ENGINEERS IRELAND

ENGINEERING CHARACTERISATION OF THE GLACIOFLUVIAL GRAVELS OF CORK CITY

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Photograph shows Eglinton St. site, Cork in October 2006

SYNOPSIS

A review of the history and ground conditions in central Cork confirms that the area is underlain by a complex series of alluvial and glaciofluvial deposits. From an engineering point of view the most important strata are the high permeability loose to medium dense sands ands gravels. Although the nature of the material is similar across the area its density varies and this may be related to the site history. Case histories are presented which show significant pumping effort is required to dewater excavations. Settlements of adjacent buildings due to under-drainage of alluvial soils, overlying the gravels, are of significant concern. Site experience suggests permeability may actually decrease appreciably with depth. This and the general variation of the deposits across the city warrant further study. More recent site investigation techniques such as cone penetration testing and geophysical methods may be useful in this regard.

1. INTRODUCTION

The recent period of sustained economic growth in Ireland has led to an increase in the use of underground space in Cork city, with some developments now including 2 to 3 basement levels. Traditionally buildings in Cork were constructed without a basement. However many recent developments include some below ground space, usually required for car parking but also for uses such as housing of plant and machinery.

Of particular concern during these developments is the estimation of the permeability of the glaciofluvial gravels, the design of retaining walls and temporary dewatering systems and the prediction of settlements of adjacent buildings due to groundwater drawdown during construction.

The purpose of this paper is to provide an update on recent developments in the understanding of the ground conditions in Cork city with respect to civil engineering projects. A particular emphasis will be placed on schemes involving deep excavations. Specifically the paper will:

- Review the background geology and history of the Cork city area
- Discuss the nature and the variation of the glaciofluvial deposits across the city by means of selected case histories.
- Discuss in more detail the permeability of the materials.
- Present some case histories on recent projects which involved underground construction and extensive dewatering.
- Suggest some site investigation techniques which may be of use in the characterisation of the ground conditions.
- Briefly summarise available pile types and their suitability for use in Cork.

2. BACKGROUND GEOLOGY

2.1 Bedrock

The description in the following section is extracted from Nevill (1969), Whittow (1979), Reilly and Sleeman (1977), Sleeman (1991), MacCarthy (2002) and Devoy (2005).

At the end of the Palaeozoic era the Caledonian mountains were built. Where once there had been a geosyncline (a long narrow trough) there now stood a range of mountains which separated broad basins. The Munster basin had a northeast to south-wast trend. The mountains were eroded and weathered and the products of this erosion were deposited (usually by rivers) in the basin. Strata of a red purple colour formed. This was the old red sandstone (ORS) and its deposition took place during the Devonian period approximately 300 million years Before Present (B.P.).

Conditions changed as the Devonian drew to a close. The northern margin of the geosynclinal sea now crossed southwest Ireland from Cork Harbour to Kenmare. Grey shales and yellowish sandstones referred to as the Kiltorcan beds (or often in the Cork area as simply the Cork beds or "transition beds") were deposited on top of the ORS.

During the Lower Carboniferous period, due to a general submergence of the land, water from the geosyncline gradually encroached upon the land pushing the shoreline ever northwards. The shallow clear water sea, which all but covered Ireland, was in sharp contrast to the deep, mud laden geosyncline of the south Cork – Kerry area. The reef limestone of Cork was built as a mass of 1,200 m in thickness at the edge of the geosyncline.

In the course of the latter period of the Carboniferous, a major phase of structural deformation took place, at the time of the Armorican mountain building.

Folding, faulting and fracturing of the sedimentary layers took place resulting in a fold belt whose general trend is east to west across southern Ireland. The anticlinal ridges of this fold belt bring ORS to the surface for the Carboniferous has been eroded from their crests. The synclines, by contrast, still retain Lower Carboniferous rocks (Figure 1).

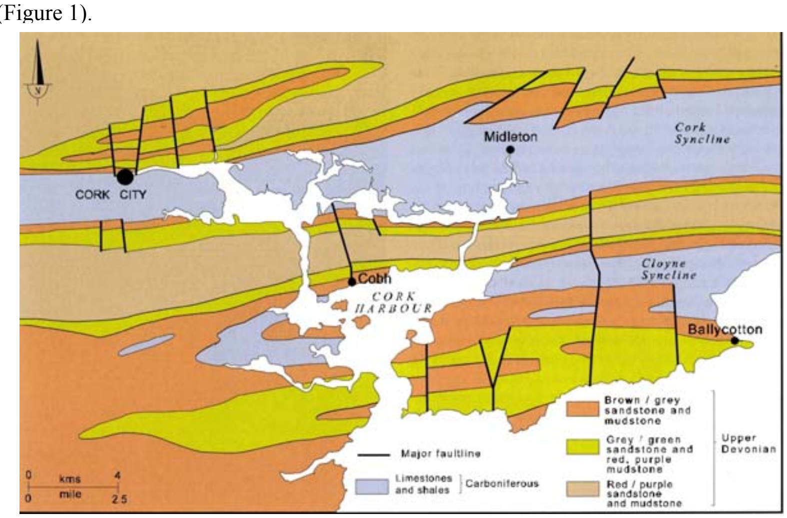


Figure 1. Solid geology of Cork city centre area (Devoy, 2005 and MacCarthy, 2002)

Figure 1 shows the Cork city centre area to be underlain by Carboniferous limestone, with the Cork beds and the ORS, in turn, becoming the underlying bedrock.

The geological history of southern Ireland as recorded in the "solid" rocks ends abruptly in the Carboniferous. The overlying sediments belong to the much younger "drift" deposits, which are mostly of Quaternary age and therefore only one to two million years old.

2.2 Superficial deposits

The present River Lee floodplain overlies a buried valley or "gorge", which was formed in the Carboniferous and Devonian rock 20,000 to 16,000 years B.P during the Pleistocene glaciation, see Figure 2. This occurred when sea level fell to about –130 mOD and glacier action together with melt water release cut down to the new base level to meet these low sea-level positions. The result was the creation of a classic U-shaped glacial trough. (Devoy, 2005). The Lee Buried Valley runs from Crookstown in the west towards Youghal in the east, a distance of about 60 km. It is at least 60 m deep and 0.5 km to 0.75 km wide.

The bbedrock falls in irregular steps towards the harbour from about 10 m depth west of the city to and estimated 60 m depth in the harbour area. Locally deep ice scoured certain areas for example to 40 m at Victoria Cross on the west side of the city. It is likely that the fluvioglacial deposits are locally greater than 60 m. However the authors are unaware of any boreholes greater than about 50 m deep.

