strength range of the mudstone is between 12 to 40 MPa comparing to the 36 to 80 MPa range for limestone. Therefore, when using intact rock as a parameter in rock mass assessments, it is important to account for the varying strengths of different rock types.

Evaluating rock mass strength should consider the proportions of these lithologies using a weighted average (Marinos and Hoek, 2001).

- Weathering:
  - Weathering has significant impact on both physical and chemical properties of the rock; altering structure and the composition of the rock, which leads to lower strengths. The profile of the weathered bedrock has been assessed in this study. Where weathered bedrock is identified, the compressive strengths of the formations are expected to be significantly lower.
- Fault zones:
  - Possible presence of fractures creating anisotropy and mechanically degrading the rock.
- The orientation of loading in relation to the orientation of discontinuities:
  - When loading is applied parallel to the formation's discontinuities, it results in significantly lower values compared to loading perpendicular to the discontinuities.

6.2.2 Point Load Test

A total of 2,287 point load tests were conducted within the site boundary, allowing for the identification of characteristic Is_{50} values. Of these, 1,544 tests were performed on limestone samples, 544 on mudstone samples. The remaining 199 tests were conducted on discontinuities or calcite veins and were excluded from this analysis.

The point load test is a cost-effective alternative to UCS testing, especially for mudstone samples that are difficult to obtain. However, it is crucial to accurately record the testing procedure, particularly the orientation of the loading relative to the discontinuities, and data correction to Is_{50} values. This was not always the case for the data received.

The primary goal of this analysis is to determine whether distinct populations for mudstone and limestone can be identified and to generate sufficient data to derive a reliable correlation factor between the point load test and UCS.

6.2.2.1 Results

All Projects

<u>Before Lithological Separation:</u>

When all 2,088 point load results for mudstone and limestone are plotted together, no discernible trend with depth, whether measured in metres Ordnance Datum (mOD) or metres below ground level (mBGL), can be identified, as shown in **Figure 41** and **Figure 42**. Similar to the UCS test results, as discussed in **Section 6.2.1.2**, widespread scatter was recorded in point load test results across the three projects analysed. A trendline along this data had a very low R^2 achieved and so, was considered statistically irrelevant and removed.

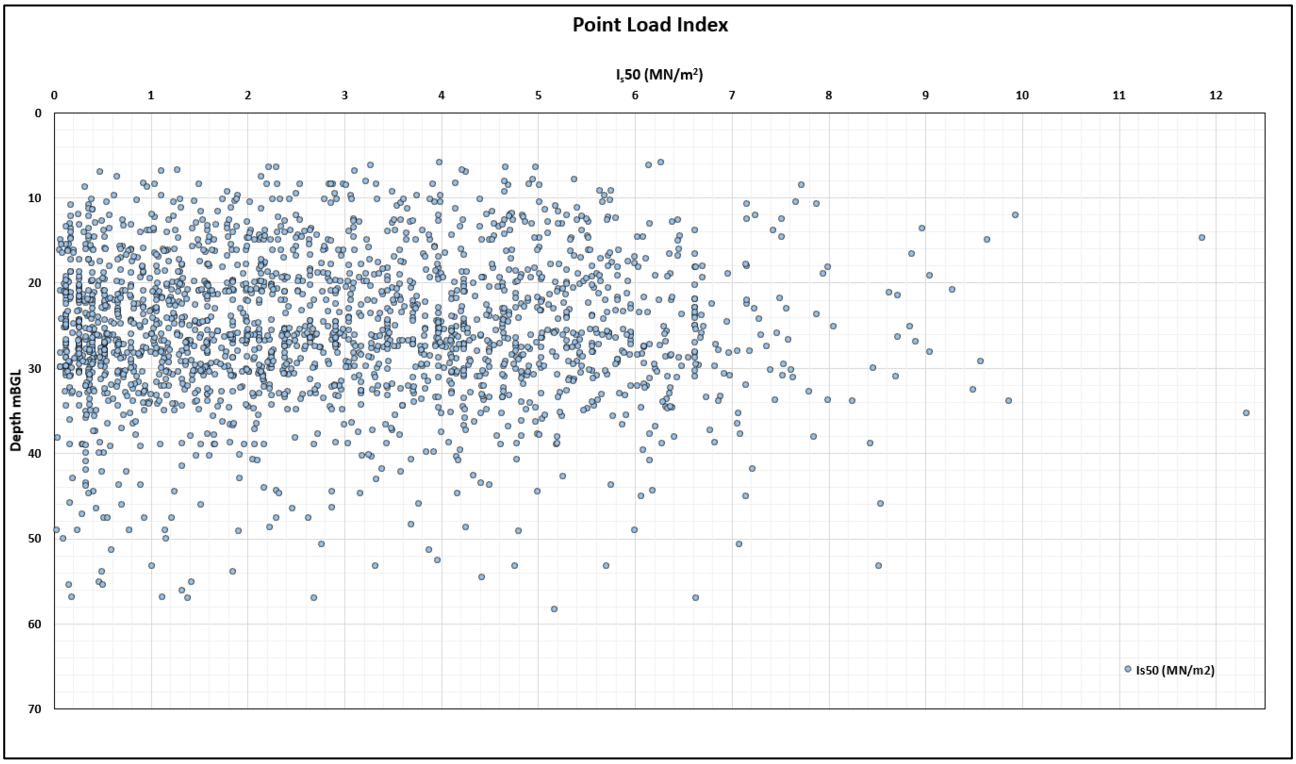


Figure 41 Corrected point load test index over depth (mBGL).

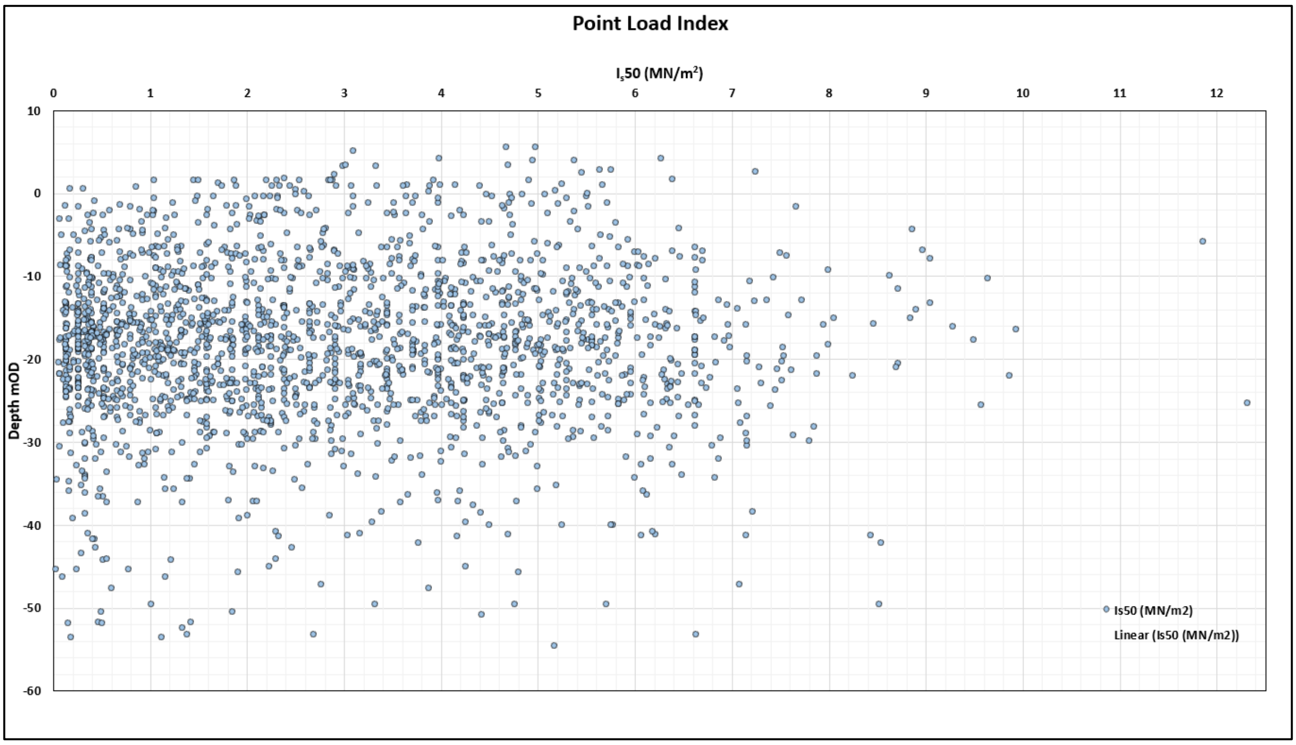


Figure 42 Corrected point load test index over depth (mOD).

When all the test results are plotted by test type, it is apparent that the axial tests yield the highest Is_{50} values, while all other types produce similar ranges of Is_{50}, as shown in **Figure 43** below.

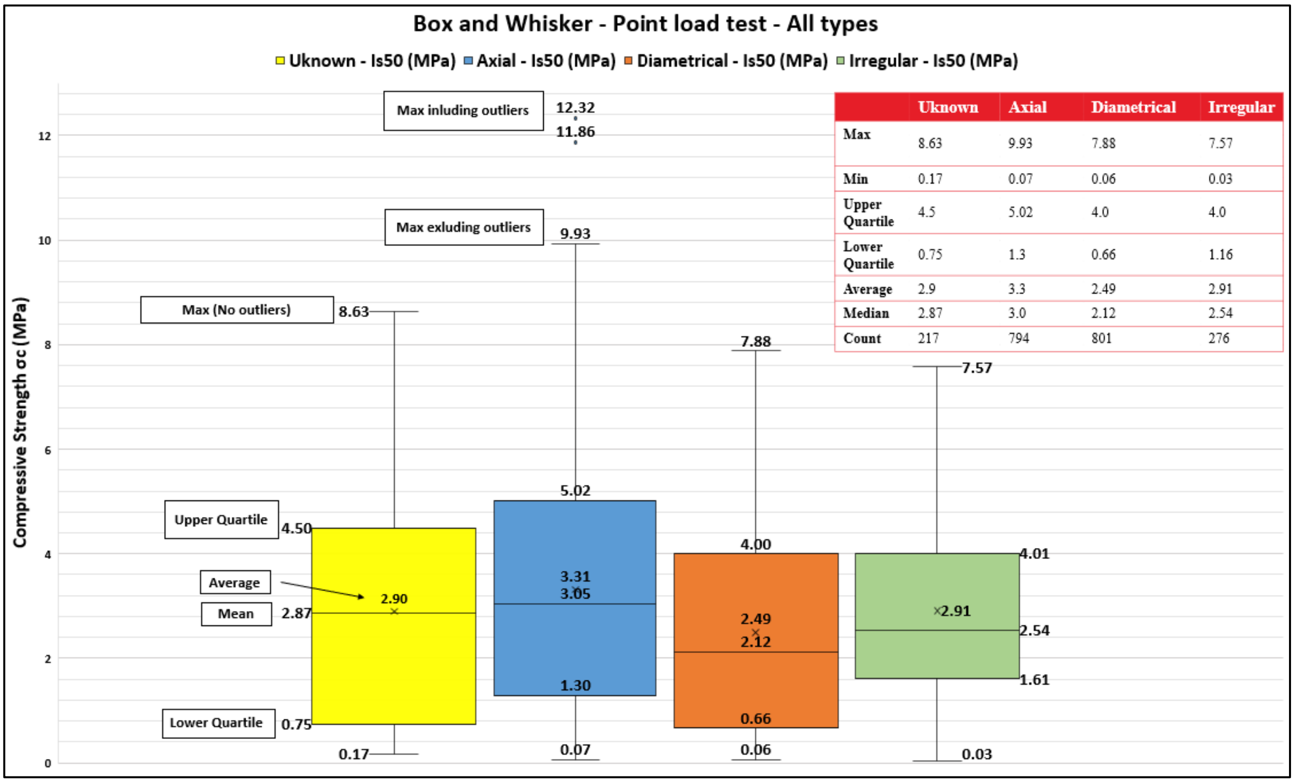


Figure 43 Corrected point load test index for each test type.

<u>After Lithological Separation:</u>

When lithologies are separated, it is apparent that there are two different populations of results, with the highest corresponding to limestone and lower values to the mudstone, as shown in **Figure 44** and **Figure 45**.

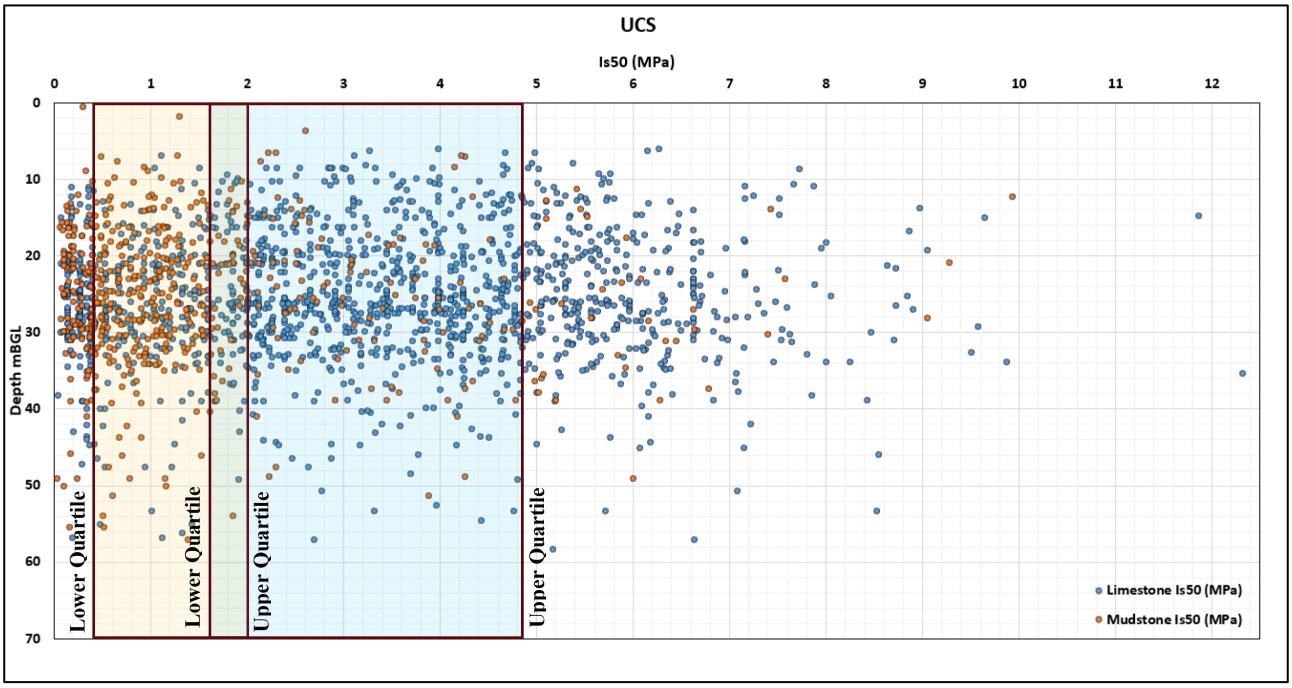


Figure 44 Corrected point load test index over depth (mBGL) for each lithology.

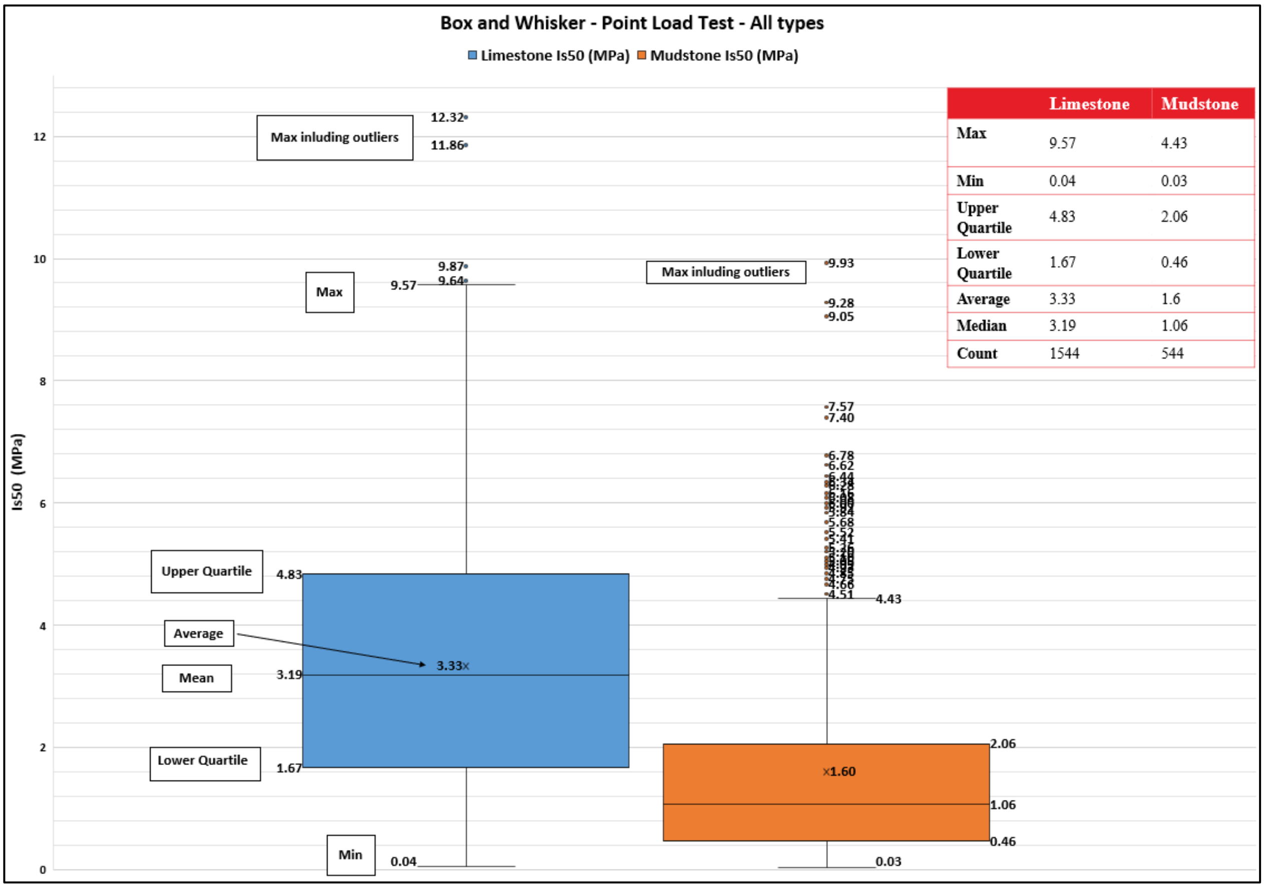


Figure 45 Box and Whisker – corrected point load test index for each lithology.

6.2.3 Correlation Factor

The three analysed projects included a total combined dataset of 382 UCS tests and 2,088 PLTs. The combined dataset was used to assess the presence of any correlation between the UCS and PLT testing for both limestone and mudstone. From this extensive dataset, 214 UCS tests were selected for correlation with point load tests conducted at similar depths in the same boreholes. Among these 214 PLTs, 77 were axial, 63 were diametrical, 21 were irregular, and 53 were of unknown type.

However, following the analysis of correlation between UCS and point load testing, it was not possible to discern a correlation factor between the two tests. Despite identifying 214 pairs of testing results, the correlation analysis demonstrated a large, widespread scatter of correlation factors. Therefore, it is not possible to identify a single correlation factor for UCS testing to the various types of point load testing conducted during the three analysed projects. This analysis indicates that previously published values must be treated with caution, particularly across a large project or over a wide spatial extent. It may be possible to identify more accurate correlation factors at a smaller, localised scale.

Limitations:

There are not enough UCS data for mudstone in order to derive a correlation factor. Therefore, it is challenging to derive either intact or rock mass strength without being able to correlate Is_{50} to a compressive strength for the mudstone material.

The orientation of discontinuities relative to the loading axis was rarely well-documented in the three analysed projects. However, considering the literature and the up-to-date findings on the structure of the Calp Limestone, bedding is the most consistent discontinuity and is likely to be intersected by a vertical borehole due to its sub horizontal dip. It is reasonable to assume that most axial point load tests were conducted perpendicular to the discontinuities, while most diametrical tests were parallel to them.

In some projects, point load tests were scheduled instead of UCS tests rather than alongside them, making it difficult to find comparable values from the same boreholes at similar depths, resulting in fewer available points for correlation analysis.

6.2.4

6.2.4 Young's Modulus

Strain was recorded and documented in only 18 UCS tests, with four from DART Underground and 14 from MetroLink. When plotting Young's modulus (E) against compressive strength, a clear and direct correlation between these values is observed (**Figure 46**). The R^2 value of approximately 0.8 indicates a statistically strong correlation, especially for samples with low values.

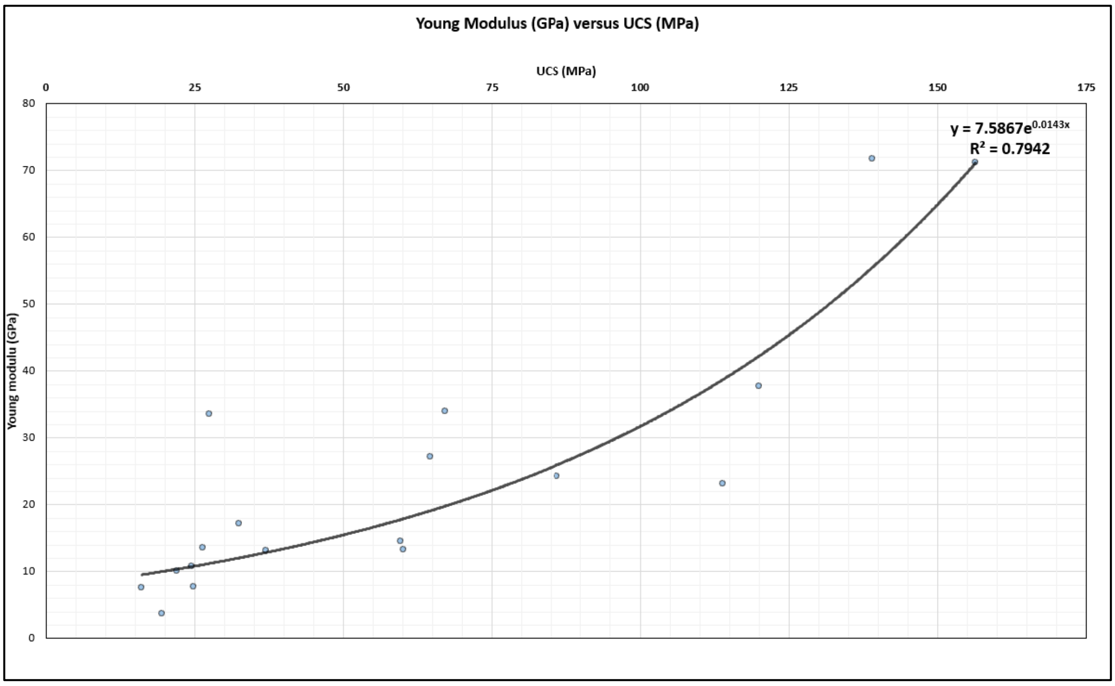


Figure 46 Empirical graph of Young Modulus for the Limestone member of the formation.

Additionally, Waltham (2009) refers to Young's Modulus as E = x * UCS (where x is around 300 for most rocks; >500 for some strong, stiff limestones; <100 for deformable rocks, clays, some shales). As such there will be a considerable difference between the limestone and mudstone layers.

6.2.5 Tensile Strength

A total of 43 tensile strength tests were conducted across all boreholes within the study area, including 25 tests for DART Underground and 18 for MetroLink, as shown in **Figure 47** and **Figure 48**. Due to the limited amount of testing that was carried out this is just a sample of the tensile strength of Calp Limestone, and it is not expected to be representative of the study area. Additionally, no mudstone samples were tested for tensile strength, and as such, the dataset includes only limestone entries. A trendline along this data had a very low R^2 achieved and so was considered statistically irrelevant and removed.

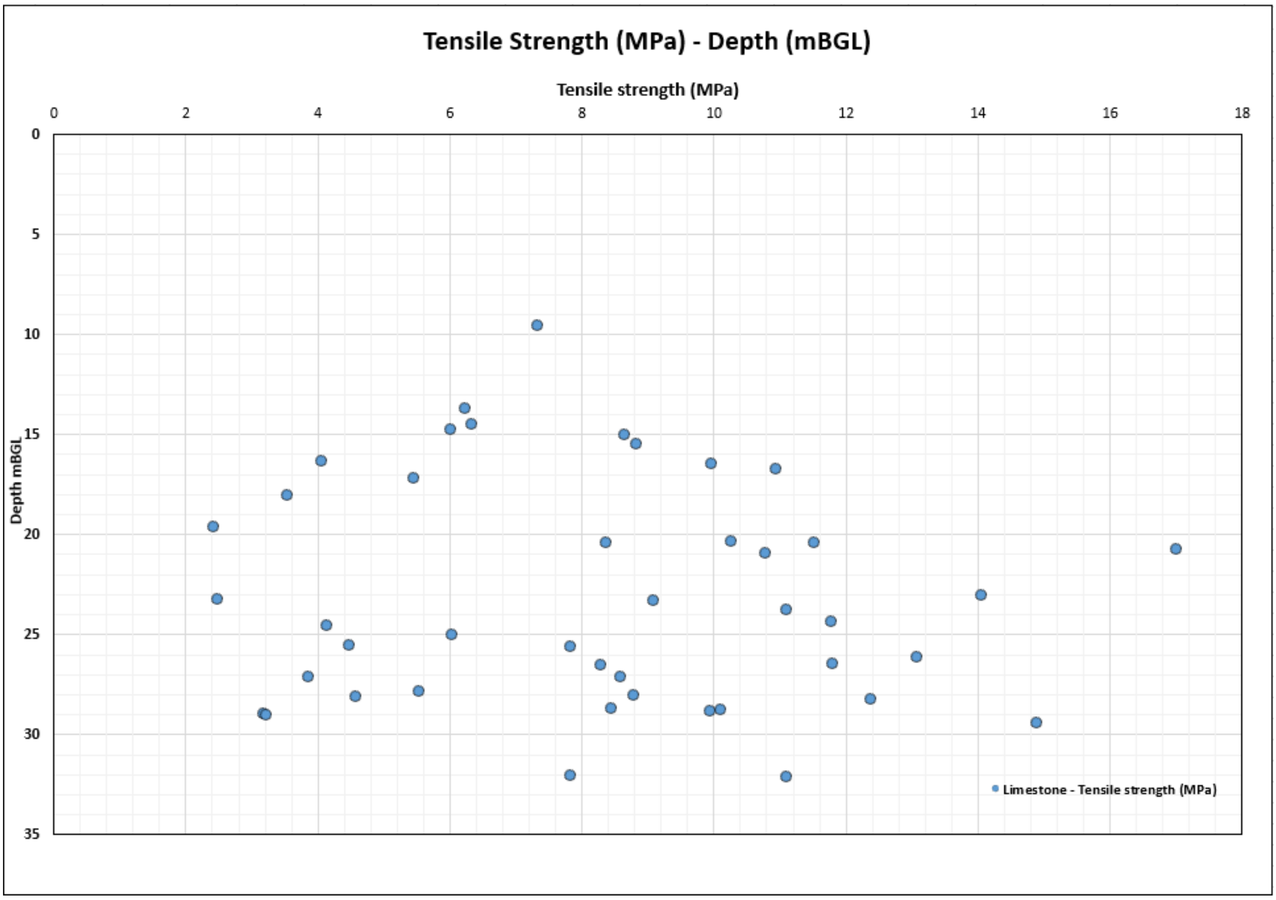


Figure 47 Tensile strength, in MPa, over depth (mBGL).

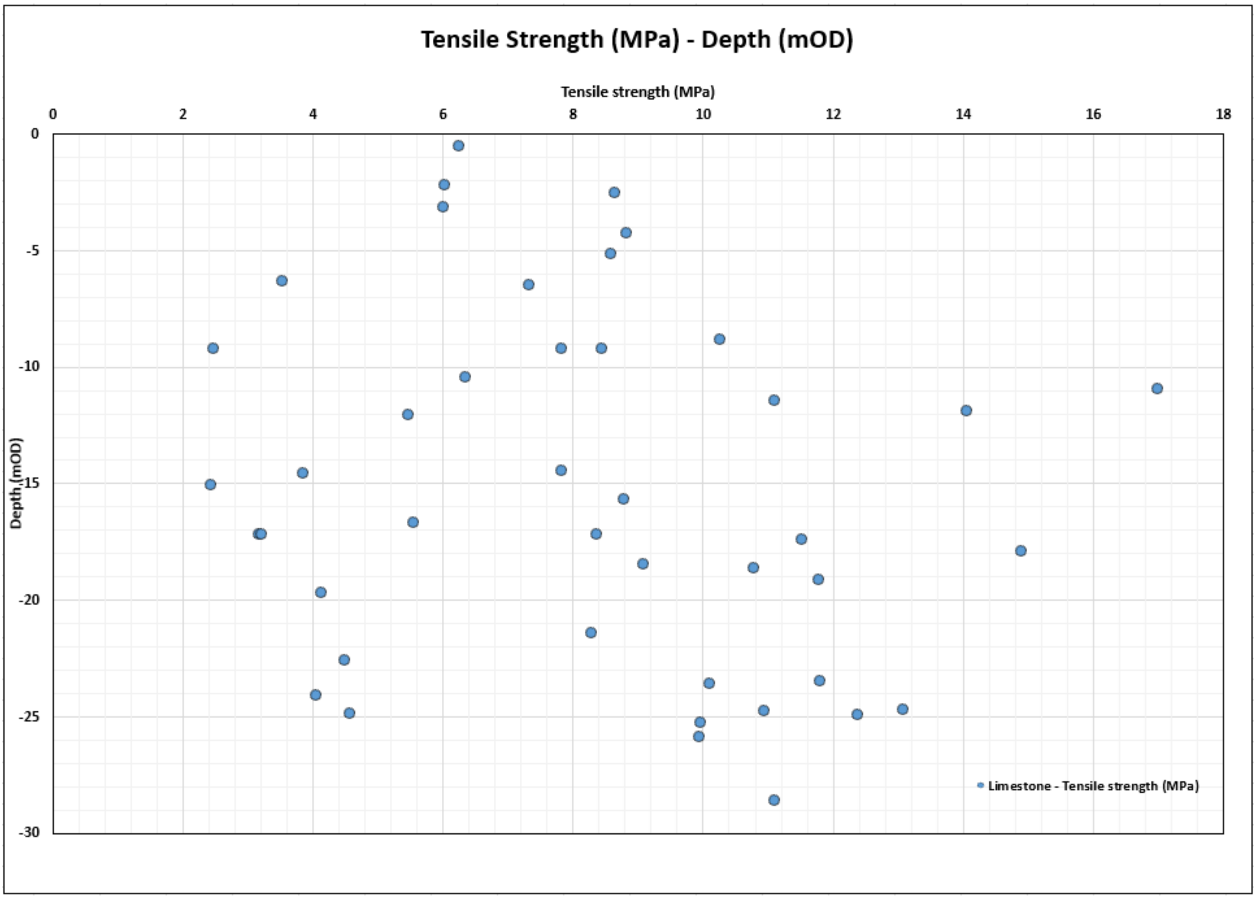


Figure 48 Tensile strength, in MPa, over depth (mOD).