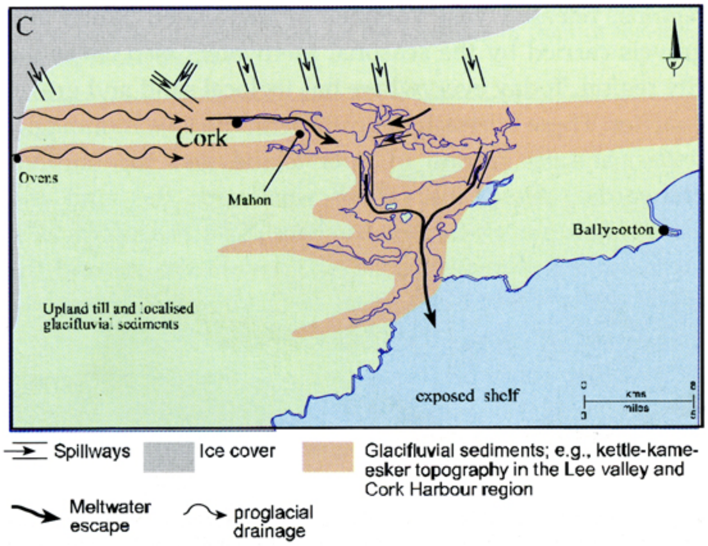


Figure 2. Deposition of glaciofluvial sediments during deglaciation 20,000 to 16,000 years B.P. (Devoy, 2005)

It is more or less directly underneath and in line with the central island of the city (Reilly and Sleeman, 1977, Milenic and Allen, 2002, Allen and Milenic, 2003). A useful map of the buried valley is presented by Davis et al. (2006). The Buried Valley is well exposed between Classes and Garryhesta in the Ballincollig – Ovens area to the west of the city where it is being quarried for sand and gravel. Here it contains a remarkably uniform succession of gravels. However beneath Cork city the details of the stratigraphy are not clear.

Conditions in the city centre area are perhaps best illustrated by an example. A very useful and detailed study of the deposits in the Eamonn DeValera bridge / Custom House Quay area was carried out by Scourse et al. (1992).

The location of the boreholes and a geological cross section through the northern part of the area is shown on Figure 3.

Borehole CS7 revealed a layer of boulder clay or glacial till at its base. This material is described as a diamicton so presumably it is a lodgement type till, commonly found in Ireland overlying bedrock. The till is overlain by gravels which in turn are overlain by estuarine deposits and made ground.

However borehole CS8, some 32 m to the east, contains a thick deposit of stiff occasionally laminated silty clay. Scourse et al. (1992) present clear evidence that this material is from a previous interglacial warm period (Gortian). Above the stiff laminated clays and silts, gravels are found.

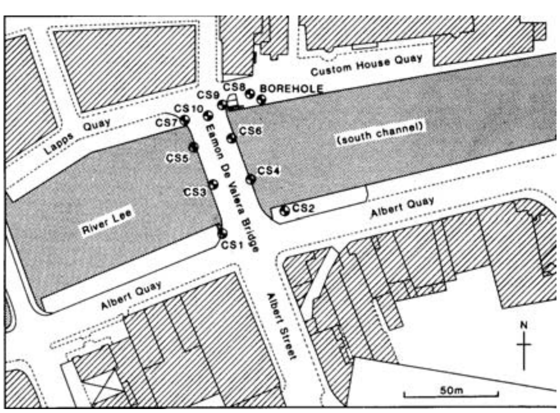
However some organic material of Holocene age was encountered within the gravel deposit at between -5.8 mOD and –6.5 mOD. Scourse et al. (1992) conclude that the deeper deposits are glaciofluvial outwash that infills the buried valley whilst that above the Holocene lens is glaciofluvial sediment reworked within the valley system by the rising sea level at the end of glaciation (c10,000 years B.P.)

Later the valley was infilled with estuarine clays, silts and peats, typically 3 to 4 m thick. Marshes formed the final shape of the upper estuary, after the sea level steadied near its present level about 6,000 years ago. At this time the river was braided, flowing in a large numbers of channels between a series of marshlands, see Figure 4. According to the poet Spencer, in the 16th century, Marshes:

“about which the spreading Lee that like an Island fayre, encloseth Corke with his divided flood”

The name Cork comes from the Gaelic “Corcach Mór Mumhan”, the great marsh of Munster.

These marshlands were progressively embanked and reclaimed, the channels culverted and the islands urbanised (O’Flanangan, 2005). Ultimately the majority of the Cork waterways were covered over to accommodate the spacious streets required by 18th Century planners. Grand Parade, South Mall and St. Patrick’s St. appeared in this way, leaving today the North and South channels of the Lee (Whittow, 1974).



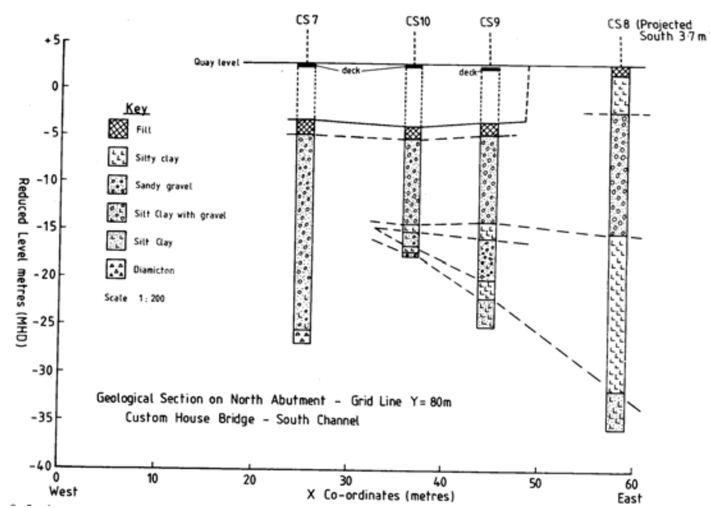


Figure 3. Borehole locations and geological cross section at Eamonn DeValera bridge / Custom House Quay (Scourse et al., 1992)