A statistical analysis of the tensile strength results was conducted, and the results are presented in **Figure 49.** The accompanying box and whisker graph, along with the table, reveals that most tensile strength values for the limestone fall within the range of 5.5 to 10.9MPa.

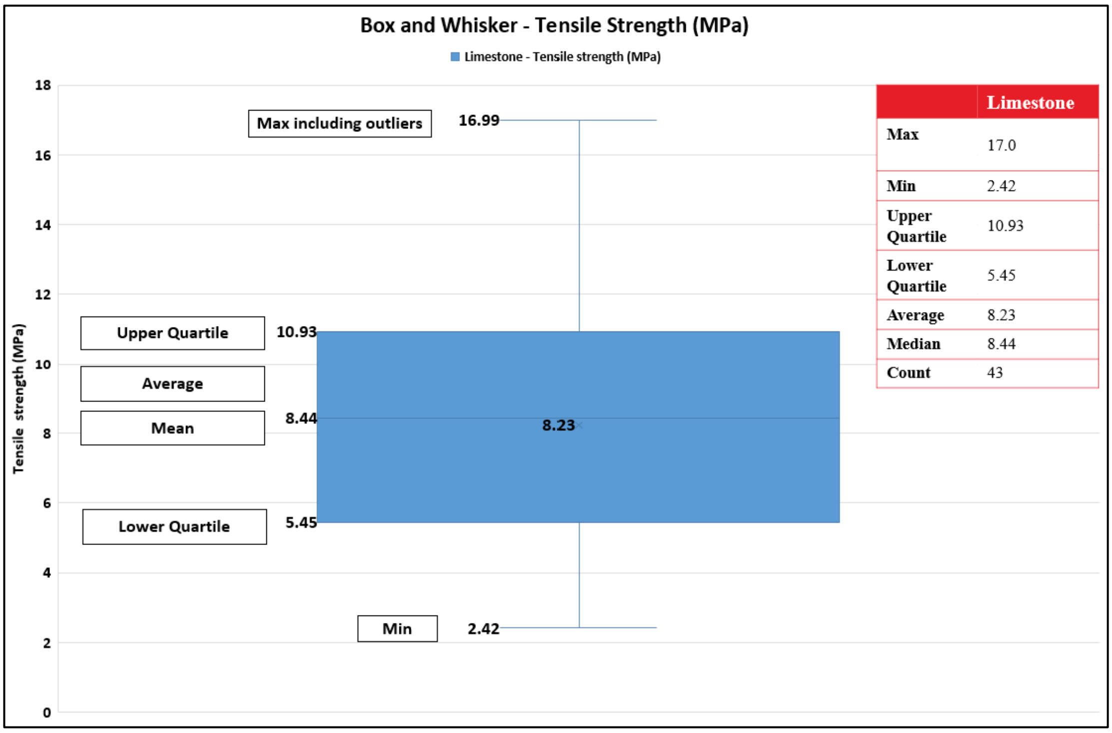


Figure 49 Box and Whisker – tensile strength, in MPa, for limestone.

An additional graph was created to explore whether there is a direct relationship between the tensile and compressive strength and the natural anisotropy of the limestone. For this analysis, MetroLink samples were chosen because both tensile and UCS tests were conducted on samples taken from the exact same depths. However, as shown in Figure 50, the relationship is not strong enough to reliably represent a direct correlation between the two strengths.

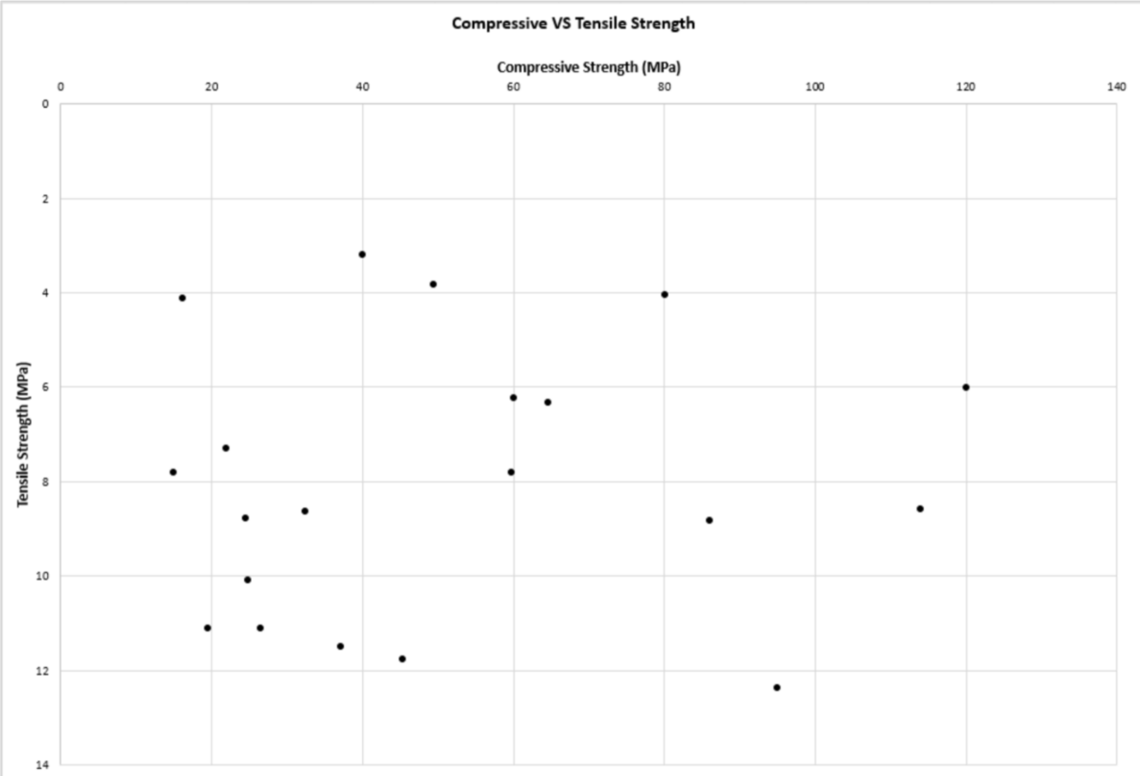


Figure 50 Compressive versus Tensile strength, both in MPa.

6.3 Rock mass analysis

Rock mass behaviour is dependent on the orientation, density, nature, and extent of the discontinuities within the rock mass along with the intact rock strength, mineralogy and lithology, weathering, and groundwater conditions (and any historical manmade interventions).

6.3.1 Discontinuities

Based on the discontinuity sheets that were provided along with the borehole logs for DART Underground the following descriptions were given as characteristic for the discontinuities in the Calp Limestone.

Discontinuity 1 (Bedding):

This discontinuity is described as very closely spaced within the mudstone and medium to widely spaced in the limestone. It is a sub-horizontal to locally 40° dipping with a planar surface discontinuity. The aperture ranges from tight (0.1 to 0.5 mm) to open (2.5 to 10 mm). This is frequently described as clean without signs of weathering in the limestone and slightly weathered when within the mudstone which was encountered in shallow depths. Clay smeared material or pyrite was observed as infill and occasional calcite veins were observed running along the bedding.

Discontinuity 2 (Sub-vertical joints J1 and J2):

This discontinuity is described as very widely to occasionally very closely spaced. It is a sub vertical dipping (65° to 90°) with planar, smooth to rough surfaces. The aperture ranges from moderately open to open. This discontinuity was described as being clean or having clay smeared or calcite lined infill. Orthogonal joint sets were observed during the Belgard Quarry site visit, which potentially represent J1 and J2, (see **Figure 83** in **Section 7.1.5**).

Spacing:

The spacing of the bedding planes is quite variable, but typically in the range 20 to 1000 mm (significantly thinner in some areas of mudstone) as shown on **Figure 51**.

Figure 51 Typical discontinuity spacing (BH54; DART Underground)

The spacing of the J1 and J2 joints (discontinuity set 2) are typically in the range of medium to very widely spaced (200 mm to 6 m).This results in a bedrock structure that consists of blocks which are typically equant/irregular to tabular in shape as shown on **Figure 52**.

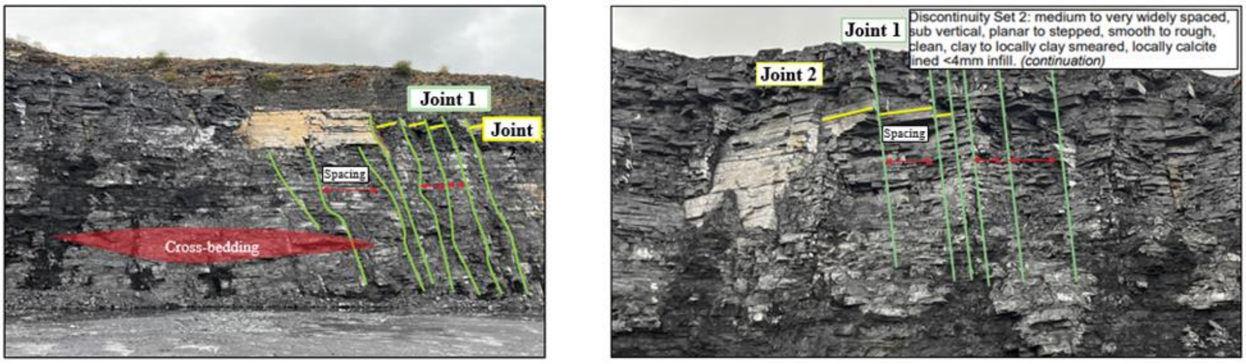


Figure 52 Discontinuity Set 2 (Belgard Quarry)

Aperture and Alteration:

The majority of joints in the Calp Limestone are either clean or have "local clay smears or infill" suggesting that the behaviour of those joints will be governed at laboratory scale by the joint roughness, i.e. through the joint roughness coefficient (JRC) values.

As shown on **Figure 53,** infill was observed along the sub-vertical jointing as opposed to the bedding planes.

Figure 53 Belgard Quarry

This was also observed in a number of the borehole logs where bedding only was observed as shown on **Figure 54** below. It is important to note that open discontinuities in rock core may be drilling induced or as a result of handling of the rock core.

Figure 54 Core photograph of DART Underground BH29 showing aperture range from open to wide (0.05m to 0.10m spacing) without infilling

Pyrite is also observed on occasion along with calcite veining. However, a small proportion of the discontinuities observed (less than 10%) are described as clay infilled.

For infilled joints the relationship between the asperity height and the thickness of the fill has been found to govern the shear strength of the joint (Toledo & de Freitas, 1993).

6.3.1.1 Downhole Geophysics

To analyse the structure of the Calp Limestone, downhole geophysics data provided by TII across the DART Underground, MetroLink, and Metro North projects were interpreted. The data interpreted included the acoustic and optical downhole geophysics logs, which provide information on the orientation of discontinuities within the borehole.

As well as the optical and acoustic televiewer data, natural gamma ray, density, resistivity, and calliper tests were carried out. However, not all the data is available for each borehole and there are many gaps in information. A summary of the total number of rotary core boreholes in the study area and the number of boreholes with downhole geophysical surveying for stereonet analysis is presented in **Table 3** below.

Table 3 Discontinuity orientation information in the study area.

DART Underground		Metro North		Metrolink	
Boreholes in study area	Boreholes with downhole geophysics	Boreholes in study area	Boreholes with downhole geophysics	Boreholes in study area	Boreholes with downhole geophysics
86	14	67	20	37	3

6.3.1.2 Orientation

<u>Stereonet Analysis</u>

A stereonet is a 2D graphical tool used to analyse and demonstrate how discontinuities are orientated within a rock mass. The discontinuity data (dip and dip direction) collected during a ground investigation is analysed in order to identify dominant discontinuity sets, assess variability, and in turn evaluate potential rock failure mechanisms.

A discontinuity is represented on a stereonet as a plane (or great circle) that has a dip (angle from 0° to 90° that a discontinuity dips downward) and dip direction (compass direction of the dip). The data collected from the downhole geophysics provided the dip and dip direction of each discontinuity encountered in the respective borehole measured. A pole is a single point plotted 90° perpendicular to a plane on a stereonet. Due to the amount of project data, poles were used to allow for easier visualisation and statistical analysis.

The dip orientation of a pole data point is determined by the compass position (0º to 360º). The dip angle of a data point is determined by location of the point relative to the centre of the stereonet plot. Poles which plot at the centre of the stereonet have a shallow discontinuity angle of 0º, whereas those poles which plot around the periphery of the stereonet have a steep discontinuity dip angle of 90º.

In total, stereonet analysis was conducted for 37 boreholes with a combined total of 4,033 discontinuity poles (dip/dip direction) within the study area. As can be seen in **Figure 55**, the data is noisy as there is such a large number of data points imported. However, once a contour plot was generated (**Figure 56**), it was much easier to identify the densely populated areas which have been correlated to the gently dipping bedding and two joint sets as expected from the literature. Folding of the rock has also been identified from an analysis of the stereographical data.

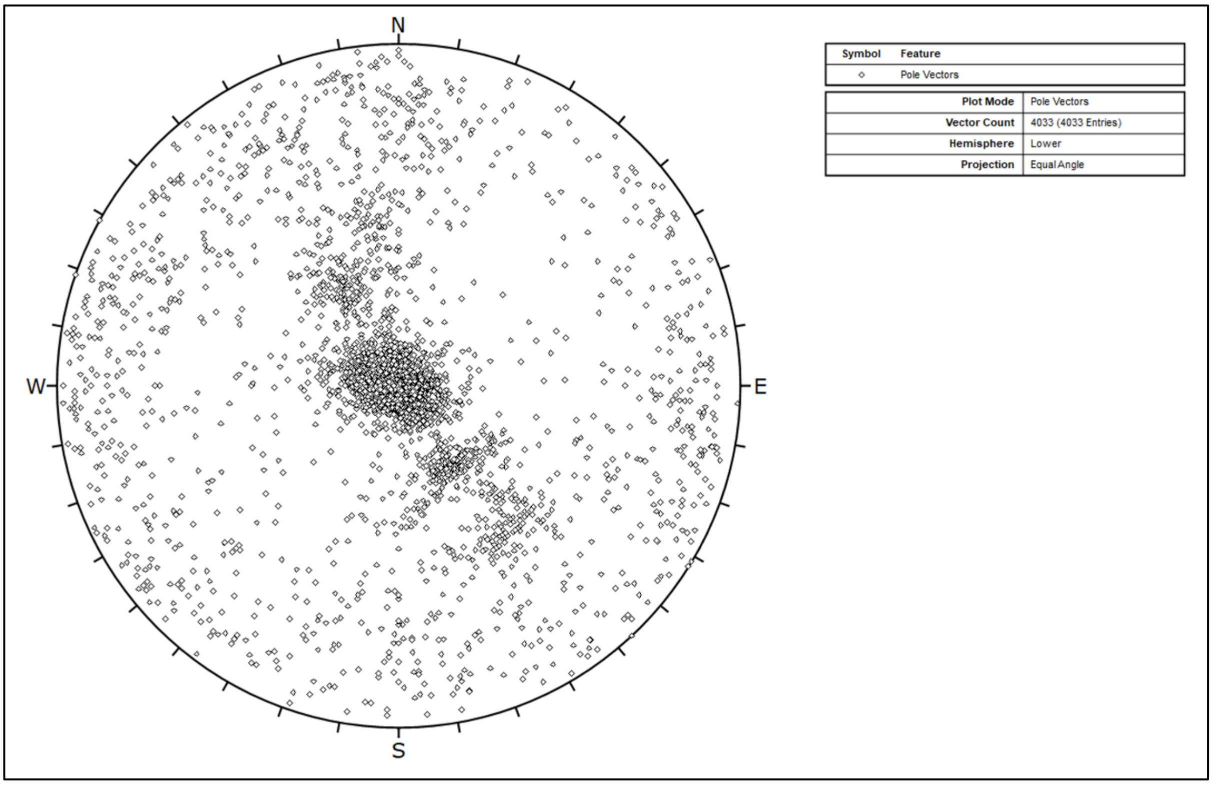


Figure 55 Stereonet of all the poles data points across DART Underground, Metrolink, and Metro North within the study area. The dip orientation of a pole data point is determined by the compass position (0º to 360º). The dip angle of a data point is determined by location of the point relative to the centre of the stereonet plot. Poles which plot at the centre of the stereonet have a shallow discontinuity angle of 0º, whereas those poles which plot around the periphery of the stereonet have a steep discontinuity dip angle of 90º.

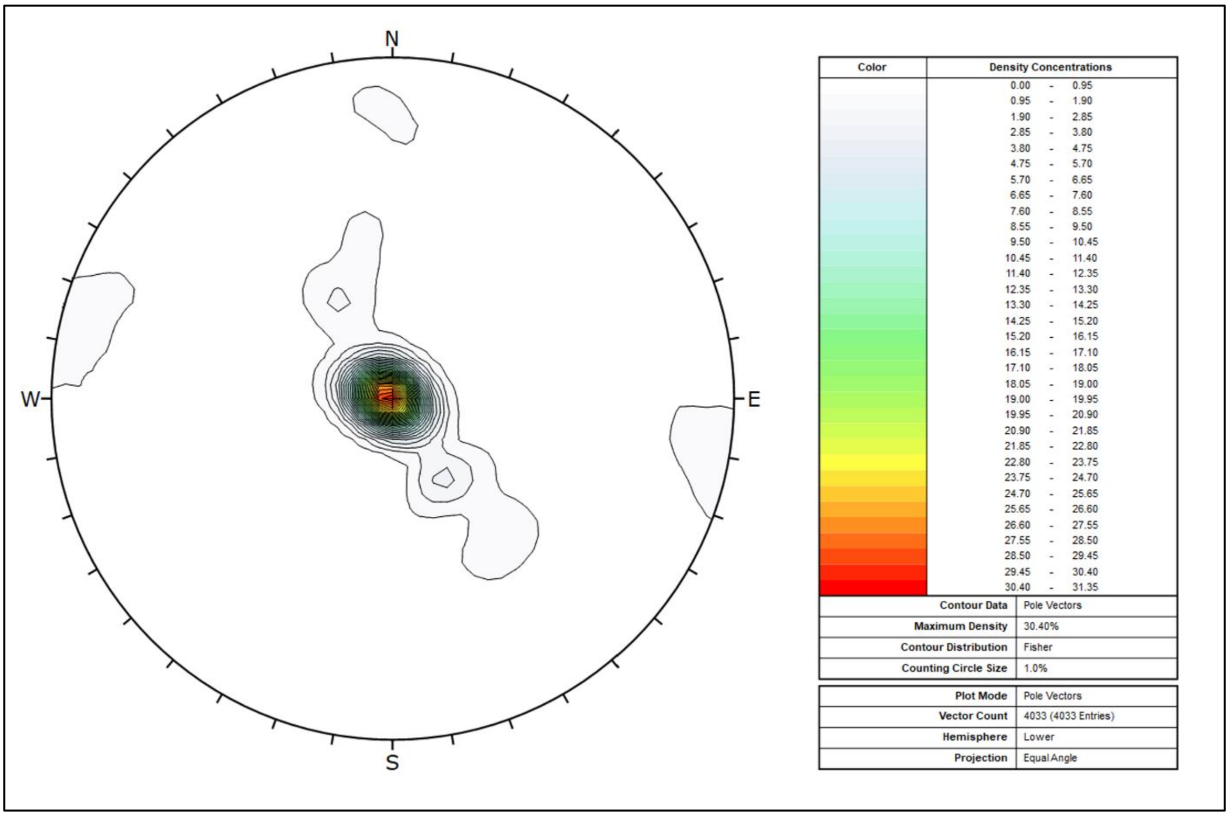


Figure 56 Stereonet contour plot showing the most densely populated readings between the three drilling programmes.

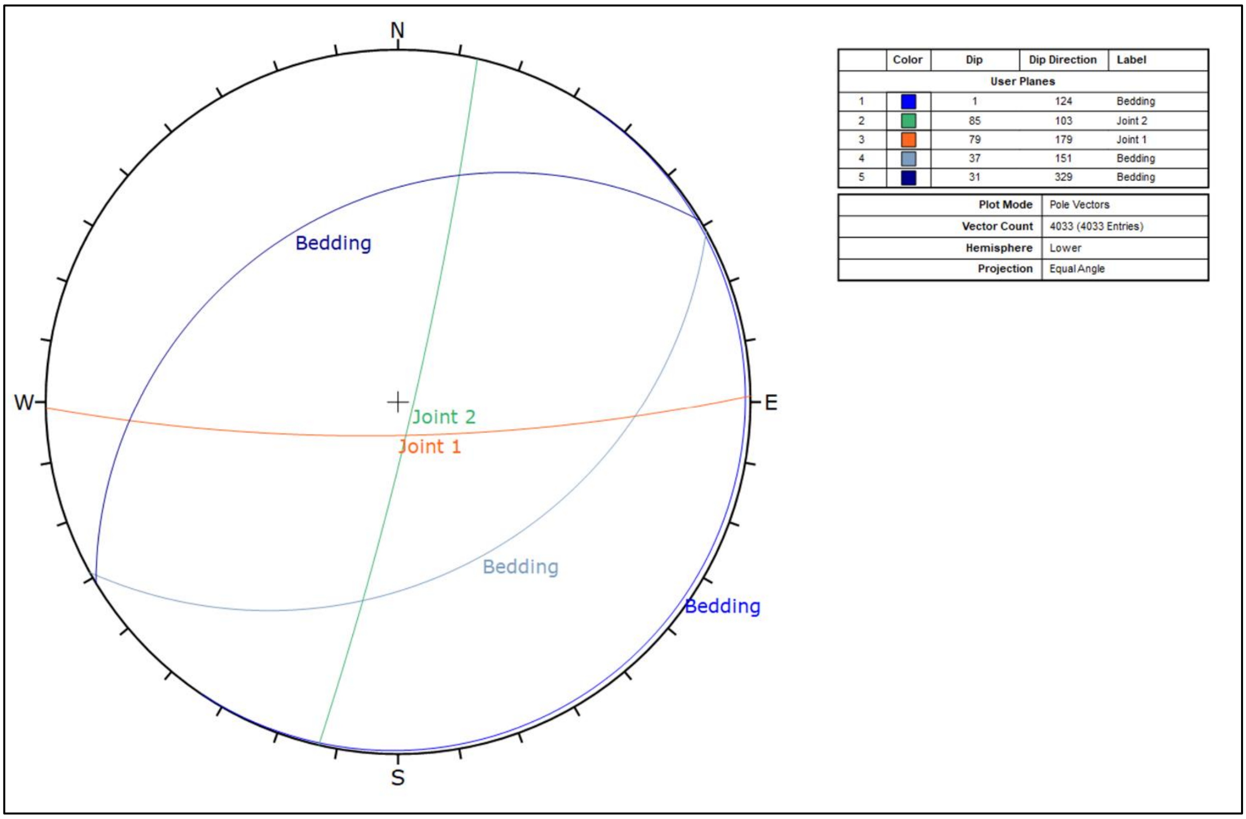


Figure 57 Prominent planes in the study area constructed using the above contour plot.

While these planes represent the most densely populated areas of the stereonet, they fail to account for discontinuities with orientations that are scattered chaotically across the stereonet, shown in **Figure 55**.

For example, in BH28 from the DART Underground project, a very clean pole vector plot can be seen (**Figure 58**) with highly concentrated gently dipping bedding readings and two subvertical joint sets demonstrated by the great circles (**Figure 59**). This is not uniformly seen across the study area, with some boreholes such as BH30 from the DART Underground project (**Figure 60**), only picking up on one of the two joint sets. Due to borehole diameter and in general vertical orientation, vertical discontinuities may not be encountered by a borehole.

While bedding in the Calp Limestone is generally considered to be horizontal to sub-horizonal dipping (0º to 20º), a more pronounced bedrock dip was noted in a number of boreholes. Of the 37 boreholes examined, seven have a notably steeper dip angle closer to 45º, as illustrated in **Figure 60** and **Figure 61**.

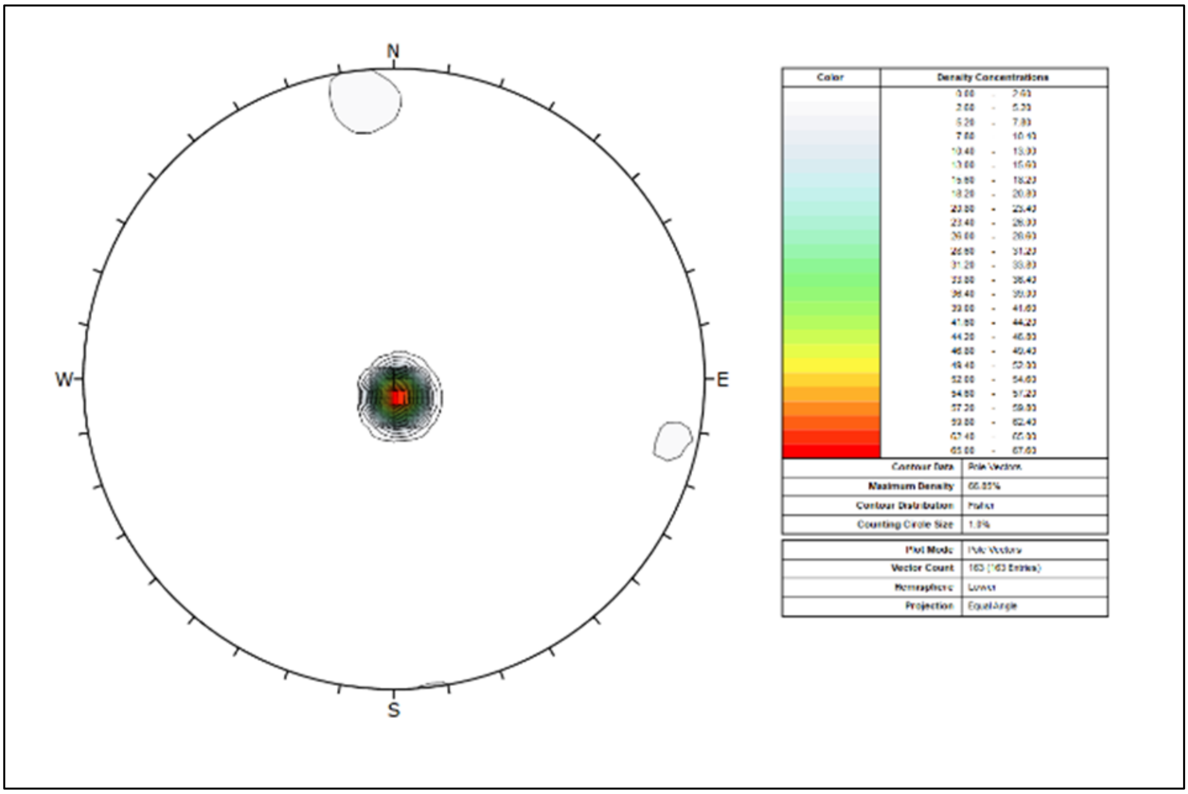


Figure 58 DART Underground BH28 poles stereonet plot.

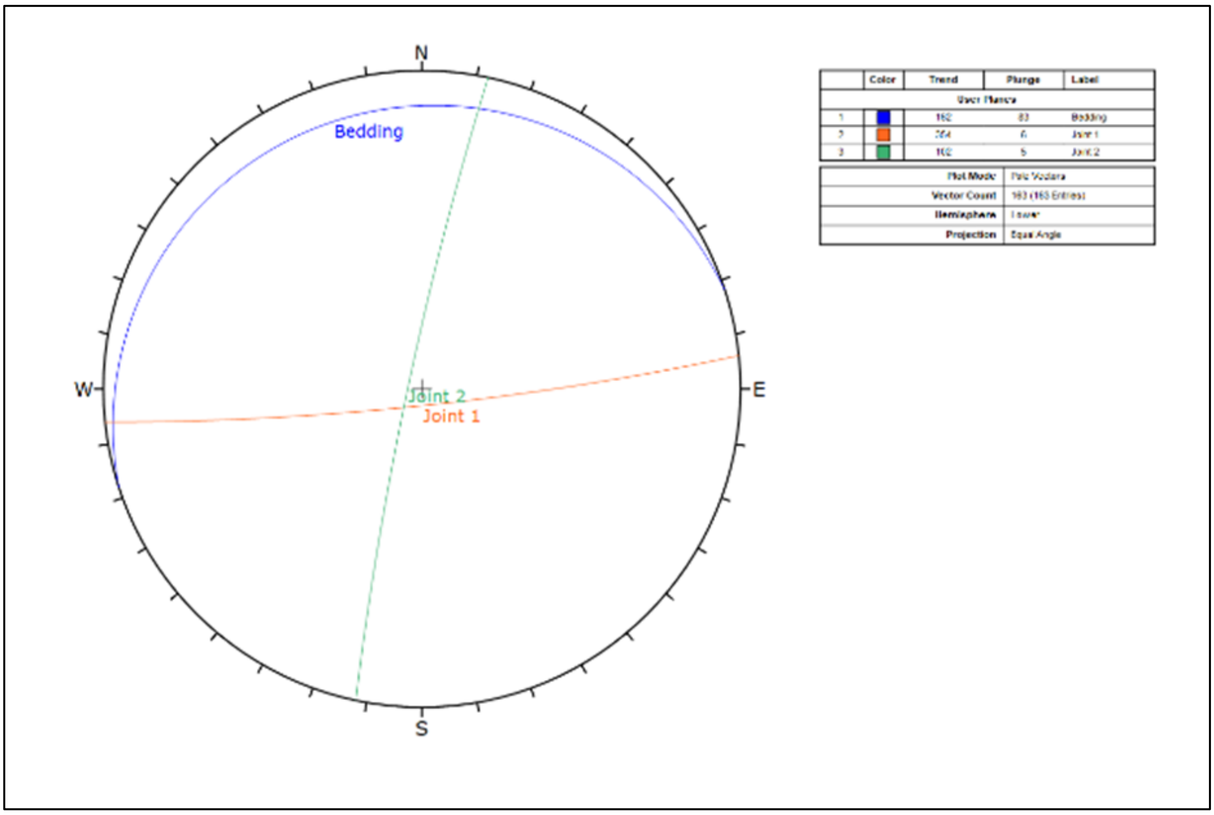


Figure 59 DART Underground BH28 stereonet representative planes plot.

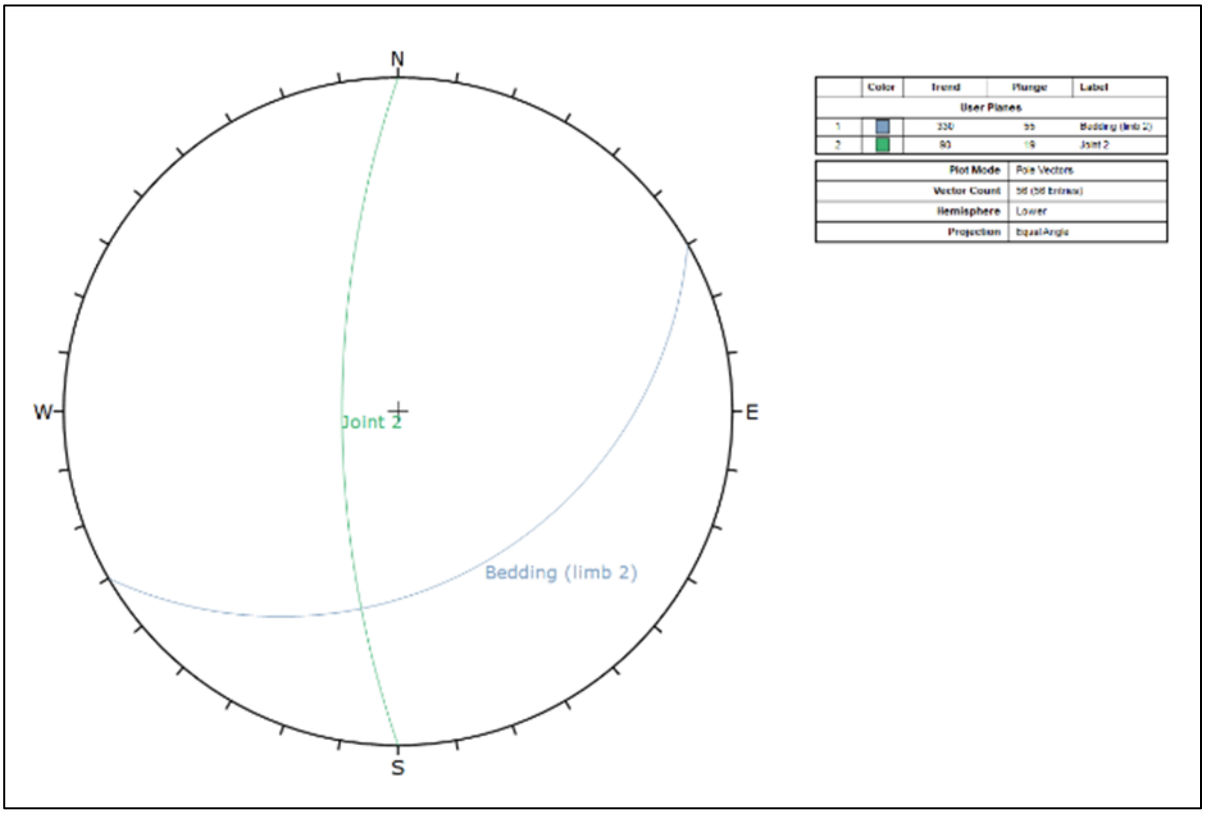


Figure 60 DART Underground BH30 representative planes.

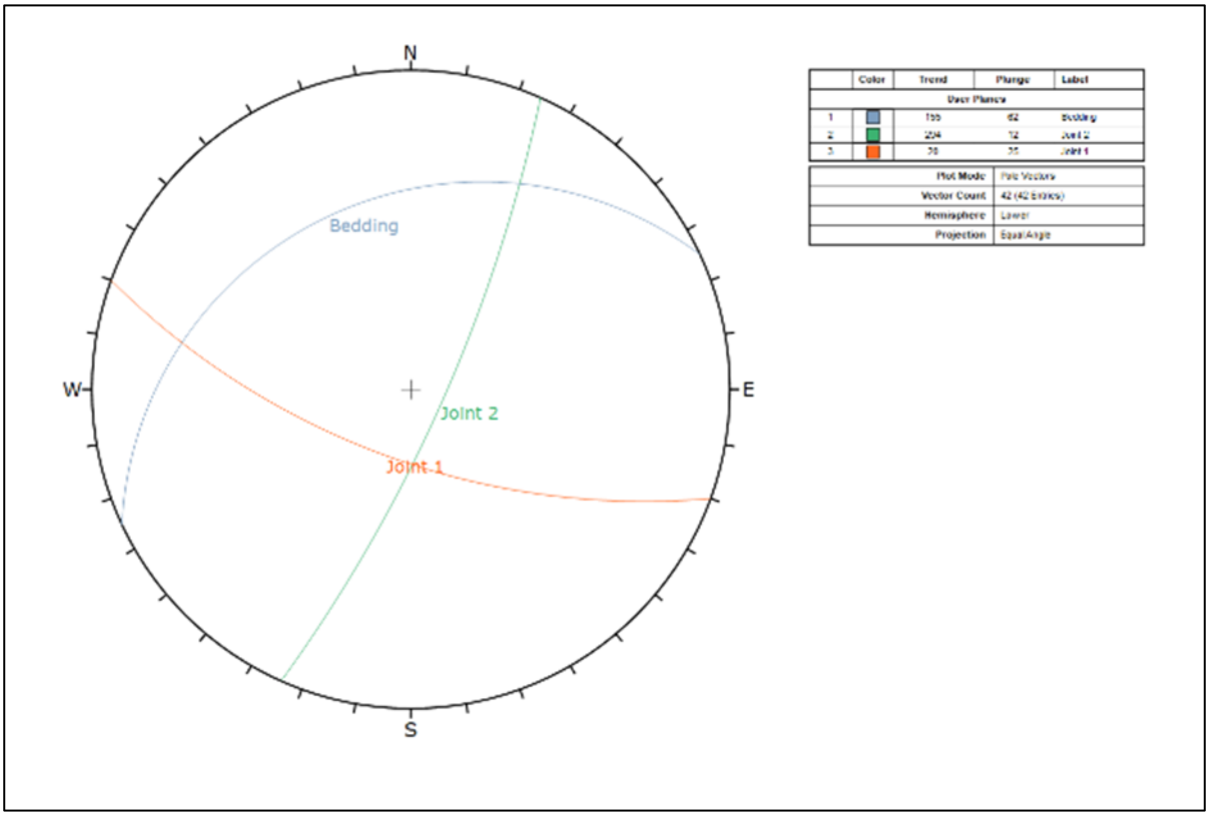


Figure 61 Metro North MGI/BH/730 representative planes.

6.3.2 Core recovery parameters

Core recovery parameters, or mechanical indices, are commonly used in rock mass analysis. Mechanical indices are measured from rock cores recovery during drilling activities. Core recovery parameters, in accordance with BS5930:2015, which built on the work of Deere *et al*., 1967, can be defined as follows:

- Total core recovery (TCR): Length of core recovered (solid and non-intact) expressed as a ratio of the length of core run.
- Solid Core Recovery (SCR): Length of solid core recovered expressed as a ratio of the length of core run. Solid core has a full diameter, uninterrupted by natural discontinuities, but not necessarily a full circumference and is commonly measured along the core axis or other scan line.
- Rock Quality Designation (RQD): Length of solid core each piece longer than 100 mm expressed as a ratio of the length of core run.
- Fracture Spacing (If): The average length of solid core pieces over lengths of core of uniform lithology (in mm).
- Fracture Index (FI): Number of fractures per metre.

However, it should be noted that whilst machinal indices are often used for rock mass analysis, limitations have been noted with regards to the use of the mechanical indices, particularly RQD, in the determination of rock mass intactness (Quigley & McSwiney, 1996).

All entries (2,505) were plotted against depth to identify trends in how rock structural information varies with depth. The mechanical indices TCR, SCR, and RQD values all increased with depth.

6.3.2.1 Total Core Recovery (TCR)

For TCR, it can be observed that at depths less than 20 metres, 11% of the entries (97) have a TCR value between 0 and 25, while at depths greater than 20 metres, almost all of the TCR values are above a value of 25. TCR results are shown in **Figure 62** and **Table 4** below.

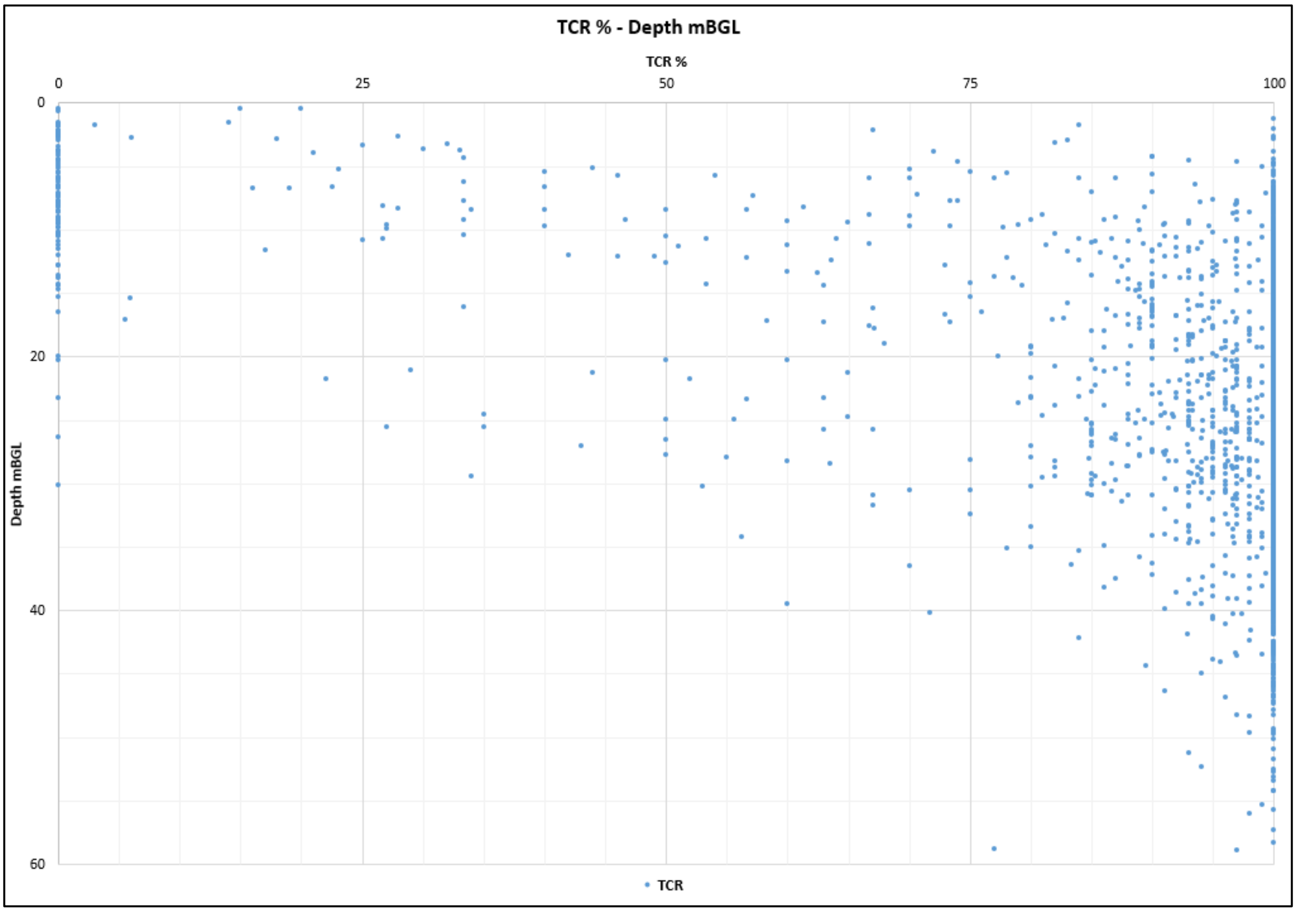


Figure 62 Total Core Recovery (TCR%) with Depth (mBGL).

Table 4 Percentage counts of specific TCR ranges across stratigraphic depth profiles.

Recovery Percentage (%)	Depth range (m BGL)		
	0 – 20	20 – 40	>40
0 – 25%	10.8%	0.3%	0.0%
25 – 50%	3.3%	0.7%	0.0%
50 – 75%	4.7%	1.5%	0.8%
75 – 100%	81.2%	97.4%	99.2%
Count (no.)	**886**	**1486**	**133**

6.3.2.2 Solid Core Recovery (SCR)

SCR values also increase with depth. Within the first 20 metres, 50% of the entries (443) have a Solid Core Recovery (SCR) value between 75 and 100. Between 20 and 40 metres, 73% of the entries fall within this range, and at depths greater than 40 metres, 74% of the entries receive the same score. SCR results are shown in **Figure 63** and **Table 5** below.

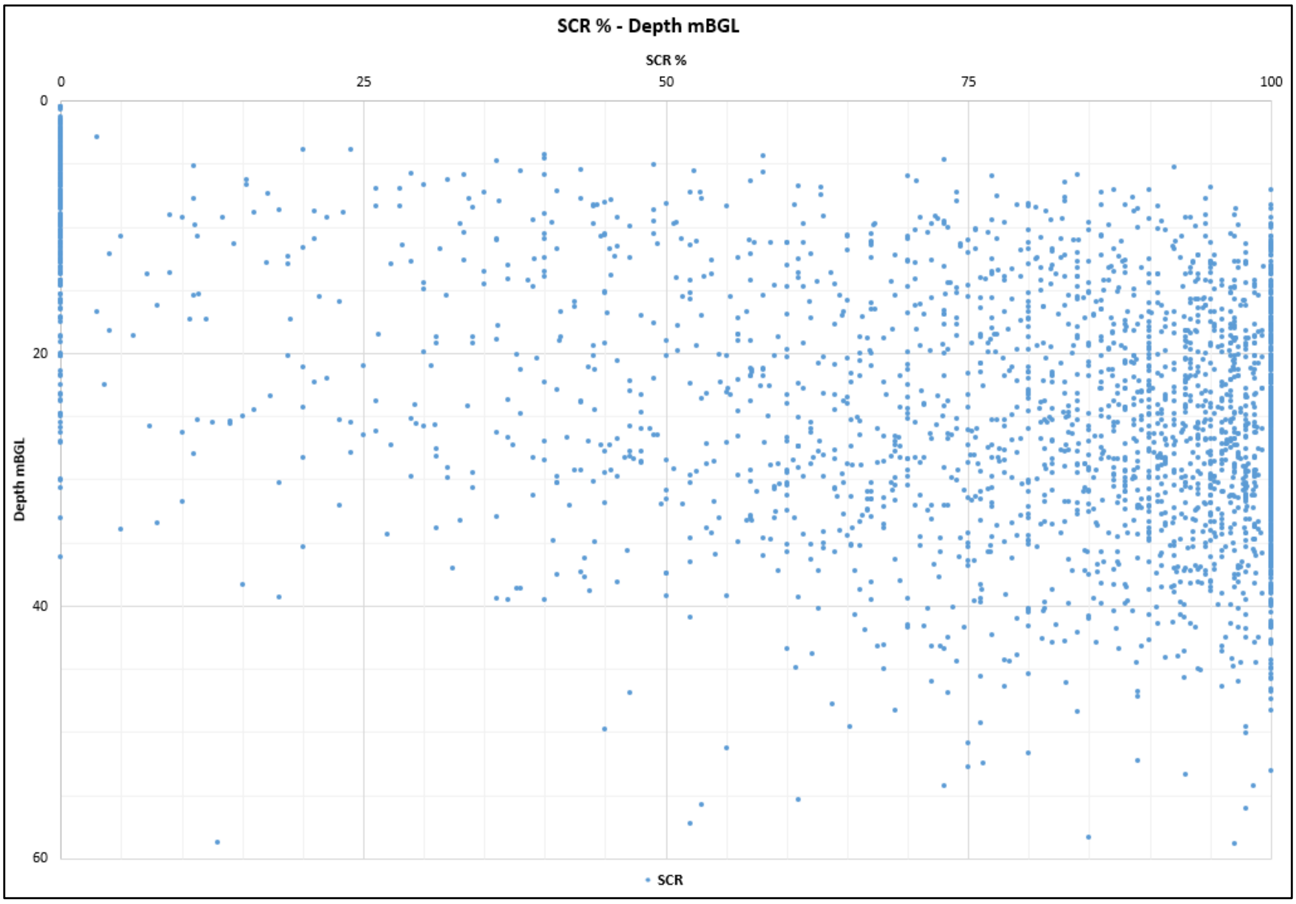


Figure 63 Solid Core Recovery (SCR%) with Depth (mBGL).

Table 5 Percentage counts of specific SCR ranges across stratigraphic depth profiles.

Recovery Percentage (%)	Depth range (m BGL)		
	0 – 20	20 – 40	>40
0 – 25%	23.8%	3.7%	0.8%
25 – 50%	10.3%	6.7%	1.5%
50 – 75%	16.5%	16.8%	24.1%
75 – 100%	49.4%	72.9%	73.7%
Count (no.)	**886**	**1486**	**133**

6.3.2.3 Rock Quality Designation (RQD)

The increase in RQD is the most significant among the core running information parameters. Most entries between 0 and 20 metres show RQD values between 0 and 25. However, between 20 and 40 metres, most entries fall between 25 and 100, and at depths greater than 40 metres, the majority of entries exhibit RQD values over 50, with 75-100 being the most common range. However, it is noted that most of the borehole logs encountered bedding only and not the sub-vertical joints so the RQD may not be wholly representative of the rock mass. RQD results are shown in **Figure 64** and **Table 6** below.

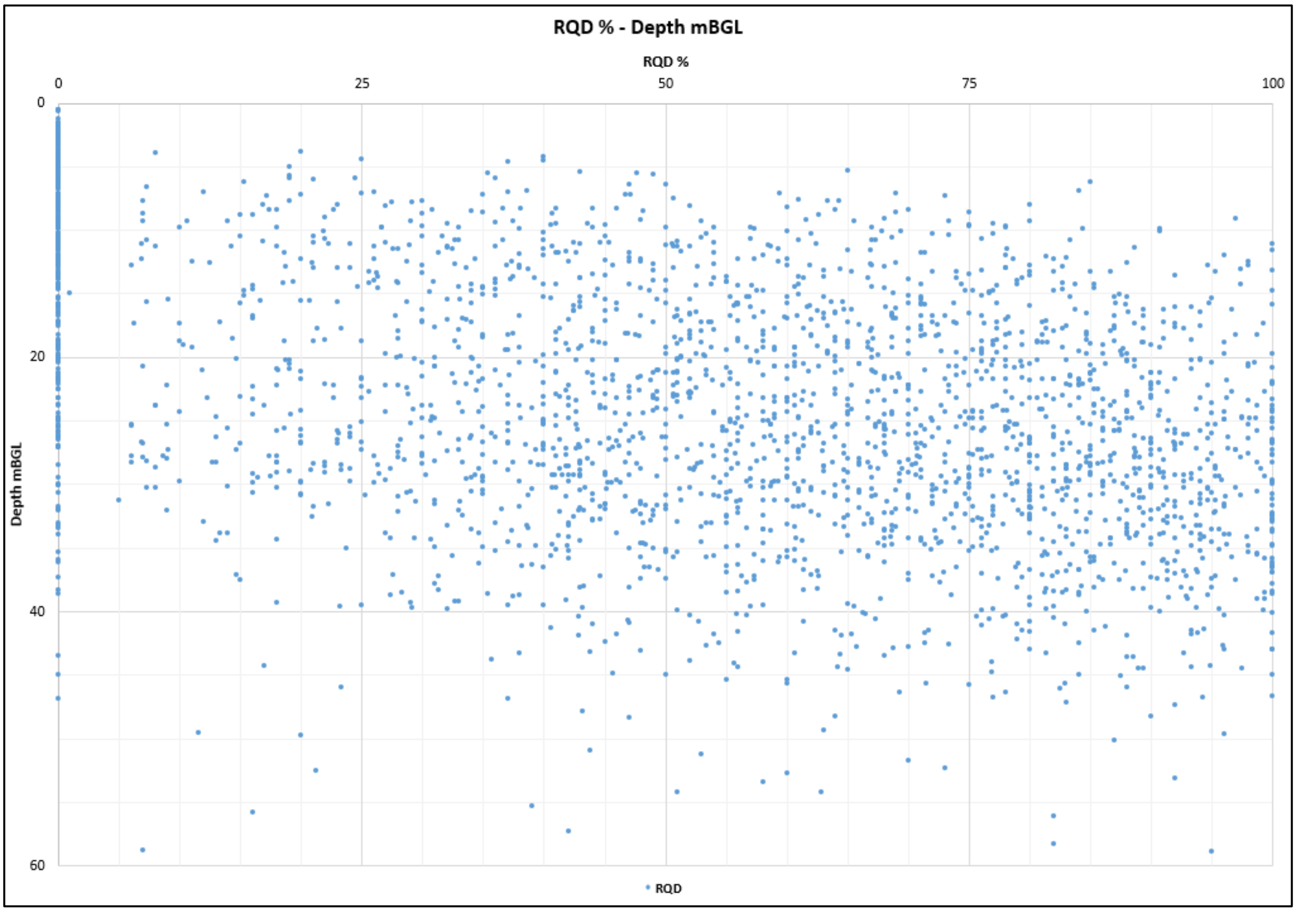


Figure 64 Rock Quality Designation (RQD%) with Depth (mBGL).

Table 6 Percentage counts of specific RQD ranges across stratigraphic depth profiles

Recovery Percentage (%)	Depth range (m BGL)		
	0 – 20	20 – 40	>40
0 – 25%	34.2%	11.4%	7.5%
25 – 50%	23.1%	22.3%	15.0%
50 – 75%	26.0%	28.9%	33.1%
75 – 100%	16.7%	37.3%	44.4%
Count (no.)	**886**	**1486**	**133**

6.4 Rock Mass Rating Systems and the Calp Limestone

Rock Mass Classification systems are mainly dominated by the discontinuity properties. Most are designed for different applications and may not always be applicable (experience & engineering judgement needed).

Common systems include:

- RMR – Rock Mass Rating (Geomechanics System developed by Beniawski) – a quantification of strength and discontinuities to give a rating between 0 and 100. Typically used for design of tunnel support systems. (Bieniawski, 1989).
- Norwegian Q-System (Rock Mass Quality) – combines various factors primarily from discontinuity sets, to give a rating between <0.01 to >100. Typically used for design of tunnel support systems. (NGI, 2025).

- Geological Strength Index (GSI) – a qualitative assessment of the 'blockiness' of an outcrop, and the degree of interlocking blocks to give a small range of values for a jointed rock. It estimates rock mass properties and typically is used for input into the Hoek-Brown criterion. (Hoek & Brown, 2018).

A trial of the various rock mass classifications systems above was undertaken to determine the efficacy and appropriateness of using discontinuity data from borehole logs and discontinuity datasheets only.

Based on our understanding of the rock mass, from analysis of ground investigation data and site walkovers, it is acknowledged that the borehole data may not accurately represent the frequency of sub-vertical joint sets within the rock mass. An assessment of the Geological Strength Index (GSI) for BH29 is presented in **Figure 65** below.

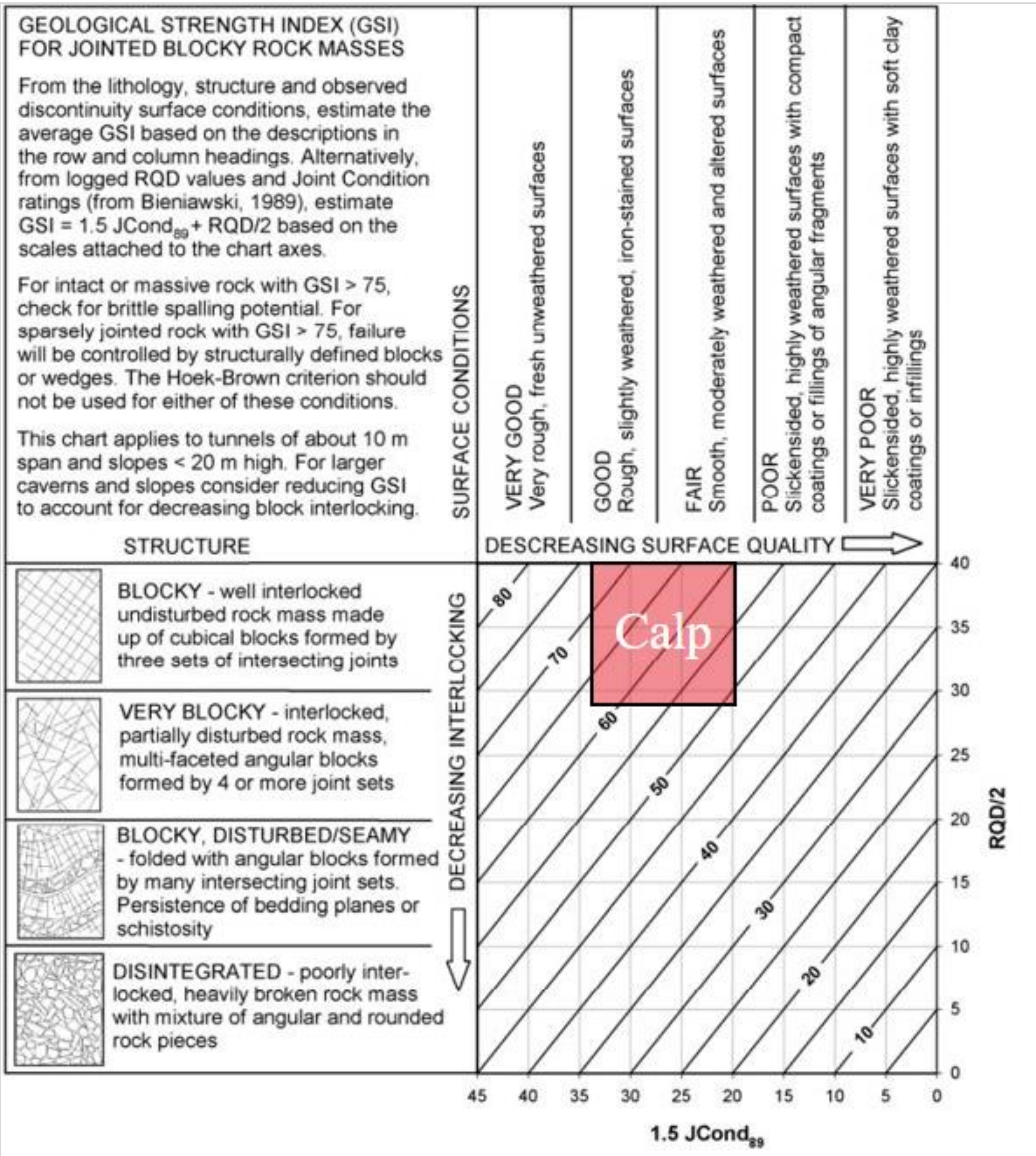


Figure 65 Geological Strength Index (GSI) of BH29, from Rocscience (2013). Rock structure is measured as RQD/2, whereas the surface conditions of discontinuities, including roughness, separation/aperture, continuity/persistence, weathering, and infilling is given by 1.5 x Joint Condition rating (from Bieniawski, 1989).

6.5 Conclusions

The following conclusions can be made following the completion of the rock mass analysis:

- The proportion of bedding readings is significantly higher than that of any other discontinuities in the bedrock. The concentration of bedding data enhances confidence in detecting changes in the bedding orientation. Further examination of the stereonets and the spatial relationship between boreholes potentially allows for the identification of large-scale folding trends within the formation.
- The subvertical Joint Sets 1 and 2, were more challenging to identify due to the vertical nature of the borehole, resulting in a lower proportion of readings corresponding to these features. When these joints are observed in the stereonets, two distinct populations are often noticed with dips ranging from 60º to 90º.
- Identifying individual features of faulting through stereonets alone is not feasible as this type of analysis is suitable for identifying overall trends in boreholes. It is unclear what the outlying poles on the stereonets correlate to. One possible explanation is that these poles relate to faults picked up by the boreholes. Faults would not produce dense poles on a stereonet plot due to a combination of their generally steeply dipping orientation, and their wider spacing than that of joints and bedding which would make them difficult to pick up in vertical boreholes. It would require careful examination of the core photographs as well as verification of core analysis through visual observation to confirm whether any of these discontinuity poles can be correlated to faulting.
- Calcite veining is found predominantly in sub-vertical joints, due to their role as the primary conduits for water circulation in the otherwise impermeable formation, possibly having greater apertures when compared to the extremely tight bedding planes. However, downhole geophysics data also shows calcite present along bedding planes. It is possible this indicates stress relief which might have increased the aperture of tightly spaced bedding allowing fluids to deposit calcite.
- To determine whether there is any folding in the Calp Limestone within the project area, a map correlating the borehole locations and the representative bedding orientations would be beneficial. This would help assess whether the atypical bedding readings are isolated anomalies or indicative of folding within the formation. Additionally, inclined boreholes were excluded from the dataset to minimise alterations and therefore mistakes to the original data.