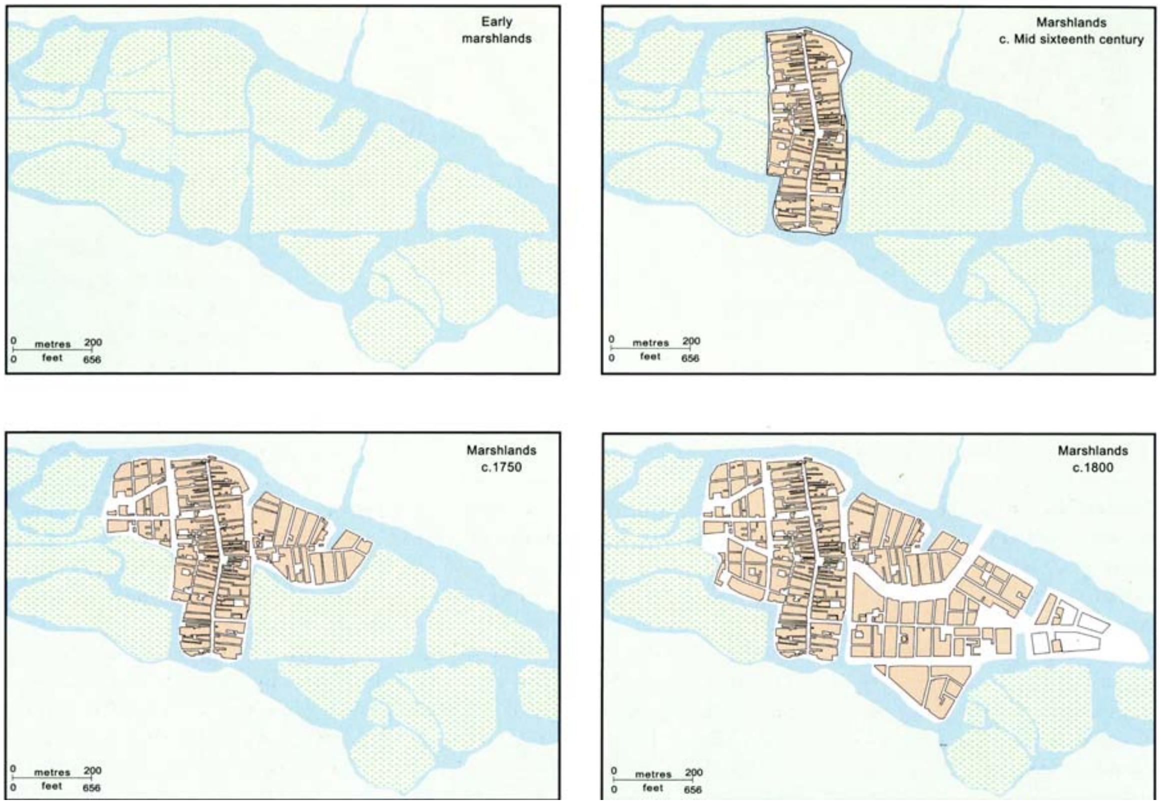


Figure 4. Development of marshlands (O'Flanagan, 2005)

3. NATURE AND VARIATION OF THE GLACIOFLUVIAL DEPOSITS

3.1 Introduction

The first known geotechnical report of the area comes from a visitor to Cork c1100 who noted:
"Cork wherein sweet bells ring – sour is its soil – its soil is sand".

This nicely sets the scene for the discussion which follows on the variation of the nature of the glaciofluvial sand and gravel deposits across the city. Most geotechnical investigations of the area are limited to cable percussion (shell and auger) boreholes with standard penetration tests (SPT) together with laboratory particle size distribution analyses on bulk samples extracted from the boreholes. These data form the basis of the following summary.

Figure 5 is a location plan showing the sites considered.

3.2 Central Island – south side

Perhaps the most well characterised site in the central island of the city is the site of the Clarion Hotel on Lapps Quay (Long et al., 2007, Holmes and Roberts, 2005). Ground conditions at the Lapps Quay site (see also geological cross section on Figure 3) comprise up to 5 m of made ground and alluvium overlying glaciofluvial gravels, see Figure 6. Below the gravels some of the site investigation boreholes proved the existence of stiff laminated silty clay (see Section 2.2). However not all the boreholes went to sufficient depth to show if this was consistent across the whole site.

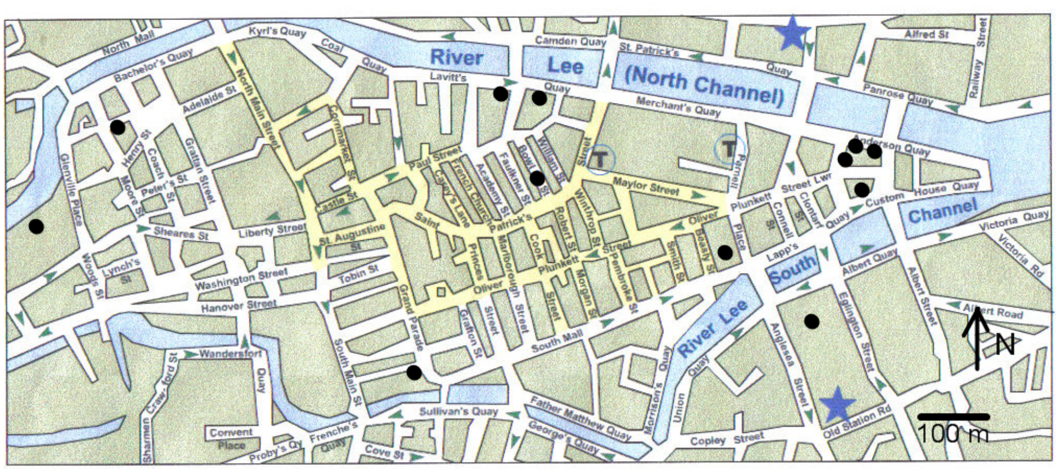


Figure 5. Location of study sites

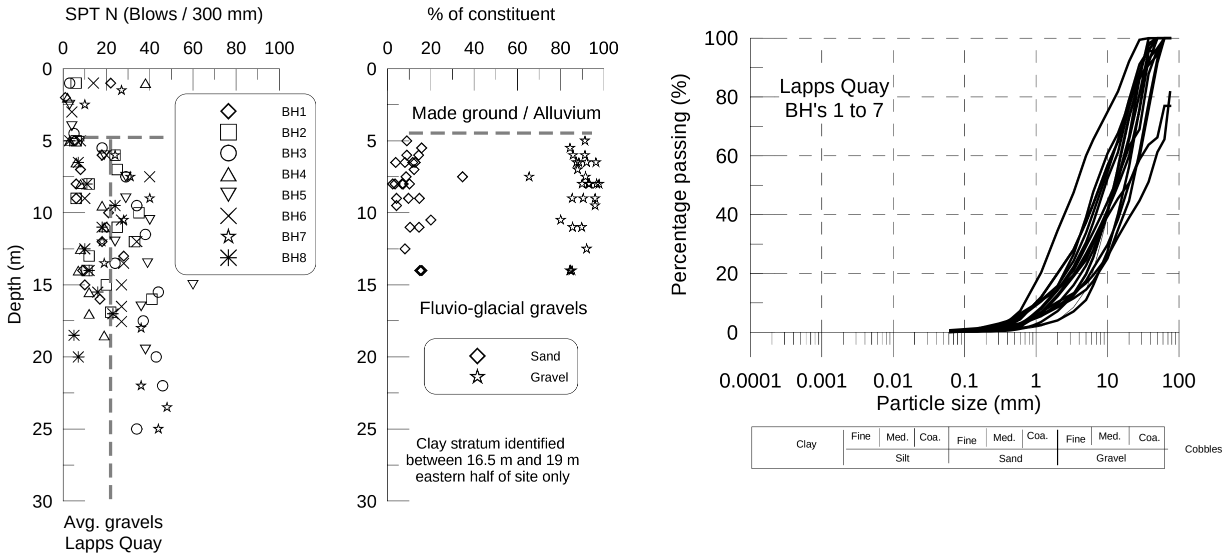


Figure 6. Clarion Hotel, Lapps Quay (a) SPT, (b) constituents with depth and (c) PSD curves (Long et al., 2007)

The glaciofluvial gravels have standard penetration test (SPT) N values increasing from about 10 (loose) to 40 (dense) with depth. There is only a gradual increase in N with depth: Average N is about 22 down to 20 m depth.

There is little apparent variation in sand and gravel content, to about 15 m depth at least, being on average 11% and 89% respectively. Particle size distribution curves, shown on Figure 6c, confirm the relative uniformity of the material.

There was no discernible trend of increasing or decreasing fines content with depth.

Data for the site in Beasley St to the west of Lapps Quay are shown on Figure 7. Some issues related to retaining wall construction, dewatering and adjacent building settlement for this site will be discussed later. This site is underlain by about 2.5 m of made ground, over 3.5 m of alluvium over sands and gravels. Like the Lapps Quay site, the gravels occasionally contain lenses of stiff laminated silty clay. SPT N values are relatively low above 20 m, with an average of about 15 and then increase dramatically at 20 m close to the maximum studied depth.

Conditions at the Grand Parade car park site are similar**.** However here one of the two boreholes drilled shows much higher SPT N values than the other. The overall average N for the sands and gravels is about 28.

3.3 Central Island – west side

Two sites on the western side of the central island, namely the UCC Tyndall Institute and a site on Millerd St. will be considered. The location of these two sites, superimposed on Rocque's map of the city from 1759, are shown on Figure 8

The Tyndall Institute site location may be unusual as it is located partly on a river channel (later used as a mill race) and partly on non-marshy ground. As can be seen on Figure 9 there is no evidence of alluvium in the borings on the site.

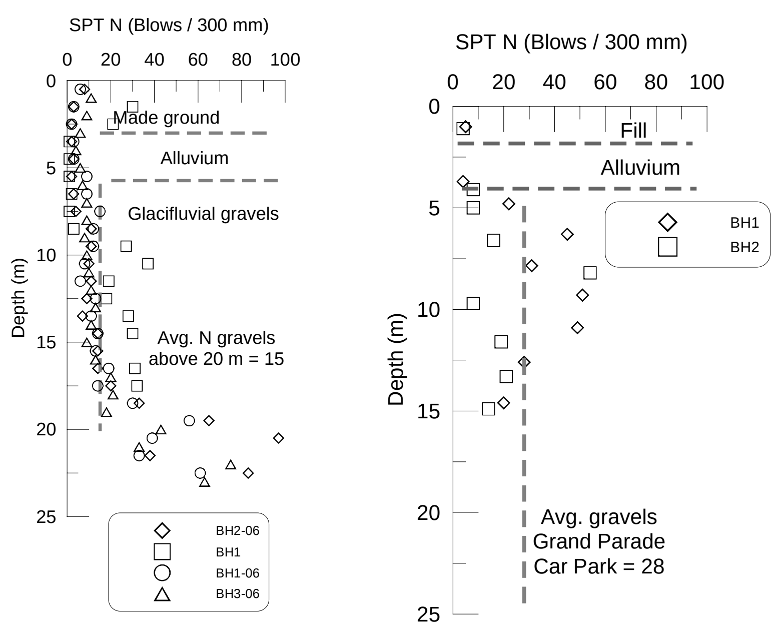


Figure 7. (a) Beasley St and (b) Grand Parade Car park

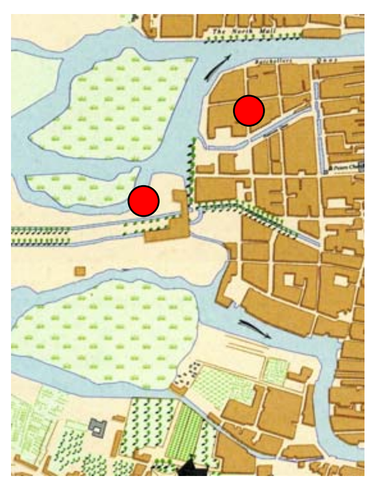


Figure 8.Location of Tyndall Institute and Millerd St sites on Rocque's map of1759

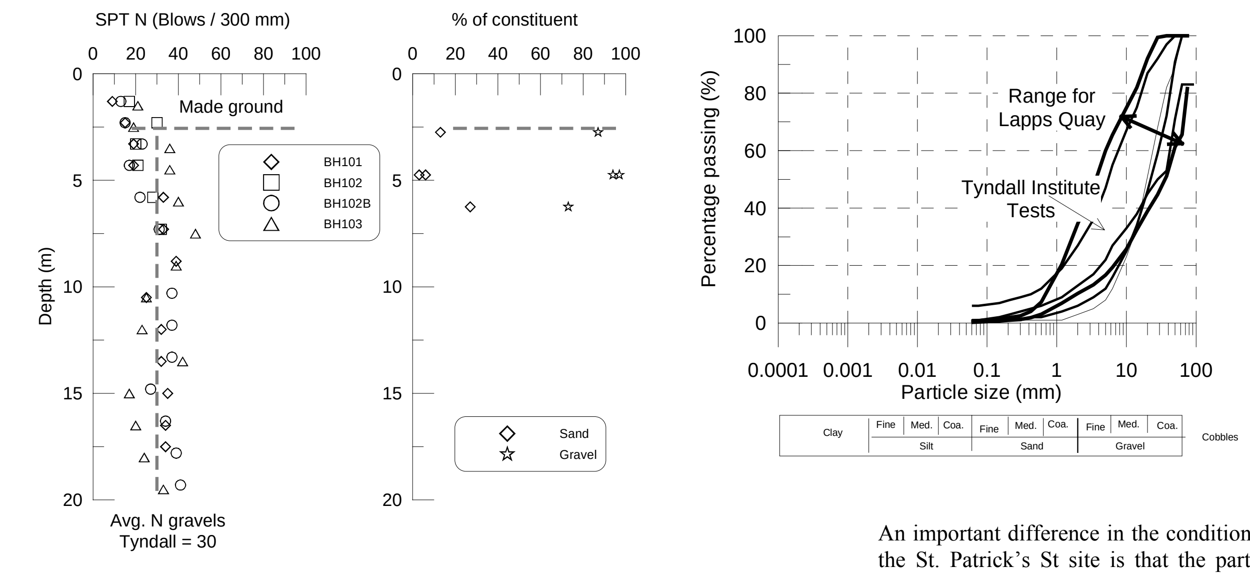


Figure 9.Tyndall Institute, UCC

Average SPT N is possibly slightly higher than for the Grand Parade site and values show no increase with depth. Particle size distribution curves are very similar to those at Lapps Quay.

At Millerd St., some 1.8 m of made ground overlies alluvium to about 4.5 m. SPT N values in the gravels clearly increases with depth and the average value is relatively high at about 35.

Understanding the history of the site can be very important and a simple desk study survey of old maps, for example, is well worthwhile for all developments.

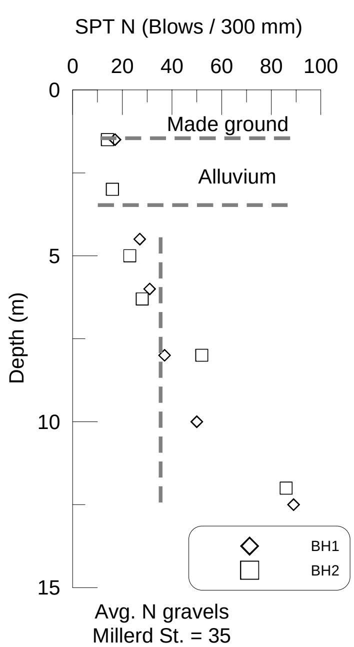


Figure 10. Millerd St.