7. Site visit

7.1.1 Overview

As part of the Calp Limestone in Dublin City Centre project, Arup organised a virtual site survey and four site visits, with participation from University College Dublin (UCD), to gain a better understanding of the geological regime of the formation at varying scales. By identifying geological features through visual observations on-site, the virtual survey and site inspections aim to address some limitations of relying solely on borehole data, providing valuable insights for the research project. The site visits focused on various exposures of the Calp Limestone at different scales and environments, as indicated in **Figure 66**.

The visits included:

- A virtual site walkover examining exposed outcrops along the M50 motorway.
- A visit to a basement excavation at Harcourt Square in Dublin City Centre, where the formation is often obscured by overlying glacial deposits or existing infrastructure.
- Outcrop mapping at Liffey Valley, identified during the virtual walkover as an ideal location for collecting structural information.

- A site walkover at Belgard Quarry, Ireland's largest limestone quarry, featuring extensive exposures of hundreds of metress of Calp Limestone faces.
- A visit to a basement excavation at One Adelaide Road in Dublin City Centre, where the Calp Limestone bedrock geology was overlain by approximately 10 metres of glacial till (Boulder Clay).

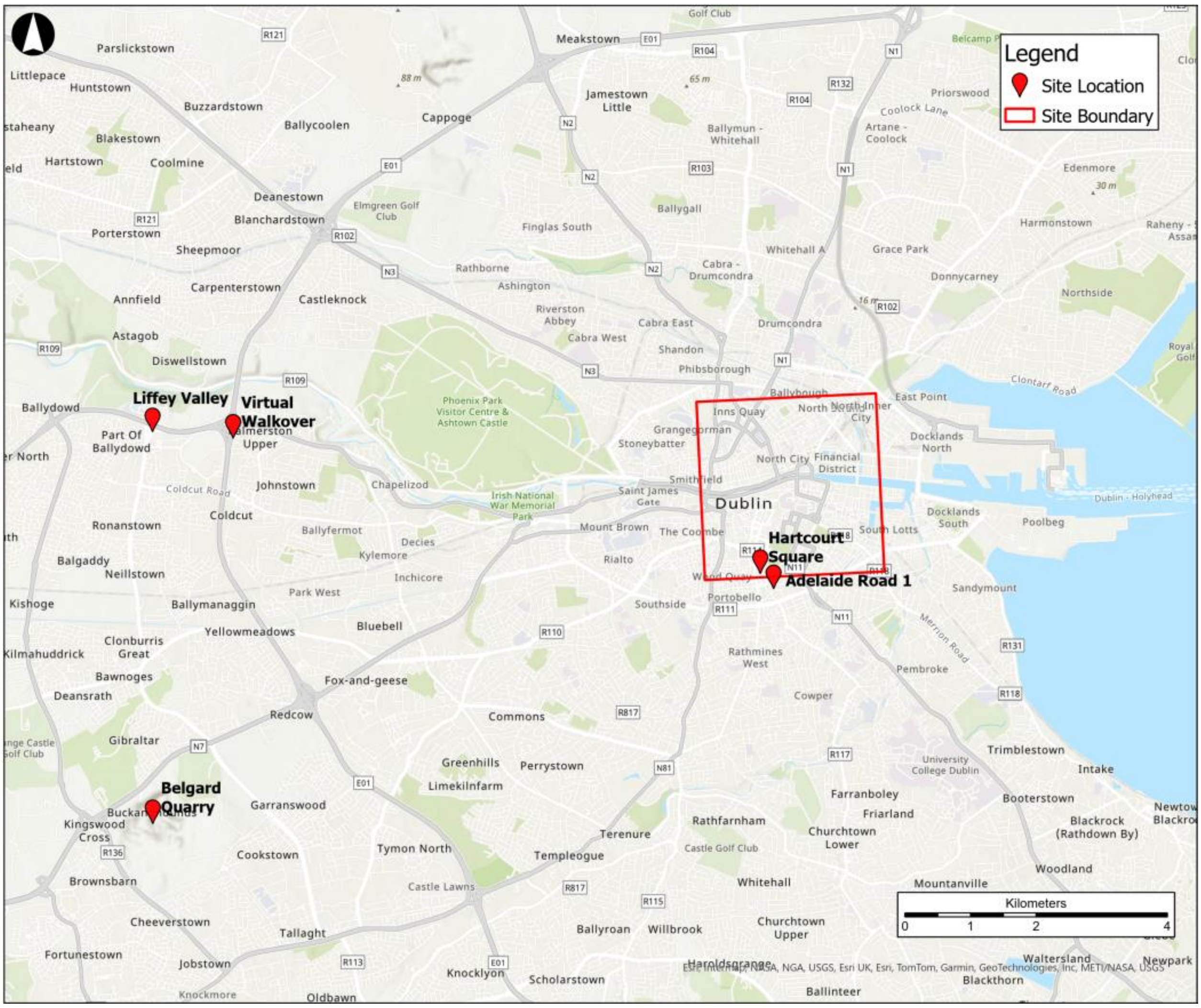


Figure 66 Location of the site visits.

7.1.2 Virtual Site Walkover

A virtual desk site walkover of known exposures within Dublin City and the surrounding area was undertaken through a review of the Google Earth street-level viewer. Abundant Calp Limestone outcrops were encountered along the M50 motorway.

One large scale outcrop was encountered along the south-bound entrance ramp at Junction 7 of the M50, located approximately 8.5 km west of Dublin City Centre, is shown in **Figure 67** below. Structural information recorded during the virtual site walkover of the south-bound entrance ramp outcrop at Junction 7 include:

- The bedding can be seen dipping to the south, clearest in the blocky limestone layers.
- Thinner and darker mudstone layers are visible.
- Two sub-vertical orthogonal joint sets are visible, giving the limestone layer a stepped appearance.

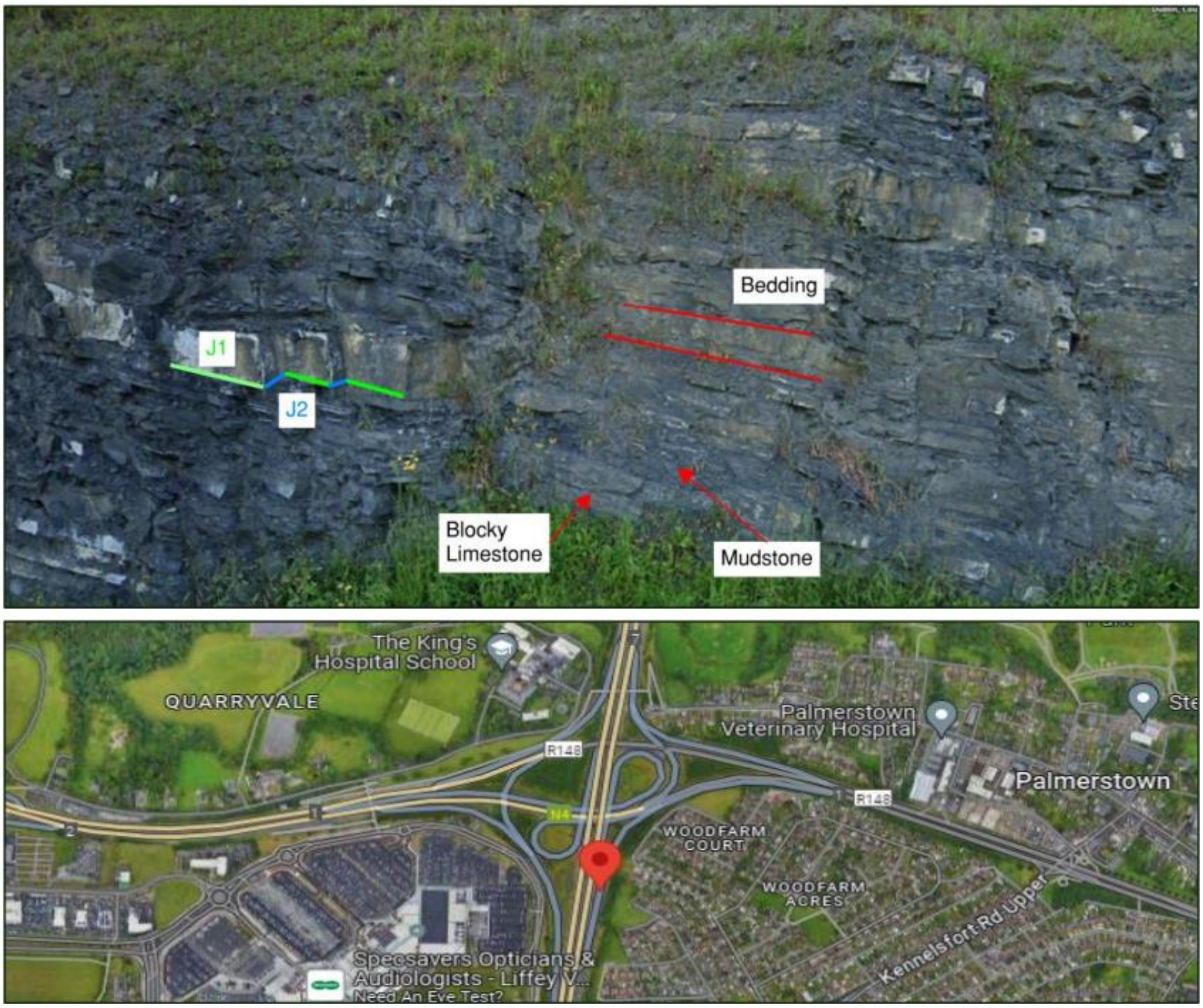


Figure 67 Exposure of Calp Limestone encountered along the south-bound entrance ramp at Junction 7 of the M50 motorway during the virtual site walkover.

A separate exposure of the Calp Limestone was encountered along the main carriageway at Junction 7 of the M50 motorway, as shown in **Figure 68** below. Structural information recorded during the virtual site walkover of the main carriageway outcrop at Junction 7 include:

- The bedding of the Calp Limestone can be seen dipping to the south and is clearly defined by the blockier limestone layers.
- The two sub-vertical orthogonal joint sets are also encountered in this outcrop.

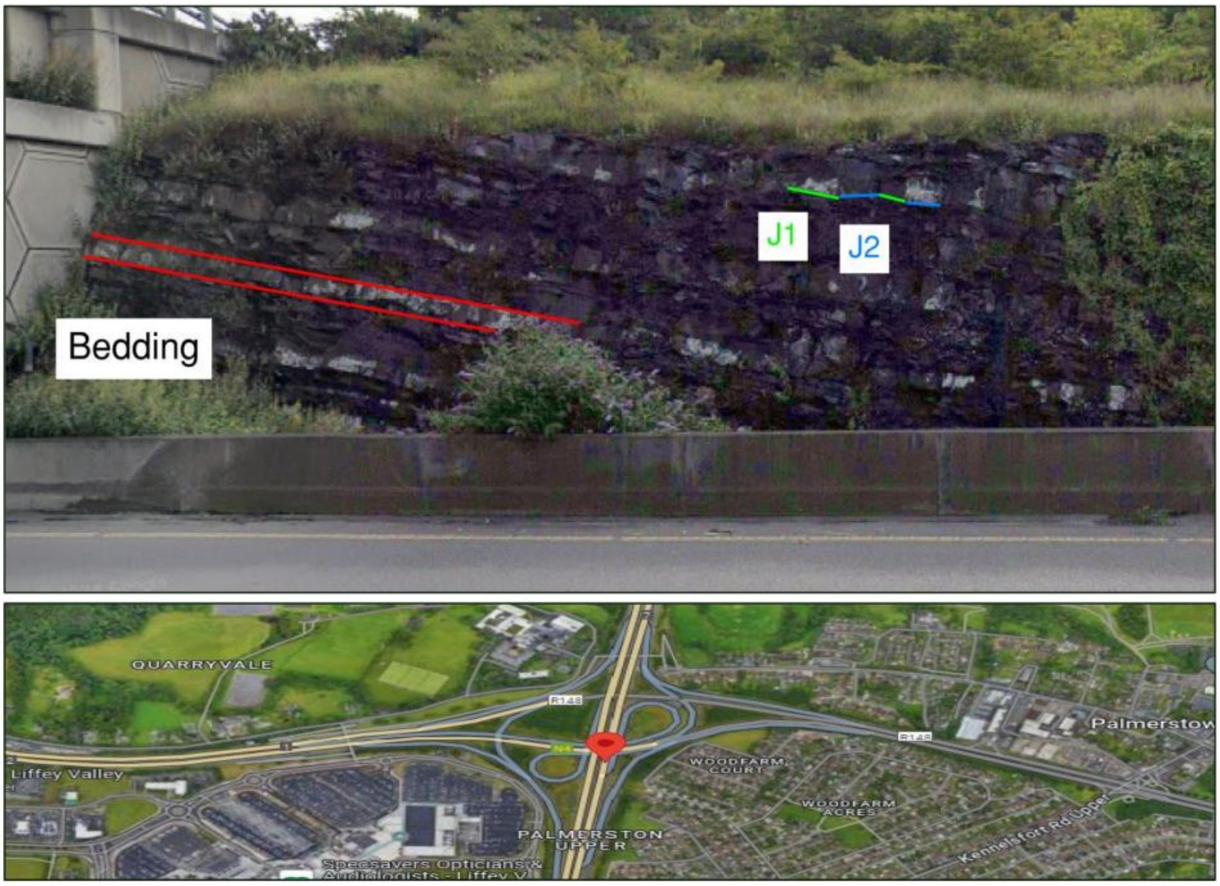


Figure 68 Exposure of Calp Limestone encountered along the main carriageway at Junction 7 of the M50 motorway during the virtual site walkover.

7.1.3 Site Walkover – Harcourt Square

In December 2023, as part of the Calp Limestone in Dublin City Centre project, Arup organised a site visit to a basement excavation in Dublin City Centre at the Harcourt Square site at the northern end of Harcourt Street, as shown in **Figure 69**. The proposed development includes a nine metre deep basement excavation, primarily through made ground underlain by glacial till (Boulder Clay) with Calp Limestone encountered at the deepest parts of the excavation.

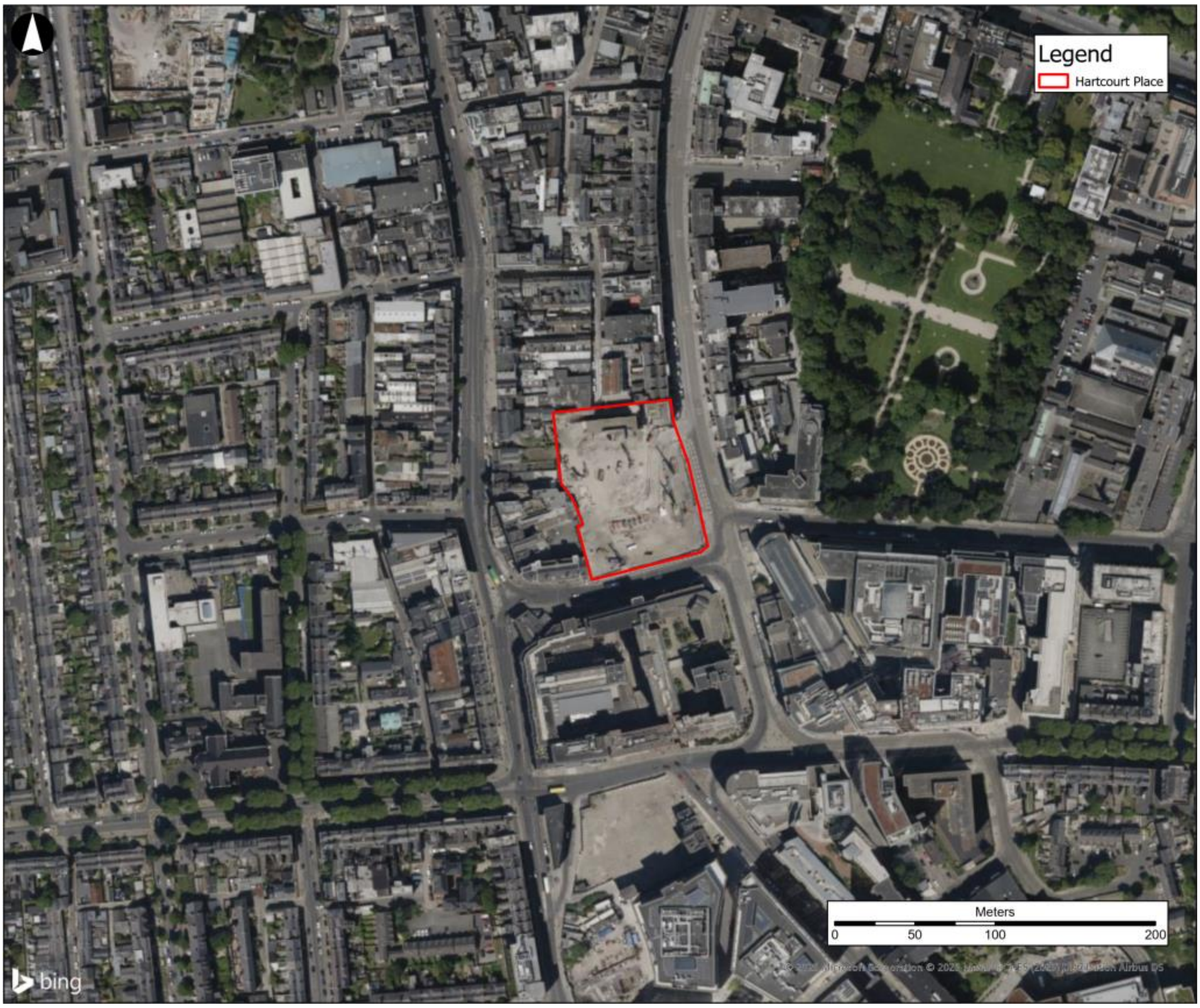


Figure 69 Location of Harcourt Square site in Dublin City Centre.

The site is operated by John Paul Construction as the main contractor, with Hegarty Demolition being the contractor responsible for demolition and excavation. A team from Arup and UCD met with Hegarty Demolition Limited (HDL) and toured the site, with the aim of observing the exposed bedrock at the base of a number of lift pits within the basement excavation.

7.1.3.1 Details of the site

The Harcourt Square site is characterised as an urban environment. The stratigraphy of the site comprises made ground underlain by glacial till deposits (Boulder Clay), underlain by Calp Limestone bedrock. The proposed development involves the excavation of a nine metre deep basement, mainly through the made ground and Boulder Clay.

At the time of the site visit in December 2023, the basement had been excavated, and a secant pile wall was installed to support the excavation (**Figure 70**).

Figure 70 Overview of excavation, looking north.

The secant pile wall was constructed as a soft-hard wall, which included one layer of anchors. It was noted that temporary fibreglass anchors were used, which could be identified through the presence of four strands being visible in the piled wall, as shown in **Figure 71**.

Figure 71 Soft-soft-hard wall with anchors, eastern side of the site.

7.1.3.2 Details of the visible bedrock

Bedrock geology was evident at the deepest parts of the excavation. A number of locally deeper pits had been excavated to facilitate the construction of lift pits. These holes were noted to contain water but also were being pumped by HDL.

The most notable feature of the excavations, apart from the presence of the standing water, was the ambiguous location of the contact or transition between the Black Boulder Clay and the Calp Limestone bedrock. Large tabular pieces of limestone were clearly visible which all appeared to be dipping northwards, The presence of a clear weathered bedrock layer was not observed during the site visit.

Figure 72 On the left Image looking north-east into lift pit excavation and on the right Image looking northwest of lift pit excavation depicting the subvertical joints.

7.1.3.3 Conclusions

Based on the limited access available to the survey inspection team, kindly facilitated by JPC and HDL, it was clear that the nature of the contact between the overlying glacial till deposit and the underlying bedrock is complex. It is believed that the presence of the weaker mudstone bands within the Calp Limestone can be considered as planes of weakness. Large, jointed blocks of limestone, which were observed on site, were sheared off along these planes of weakness and incorporated into the glacial till. In addition, it is expected that weathered mudstone layers might appear compositionally similar to the highly over-consolidated Black Boulder Clay present beneath Dublin City. Careful review of the available borehole logs is required to ensure that strata descriptions are accurate.

7.1.4 Site Walkover – Liffey Valley

In July 2024, as part of the Calp Limestone in Dublin City Centre project, Arup organised a site visit to Liffey Valley in west Dublin, as shown in **Figure 73** to study a roadside Calp Limestone outcrop to gather structural information about the formation. A scanline survey was carried out at the rock face along the junction of R113 indicated on **Figure 76** in order to identify consistent features in the bedrock.

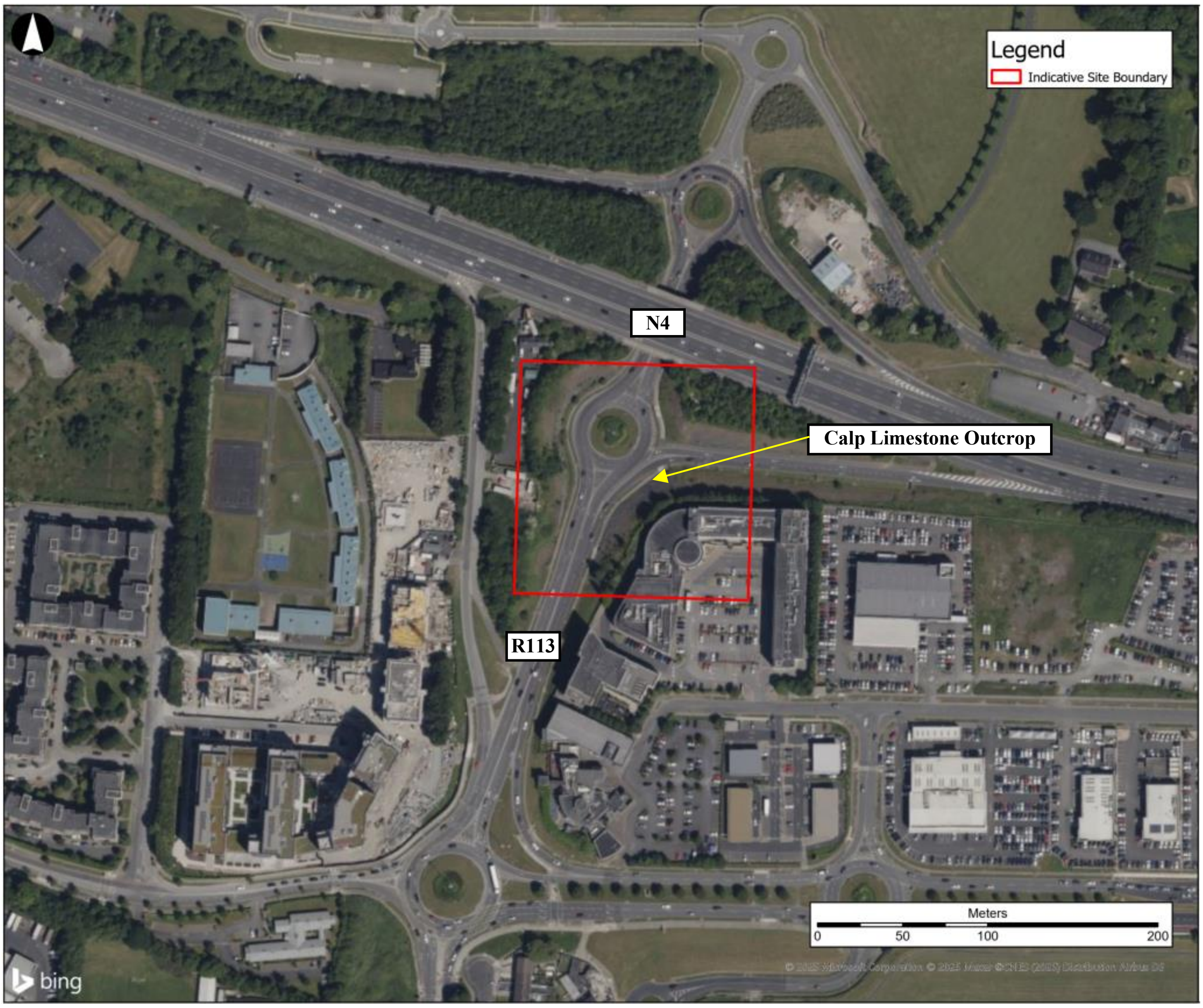


Figure 73 Liffey Valley - Site Location Plan.

7.1.4.1 Observations

The Calp Limestone outcrop section studied during the Liffey Valley site visit is shown in **Figure 74**, with more detailed sections of the exposure presented in **Figure 75**. The lower part of the outcrop, located to the east, primarily consists of medium-bedded limestone strata. Moving westwards, the geology transitions to thinly spaced mudstone strata interbedded with medium-bedded limestone layers (refer to **Figure 75**).

Figure 74 Photograph of the Calp Limestone Outcrop in Liffey Valley. (Red lines indicate the formation's bedding).

Figure 75 Photographs of the studied rock face at the Liffey Valley site.

A scanline survey, and associated hand drawn sketching, was undertaken along the eastern portion of the Liffey Valley outcrop, as shown in **Figure 76** below. The survey line measured five metres in length with an east to west strike. All discontinuities encountered along the survey line were mapped and described based on the BS5930:2015 Rock Mass Discontinuities description.

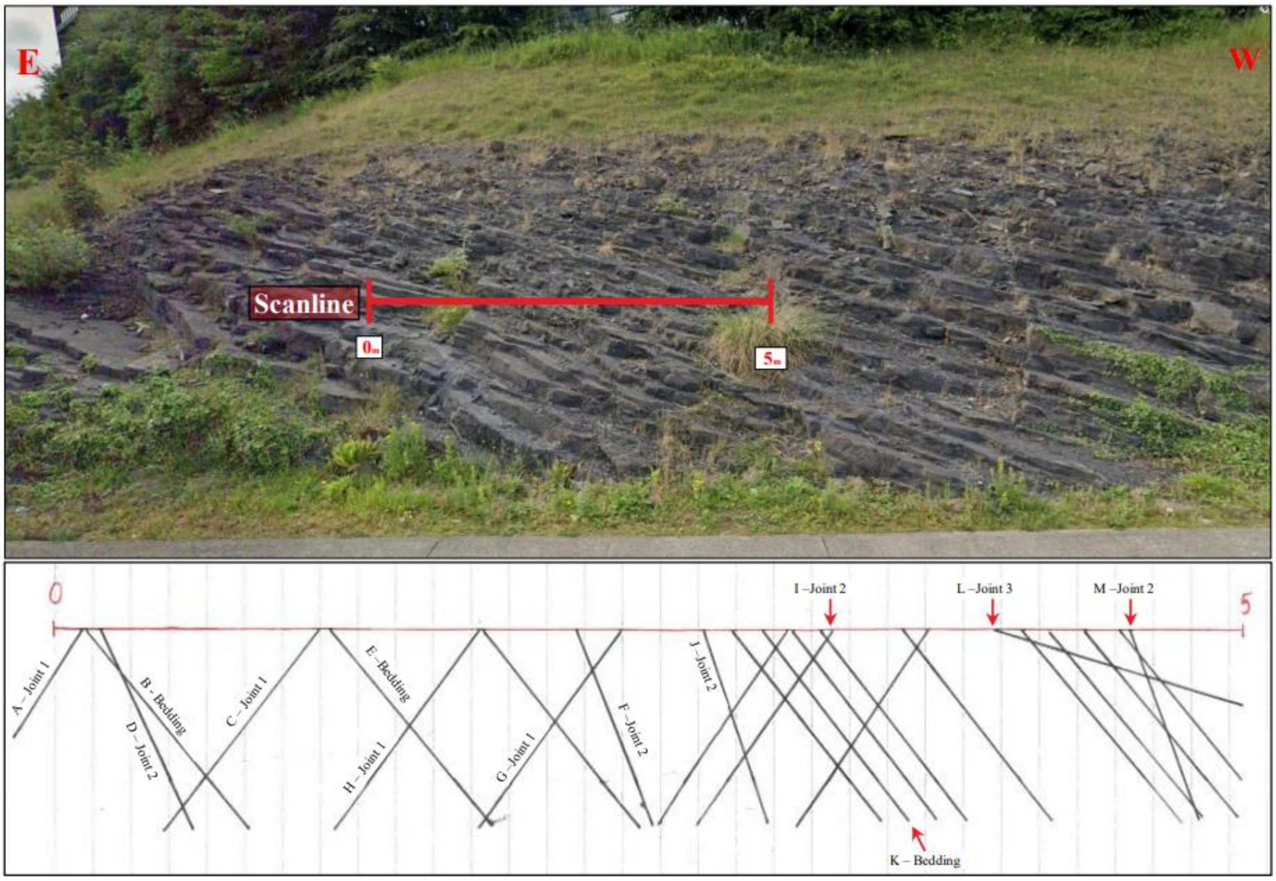


Figure 76 Scanline survey completed during the Liffey Valley site visit.

Following an analysis of the survey scanline observations taken during the site visit, it was determined that three distinct discontinuity sets were present within the Liffey Valley Calp Limestone outcrop. The discontinuity sets identified are presented in **Figure 77**, and included:

- Bedding (250º/15º)*;
- Joint set no. 1 (236º/80º) – sub-vertical joint set
- Joint set no. 2 (321º/85º) – sub-vertical joint set, and;
- Joint set no. 3 (188º/80º) – encountered only locally; terminating on bedding plane.