3.4 Central Island – north side

Three sites are considered here namely:

- Half Moon St where 2.5 m of made ground overlies about 2 m of alluvium
- St Patrick's St, where there is 2 m of made ground over 1.8 m of alluvium
- Lavitt's Quay where there is 2.9 m made ground and no alluvium was reported

The reason for the absence of alluvium at Lavitt's Quay is again apparent from an examination of Rocque's 1759 map (Figure 10), where the site is shown to be located on an old dock which has since been infilled.

As can be seen on Figure 11, SPT N values for Half Moon St and St. Patrick's St are similar to those from the opposite side of the central island. Values show no significant increase with depth and average about 21. The values for Lavitt's Quay are slightly higher, in particular just below the made ground, probably reflecting the history of the site.

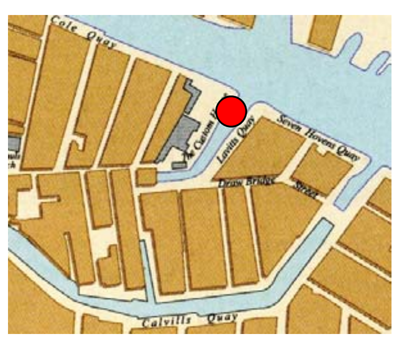


Figure 10. Lavitt's Quay detail from Roque's map of 1759

An important difference in the conditions at the St. Patrick's St site is that the particle size distribution of the material changes with depth as illustrated on Figure 12a. Below approximately 22.5 m there is an appreciable increase in the sand content. This can also be seen in the particle size distribution curves presented on Figure 12b where the curves from below 24 m are appreciably different from those reported from elsewhere.

This may have important implications for construction of piles or for dewatering as the permeability of the ground may vary with depth. This is consistent with the findings of Long et al. (2007) for the Clarion Hotel site who reported that it was necessary to assume a reduced permeability with depth in order to better fit measured site data.

3.5 Central Island – east side

Data for three sites at the eastern end of the central island, namely Anderson's Quay, Reliance Bearing and Jury's Hotel are shown on Figure 13. Conditions are very similar at all three sites with a total of about 4.5 m of made ground and alluvium overlying the gravels. SPT N values all average about 22 and show more or less no increase with depth.

The particle size distribution analyses for Anderson's Quay (Figure 13d) show a similar pattern to those at St. Patrick's St with a marked increase in sand content, particularly below about 15 m. Sand content decreases again at about 28 m.

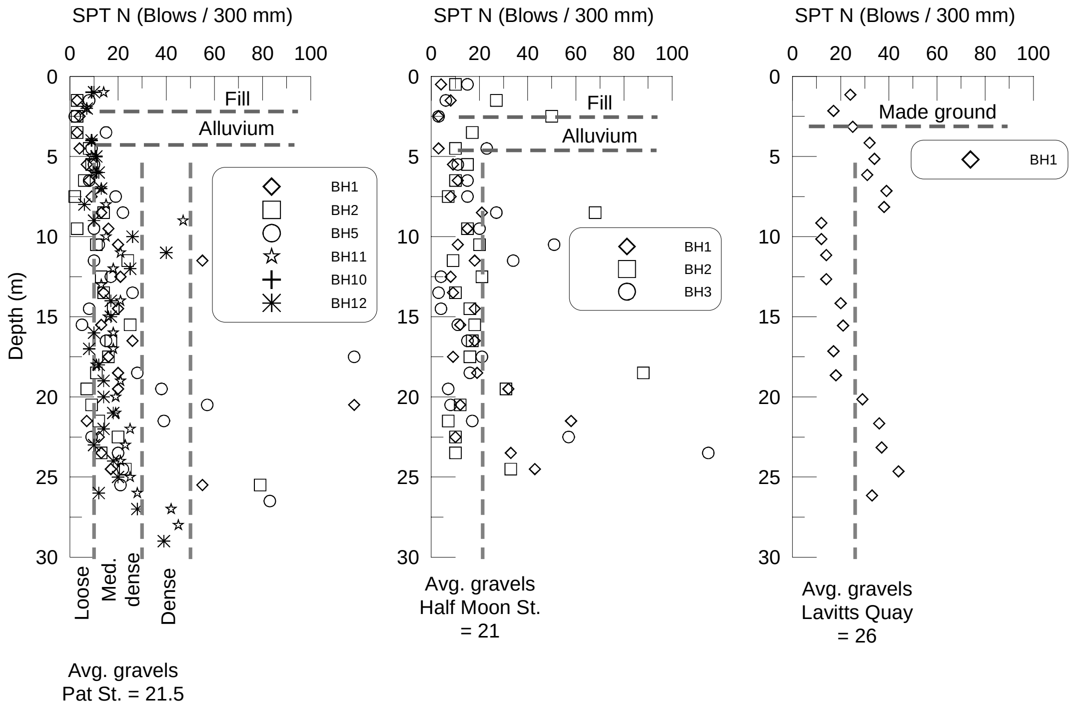


Figure 11.SPT N values for sites on north side of central island (a) St. Patrick's St., (b) Half Moon St and (c) Lavitts Quay.

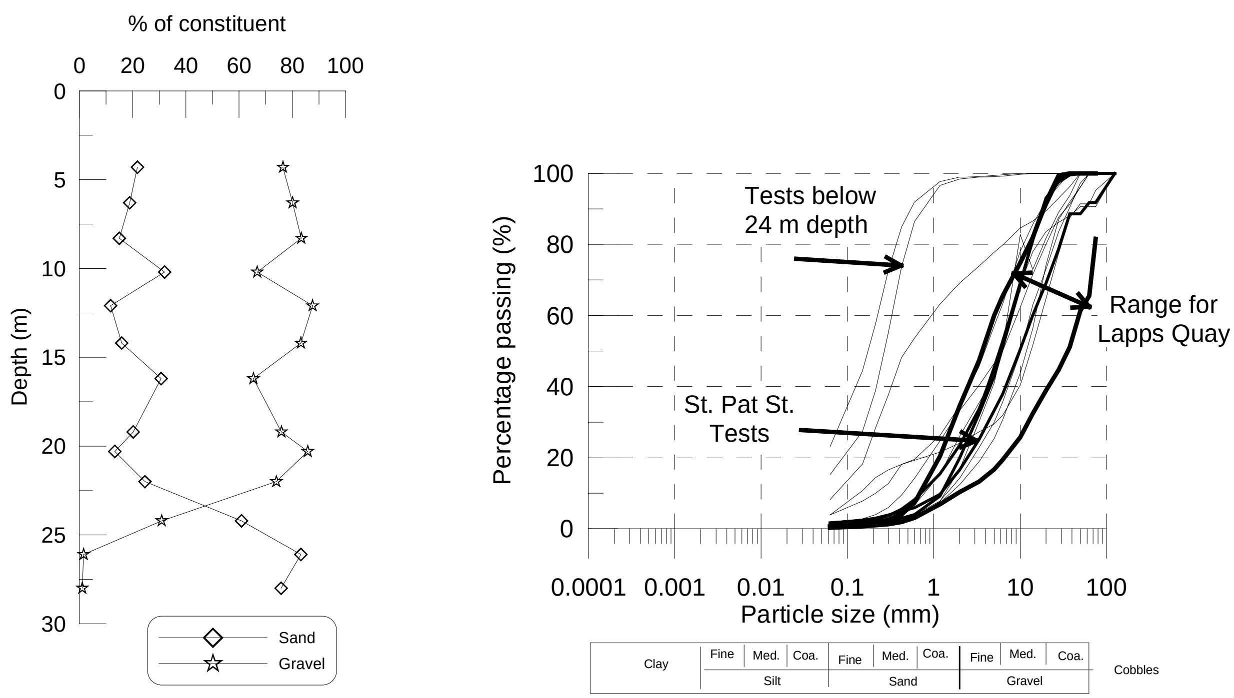


Figure 12. (a) Variation in constituents with depth and (b) particle size distribution for St. Patrick's St. site

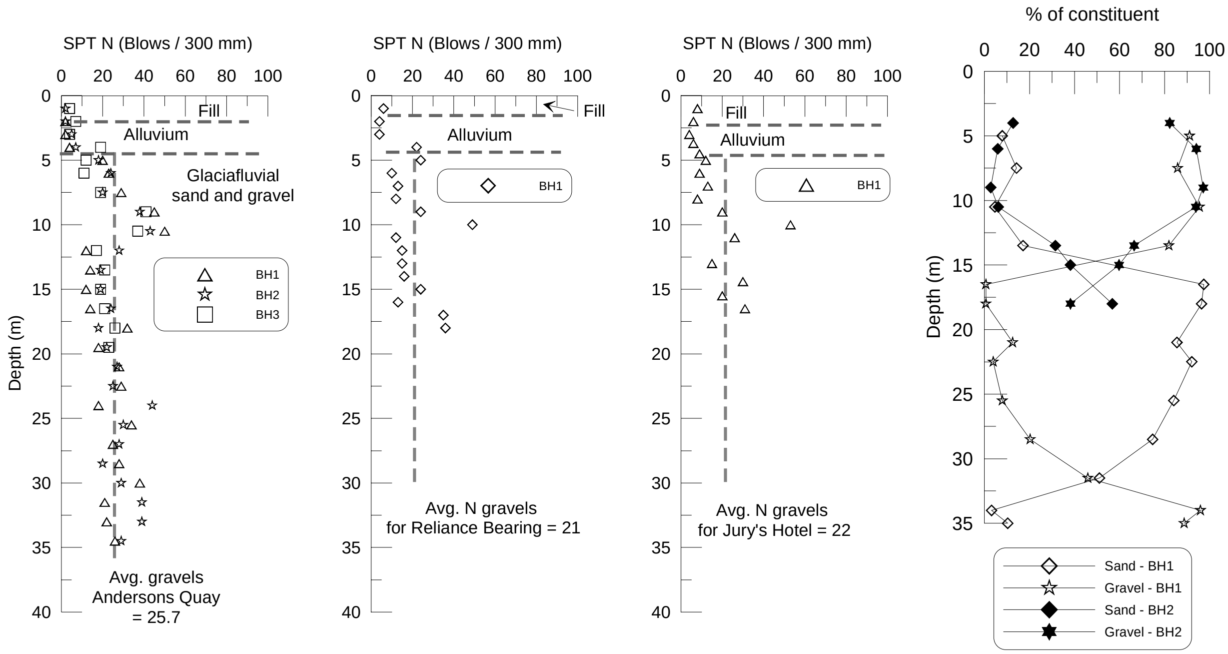


Figure 13.SPT N values for sites on east side of central island (a) Anderson's Quay (b) Reliance Bearing, (c) Jury's Hotel and (d) variation in sand and gravel content with depth for Anderson's Quay

3.6 South of Central Island

Data for the New Cork City Council offices on Anglesea St. (Figure 14) show unusually high SPT values with average N of about 44 and also showing a distinct increase with depth. The reason for this is not clear.

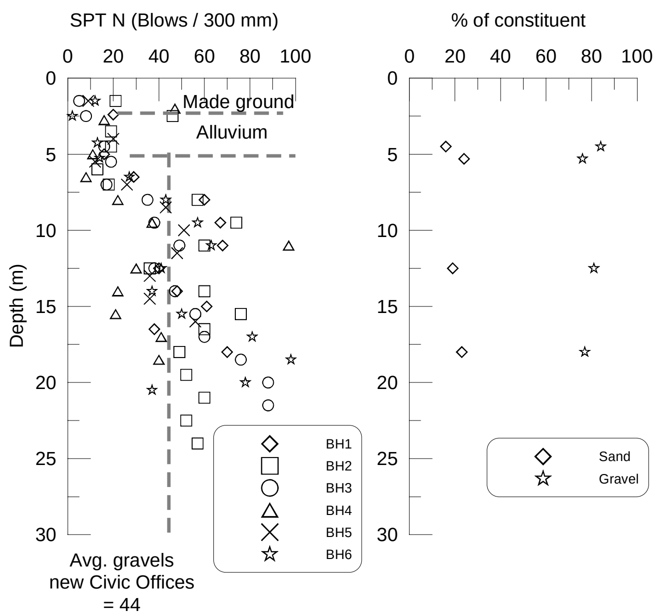


Figure 14. Data for New Cork City Council Offices Anglesea St

The nature of the material is very similar to that encountered elsewhere with average gravel and sand content of about 80% and 20% respectively

4. ALTERNATIVE SITE INVESTIGATION TECHNIQUES

4.1 Cone penetration testing

Cone penetration testing or piezocone testing (CPTU) has become the most common site investigation tool in use world-wide in softer deposits.

It also has use and application in granular deposits. So far its use in the Cork area has been limited. Some CPTU testing was carried out during the site investigation for the Lee (now Jack Lynch) tunnel in Cork Harbour.

Recently some work has been carried out by Trinity College Dublin for Niall Fitzsimons and Co. in conjunction with the St. Patrick's St Development and some results are shown on Figure 15. Testing involves measurement of cone end resistance (q_t), sleeve friction (f_s) and pore pressure (u_2).

The boundary between the peaty silt and the underlying gravels is clearly defined by the friction ratio (f_s/q_t) and the developed pore pressure. The pore pressure parameter (B_q) is also very useful in this regard.

The tests show the sand and gravel deposits to be of varying density. This is consistent with the findings from simple SPT tests as described above but warrants further study.

4.2 Geophysics – surface waves

In Ireland and elsewhere there is a growing use of geophysical techniques in conjunction with civil engineering site investigations. This is because of the general non-intrusive nature of the tests and the speed at which they can be carried out. Recent developments in data acquisition systems and software have improved the quality and the reliability of the tests.