*(Dip directionº/Dip Angle°)

ARUP

OVE ARUP & PARTNERS

ROCK DISCONTINUITY SURVEY DATA SHEET

Job No.	Sheet No.	Rev.
297502	1	

Job title: Characterisation of Calp Limestone in Dublin City Centre

Location: Liffey Valley

Date: 23-Jul-24

Log by. LI, BOD

NATURE AND ORIENTATION OF DISCONTINUITIES

Location:	Type	Dip direction	Dip	persistence	Aperture	Infilling	Consistency	Uneveness	Waviness	Waviness	Differentially weathered zone width around discontinuity (mm)	Water	Remarks	Joint No.
A	Joint	40	72	Very High	5	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 1
B	Bedding	248	16	Very High	6-7	0	-	7	-	-	-	1	Very thinly to thinly bedded	Bedding
C	Joint	250	82	Very High	3	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 1
D	Joint	316	90	Very High	4	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 2
E	Bedding	238	15	Very High	6-7	0	-	7	-	-	-	1	Very thinly to thinly bedded	Bedding
F	Joint	320	83	Very High	4	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 2
G	Joint	220	78	Very High	5	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 1
H	Bedding	262	13	Very High	6-7	0	-	7	-	-	-	1	Very thinly to thinly bedded	Bedding
I	Joint	50	74	Very High	5	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 1
J	Joint	318	80	Very High	4	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 2
K	Joint	240	86	Very High	3	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 1
L	Joint	188	80	Termination on bedding	5	1	-	5	-	-	-	1	Widely spaced	Joint 3
M	Joint	330	88	Very High	4	1	-	5	-	-	-	1	Medium to Widely spaced	Joint 2

TYPE	Dip direction,Dip	Persistence	Aperture	Nature of infilling	Consistency of infilling		Uneveness	Waviness	Water
0. Fault zone	Expressed in degrees	Maximum dimension	1. Wide (>200mm)	0. Clean	Soil strength	Rock strength	(Small-scale roughness)	(large-scale	1. Dry
2. Joint		of trace length	2. Mod.wide (60-200mm)	1. Sur. staining	1. Very soft	11. Strong	1. Rough stepped	roughness)	2. Damp/wet
3. Cleavage		on exposed face	3. Mod.narrow(20-60mm)	2. Decomposed/	2. Soft	12. Very strong	2. Smooth stepped	Express	3. Seepage
4. Schistosity		expressed in metres	4. Narrow(6-20mm)	disintegrated rock	3. Firm	13. Extremely strong	3. Slickensided stepped	wavelength	present
5. Shear plane			5. Very narrow(2-6mm)	3. Non-cohesive	4. Stiff		4. Rough undulating	& amplitude	(estimate
6. Fissure			6. Ext.narrow(>0-2mm)	4. Cohesive	5.Very stiff or hard		5. Smooth undualating	in metres	quantity
7. Tension crack			7. Tight (zero)	5. Quartz	6. Extremely weak		6. Slickensided undulating		seperately
8. Foilation				6. Calcite	7. Very weak		7. Rough planar		in litres/sec
9. Bedding				7. Manganese	8. Weak		8. Smooth planar		or litres/min)
				8. Kaolin	9. Moderately weak		9. Slickensided planar		
				9. Other-specify	10. Moderately strong				

Figure 77 Rock Discontinuity survey data sheet.

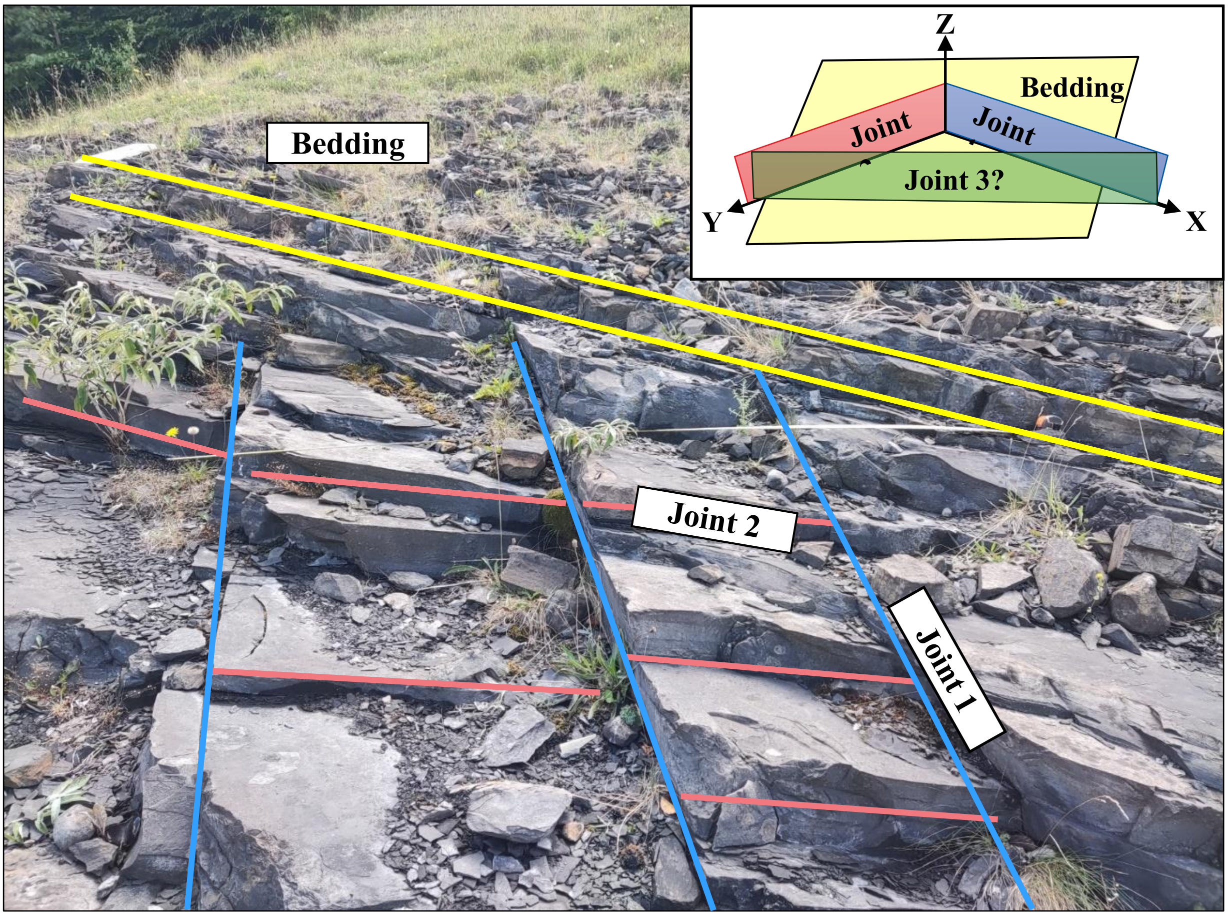


Figure 78 Discontinuity sets identified during the Liffey Valley site visit.

7.1.5 Site Walkover – Belgard Quarry

In July 2024, as part of the Calp Limestone in Dublin City Centre project, Arup organised a site visit to Belgard Quarry, located in Tallaght, Co. Dublin, as shown in **Figure 79**. Belgard Quarry, operated by Roadstone Ltd., is the largest limestone quarry in Ireland.

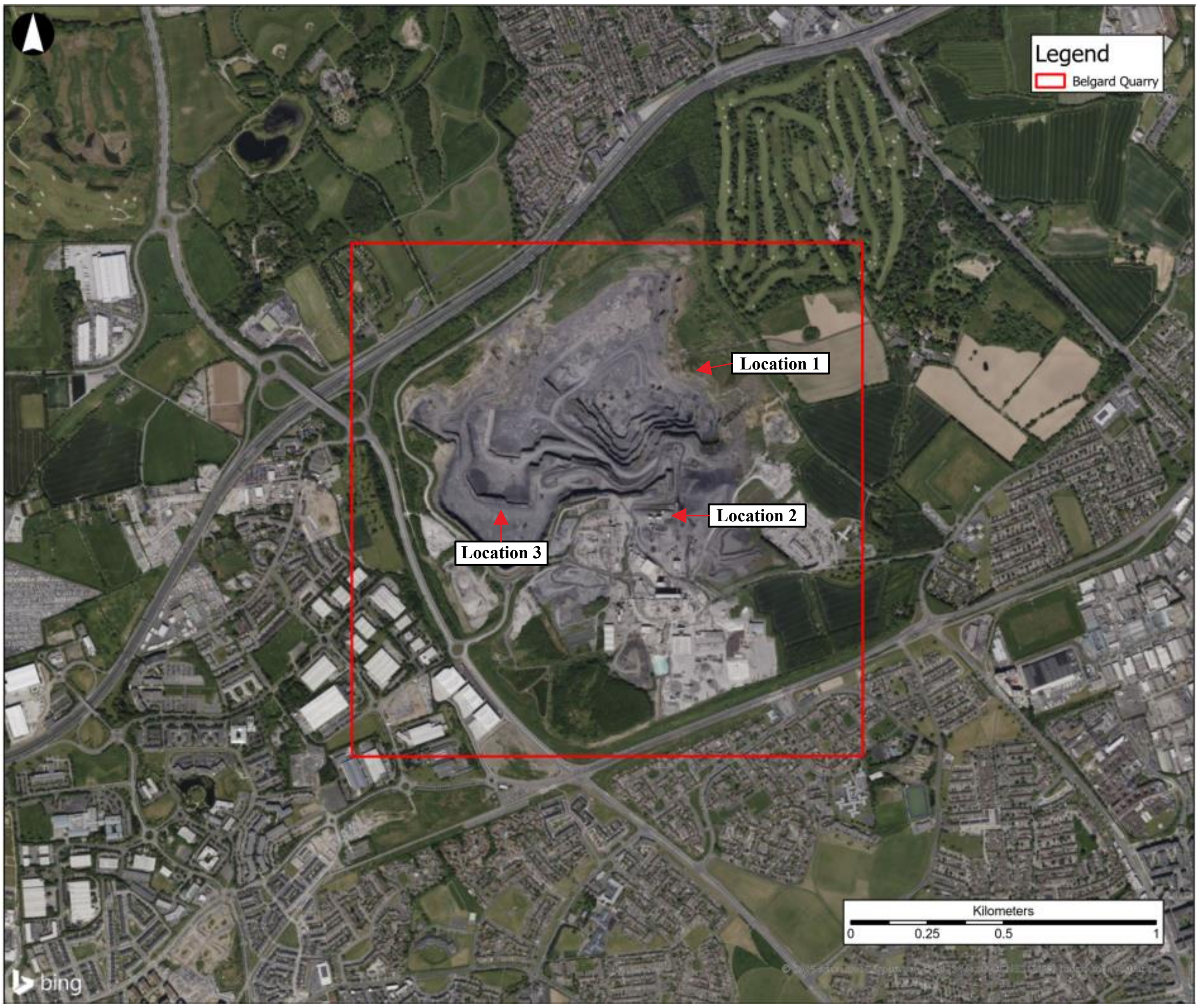


Figure 79 Belgard Quarry – Site Location Plan.

7.1.5.1 Observations

The first location visited during the site visit was Location 1, as shown in **Figure 80**. Location 1, located on the upper outer rim of the quarry, offered panoramic views of the quarry excavation from which areas of interest for detailed study were identified. Based on these observations, Location 2 was chosen due to the bedrock being heavily folded with fault features present. Location 3 was selected because the freshly exposed faces were ideal for studying the discontinuities of the rock mass.

Figure 80 Panoramic view of Belgard quarry (Location 1).

Location 2

Location 2, located in the central portion of the quarry excavation, was chosen due to the prevalence of folding and faulting of the rock mass. In the western section of Location 2, the rock face was relatively uniform in stratigraphy, as shown in **Figure 81**. The upper portion of the rock face was characterised predominantly by sub-horizontally, thinly bedded mudstone. The laminations and thin beds of mudstone gave this portion of the rock face a more massive appearance. The lower portion of the rock face was characterised predominantly by sub-horizontally, thickly bedded limestone which was blocky in structure.

Iron oxide staining, over approximately two metres, was observed on the exposed face. The oxidation appears to be associated with the minor interbedded mudstone layers, leaching down the exposed quarry face.

Figure 81 Belgard Quarry (Location 2) – western section.

In the central and eastern section of Location 2, increased folding and faulting of the rock mass was observed. It was observed that the competent limestone layers were less easily deformed than the weaker mudstone layers, as seen in **Figure 82**.

A zone of brecciated (reworked) material that more closely resembles soil than rock was noted in the central portion of Location 2. Clay infilling was observed in the open discontinuity with vegetation growth and water seepage strongly indicating the presence of a fault and a potential tufa spring (**Figure 82**). The dip of mudstone and limestone bedding was observed to change on either side of the central brecciated zone (indicated by straight red lines in **Figure 82**). Whilst folding and potential fault zones were common at Location 2, folding at the other faces of the quarry which were visited was minimal or absent.

Figure 82 Belgard Quarry (Location 2) – eastern section.

Location 3

Location 3 was chosen due to the freshly exposed faces along this section of Belgard Quarry. Location 3 consisted mostly of limestone with interbedded thin layers of mudstone. The fresher rock faces allowed for easy identification of the rock mass discontinuities (**Figure 83**).

The rock faces at Location 3 consistently exhibited two subvertical joint sets and bedding as discontinuities. A third joint was potentially observed locally (**Figure 83**), which, due to its orientation, could act as a releasing surface between Joint 1 and Joint 2. However, the data is insufficient to determine whether this is a unique joint set or simply a variation of Joint 1 with a slightly different dip direction.

Furthermore, cross bedding was potentially identified in the limestone layers, as shown in **Figure 83**. The bedding is seen dipping gently to the southwest.

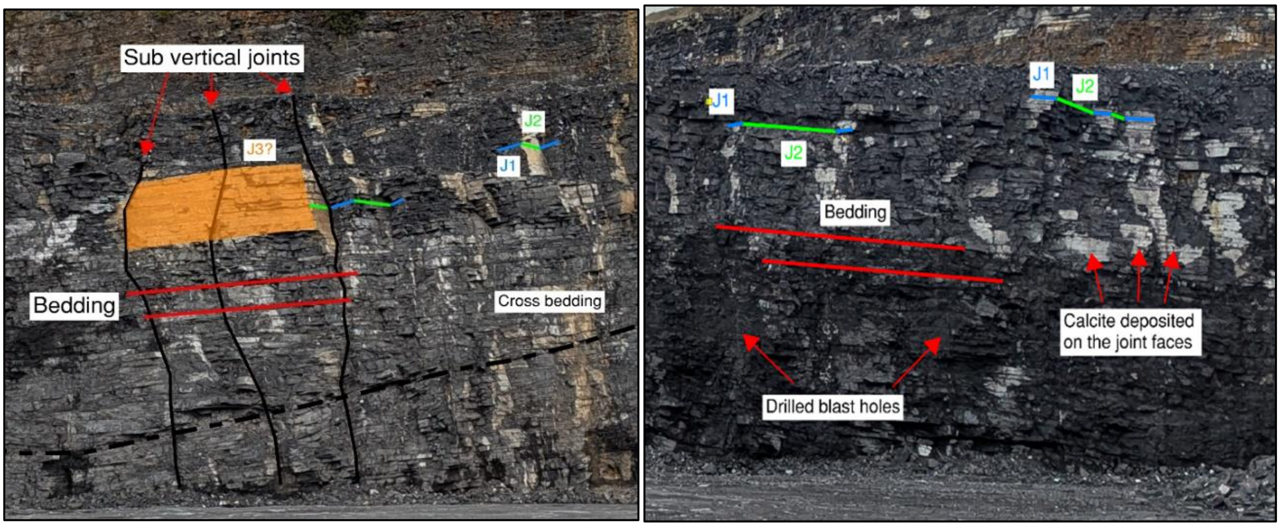


Figure 83 Belgard Quarry rock mass discontinuities.

7.1.6 Site Walkover – One Adelaide Road

In June 2025, a group from Arup visited the site at One Adelaide Road, Dublin 2, where excavation work was underway for the foundations of a multistorey development with two basement levels, as shown in **Figure 84**.

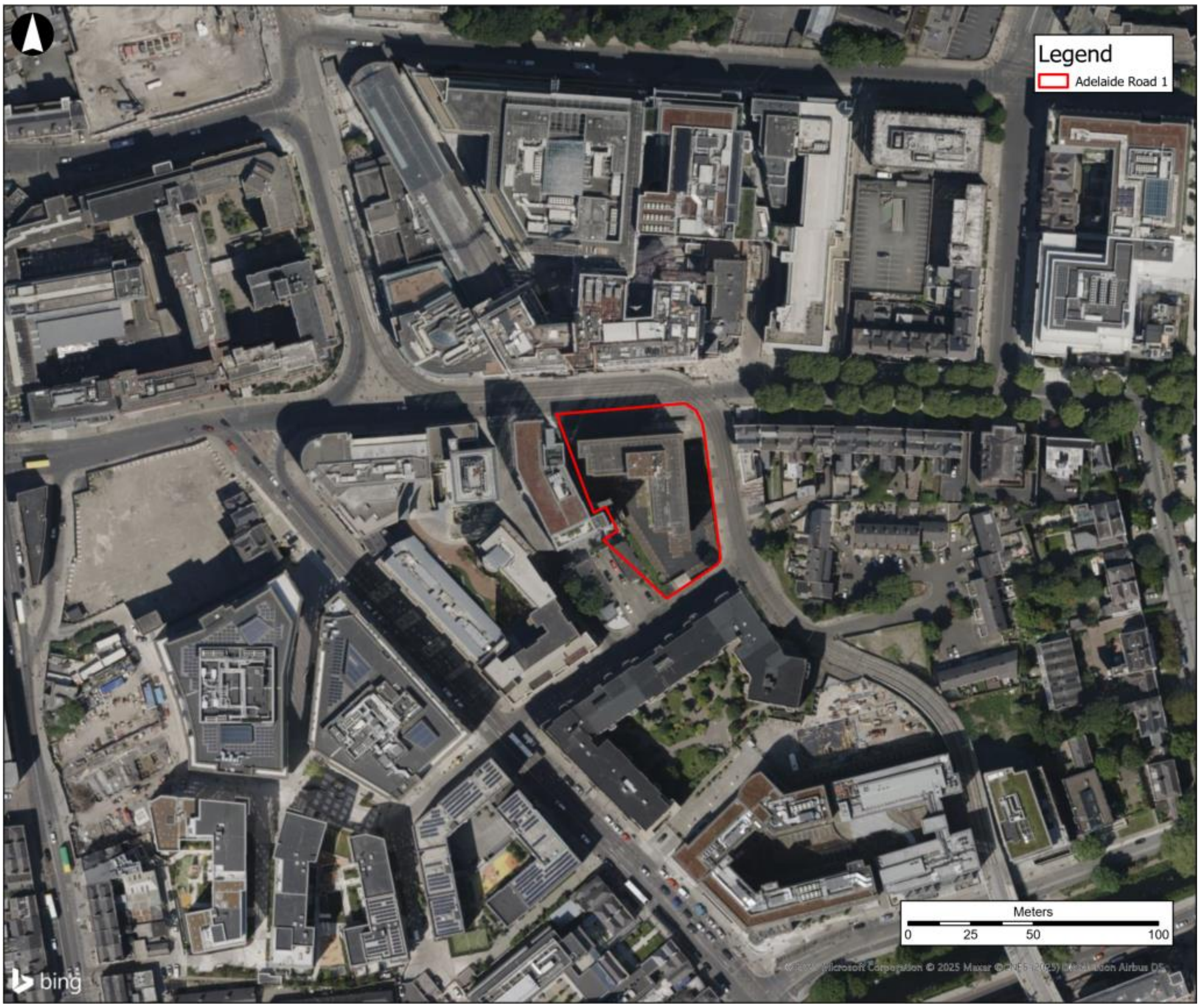


Figure 84 One Adelaide Road – Site location plan.

Walls, the contractor responsible for the works on site, was present to give a short introductory briefing and grant site access. Further briefings were also provided, during which the following topics were discussed:

- Settlement and vibration monitoring to assess impact on the adjacent Luas line and nearby buildings;
- Ground conditions encountered across the site during excavation;
- The sequence of the works on site; and
- Temporary construction activities including secant pile walls and dewatering of the site.

Figure 85 Photograph of the face of the excavation.

7.1.6.1 Ground Conditions

The excavation exposed faces approximately 10 metres in length, and locally particularly near the centre reaching depths of around 12 metres. These faces revealed a sequence of brown boulder clay overlying black boulder clay, which in turn overlies the bedrock. The black boulder clay was observed standing in near-vertical slopes without any signs of instability or collapse, while excavators were operating safely at the top of these slopes.

Figure 86 Photograph showing the vertical faces of the excavation and the bedrock exposure at distance.

7.1.6.2 Bedrock – Calp Limestone

The bedrock was the typical Calp Limestone encountered across Dublin City Centre. A highly heterogeneous rock mass consisted of interbedded thin layers of mudstone and limestone. The rock mass encountered can be typically described as fresh to partially weathered medium strong to strong, thinly to medium bedded, light/dark grey, fine to medium grained, LIMESTONE. Interbedded with weak, thickly laminated to thinly bedded, light/dark greyish black, very fine-grained MUDSTONE. Occasional calcite veins. Blocky jointing.

An orthogonal set of discontinuities was observed, consisting of two subvertical joint sets and bedding planes. The bedding was particularly evident in the thicker limestone layers and exhibited a sub-horizontal dip, trending towards the unexcavated portion of the site. It was also noted that soft piles tended to terminate (refuse) at the thicker limestone beds, whereas hard piles were able to penetrate these layers and extend to greater depths.

No evidence of weathered bedrock was observed during the site visit; however, if present, it may have been covered by the secant pile wall. Calcite veins were occasionally visible, typically along vertical joints.

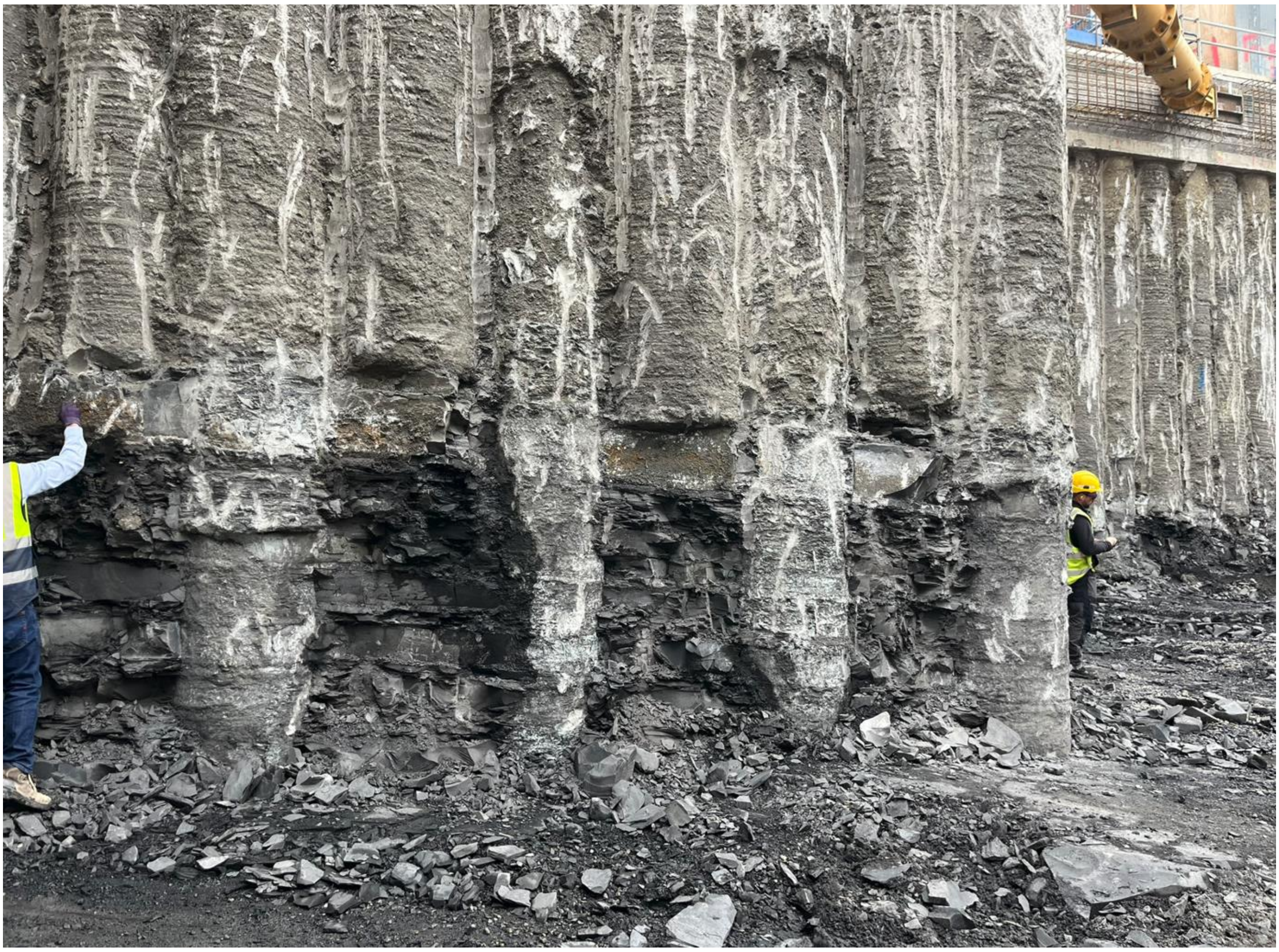


Figure 87 Calp Limestone exposure at the One Adelaide Road site.

Additionally, the rock exposed beneath the secant piles was wet in places, potentially indicating groundwater ingress into the excavation. The dewatering through pumping of the site is expected to stop after the construction of the third floor of the building.

Figure 88 Calp Limestone exposure at the One Adelaide Road site.

The current level of excavation, as can be seen in **Figure 89** below was not yet completed at the time of the site visit. A protective layer of 150mm of intact bedrock geology had been retained above the design formation level in order to protect the subformation from exposure. Water ponding, either as a result of surface water ponding or groundwater ingress, was observed at the base of the excavation.

Figure 89 Surface of excavation at the One Adelaide Road site.

7.1.7 Site visit findings

Visual observation of the rock mass during site visits of locations around Dublin City provided invaluable insights into better understanding the geological regime of the Calp Limestone. Geological features, which are typically studied with limitations in boreholes, were visible across differing scales from shallow excavation to hundreds of metres of exposed faces in Belgard Quarry.

The main findings from the site visits are summarised below:

- No distinctly weathered bedrock or significant thicknesses of weathered bedrock were observed at the contact between the overburden and bedrock.
- It is clear that varying proportions of mudstone and limestone will yield different mechanical indices for the rock mass under certain applications.
- Folding and faulting are particularly challenging to identify and study in boreholes. For that reason, the on-site study of the structural trends visible in the exposed faces of Belgard Quarry are expected to yield valuable context which can be applied to the dip measurements from boreholes and their relationship to the structural regime within the Calp Limestone.
- Based on the observations of the Calp Limestone sections at Belgard Quarry, consistent features in the bedrock were identified, including two subvertical joint sets and the bedding. These in situ observations correspond with the consistent bedding and joint sets identified in the stereonets from the study area, aligning with findings from previous site visits, and matching expectations from the literature.
- Site visits to Belgard Quarry and Liffey Valley confirmed the presence of two subvertical joint sets. However, a potential third set was also identified, which is not always observed through stereographic analysis. The prevalence of the potential third joint set should be investigated further based on analysis of downhole geophysical data and drone surveying.

8. Engineering Considerations

This section discusses the engineering considerations of working with the Calp Limestone. Potential uses of the Calp Limestone material are discussed. Potential ground investigation techniques for consideration when sampling and testing the Calp Limestone, including intrusive methods, non-intrusive methods, and laboratory testing, are also presented.

8.1 Engineering implications and considerations

The engineering considerations for the Calp Limestone will vary dependant on the scale of project, type of works proposed (e.g. depth, scale and purpose of excavation or interaction with the Calp Limestone).

Shallow foundations, while less common in Dublin City Centre due to overburden thickness, may interact with weathered bedrock surfaces and risk potential differential settlement where bedrock undulates.

When deeper piled foundations are necessary, their interaction with the Calp Limestone may occur in several ways:

- End-bearing on competent limestone:
  - Variations in shaft resistance can arise due to transitions between stiff glacial till, weathered and competent Calp Limestone.
  - The presence of fractures, joints, and weak mudstone interbeds may locally diminish rock mass strength or create potential slip planes.
- Rock socketed into the Calp Limestone:
  - Foundations are socketed into competent limestone.
  - Socket capacity may be controlled more by rock mass quality (RQD, fracture frequency) than by intact strength due to interbedded mudstones.

Major city-centre projects (e.g. deep basements, MetroLink) typically require deep excavations or retaining systems interacting directly with Calp Limestone. Common interaction mechanisms include:

- Founding of retaining structures where excavation meets rock head.
- Rock mass instability arising from blocky structure and oriented joint sets.
- Groundwater inflow along fractures or shale partings, even though Calp Limestone is generally non-karstic.
- Transition challenges where overburden–rock interface is highly irregular.
- Overnight softening of material in drillhole shafts (for example, Heuston Station).

Tunnelling considerations within the Calp Limestone include:

- Tunnel Boring Machine (TBM) selection
- Stress redistribution within fractured Calp Limestone.
- Potential overbreak where encountering shale bands or blocky jointed zones.

8.1.1 Sampling Bias

Due to the requirements for intact rock strength laboratory measurements, samples tend to be selected from more intact pieces of core, namely the limestone. As noted in **Section 6.2.1** there is very limited data available for the mudstone, with only seven UCS tests conducted on mudstone samples compared to 378 for limestone.

8.1.2 Geotechnical Design Considerations

The following issues are considered to be important for future geotechnical design in the Calp Limestone:

- Whilst the risk of deep glacial disturbance appears to be low, the potential variations in rock head and depth of glaciotectonised rock along with the effect on foundation depth and stability of retaining structures should be carefully assessed.
- A rigorous assessment of project specific ground investigation information is critical in ensuring the nature of the Calp Limestone within a specific project site is understood and a comprehensive borehole log produced to avoid underestimating fracture frequencies.
- In the Calp Limestone, the sub-horizontal bedding and sub-vertical orthogonal joints can be favourable for the sidewall stability of a basement or deep excavation. However, the rock mass is very blocky so stability of the overall rock mass shear strength and stiffness should be assessed.
- It was noted in a number of locations across the study area that the principal bedding parallel discontinuity set is moderately inclined, most likely due to folding or faulting. This inclination may potentially be at angles in excess of the peak friction angles of the discontinuities. Due to the potentially high persistence of the bedding set, where dipping bedding planes occur or for sloping excavations, the risk of sliding failure may need to be assessed.
- Discrete failure mechanisms will need to be assessed to identify the influence of other inclined joints on excavation stability. Whilst much lower in persistence, these other joint sets may result in local block failure.
- The quarry exposures assessed during this study suggest that sudden re-orientations of bedding can occur near fold hinge zones and faults. In addition to stability considerations, the generally more fractured nature of the rock, and hence the elevated risk of greater groundwater inflows, will need to be considered.
- The potential for high ground water inflows through high persistence bedding planes/shale beds should also be considered.
- The presence of fault gouge zones at a low angle to an excavation or tunnel alignment could result in significant sections of the drives at risk of face and crown instability and potentially ravelling ground conditions. Appropriate measures, for example forward probing, will need to be considered.
- The potential for high persistence, low shear strength, carbonaceous shale laminae/beds needs to be considered in design.