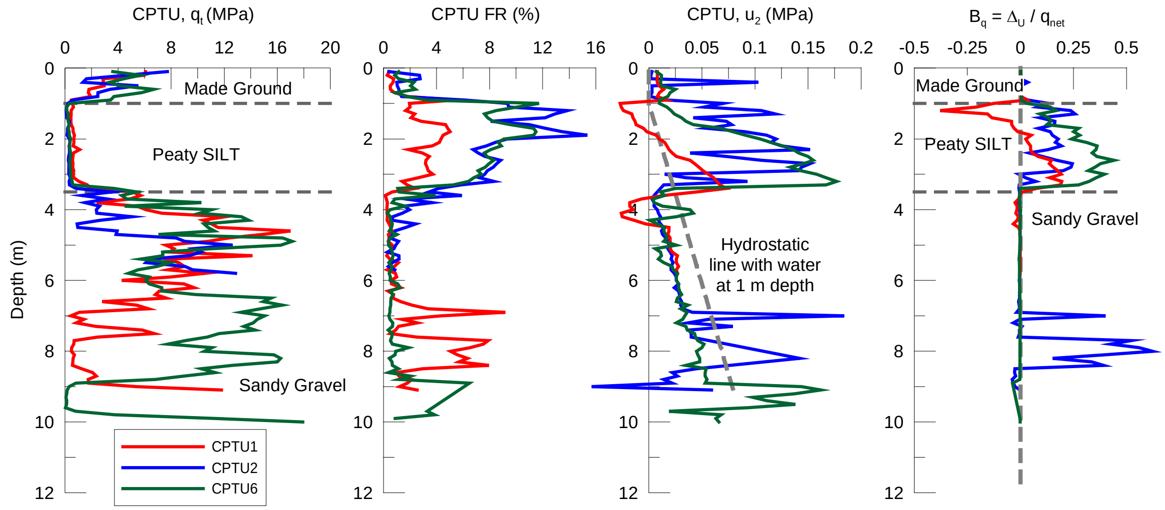


Figure 15. Results of CPTU tests at Patrick St. site

One such method which has been used extensively in Ireland is the MASW (multichannel analysis of surface waves) technique (Donohue et al., 2003, 2004, 2007). As well as generating profiles of shear wave velocity (V_s) with depth, this technique can also yield 2D stiffness profiles.

Some examples from five sites in the UCC / Mardyke / Fitzgerald's Park area are shown on Figure 16. The data for the Mardyke GAA grounds and the UCC Glucksman gallery are compared with SPT test results in Figure 17.

The MASW data are similar to the SPT values only in that they show only a gradual increase in V_s with depth. SPT N values are at the higher end of those measured in the central island area. The relationship between N and V_s is not clear and further study is required to explore this.

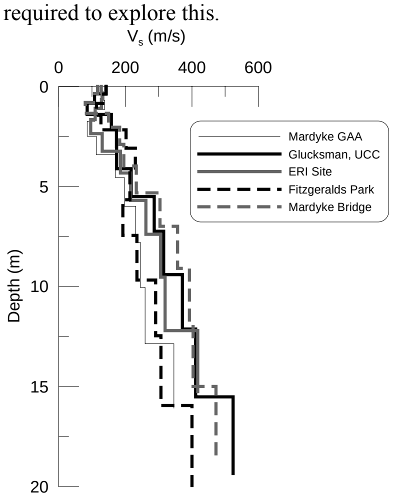


Figure 16. MASW results – all sites

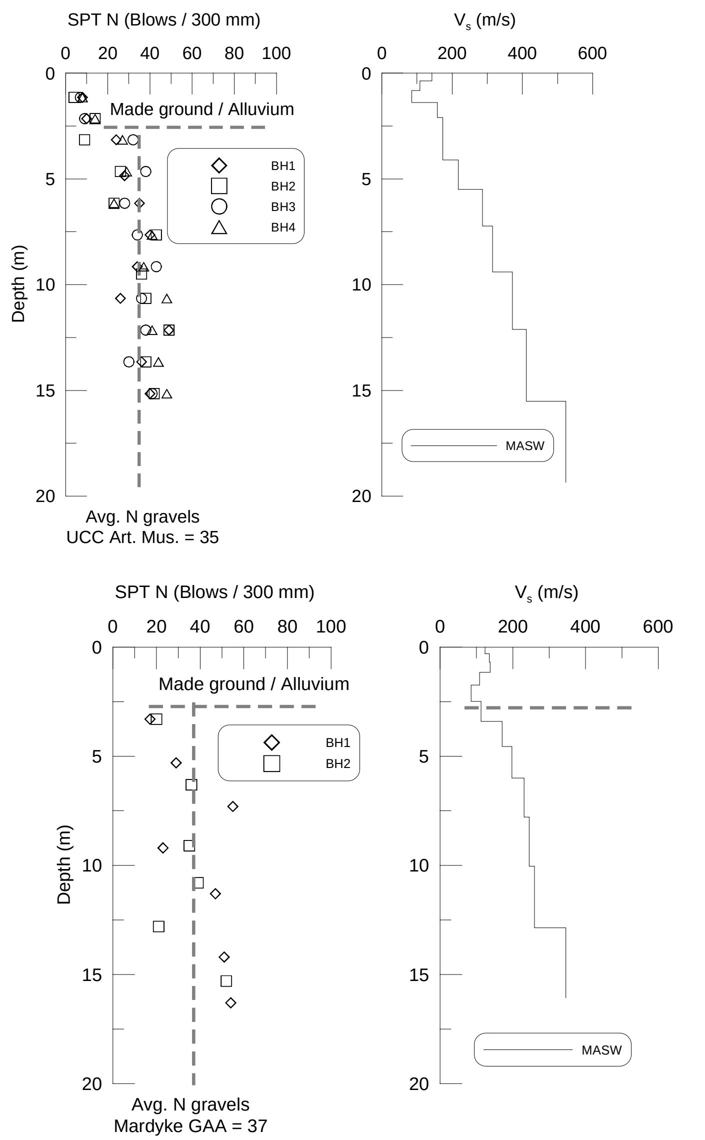


Figure 17. MASW results (a) Glucksman, UCC, (b) Mardyke GAA

4.3 Geophysics – resistivity

Similarly resistivity techniques have significantly developed in recent years due to improved technology and experience. A typical profile taken by Sophie O'Connor, a PhD student at UCD and APEX Geoservices, for the Mardyke GAA pitch is shown on Figure 18. The following test parameters applied:

- Profile length: 124m
- Electrode Spacing: 4m
- Section Depth: 1.0-23.4m bgl
- Min value: 54 Ωm
- Max value: 885 Ωm

It shows predominantly saturated gravel from surface to 23.4m bgl. The least resistive (< 100 Ωm) material found was from 3.3 – 9m and from 2-8m bgl on NW and SE sides of section respectively. Although clear layering is present in the deposits, further work is required to link the material parameters to measured resistivity. It should also be noted that a relatively large area is required for resistivity studies and that ambient noise in urban area may influence the results

4.4 LPT testing

Currently much reliance is placed on standard penetration (SPT) testing in Cork and elsewhere. However due to the small size of the SPT cone and the relative large size of the gravel pieces one would have to question its use in Cork deposits. Daniel et al. (2003) concluded that the SPT is too small for use in gravely soils. Also it is likely that significant energy losses occur at joints in the rods, in the driving hammer etc. Equipment is rarely calibrated and is often in poor condition.