8.2 Earthworks and Reusability

8.2.1 Excavatability

It is possible to assess the excavatability of the Calp Limestone rock mass based on the intact strength of the rock and the frequency of discontinuities. Geophysical measurements of P-wave velocities within the rock mass are also useful when assessing rock mass excavatability, however, this was not included in this study.

A preliminary assessment of the excavatability of the rock mass can be made, based on the geotechnical rock mass assessment described in **Section 6**. The following cases have been assessed:

- Calp Limestone – limestone material:
  - typical bedding spacing 100 to 600 mm;
  - sub-vertical joint spacing 300 to 1500 mm;
  - intact point load strength 6.5 MPa;
- Calp Limestone – mudstone/shale material:
  - typical bedding joint spacing 100 to 500 mm;

- sub-vertical joint spacing 1 to 3 m (based on minimal data set);
- intact point load strength 3.0 MPa;

Findings from this assessment include:

- Mechanical methods are potentially feasible to excavate the Calp limestone and mudstone/shale.
- Whilst mechanical excavation is beneficial in terms of minimising the excavation disturbance zone around the excavation, the actual choice of excavation method will depend on the Contractor's preferred methods of work, programme, and equipment available.

8.2.2 Testing standards and guidance

Excavated or quarried bedrock material, as shown in **Figure 90**, may be used as aggregates for construction. Common uses include as unbound granular fill or as aggregate for concrete.

Figure 90 Calp Limestone, Belgard Quarry, Dublin

For bedrock to be shown as suitable for use, it must be shown to fulfil the relevant engineering specifications corresponding to their proposed use, in accordance with relevant guidance, as shown in

Earthworks Specification for National Roads

CC-SPW-00600

September 2024

NSAI Standards

Standard Recommendation S.R. 16:2016

Guidance on the use of I.S. EN 12620:2002 +A1:2008 - Aggregates for concrete

Road Pavements – Unbound and Hydraulically Bound Mixtures

CC-SPW-00800

October 2023

NSAI Standards

Standard Recommendation S.R. 21:2014+A1:2016

Guidance on the use of I.S. EN 13242:2002 +A1:2007 – Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction

Figure 91 below. Some examples are provided below:

- Transport Infrastructure Ireland (TII), Series 600, CC-SPW-00600, Earthworks specification for national roads;

- Transport Infrastructure Ireland (TII), Series 800, CC-SPW-00800, Road Pavements – Unbound and Hydraulically Bound Mixtures;
- Standard Recommendation (SR) 16:2016, Guidance on the use of IS EN 12620:2002+A1:2008 – aggregates for concrete; and,
- Standard Recommendation (SR) 21:2014, Guidance on the use of IS EN 13242:2002+A1:2007 – Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction (+A1:2016)


Earthworks Specification for National Roads

CC-SPW-00600

September 2024

Road Pavements – Unbound and Hydraulically Bound Mixtures

CC-SPW-00800
October 2023

NSAI Standards
Standard Recommendation
S.R. 16:2016

Guidance on the use of I.S. EN 12620:2002 +A1:2008 - Aggregates for concrete

NSAI Standards
Standard Recommendation
S.R. 21:2014+A1:2016

Guidance on the use of I.S. EN 13242:2002 +A1:2007 – Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction

Figure 91 Relevant standards and guidance documents for reuse suitability testing.

8.2.3 Material Composition

A critical parameter which needs to be considered that will have an impact on the performance of the bedrock as an aggregate is the actual rock type itself.

The nature of the rock, such as features like the mineralogy, fabric, and inherent structure, will impact upon its performance for various uses.

Some rock types are specifically excluded from certain uses, such as mudrocks for structural fill. This is due to their weak strength, laminated structure leading to high water absorption, and the possibility of encountering fine grained sulfide minerals such as pyrite which could oxidise leading to a number of potential problems.

The rock material should be described in detail, using the standardised BS5930:2015 methodology which details the grain size, mineralogy, and provenance of the rock.

If there is any ambiguity on the composition or provenance of the rock, additional methods beyond a visual description can be employed, such as:

- Preparation of thin sections to facilitate a petrographic assessment of the rock to understand the fabric and mineralogy of the rock, as shown in **Figure 92**.
- X-ray diffraction, which provides a semi-quantitative assessment of the different minerals present and their relative proportions.
- Scanning Electron Microscopy (SEM), and EDAX (Energy Dispersive Analysis of X-rays) testing to look at high resolution images at massive magnifications along with a breakdown of the elemental composition of grains, as shown in **Figure 93**.

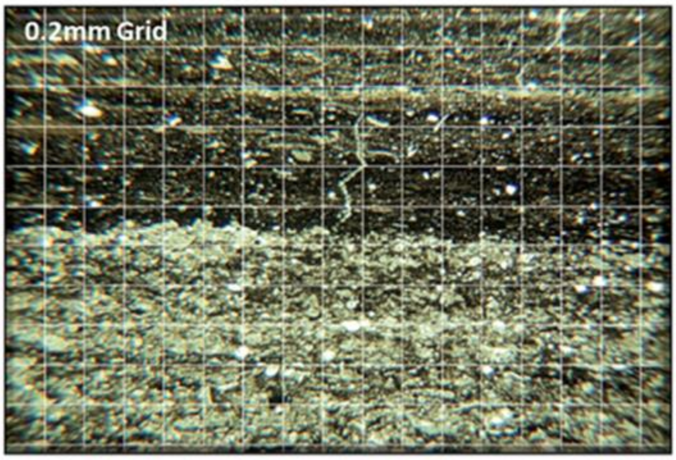
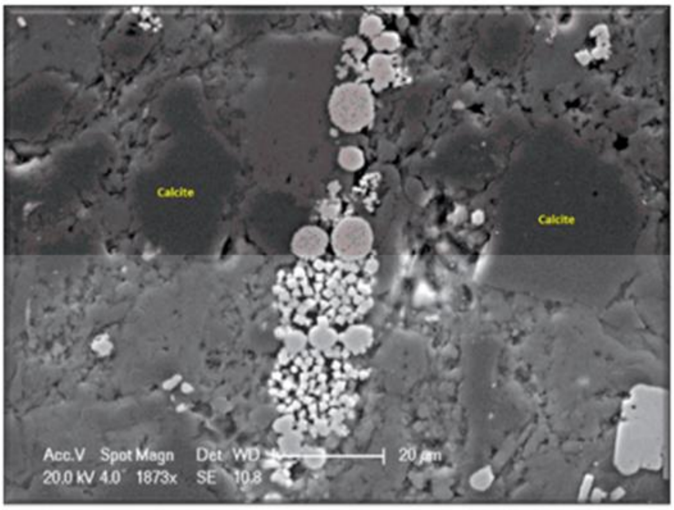


Figure 92 Thin section of bedded mudstone with cross-fractures from the Dublin region (Matheson and Quigley, 2014).



(Orig. Magn. 1873x) 20µm

Figure 93 Pyrite Framboids within mudstone samples from the Dublin region as viewed under a Scanning Electron Microscope (SEM) (Matheson and Quigley, 2014).

8.2.4 Common tests for aggregates

In accordance with the standards and guidance documents listed in **Section 8.2.2**, there are several common aggregate tests which are used to assess the suitability of bedrock for use as aggregates, including:

- Grading
- Los Angeles (LA) Abrasion - Durability
- Micro Deval - Durability
- Slake Durability - Durability
- Magnesium Sulfate Soundness – weathering resistance
- Water Absorption – weathering resistance
- Plasticity Index - Workability
- Particle Density – Physical property
- Flakiness Index – Shape of clasts

Chemical testing, which is important for concrete aggressivity analysis and the identification of potentially deleterious sulfides, includes:

- Total sulfur
- Acid soluble sulfate
- Water soluble sulfate
- Chloride
- Carbonate Content
- pH

A number of these properties are functions of the processing of the rock and, as such, the processing can influence some properties. However, a number of these parameters are intrinsic to the type of rock tested, and therefore independent of processing, such as those relating to durability, shape, and chemical composition.

The main tests carried out on the bedrock in the studies reviewed as part of this project were rock strength testing (UCS / PLTs).

8.2.5 Conclusions and Recommendations

To fully assess the re-use potential of the bedrock beneath the study area, accurate descriptions of the bedrock material and rock mass are required. As detailed in **Section 8.2.3**, mudstones and mudrocks are typically not suitable for reuse as aggregates.

Given the interbedded nature of the bedrock, an element of processing would be required to eliminate the undesirable mudstone from the arisings. Careful sampling is required to ensure that the tested material is representative of what is proposed to be used. The presence of interbedded mudrocks would have an impact on the test results.

Testing would need to be carried out on the limestone element of the Calp Limestone to determine its suitability for use. Freshly blasted Calp Limestone prior to processing can be seen in **Figure 94**. The ultimate test suite would have to reflect the proposed use for the material.

Figure 94 Blocky Calp Limestone as a result of blasting in Belgard Quarry.

8.3 Ground Investigation

8.3.1 Introduction

This section looks at the suitability of various ground investigation techniques within the Calp Limestone and makes a recommendation for the optimal ground investigation scope (subject to the requirements of a project). An overview of commonly used drilling and testing techniques are presented. However, there is no standardised ground investigation scope that is universally preferred.

The choice of investigation method depends on the specific objectives of a project and the ground conditions anticipated, which can vary significantly within a site boundary. To address this variability, this section recommends techniques that are considered suitable under specific applications. The purpose of this section is to offer general guidance, not to prescribe fixed methods.

The proposed drilling techniques selection table should be adapted to the needs of each project and not applied without considering site-specific conditions.

The standards and guidance documents relating to ground investigations in Ireland, as shown in **Figure 95**, include:

- CEN (2007) Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing (I.S. EN 1997-2:2007). Brussels: European Committee for Standardization.
- Engineers Ireland (2016**)** Specification and Related Documents for Ground Investigation. Dublin: Engineers Ireland.

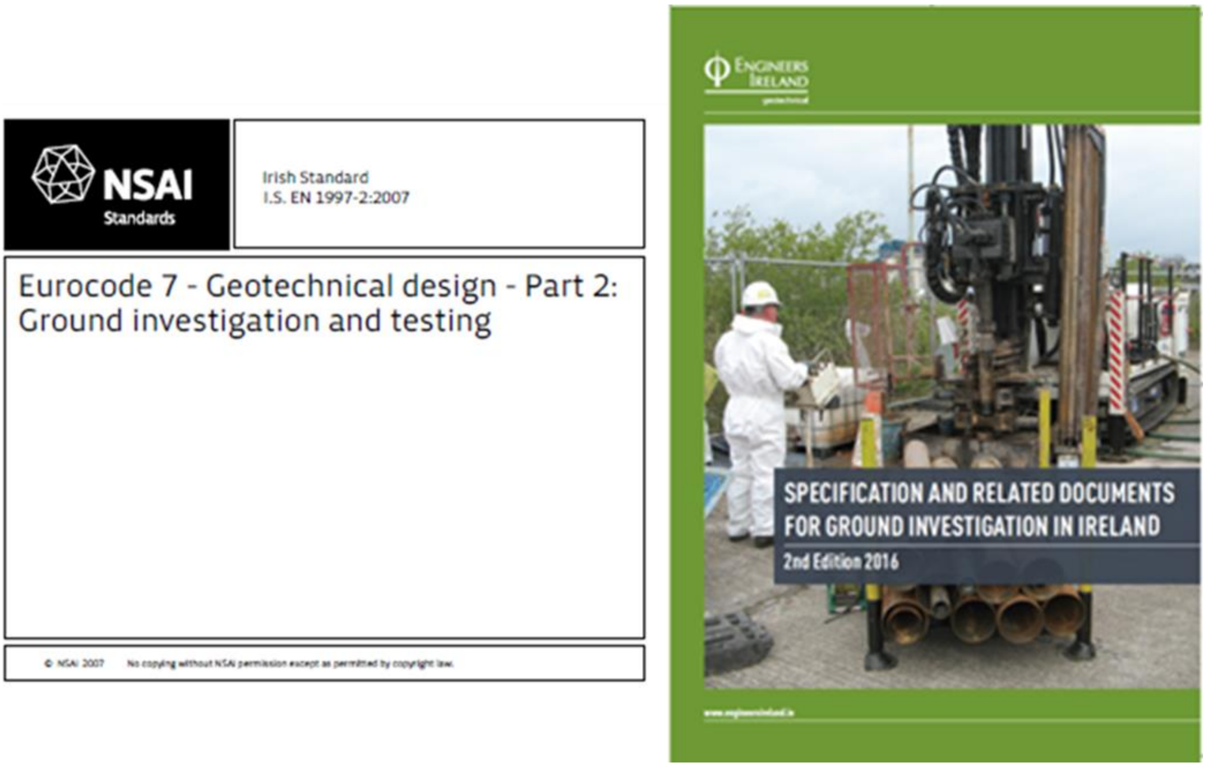


Figure 95 Standards and guidance documents relating to ground investigations. Left) Eurocode 7 – I.S EN 1997-2:2007; Right) Specification and related documents for ground investigation, Engineers Ireland, 2016.

8.3.2 Ground Investigation Methodology

8.3.2.1 Desk Study

Desk Study

Conducting a desk study before scoping a ground investigation is a crucial step in understanding the underlying Calp Limestone and overall site conditions. A thorough desk study can help in designing a more focused and efficient ground investigation. By understanding the anticipated site conditions beforehand, unnecessary or redundant investigation techniques can be avoided, saving both time, costs, and resources.

The information gathered during the desk study helps in planning the scope and methodology of the ground investigation. Desk study information allows for the identification of key areas that require detailed investigation, including high risk findings or knowledge gaps, and helps in determining the appropriate techniques and equipment to be used.

8.3.2.2 Geophysical surveying

Surface Geophysics

Surface geophysical surveying involve non-intrusive techniques that require calibrations and correlations. These techniques have environmental limitations and can be affected by cultural noise in urban settings and reinforced concrete/existing services. Spatial limitations may also affect the depth of penetration of surface applications due to spatial constraints.

There are multiple methods of surface geophysics. Two such methods, Electrical resistivity surveying and seismic surveying are particularly appropriate for the determination of subsurface stratigraphy, and these are outlined below.

Electrical resistivity surveying

In electrical resistivity surveying, or Electrical Resistivity Tomography (ERT), an electrical current (I) is introduced into the ground using two electrodes, and the resulting voltage (V) is measured across a separate pair of electrodes. The resistance is calculated as the ratio of voltage to current (V/I), and when adjusted by a geometric factor based on electrode spacing, it yields the apparent resistivity of the subsurface.

ERT is commonly used to identify:

- Depth to bedrock;
- Structural features such as faults or dykes;
- Weathering profiles;
- Karst features; and/or,
- Organic contamination in groundwater.

In the context of the Calp Limestone, along with resolving the top of rock, ERT can be useful for detecting faults and weathered zones within the rock mass. However, in Dublin City, the technique may produce unreliable results due to high levels of anthropogenic (man-made) electrical noise interfering with the signal. This can be avoided in areas such as city parks. **Figure 96** shows an ERT survey set-up completed in a greenfield site and an example of an ERT tomography profile completed in Dublin City Centre.

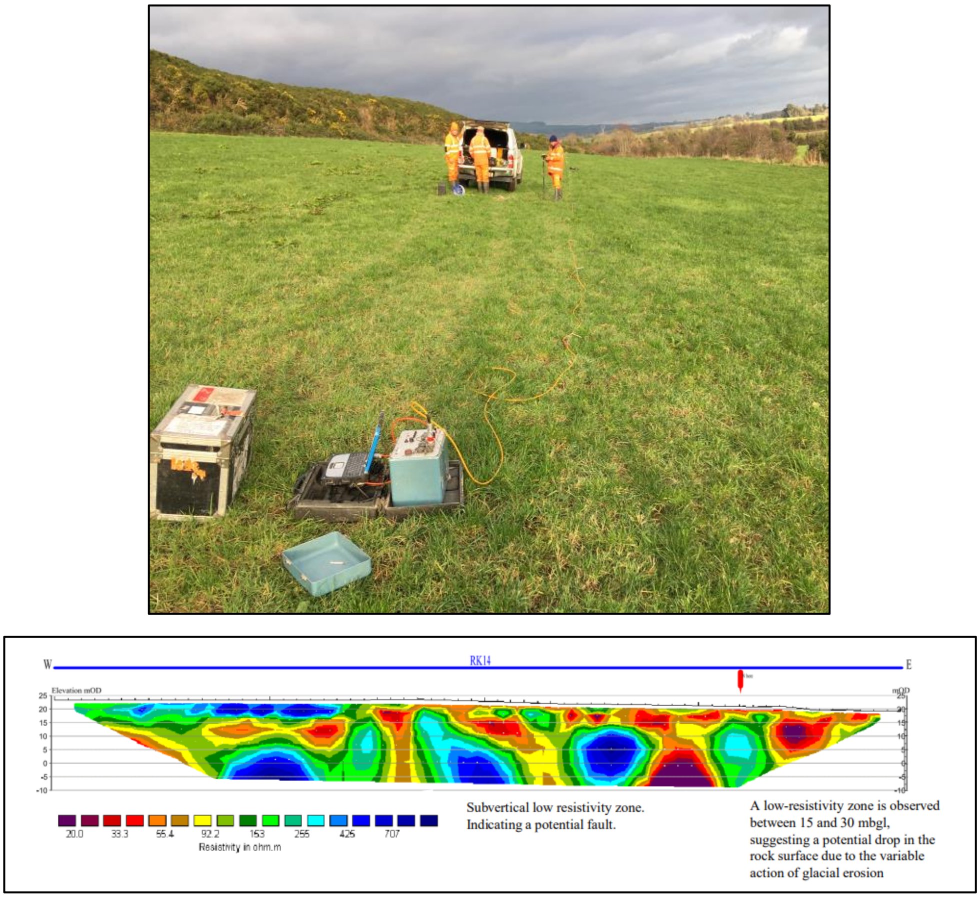


Figure 96 Above) Electrical Resistivity Tomography (ERT) survey set-up in rural environment; Below) ERT tomography profile results from Dublin City Centre.

Seismic Surveys (SRF/MASW) - Applications: Bedrock profiling and assessment of rock excavatability and rippability

Seismic surveys are the main type of geophysical survey that is expected to yield adequate results for depth to rock profile despite the challenging urban setting of Dublin City. Working constraints may include working at night to minimize disturbance from ambient urban noise ().

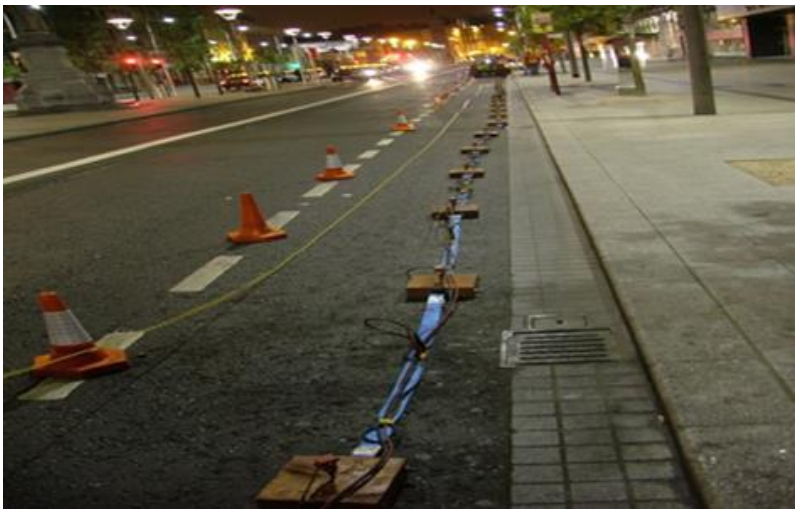


Figure 97 Surface seismic survey set up in Dublin City Centre (O'Connell Street). Set up is applicable for both Seismic Refraction (SRF) and Multichannel Analysis of Surface Waves (MASW) surveys.

Seismic Refraction (SRF) and Multichannel Analysis of Surface Waves (MASW) survey data is collected by recording the passage of an acoustic wave passed a string of geophones, but the point of interest differs.

For SRF it is the time taken for the "Primary" P wave, a longitudinal and compressional wave that travels through any kind of material, including fluids and air, to travel from the shot point to each geophone. Focus is given in the first arrival time. Changes in arrival-time trends reflect velocity changes within the subsurface.

MASW focuses on analysing those slower surface waves that arrive after the first, faster P-waves. These surface waves carry information about the stiffness of the ground. They are made up of many different wave frequencies combined. The frequency (or wavelength) of the wave controls how deep the wave can travel—lower frequencies go deeper, and higher frequencies stay near the surface. The speed of the wave depends on how stiff or soft the ground is, which relates to the shear wave velocity of the material.

Examples of both SRF and MASW tomography plots are shown in **Figure 98** below.

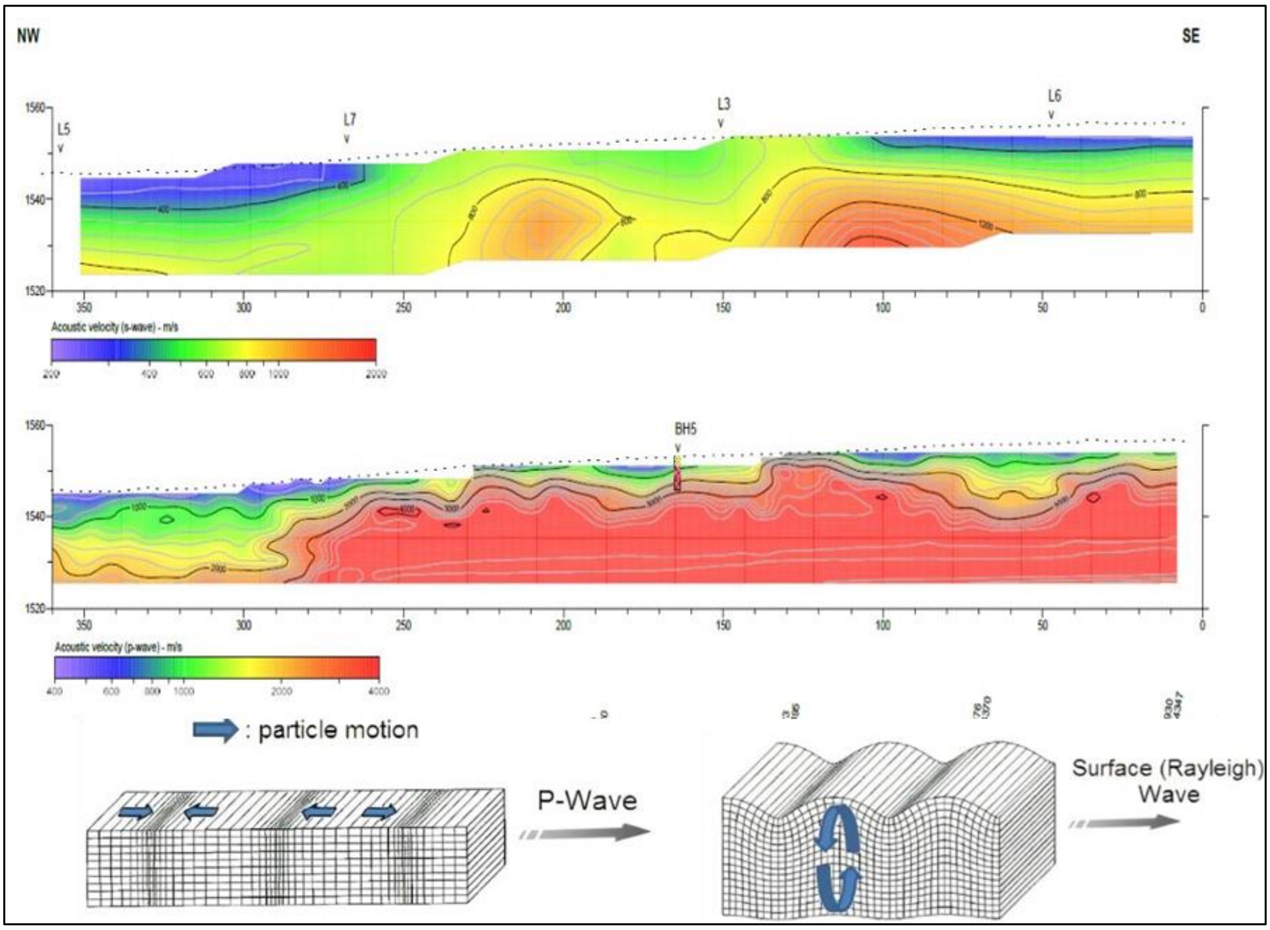


Figure 98 Seismic Refraction (SRF) and Multichannel Analysis of Surface Waves (MASW) tomography plots.

In the context of Calp Limestone, discrete changes in physical properties (from stiff Boulder Clay to weathered rock to competent rock) may not be discernible by some surface geophysical techniques. Variable thickness in overburden often exceeds the depth of penetration of surface applications due to spatial constraints, such as survey depth being limited to less than 20 metres.

Seismic surveying has been performed within the Calp Limestone of Dublin City Centre (Maggio, *et al*., 2022).

Downhole geophysical surveying

Please see **Section 8.3.2.5** for details relating to downhole geophysics.

8.3.2.3 Intrusive Ground Investigation

Intrusive ground investigation techniques involve physically penetrating the ground to collect samples and data. These techniques are essential for obtaining accurate information about the subsurface conditions and are often used in conjunction with surface geophysics to provide a comprehensive understanding of the site conditions.

Trial pits

Trial pits provide a simple, low-tech method for investigating ground conditions in most soils and soft rocks above the water table. In water-bearing deposits, dewatering with a pump may be necessary.

Mechanically excavated trial pits typically reach depths of up to 5 m. Shoring is often required in deeper or unstable ground to prevent collapse, with vertical stability being a key limiting factor.

Trial pitting, as shown in **Figure 99**, in the Calp Limestone may be suitable where rock is shallow (top of rock <4 m) and weathered (soft rock). However, if the rock is unweathered and competent, excavation usually terminates at the rock surface, as machines cannot excavate hard rock.

Figure 99 Trial pitting with protective fencing in place as a health and safety measure.

The advantages and disadvantages of trial pitting in the context of this study are summarised on **Table 7** below.

Table 7 Advantages and disadvantages of trial pitting.

Advantages	Disadvantages
It is considerably low-cost compared to other intrusive ground investigation methods.	Trial pitting is invasive and disturbs surrounding ground, so pits must be kept away from foundations and pavements; which is often challenging in Dublin's dense urban setting.
Allows for direct observation of soil and very soft rock layers, including how the different strata relate to each other.	Not suitable for investigations requiring samples from hard, competent rock.
Allows for fast and efficient coverage of the investigation area.	Trial pits often encounter shallow refusals and are generally limited to depths of less than 5.0 m using common excavators (e.g., JCB 3CX, JCB 360, Case 480G). However, bedrock on most sites in Dublin lies deeper than 5 m and typically unweathered.
Allows for in-suite testing: Plate Load test, etc.	
Allows the direct assessment of the shallow foundation sub-formation.	

Cable Percussion Boreholes

Cable percussion boreholes, as shown in **Figure 100**, consist of a power winch, a derrick (a collapsible tripod steel frame), and various boring tools connected by a steel cable. Penetration is achieved by lifting the tool about 1 m above the base of the hole and letting it fall under its own weight, driving soil into the tool for removal. A casing is advanced by surging to keep the hole open. This method is not suitable for hard rock, as the setup cannot penetrate competent rock.

Figure 100 Cable percussion borehole set up.

Cable percussion is also not well-suited to the geological conditions in Dublin City Centre. The very stiff boulder clay often contains large cobbles and boulders, which can slow progress or cause early refusal; commonly mistaken for bedrock. In practice, cable percussion boreholes in this area rarely reach depths greater than 12 m.

Anecdotally, refusal in a cable percussion borehole has often been confused with the top of rock. However, such refusal rarely indicates the top of rock where dense Boulder Clay overlies the Calp Limestone bedrock.

The advantages and disadvantages of cable percussion boreholes in the context of this study are summarised on **Table 8**.

Table 8 Advantages and disadvantages of Cable Percussion boreholes.

Advantages	Disadvantages
It is easy to mobilise to site and usually provides a cost-effective approach to acquiring ground information.	Difficult access can significantly increase cost due to the potential enabling works involved (crane lifts, scaffolding, additional plant etc).
This method provides a good depth of investigation in favourable conditions, including most soils and some weak rocks. It yields frequent, high-quality samples in soils that are free of large boulders or cobbles.	Not well-suited to the geological setting of Dublin City Centre. The very stiff boulder clay often contains large cobbles and boulders, which can slow progress or cause early refusal. Additionally, this method cannot penetrate though hard rock
Holes can easily accommodate a wide range of instruments, including various types of piezometers, inclinometers, strain gauges, and extensometers.	This is an old technology that has remained largely unchanged for over 75 years—and in basic form since the early 18th century. It presents health and safety risks due to manual handling and the movement of unguarded drilling tools.

Rotary Drilling - Conventional

The system consists of a rotary drilling rig at the ground surface, as shown in **Figure 101**, which provides torque and thrust. A flush pump sends fluid down the hole to cool the drilling components and carry rock cuttings back to the surface. A string of hollow drill rods transmits the torque, thrust, and flush fluid to the bottom of the hole. At the base, a drilling tool grinds the rock and may include a core barrel for collecting core samples.

Figure 101 Rotary drilling in residential/urban environment.

Rotary coring is suitable for collecting samples from rock strata (cemented materials) and, at times, hard soils such as glacial till materials that are difficult to sample using light cable percussion techniques. This makes rotary coring one of the most appropriate methods for the ground conditions typically found in Dublin City Centre with the advantages and disadvantages summarised on **Table 9**.

Table 9 Advantages and disadvantages of conventional rotary drilling.

Advantages	Disadvantages
The depth of investigation is not a limiting factor, provided the rotary rig and flushing system are appropriately sized for the conditions.	More expensive that cable percussion methods in typical site investigation applications.
Holes readily installed with numerous types of instruments (piezometers (various), inclinometer, strain gauges, downhole geophysics, packer tests etc.)	Health and safety concerns with regard to the lack of adequate guarding to rotating shafts.
Very good core recovery can be achieved even in challenging ground conditions, provided the appropriate equipment is used.	

Rotary Drilling – Geobore S

Geobore-S is a specific wire-line coring rotary drilling technique, as shown in **Figure 102**. In this system, the drilling rods are the same size as the outside of the core barrel. At the end of a drilling run, a special wire is lowered down through the rods and locks onto the inner core barrel. This inner barrel, along with a plastic liner holding the core, is then pulled up to the surface using the wireline. The outer rods stay in place in the hole. This method is much faster than traditional coring and is known as the triple barrel system.

Figure 102 Geobore-S in use in urban environment.

Geobore-S rotary coring is one of the most suitable investigation techniques for collecting samples in the geological conditions of Dublin City Centre. It provides continuous and excellent core recovery in dense or hard soils, such as Boulder Clay. The use of a triple-barrel system also improves recovery even for highly fractured rock and allows for high-quality testing in rock, with less disturbance from water compared to conventional rotary core drilling. **Table 10** summarises advantages and disadvantages of using Geobore-S rotary drilling as ground investigation method.

Table 10 Advantages and disadvantages of Geobore-S rotary drilling.

Advantages	Disadvantages
This method provides continuous core recovery, making it easy to observe and log changes in ground conditions—such as the transition from boulder clay to weathered rock, or from weathered rock to competent rock.	Recovery is not usually good in soft sediments. (less than 30 NSPT).
Holes readily installed with numerous types of monitoring equipment.	More expensive than the conventional rotary drilling.
Instrumentation can be installed (piezometers (various), inclinometer, data logger).	Health and safety concerns with regard to the lack of adequate guarding to rotating shafts.
	Need for a foam flush system which requires additional equipment a larger set up area.

Sonic Drilling

The sonic drilling technology, as shown in **Figure 103** below, combines harmonics (vibration) and rotation as the basis for tool advancement. Using a sonic head, drill casing and rods are brought to a vibration frequency of up to 150 Hz. These waves are transmitted through the drill string to the end of the casing and reflected, causing the casing to stretch and thin and to shorten and thicken up to 150 times per second.

Figure 103 Sonic Drilling

This intense vibration causes a very thin layer of soil particles directly surrounding the casing to lose structure. Instead of a stiff mass, the soil behaves like a fluid powder in the unsaturated zone, or as a slurry or paste in the saturated zone. This fluidisation, or liquefaction, dramatically reduces friction between the casing and the surrounding soil, allowing very rapid penetration. The technique is expensive, and the samples recovered are disturbed (and heated), but the recovery is typically good.

While this method would be the most suitable for the glacial gravels found in Dublin City Centre, it is not suitable for rock core samples, as it pulverizes the sediment. **Table 11** summarises advantages and disadvantages of using sonic drilling as ground investigation method.

Table 11 Advantages and disadvantages of sonic drilling.

Advantages	Disadvantages
Very good recovery in coarse soils.	Expensive and not usually readily available.
Holes readily installed with numerous types of instruments (piezometers (various), inclinometer, strain gauges, downhole geophysics, packer tests etc.)	Does not provide the same type of continuous recovery that Geobore-S does, making logging a bit more challenging.
	Not suitable for Calp Limestone since rock samples are recovered highly disturbed and pulverized.

8.3.2.4 Rock parameters

The following is a list of basic rock strength parameters and their applications in foundation design, as based on Wyllie, 1999, and as shown in **Figure 104** below:

- Deformation Modulus (Young's Modulus):
  - Deformation modulus is essential for settlement analysis being often applied in the calculation of settlement of foundations. Young's modulus is typically determined using plate load or pressuremeter tests.
- Compressive Strength of Rock Mass:
  - The uniaxial compressive strength of the rock mass is a key input in bearing capacity calculations and is often estimated using empirical correlations or triaxial tests.
- Compressive Strength of Intact Rock:
  - Intact rock strength is used in design of anchors and socketed foundations and can be measured via uniaxial compression tests which can be applied to assess influences bond stress of socketed piers and tensioned anchors, based on empirical correlations.
- Shear Strength:
  - Shear strength is critical for evaluating interface friction and slope stability and is assessed through direct shear or triaxial tests. Applications of shear strength include shear resistance at the interface between structure and foundation and stability of sliding blocks.
- Tensile Strength:
  - Tensile strength is important in layered rock systems and is typically measured using Brazilian or flexural tests. Tensile strength is relevant for punching or flexural failures, especially where a weak bed underlies a stiffer rock layer.
- Time-Dependent Properties:
  - Time-dependent behaviour such as creep and weathering-induced degradation affects long-term settlement and stability.

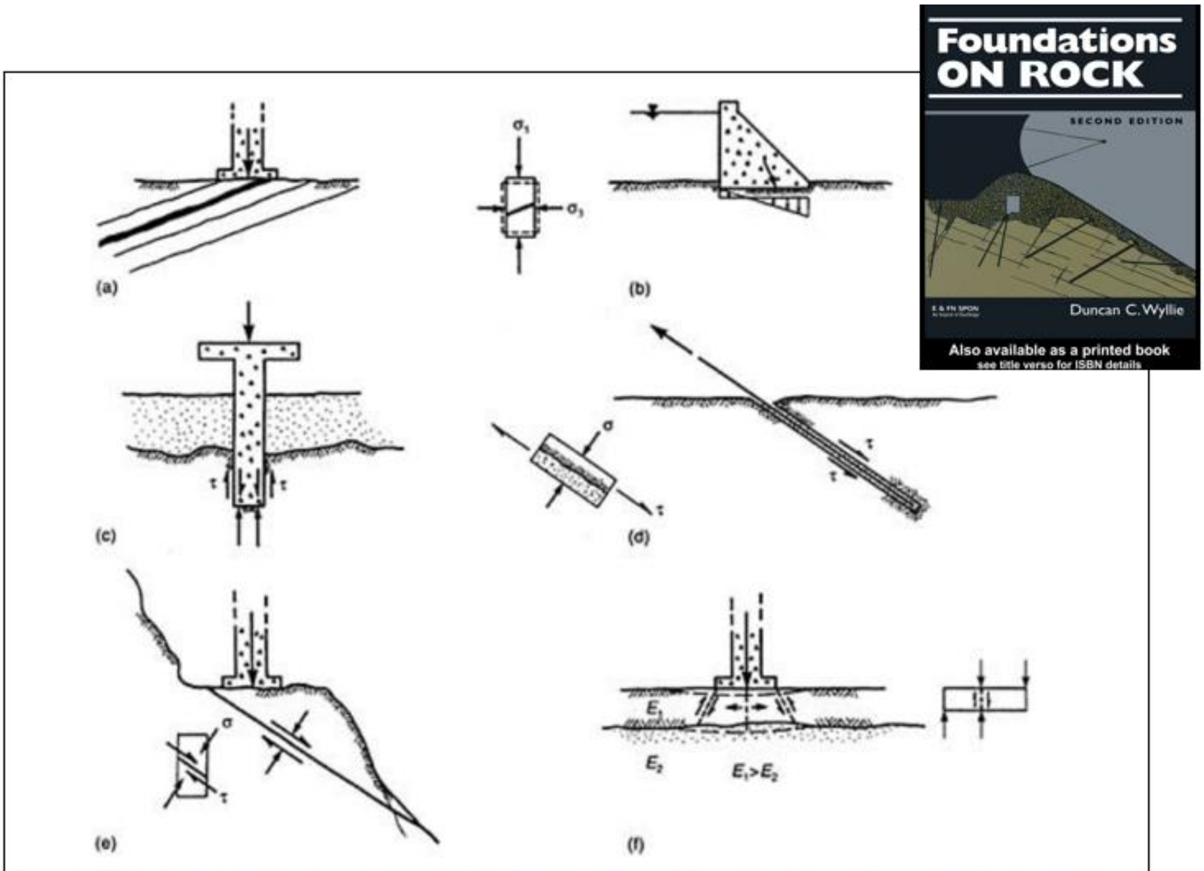


Figure 15: Rock strength parameters related to the design of rock foundations: (a) settlement due to compression of soft seams and intact rock; (b) shear and deformation of fractured rock mass; (c) side-wall bond strength and end bearing of a socketed pier; (d) shear strength of rock-grout interface; (e) shear failure on a continuous fracture dipping out of the face; and (f) punching or flexural failure of a thin bed of rock overlying weaker material.

Figure 104 Rock strength parameters related to the design of rock foundations. Extract from Wyllie, 1999.

8.3.2.5 In-Situ Testing

During a ground investigation, in-situ testing of the Calp Limestone is generally limited to within a project specific borehole, unlike exposures within a quarry environment or outcropping rock.

Downhole Geophysics

Downhole geophysical surveying can be used to supplement both surface geophysical surveys and intrusive investigations by improving understanding of subsurface stratigraphy and in situ properties. Downhole geophysical surveys are undertaken following the completion of an intrusive ground investigation techniques, particularly at a borehole location. This allows for the collection of information regarding the orientation of discontinuities, which is otherwise impossible to obtain in urban areas where rock exposures are not available.

An optical televiewer is used to locate and orient bedding and fractures in boreholes that are dry or have clear water, usually a day or two after drilling when the well has settled. It delivers a resolution of 1 mm, generating a virtual core that can be examined from any angle. Dip and strike measurements are obtained using specialized software. The device requires a minimum borehole diameter of 96 mm. Examples of optical downhole geophysical surveying within the Calp Limestone are shown in **Figure 105** and **Figure 106** below.

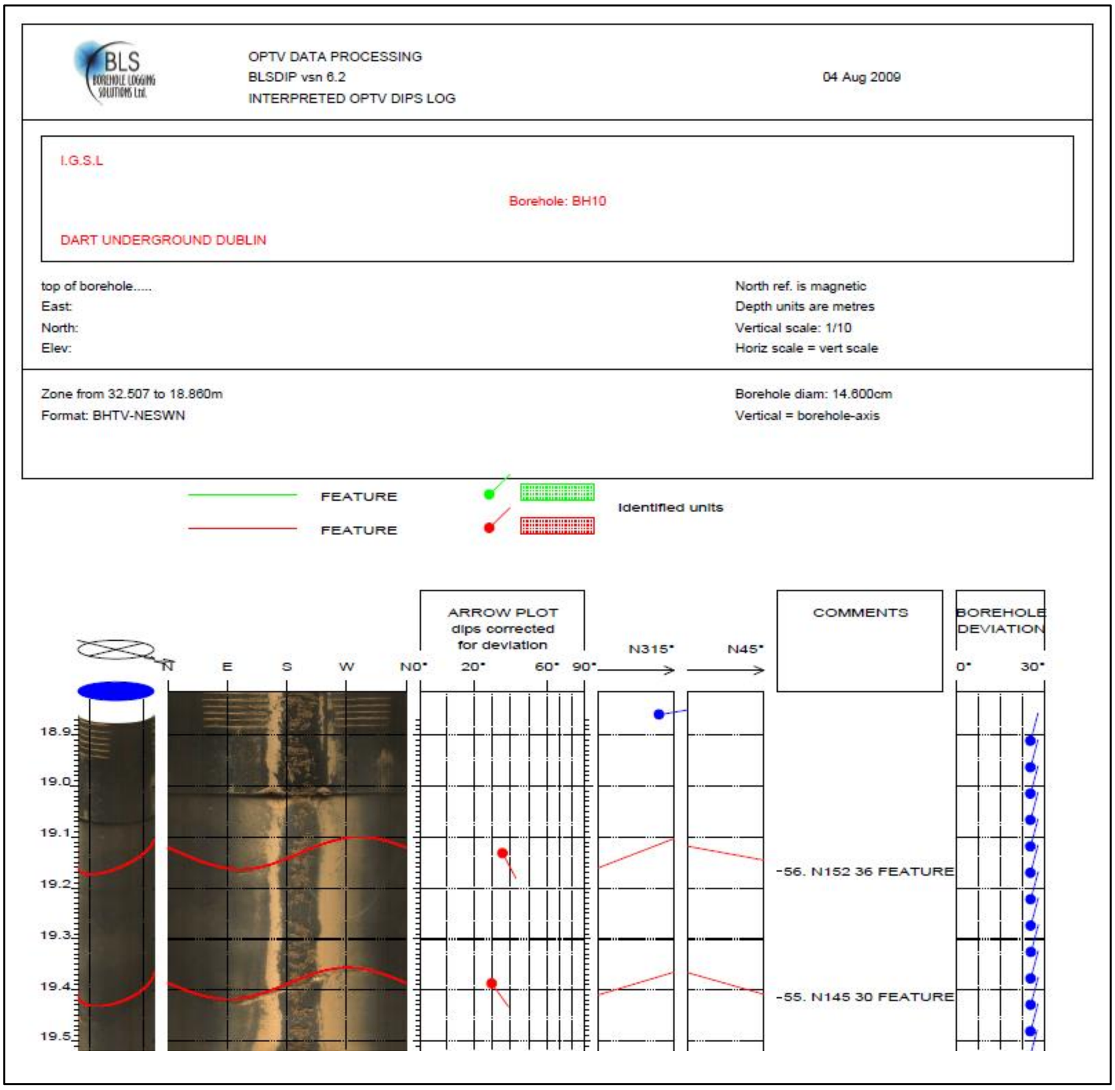


Figure 105 Extract from a downhole geophysics log for the DART Underground project.

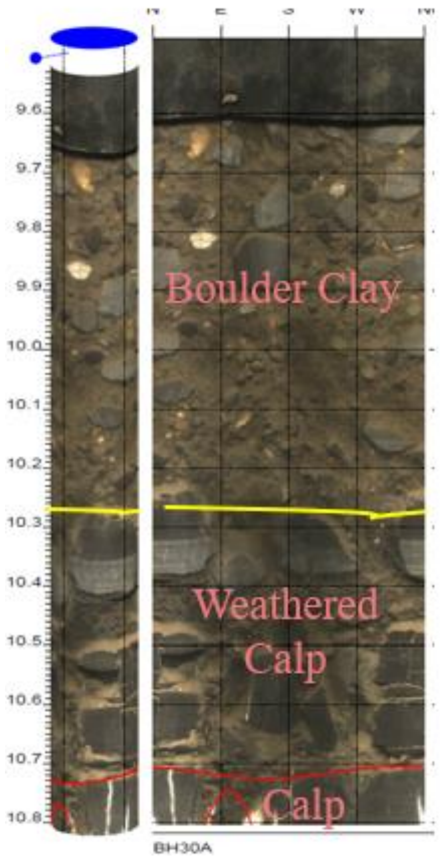


Figure 106 Optical Televiewer from bottom of casing in stiff boulder clay through weathered rock onto competent rock (DART Underground Ground Investigation – Fishamble St.).

Acoustic televiewer identifies and orients bedding and fractures in water-filled holes, whether open or plastic-cased (not steel, as it interferes with magnetometers). It performs best in hard rock, clearly detecting banded bedding and providing deeper borehole coverage and better fracture detail than the optical tool. It offers 2 mm resolution, with dip and strike data processed using relevant software. Minimum hole diameter is 96 mm.

The benefits of downhole geophysics cannot be understated providing valuable information on the orientation of discontinuities within the bedrock along with the transition from weathered rock to competent rock in some cases, as seen in **Figure 106**.

Table 12 outlines typical downhole probe types that can also be used during a ground investigation and their applications.

Table 12 Typical Downhole Geophysical probe types.

Additional probes	Application
Arm Calliper Probe	Gives a good indication of the borehole stability and is often used to determine whether to run radioactive sources in potentially unstable holes.
Gamma Density Probe	Gives qualitative rock densities. The data is captured in counts per second and correlated with geological texts to give relative densities.
Dual Guard Log Probe	Records focused formation resistivity values, identifying thin beds and high resistivity rocks. Also aids in the determination of water quality, Indication of permeable zones and porosity, Indication of fractures and permeable zones, Bed-boundary and thickness measurements.

Packer Testing
Packer testing uses inflatable rubber bladders (one or two) to isolate a segment of an uncased borehole. A series of tubes pass through the central axis of the packers, which allow water to be pumped into the isolated section of borehole below the top packer, enabling the hydraulic conductivity (k) of a specific substratum of interest to be investigated. Single packer systems can only isolate the bottom section of the borehole. Double packer systems can isolate an intermediate sub-stratum located part way down a borehole, as shown in **Figure 107**.

The Calp Limestone is not expected to have significant primary porosity, as it is a Carboniferous formation that has undergone compaction, cementation, and consolidation hundreds of millions of years ago. While minor porosity may be present, it is unlikely to be well connected or capable of supporting significant groundwater flow.

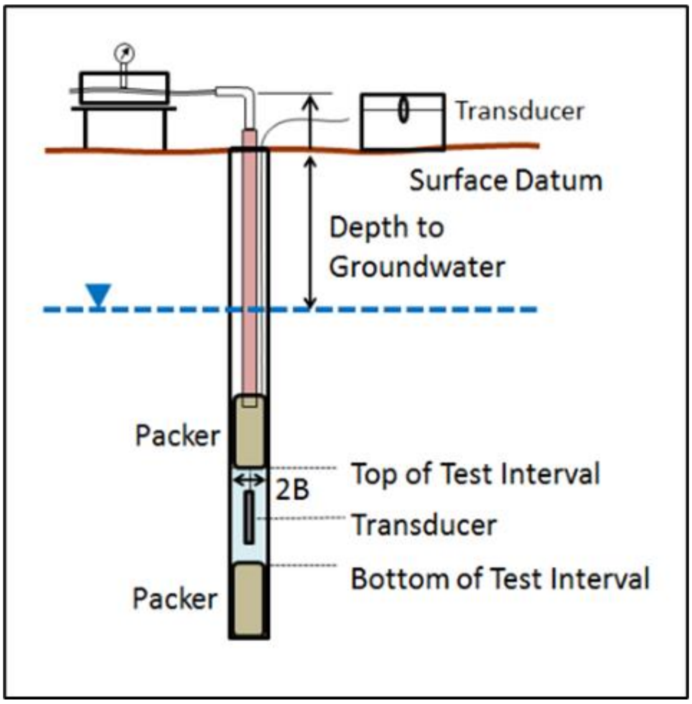


Figure 107 Illustration of a typical setup for a double packer test (https://forumautomation.com/t/what-is-packer-test/5759).

Instead, groundwater movement is expected to occur mainly through secondary porosity, such as fractures, joints, and faults. There are concerns about the reliability of packer test results in this context especially in the weaker mudstone layers, where the water pressure applied during testing may wash out fine material, artificially inflating the measured permeability and introducing uncertainty into the interpretation.

Attempts have been made to correlate RQD (as it represents a measurement of structure in the rock) with Lugeon values (as these values represent the hydraulic conductivity through these structures), however, this approach is not suitable for the Calp Limestone. RQD primarily captures bedding-related features, while in the Calp Limestone, a significant proportion of groundwater is likely to circulate through subvertical discontinuities, which are difficult to detect from vertical boreholes. To better characterise these features, inclined boreholes may be worth considering when designing packer testing programs.

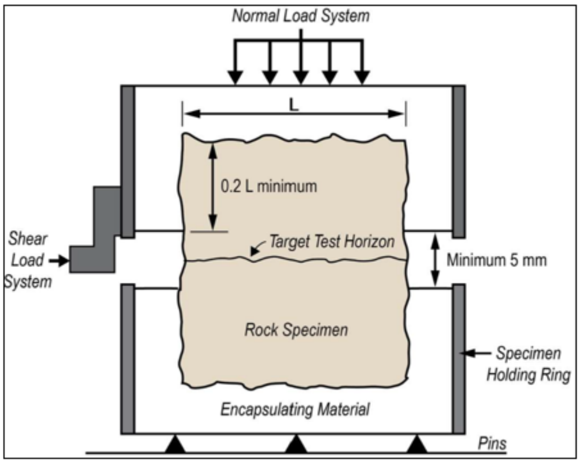
8.3.2.6 Laboratory Testing

Direct Shear
Rock is generally competent enough to support typical structural loads, and shear failure is not usually a concern. However, if large structures such as dams or bridges are planned on the Calp Limestone formation, it is recommended to perform shear testing to assess the rock behaviour under higher stress. This type of testing is generally not considered necessary for developments within Dublin City Centre with the exception of deep open excavations such as shafts and tunnels.

Another valuable application of direct shear testing is in the analysis of deep excavations. In such cases, the stability of the rock mass is largely controlled by its geometry and the properties of its weakest discontinuities. For example, in the Calp Limestone, this may be the mudstone bedding.

In the case where geometrical criteria are met; failure is likely to occur along the weakest discontinuity if the driving forces including applied loads exceed the shear strength. The direct shear test enables engineers to determine the cohesion and friction angle of these planes of weakness, which are essential for calculating the analytical factor of safety.

Figure 108 highlights the direct shear test setup and examples where sliding geometric conditions are met.



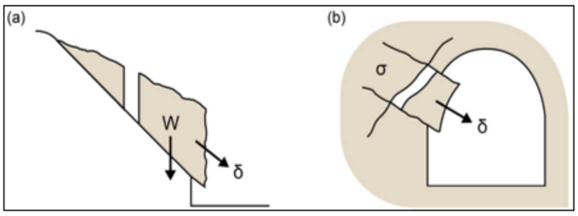


Figure 108 (Left) Illustration of a direct shear test setup used to estimate the shear strength of a discontinuity. (Right) Examples where geometric conditions for sliding are met, and failure is controlled by the shear strength of the discontinuity (reproduced from MacDonald, *et al.*, 2023).

Tensile Strength (Brazilian)

The tensile strength of rock is an important parameter in geotechnical design, as it is significantly lower than the compressive strength and exhibits nonlinear behaviour. Tensile stresses are related to the bending of the rock (**Figure 109**).

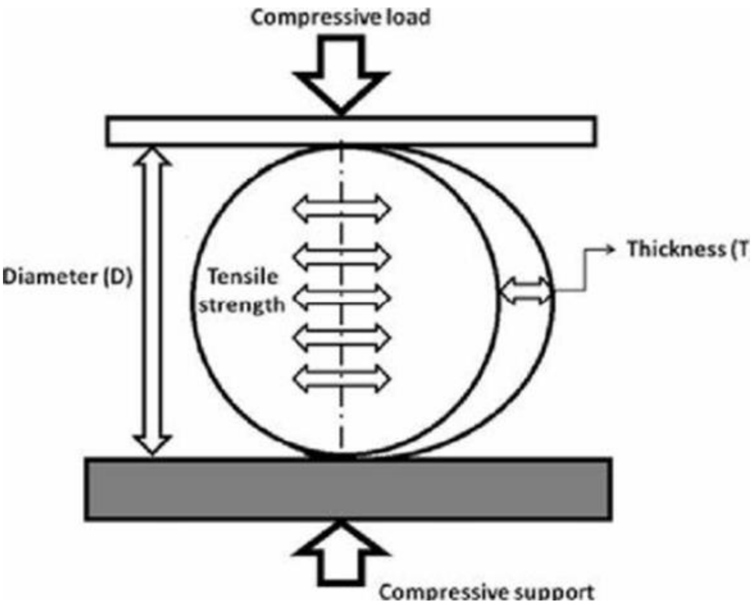


Figure 109 Illustration of a Brazilian test, an indirect method used to estimate the tensile strength of intact rock (Al-allaq, A.A, et al., 2021).

Direct tensile testing of rock is technically challenging, so the Brazilian Test, an indirect method, is widely accepted and commonly used in rock engineering to estimate tensile strength.

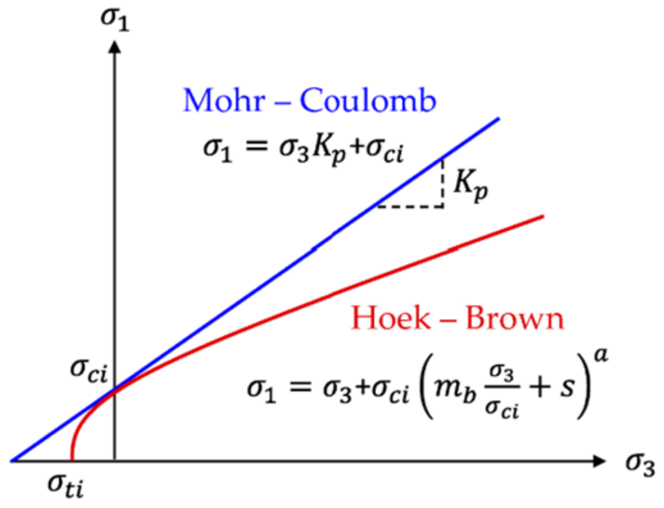


Figure 110 Mohr-Coulomb criterion overestimation of the tensile strength of rock, as tensile strength is actually a nonlinear function better represented by Hoek and Brown's model (reproduced from Lee *et al.*, 2024).

Triaxial Testing

In the urban setting of Dublin City Centre, typical applications involving Calp Limestone include deep excavations for basements or tunnelling. These works generally do not impose very large loads on the rock mass, unlike infrastructure such as dams or bridges. Therefore, shear failure of the rock is unlikely to be the primary concern.

In such cases, parameters like Uniaxial Compressive Strength (UCS) and empirical factors such as mi, s, a, and the Geological Strength Index (GSI) are possibly sufficient to define the critical failure plane and assess the shear strength of the rock mass.

However, there is the possibility that deformability may be a concern when tunnelling in the Calp Limestone. Given that the Calp Limestone includes interbedded mudstone, and considering its clay-rich nature, there is a possibility that the reduction in confinement pressure due to excavation could lead to significant deformation. Triaxial testing may be a useful tool in assessing this risk (**Figure 111**).

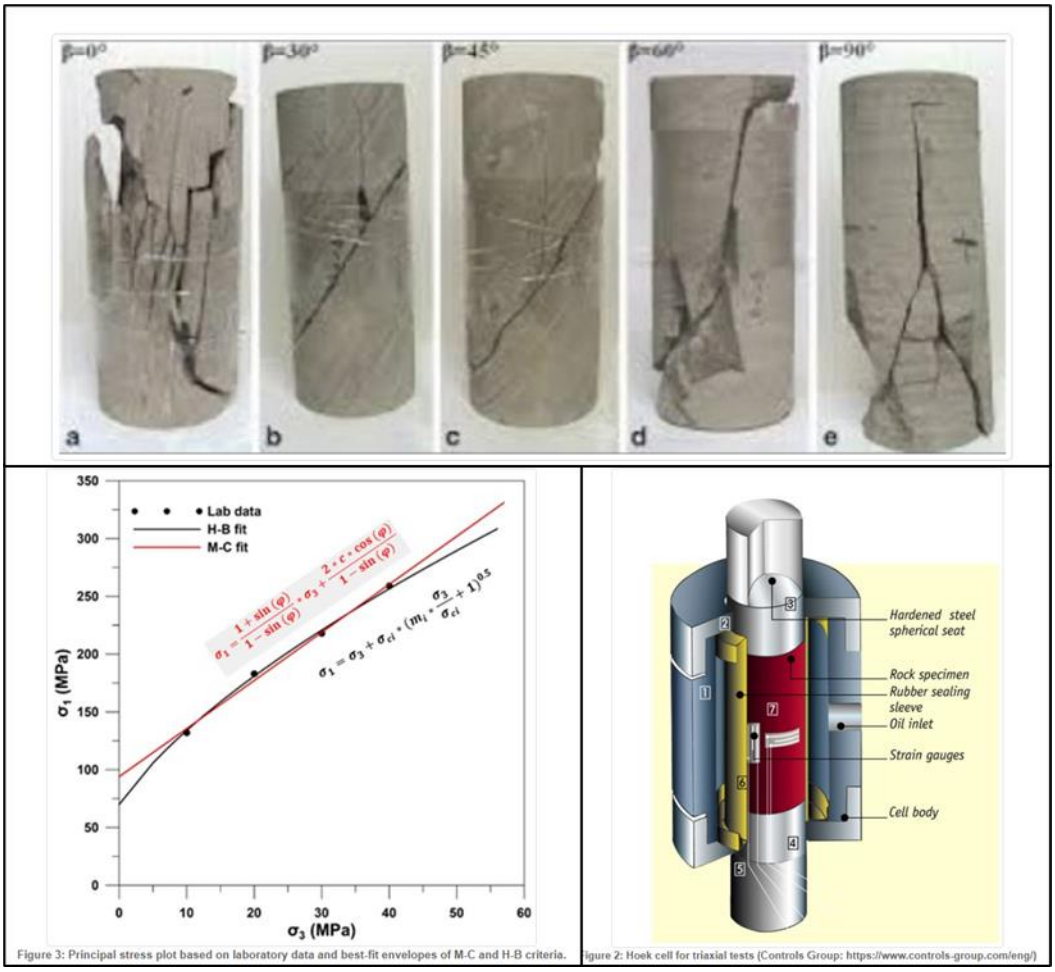


Figure 111 Triaxial Compression Test in Rock (Geoengineer.org, 2020)

Abrasiveness Suite of Rock Testing

A suite of tests is typically conducted on rock material to classify it and determine the appropriate drilling method. One of the most important properties in this context is the abrasiveness. Two commonly used tests to assess the abrasiveness are the Cerchar and the Sievers' J (SJ) tests. Abrasiveness testing has also been carried out within the Dublin glacio-fluvial gravel deposits which overlie the Calp Limestone (O'Connor, e*t al*, 2020). An example of a TBM can be found in **Figure 112**.

Figure 112 TBM Cutter Head used in New Zealand's City Rail Link in Aukland (City Rail Link, 2022).

Sievers' J Test (SJ)

The SJ test measures the surface hardness or resistance to indentation of rock. It is defined as the mean depth (in 1/10 mm) of drill holes created by a miniature 8.5 mm drill bit after 200 revolutions.

- The test is typically carried out with 4 to 8 drillings, depending on the texture variation of the sample.
- The reported SJ value is the average of these measurements.
- Abrasiveness can also be assessed using the Sievers' J Interception Point (SJIP), which is determined by identifying the intersection of two tangents at the beginning and end of the penetration depth vs. time curve (Dahl *et al*., 2007).

Cerchar Test

The Cerchar test evaluates rock abrasiveness by scratching a freshly broken rock surface over a distance of 10 mm using a heat-treated steel alloy pin under a static load of 70 N.

The Cerchar Abrasivity Index (CAI) is calculated by measuring the wear diameter (d) on the pin tip under a microscope, with a precision of 0.01 mm.

The CAI is given by the formula:

$$CAI = d \; x \; \frac{C}{10}$$

where c = 1 mm is a unit correction factor.

Additional testing

Additional material properties and indexes typically tested as part of a TBM suite of testing include:

- Swedish Brittleness Value
- Flakiness
- Compaction Index
- Density

- Abrasion Value Steel (AVS)
- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)

8.3.2.7 Aggregate Testing

Common tests for aggregates are discussed in **Section 8.2.4** above.

9. Findings – Gap analysis

9.1.1 Introduction

This project benefited from the opportunity to integrate and build upon a diverse range of datasets from three large-scale, linear ground investigations for previously proposed infrastructure projects. The large datasets acquired enhanced the depth and breadth of the analysis undertaken during this project.

The project has focused on an area of central Dublin City where there is a dense coverage of ground investigation data. This project has implemented a systematic process of data collection, validation, and digitisation which enabled the development of an updated bedrock ground model of the study area.

Data quality issues encountered during this project, such as bedrock misinterpretation, inconsistencies in logging, and structural information of the Calp Limestone, have been addressed. For other challenges, including limited ground investigation coverage in areas of the study area and the scarcity of Calp Limestone exposures within Dublin City centre, the project has sought to enhance the current understanding and highlight areas requiring further investigation.

This section highlights some of the gaps and challenges encountered during the project along with recommendations for those specifying investigations or designing in the Calp Limestone.

9.1.2 Data Gaps

9.1.2.1 Limited Bibliographical Sources

There is a lack of geotechnical and engineering geology literature specific to the Calp Limestone. Existing references are mainly sedimentological in nature, such as Marchant and Sevastopulo (1980), who identified three lithological variants. Nolan's 1986 thesis offers some insight into the structural geology of the Dublin Basin, with inferred fault and fold structures extended from adjacent formations. However, these interpretations have not been independently verified.

This lack of updated and focused geotechnical literature presents an ongoing gap, underscoring the need for further academic and industry-led studies.

9.1.2.2 Ground Investigation Coverage

As shown in **Figure 2**, the ground investigation data provided for the study area is limited to a linear footprint, leaving significant portions of the study area without adequate coverage. These spatial gaps present challenges in interpretation, resulting in low model confidence in these areas.

Even within investigated areas, the spacing between boreholes can be too large, reducing the resolution necessary for identifying geological trends (structural or stratigraphic features). To improve confidence in the geological model, additional datasets should be incorporated as they become available or as further ground investigations are undertaken within the study area.

The potential for further ground investigation, particularly non-intrusive techniques, was also considered during the development of recommendations aimed on improving dataset coverage within the study area.

However, it was ultimately concluded that geophysical surveys in urban settings pose significant challenges. These include high levels of ambient noise, the density of underground services affecting the effectiveness of specific techniques and limited physical space to carry out investigations. Furthermore, subsurface conditions such as the substantial thickness of glacial till and the similar geophysical responses of Black Boulder Clay and weathered Calp Limestone complicate data interpretation.

Techniques such as Electrical Resistivity Tomography (ERT), which are typically employed to identify faults and weathered zones within the rock mass, are particularly susceptible to signal disturbance from anthropogenic noise, hence are not recommended. However seismic methods like (SRF and MASW), combined with intrusive borehole techniques for verification, could potentially help to fill current spatial gaps like depth to bedrock or rock rippability.

9.1.3 Data Discrepancies

The core ground investigation data used to develop the geological model was sourced from three separate projects, each undertaken by a different ground investigation contractor over a large period of time. This has resulted in notable inconsistencies in reporting styles, drilling and testing methodologies, and the terminology used in borehole logs.

A clear example of this discrepancy lies in the variation of rock descriptions. For instance, the DART Underground project used terms such as sandy Limestone, argillaceous Limestone or Mudstone/Shale. In contrast, the MetroLink project adopted a simplified classification, referring only to Limestone and Mudstone. These differences in lithological descriptions have direct implications for engineering design, as different rock types exhibit distinct mechanical behaviours.

To address this, a standardised distinction between limestone and mudstone was applied across the dataset. However, to ensure consistency and improve data reliability in future investigations, it is recommended that a more rigorous and unified methodology for lithological descriptions of the Calp Limestone be developed and implemented. Clear guidelines for logging and reporting should be established and communicated to all contractors involved in geotechnical investigations.

9.1.3.1 Recommended typical descriptions for Calp Limestone

Rock Material description:

A summary of material characteristics and typical descriptions expected for the limestone and mudstone components of the Calp Limestone formation are presented in **Table 13** below.

Table 13 Typical descriptions of material characteristics encountered in the Calp Limestone

Material Characteristics	Limestone	Mudstone
Strength	Medium strong to Strong (30 to 80 MPa)	Weak (5 to 25 MPa)
Structure	Thinly to Thickly bedded (60 to 2000 mm)	Thickly laminated to Thinly bedded (6.3 to 2000 mm)
Colour	Light to Dark grey	Light to Dark greyish black
Texture	N/A	N/A
Grain size	Fine to Medium grained (0.002 to 2 mm)	Very fine grained (<0.002 mm)
Nomenclature	LIMESTONE	MUDSTONE

Rock Mass description:

A typical description of the Calp Limestone has been developed following a review of the available data, as follows:

Fresh to partially weathered medium strong to strong, thinly to medium bedded, light/dark grey, fine to medium grained, LIMESTONE. Interbedded with weak, thickly laminated to thinly bedded, light/dark greyish black, very fine-grained MUDSTONE. Occasional calcite veins and pyrite.

The main discontinuities encountered are described as follows:

- Discontinuity Set 1 (Bedding)
- Discontinuity Set 2 (Joint Set 1 and 2) Orthogonal to each other and perpendicular to bedding
- Discontinuity Set 3 (Joint Set 3)

Discontinuity characteristics are based on Table 30 of BS5930:2015. Typical values expected for bedding and Joint Set 1 & 2 for a variety of discontinuity characteristics are presented in **Table 14** below.

Table 14 Typical descriptions for discontinuity characteristics encountered in the Calp Limestone

Discontinuities Characteristics	Discontinuity Set 1 (Bedding)	Discontinuity Set 2 (Joint 1 & 2)
Orientation*	Varied orientation – Dip typically 1° to 37°	Variable orientation but typically subvertical
Spacing	Very close to Medium (20 to 600 mm)	Medium to Widely (200 mm to 2 m)
Persistence**	Very high (>20 m)	Medium to Very high (3 to >20 m)
Termination**	x (outside exposure), r (within rock), d (against discontinuity)	x (outside exposure), r (within rock), d (against discontinuity)
Roughness	Planar to Undulating; Smooth to Rough	Planar to Undulating; Smooth to Rough
Aperture**	Very tight to Open (<0.1 to 2.5 mm)	Open to Moderately wide (0.5 to 10 mm)
Infilling	Clean (Rare calcite veins)	Clean (Occasional soil infill; Occasional calcite veining)
Seepage**	Variable	Variable

*In situ measurement within borehole – can only be described if downhole geophysical surveys are carried out.

**Cannot normally be described from extracted cores.

9.1.4 Digitalisation

The large volume of data available for this study required substantial effort to convert the data into a usable format. Given project timelines, full digitalisation of all relevant datasets was not always feasible, resulting in some information remaining unprocessed and therefore not suitable for inclusion in the model. For example, some of the rock testing data had to be manually digitised before analysis, which delayed its integration into the model. Additionally, the Dublin Light Railway (Sandyford to Ballymun) ground investigation data was available only in PDF format, making it difficult to incorporate, despite the fact that this dataset covers a significant portion of the gap in the northwestern corner of the site boundary. In this second instance, the issue was partially addressed by extracting selected information from the report; for example, the depth to rock from the rotary drilling boreholes was digitised and incorporated into the Seequent Leapfrog® software package to improve model accuracy.

To improve efficiency in future projects, the use of digital cloud-based information platforms is strongly recommended. These platforms allow all geotechnical data to be stored in a single digital environment, ensuring that datasets are readily available for analysis and interrogation. Additionally, some support seamless integration with 3D geological modelling software, such as the Seequent Leapfrog® software program used during this study.

9.1.5 Site Visits

The site visits undertaken during this study provided valuable insights through in-situ observations, allowing for direct verification of major discontinuity sets and first-hand geological descriptions, thereby reducing reliance on photographs or variable project records. However, several limitations affected the scope and integration of these observations. Most site visits were conducted outside the project boundary due to the limited availability of accessible Calp Limestone outcrops within the study area.

Two site visits within the study area, namely the basement excavations on Harcourt Street and Adelaide Road, which served as representative exposures.

During the Belgard Quarry site visit, members of the UCD School of Geology were invited to conduct drone-based mapping of the quarry to obtain digital structural data.

Additionally, core logging is currently under discussion, with a focus on selected cores that target specific geological features such as brecciated zones, weathered intervals, and the transition from glacial till to bedrock. However, the unavailability of some of the requested core samples has further limited the amount of data available for detailed analysis.

9.1.6 Gaps in engineering parameters

9.1.6.1 Intact rock

The compressive strength of the intact rock was studied in detail. The Calp Limestone consists of interbedded limestone and mudstone layers; however, the limestone beds have been studied more extensively than the mudstone due to difficulties in obtaining high-quality mudstone samples. Only seven uniaxial compressive strength (UCS) tests were conducted on samples identified as mudstone in the provided logs, compared to 197 tests on limestone.

Going forward, designers should not overlook the presence of mudstone beds, as this could lead to an overestimation of the rock mass strength. Emphasis should instead be placed on properly retrieving mudstone samples and conducting UCS tests where applicable. Additionally, key factors such as mechanical degradation during drilling and the conditions to which samples were exposed prior to testing remain unknown. The orientation of major discontinuities in relation to the loading axis was not always recorded, suggesting that a standardised approach was not followed and making some results difficult to assess. To improve the confidence and reliability of analysis, critical parameters such as lithology, potential mechanical degradation during drilling, extent of exposure after core recovery, bedding orientation relative to the loading axis, and degree of weathering (based on BS5930:2015-compliant descriptions) should be documented.

9.1.6.2 Rock Mass

Rock mass is governed by the three dominant discontinuity sets (bedding and two orthogonal joint sets). However, the heterogeneous nature of the Calp Limestone introduces additional complexities, necessitating further study. A key challenge lies in the variation of input values, particularly in distinguishing between limestone and mudstone properties. Intact rock properties differ significantly, with limestone and mudstone exhibiting a wide range of strength and deformability. Discontinuity spacing also varies, with mudstone generally showing more closely spaced bedding than limestone. Surface roughness affects the interlock between discontinuities, influencing shear strength; for example, fine-grained mudstone provides less interlock than coarser-grained limestone. Selecting input parameters based on a conservative approach that assumes failure in the weakest formation (e.g., mudstone with lower-bound values) could lead to overengineered and costlier solutions. Conversely, using upper-bound values representative of limestone may overestimate rock mass competency.

Therefore, engineering judgment and field experience remain essential. Relying solely on borehole data is considered insufficient. It is recommended that a more comprehensive approach integrating field mapping, core logging, and visual observations is necessary to accurately characterise rock mass behaviour for engineering applications.

10. Conclusions and Recommendations

10.1 Conclusions

The 3D Ground Model provides an overview of the Calp Limestone in the study area with the depth to bedrock varying from north to south of the study area.

A 3D ground model of the study area has been created in Seequent's Leapfrog® geological modelling software. A total of 397 no. rotary core boreholes were used in the development of the ground model. This includes 209 no. boreholes from the dataset provided by TII, 167 no. from the publicly available GSI database, and 21 no. boreholes from Arup in-house projects. The GSI boreholes were used solely to fill data gaps and to provide information on the depth to bedrock, as no additional lithological data accompanies the publicly available package.

The 3D Ground Model provides an overview of the Calp Limestone in the study area with pronounced variability in bedrock depth across Dublin City Centre. These variations are likely the result of a combination of glacial erosion on the underlying Calp Limestone and potential structural controls such as faulting and folding.

Bedrock is deepest north of the River Liffey, reaching 30 to 35 mBGL around Phibsborough and Drumcondra. South of the river, it is much shallower; around Trinity College and Christ Church Cathedral depths range from 1 to 10 mBGL, while St. Stephen's Green has depths of 6 to 15 mBGL.

Weathered Rock

The impact of glaciation and the thickness and stiffness of the overlying Quaternary sediments often influence the determination of the thickness and extents of weathered rock in the study area with loose rock plucked and transported during glaciation and redeposited as glacial sediments.

Where encountered (logged), the weathered rock thickness at the top of rock averages 0.7m but it can be difficult to distinguish from the base of overlying Boulder Clay without full core recovery or an open excavation. Thicker zones of weathered rock up to 2m thickness were encountered in a number of boreholes.

Deeper weathering within the rock mass is generally associated within the impacts of recent and past tectonic activity.

Rock Mass Strength and Structure

The intact rock strength should also consider the strength of both the limestone and mudstone layers. Due to the requirements for intact rock strength laboratory measurements, samples tend to be selected from more intact pieces of core, namely the limestone.

The overall rock mass strength is governed by the presence of three prevailing sets of discontinuities, namely bedding and two orthogonal joint sets as follows:

- Within the borehole data used for this assessment, the quantity of bedding readings is notably higher than other discontinuities, enhancing confidence in identifying bedding orientation changes and suggesting potential large-scale folding trends.
- Subvertical joints were harder to identify due to the vertical boreholes, showing distinct populations on stereonets with dips between 60º to 90º.
- Field visits confirmed two joint sets and hinted at a third, not reflected in stereonet data.

10.2 Recommendations for Ground Investigation

A recommendation for a typical ground investigation scope to assess the Calp Limestone bedrock for a typical engineering project may include the following:

- Desk study:
  - Define the objectives of the project.
  - Conduct a desk study of available information to assess the potential depth to the top of the bedrock and identify any geomorphological or structural geological characteristics.
- Non-intrusive ground investigation:
  - If the site proves suitable, proceed with a preliminary geophysical survey.
  - Utilise the results to plan the intrusive ground investigation.
- Intrusive ground investigation:
  - If the anticipated depth to rock exceeds 3.5 m, trial pits may not be effective.
  - Assess the presence of gravel.
  - Ensure the recovery of a sufficient length of intact rock core (generally 3m) is specified to prevent the interpretation of a false rockhead level.
- In-situ testing:
  - Perform downhole geophysics if orientation data of the rock is necessary (e.g., for basements, slopes, or tunnels).
  - Conduct packer testing.
  - Install standpipes/piezometers within completed boreholes to assess the hydrogeological regime.
- Laboratory testing:
  - General assessments include material properties such as Unconfined Compressive Strength (UCS) and point load testing. Additional testing may be required based on the proposed engineering impacts on the Calp Limestone (e.g. foundations, tunnelling, slope construction, material reuse).

10.2.1 Comparison of drilling techniques

Table 15 provides a comparison of the different ground investigation techniques outlined in above. It evaluates various factors such as cost, availability, time, environmental impact, and suitability for different ground conditions in a typical Dublin City Centre site.

The techniques compared include:

- Trial Pitting (TP)
- Cable Percussion (CP)
- Cable Percussion with Rotary Core (CP+RC)
- Geobore-S (GEO-S)
- Cable Percussion with Geobore-S (CP+GEO-S)
- Sonic Drilling (SONIC)

Each technique is rated based on these factors, and the overall scores are presented to help determine the most suitable approach for specific ground conditions and project requirements.

Table 15 as completed below is an example only and can be updated depending on the project considerations and site-specific conditions.

Table 15 Comparison of Drilling Techniques

Weight	Category	Subcategory	Rating for each category	MAX rating before weight	TP	CP	CP+RC	GEO-S	CP+GEO-S	SONIC	Contribution (%)
0.5	Time and cost related factors	Cost	0 -5	20	5 (Very low)	4 (Low)	2	2 (more expensive than RC)	1	1 more expensive than GEO-S	10
		Availability	0 -5		5	5	4	3	3	2 (Hard to find the crew and the rig available ,since it has to come from another coutry)	
		Time	0 -5		5	2 (Chieseling in clay)	3	4	3	5 (Moves faster than rotary drilling)	
		Experience in the market	0 -5		5	5	5	4	4	3 (less than rotary drilling)	
0.5	Environment related(What's the setting of the GI? Urban or rural area? How does the access look like?)	a)Accessibility	0 -5	20	2 (Might be hard in urban setting)	3	2	2	2	2	10
		b) Noise/Vibration	0 -5		3	4	2 (Significant noise and vibration)	2	2	1	
		c) Invassiveness	0 -5		1	3	2 (Significantly invessive)	4 (less than RC)	3	5 (drilling without use of excess water)	
		d) Footprint after reinstatement	0 -5		1	4	3	4	3	4	
3.2	Does it provide the most suitable approach in terms of continuous sampling and quality of sampling for testing taking into account the expected ground conditions?	-	0 -5	5	4	3	4 (Gap between CP refusal and start of RC)	4 (loss of recovery for slected ground conditions,however good if calp is targeted)	5	3	16
3.1	Does it reach the desired depth?	-	0 -5	5	1	2	5	5	5	2 (no because it pulverizes the rock)	15.5
1.1	Suitability for ground profile	Made Ground / Topsoil	0 -5	25*	4	3	3	3	3	5 (very good for made ground)	27.5
		Soft sediments	0 -3		2 (collapsing of walls)	3	3	0	3	2 (issues with the vibrations)	
		Glacial till	0 -5		3	2	2	5	5	4	
		Glacial gravels	0 -5		3	3	3	0	3	5 (very good with gravels)	
		Calp Limestone	0 -7		0	0	5 (Possibility to lose the first 0.5-1 meter of rock before starting the core recovery)	7	7	1 (not applicable for hard rock)	
1.5	Installations	Standpipes, Piazometers, Inclinometers etc	0 -5	5	0	2 (yes, but depth shallow and not in rock)	5	5	5	2 (yes, but depth shallow and not in rock)	7.5
1.5	In-situ testing	SPT,Downhole geophysics, Packer tests etc	0 -5	5	2 (Maybe CBR for shallow foundation in weak rock is shallow)	2 (yes but not in rock)	5	5	5	2 (yes but not in rock)	7.5
1.2	Health and Safety concerns	-	0 -5	5	2	3	3 (easily mitigated)	3	3	4	6
			OVERALL SCORE	100	48	51.4	77.1	75.9	83.7	62.4	100

* The max rate of 25 should always remain the same, however the range of rating for each lithology can vary depending on expected ground conditions and aims of the project.

10.3 Calp description and analysis

In addition to the technical limitations discussed in Section 9, a particular data discrepancy found during the study was in the rock description. It is recommended that a more rigorous and unified methodology for lithological descriptions of the Calp Limestone be developed and implemented. A tentative suggestion for such a description is as follows:

"Fresh to partially weathered medium strong to strong, thinly to medium bedded, light/dark grey, fine to medium grained, LIMESTONE. Interbedded with weak, thickly laminated to thinly bedded, light/dark greyish black, very fine-grained MUDSTONE. Occasional calcite veins and pyrite. Blocky jointing".

10.4 Recommendations for Future Work

A better understanding of the mudstone members in the formation is essential, as they are expected to play a critical role in controlling failure, particularly in areas where mudstone is predominant and rock-to-rock contact between limestone blocks may be limited. Currently, the mudstone is much less understood compared to the limestone. If UCS testing of the mudstone layers proves difficult, point load tests should be considered. However, determining a reliable correlation factor for the mudstone is nearly impossible given that only seven tests have been conducted within the study area.

It is recommended to continue to update model as new data becomes available either from GI's or new excavations in the study area. To determine whether there is any folding in the Calp Limestone within the project area, a map correlating the borehole locations and the representative bedding orientations would be beneficial. This would help assess whether the atypical bedding readings are isolated anomalies or indicative of folding within the formation. Additionally, inclined boreholes were excluded from the dataset to minimise alterations and therefore mistakes to the original data.

Further studies may also include:

- An investigation of the prevalence of the potential third joint set from downhole geophysical data and UAV/drone surveying of Calp Limestone exposures.
- An analysis of the groundwater flow through the Calp Limestone.
- Shear box testing on mudstone to reveal parameters for slope stability analyses
- A reconsideration of geophysical techniques is warranted. While it is well-established that resistivity methods present significant challenges in urban environments, there remains potential for greater utilisation of shear wave or P wave velocity measurements. Although relevant data are available, further processing and analysis are required.
- Physical examination of a selected number / a few existing cores with an emphasis on weathered rock
- Abrasivity of the Calp Limestone to tunnel boring machines, and
- Capacity of piles in Calp limestone

11. References

Al-allaq, A.A., Kashan, J.S., El-Wakad, M.T., Soliman, A.M. (2021) 'The bio-composites (Hydroxyapatite/High-density polytheylene) materials reinforced with Multi-walled carbon nanotubes for bone tissue repair'. *Journal of Ceramic Processing Research*, **22**(4), pp. 446–454.

Bieniawski, Z.T. (1989) *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists*. New York: Wiley-Interscience.

Bentley Systems, Inc. (2023) *gINT: Geotechnical and Geoenvironmental Data Management Software*. Available at: https://www.bentley.com/software/gint/

British Standards Institution (2015) *BS 5930:2015+A1:2020. Code of practice for ground investigations*. London: British Standards Institution. Available at: https://knowledge.bsigroup.com/products/code-of-practice-for-ground-investigations

British Standards Institution (2018) *BS EN ISO 14689:2018. Geotechnical investigation and testing. Identification, description and classification of rock. Part 1: Identification and description*. London: British Standards Institution. Available at: BS EN ISO 14689:2018 - Geotechnical investigation and testing. Identification, description and classification of rock. Part 1: Identification and description

Casey, P. and Fleming, M. (2014) 'A systematic review of common correlations between unconfined compressive strength and point load index for Dublin Calp Limestone', *Proceedings of the Civil Engineering Research in Ireland (CERI) Conference, Dublin, Ireland.*

CEN (2007) *Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing (I.S. EN 1997-2:2007).* Brussels: European Committee for Standardization.

Clarke, A., Parkes, M. & Gatley S. (2007) *The Geological Heritage of Fingal. An audit of County Geological Sites in Fingal.* Geological Survey of Ireland. Unpublished Report. Available at: https://www.gsi.ie/en-ie/publications/Pages/Fingal-County-Geological-Sites-Audit.aspx

City Rail Link (2022). 'Final TBM journey nears'. Available at: https://www.cityraillink.co.nz/newsletter-july-2022/final-journey-for-the-tbm-awaits.

Dahl, F., Grøv, E., Breivik, T. (2007) 'Development of a new direct test method for estimating cutter life, based on the Sievers' J miniature drill test', *Tunnelling and Underground Space Technology*, **22**(1), pp. 106–116.

Deere, D.U., Miller, D.W. (1967) 'The Rock Quality Designation (RQD) index in practice', *Classification systems for Engineering Purposes*, ASTM STP, American Society for Testing and Materials, Philadelphia, PA, pp. 91–101. https://doi.org/10.1520/STP48465S.

Engineers Ireland (2016) *Specification and Related Documents for Ground Investigation*. Dublin: Engineers Ireland.

Esri (2023) *ArcGIS Pro*. Redlands, CA: Environmental Systems Research Institute. Available at: https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Farrell, E., & Wall, D. (1990) 'Soils of Dublin', *Transactions of the Institution of Engineers of Ireland,* **114**, pp. 78–97.

Gallagher, V., Meehan, R., Parkes, M., Hennessy, R. and Gatley, S. (2014) *The Geological Heritage of Dún Laoghaire-Rathdown. An Audit of County Geological Sites in Dún Laoghaire-Rathdown*. Geological Survey of Ireland. Unpublished Report. Available at: https://www.gsi.ie/en-ie/publications/Pages/D%C3%BAn-Laoghaire-Rathdown-County-Geological-Sites-Audit.aspx

Geoengineer.org (2019) *Unconfined Compression Test*. Available at: https://www.geoengineer.org/index.php/education/laboratory-testing/unconfined-compression-test

Geoengineer.org (2020) *Triaxial Compression Test in Rock*. Available at: https://www.geoengineer.org/index.php/education/laboratory-testing/triaxial-compression-test-in-rock

Geotech.hr (n.d.) *Point Load Test (PLT)*. Available at: https://www.geotech.hr/en/point-load-test-plt/

Hennessy, R., Meehan, R., Parkes, M., Gallagher, V. and Gatley, S. (2014) *The Geological Heritage of South Dublin County. An audit of County Geological Sites in South Dublin County*. Geological Survey of Ireland. Unpublished Report. Available at: https://www.gsi.ie/en-ie/publications/Pages/South-Dublin-County-Geological-Sites-Audit.aspx

Hoek, E. & Brown, E.T. (2018**)** *The Hoek–Brown failure criterion and GSI – 2018 edition*. Journal of Rock Mechanics and Geotechnical Engineering. Available at: https://static.rocscience.cloud/assets/resources/learning/hoek/2019-The-Hoek-Brown-failure-criterion-and-GSI-2018-edition-1.pdf

Jaeger, J. C., Cook, R. and Zimmerman, R. (2007) *Fundamentals of rock mechanics*. 4th edn. Oxford: Blackwell Publishing.

Johnson, D. (2022) *Geotechnical properties of Calp Limestone for the design of deep foundations*. Masters Thesis, School of Civil Engineering, UCD [Unpublished manuscript].

Kealy, S., Long, M., McCarron, S., Fleming, M. and Friedman, M. (2021) 'Characterisation of gravel deposits in the pre-glacial channel, Central Dublin', *Irish Journal of Earth Sciences (IJES)*. Royal Irish Academy (RIA), 39, pp.71 - 88. https://doi.org/10.3318/IJES.2021.39.4

Kirwan, R. (1794) *Elements of mineralogy*, 2nd Edition. London. P. Elmsly.

Lee, Y.-L., Chen, C.-S. and Lee, C.-M. (2024) 'Explicit analysis for the ground reaction of a circular tunnel excavated in anisotropic stress fields based on Hoek-Brown failure criterion', *Mathematics*, **12**(17), p.2689.

Long, M. and Murphy, J. (2003) 'Difficulties with ground anchorages in hard rock in Dublin', *Geotechnical & Geological Engineering*, **21**, pp.87–111.

Long, M. and Menkiti, C. (2007) 'Geotechnical properties of Dublin boulder clay', *Géotechnique*, **57**, pp.595–611.

MacDonald, N.R., Packulak, R.M. and Day, J.J. (2023) 'A critical review of current states of practice in direct shear testing of unfilled rock fractures focused on multi-stage and boundary conditions', *Geoscience*, **13**(6), p.172.

Maggio, G., Subašić, S., Bean, C.J. (2022) 'Subsurface characterisation using passive seismic in the urban area of Dublin City, Ireland', *Geophysical Prospecting*, **70**(8), pp. 1432–1454.

Matheson, G. D. and Quigley, P. (2014) 'Evaluating pyrite-induced swelling in Dublin mudrocks'. *Quarterly Journal of Engineering Geology and Hydrogeology*, **49**, pp.47-66.

Marinos, P. and Hoek, E. (2001) 'Estimating the geotechnical properties of heterogeneous rock masses such as Flysch', *Bulletin of Engineering Geology and the Environment*, **60**, pp.85–92.

Marchant, T. and Sevastopulo, G. (1980) 'The Calp of the Dublin district', *Journal of Earth Sciences*, **3**(2), pp.195–203.

Menzies, J. and Shilts, W. W (2002) 'Subglacial environments', in Menzies, J. (ed.) *Modern & Past Glacial Environments*. Oxford: Butterworth-Heinemann, pp.183–278.

Microsoft Corporation (2023) *Microsoft Excel*. Available at: https://www.microsoft.com/microsoft-365/excel

NGI (2025) *Using the Q-System: Rock Mass Classification and Support Design*. Oslo: Norwegian Geotechnical Institute. Available at: https://www.ngi.no

Nolan, S. C. (1986) *The Carboniferous geology of the Dublin area*. Trinity College Dublin. Ireland. [Unpublished manuscript].

O'Connor, E., Friedman, M., Dahl, F., Drevland Jakobsen, P., van Oosterhout, D., Long, M., 2020, Assessing the Abrasivity characteristics of the central Dublin fluvio-glacial gravels – a laboratory study, *Tunnelling and Underground Space Technology*, **96**, 103209.

Parkes, M., Gallagher, V., Hennessy, R., Meehan, R. and Gatley, S. (2014) *The Geological Heritage of Dublin City. An audit of County Geological Sites in Dublin City*. Geological Survey of Ireland. Unpublished Report. Available at: https://www.gsi.ie/en-ie/publications/Pages/Dublin-City-County-Geological-Sites-Audit.aspx

Pettifer, G.S. and Fookes, P.G. (1994) 'A revision of the graphical method for assessing the excavatability of rock', *Quaternary Journal of Engineering Geology and Hydrogeology*, **27**(2), pp.145–164.

Quigley, P., and McSwiney, S., 1996, Measurement and analysis of rock mass fractures and their applications in civil engineering, *Engineers Ireland Geotechnical Society lecture, 13 February 1996*, Dublin, pp. 1–25.

Rocscience (2013) *Quantification of the GSI Chart*. Available at: https://www.rocscience.com/assets/resources/learning/hoek/2013-Quantification-of-the-GSI-Chart.pdf.

Rocscience (2026) *DIPS: Graphical and Statistical Analysis Software for Orientation Data*. Available at: https://www.rocscience.com/software/dips

Seequent (2024) *Leapfrog (Version 24.1.1)*. Available at: https://www.seequent.com/products-solutions/leapfrog-geo

Tailte Éireann (2026) *GeoHive: Ireland's National Geospatial Data Hub*. Available at: https://www.geohive.ie/

Waltham, T. 2009, *Foundations of Engineering Geology*, 3rd edn, CRC Press, London

Wyllie, D. C. (1999) *Foundations on Rock: Engineering Practice*. 2nd ed. London: CRC Press. https://doi.org/10.1201/9781482295009

Characterisation of Calp Limestone in Dublin City Centre

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