Work needs to be carried out in order to check the influence of these factors. It is also recommended that use is made of the large penetration test (LPT). Various devices are in use throughout the world particularly in the US, Japan and Brasil.

Daniel et al. (20030 give some examples of devices where the outer cutting show varies between 5 cm and 14 cm in diameter and the hammer weight varies between 623 N and 1135 N.

5. DEWATERING CASE HISTORIES

5.1 Summary

Information on some recent experience of dewatering in Cork City is given on Table 1 below.

Table 1. Summary of recent experience of dewatering in Cork City

Project	Excav-ation depth (m)	Pile depth (m)	Abstraction flow (l/s)
Clarion Hotel	7.5	17	200
UCC Gallery	4-5	None	270
UCC OCS	4.0	None	200
Beasley St	6.5	23	170

Full details for the first two projects are given by Long et al. (2007) and Allen and Milenic (2003) respectively. Data for the last two projects representing a piled excavation and an open cut excavation are given in the following sections.

5.2 Piled site – Beasley St.

Ground and site conditions at the Beasley St site are shown on Figure 19a below. Ground level is at about +3.2 mOD and the required formation level was at about – 4 mOD. The perimeter retaining system comprised 23 m long secant piles installed by Bachy Ltd.

The excavation was propped in the temporary state at the top of the piles and also in some locations at a lower level, see Figure 19b.

The site is underlain by an average of 2.5 m of made ground, over 3 m of alluvium over glaciofluvial sands and gravels.

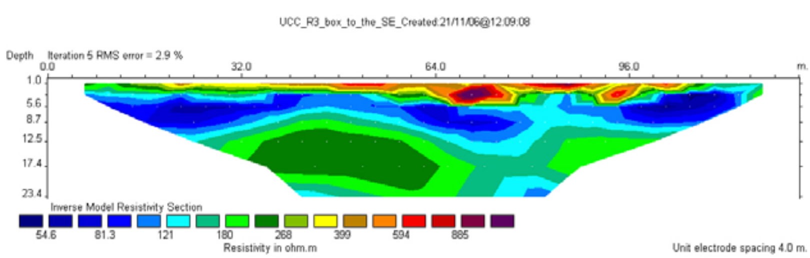


Figure 18. Resistivity profile for Mardyke GAA

The site was T-shaped in plan with overall dimensions of 55 by 50 m. Dewatering was carried out using an array of 11 No. wells installed inside the secant pile wall cut-off. The wells were pumped with electric submersible pumps which discharged to the adjacent south channel of the River Lee. The wells were installed to a depth of 14 m and were fitted with pumps of capacity 18 l/s. The pumps were operated from a central control cabin which included provision for automatic switchover to a standby generator and pump restart in the event of a mains power stoppage. The control cabin also included facility for data logger monitoring of the standing groundwater level in a number of internal and external standpipe piezometers and unpumped wells.

The initial piezometer monitoring data showed that internal drawdown to below the target excavation level (a drawdown of approximately 4.5 m) could be achieved with a total abstraction flow of approximately 170 l/s. With this pumping regime the external groundwater levels would also be reduced by approaching 3 m.

Because of the concern about the possible settlement risk to adjacent structures due to the drawdown it was decided to use recharge to limit the external drawdown to approximately 2 to 2.5 m. This was achieved using an array of 4 No. external recharge wells which accepted a recharge flow of about 35 l/s. Raising the external groundwater levels in this manner resulted in feedback and it proved necessary to increase the internal abstraction flow to over 190 l/s in order to re-establish the target internal drawdown level. The data collected during the operating phase of the dewatering system is shown in Figure 20. The extent of the tidal fluctuation is clearly evident as is difference in internal and external drawdown.

Settlements of survey points attached to the surrounding buildings were measured using total station techniques. The results are shown on Figure 21. As can be seen from the scatter in the data the readings were close to the accuracy of the measuring system (±3 mm?). However it is clear that very little settlement of the adjoining buildings occurred. Similarly lateral movement of the retaining walls was measured by inclinometers. The data for the inclinometer which showed the most movement is shown on Figure 19. It can be seen movements are very small and are at most of the order of 5 mm. This is equivalent to 0.07% of the excavation depth, which is modest compared to experience elsewhere (Long, 2001)

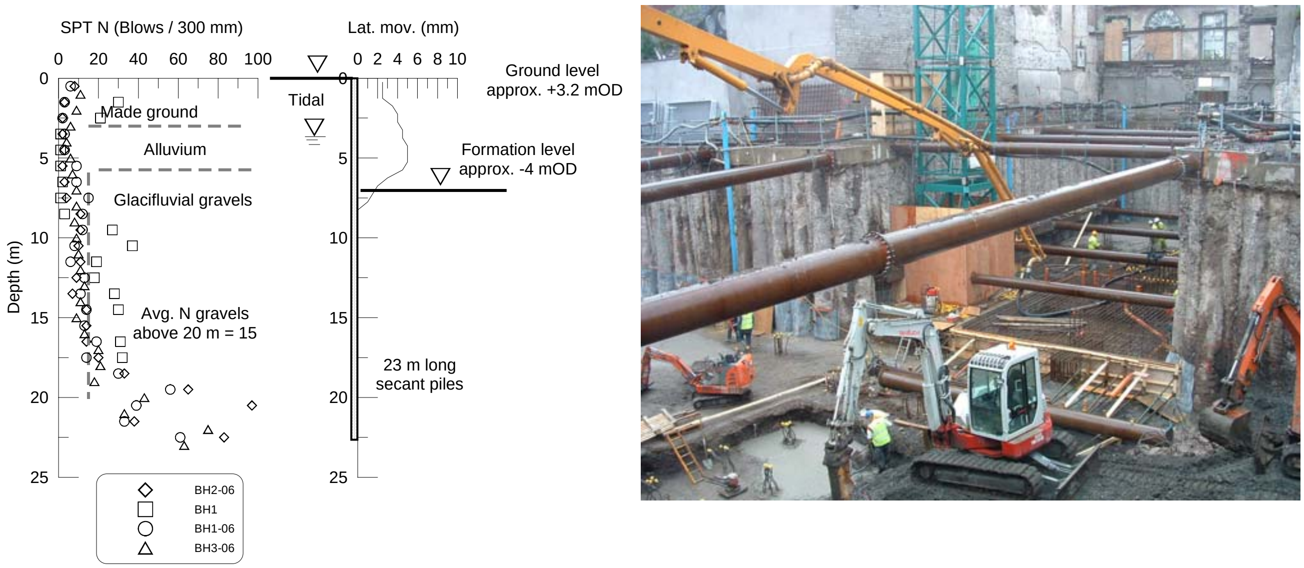


Figure 19. (a) Ground and site conditions at Beasley St (see also Fig7) and (b) site view on 13/7/07 (Photo M. Murphy – Niall Fitzsimons and Co.)

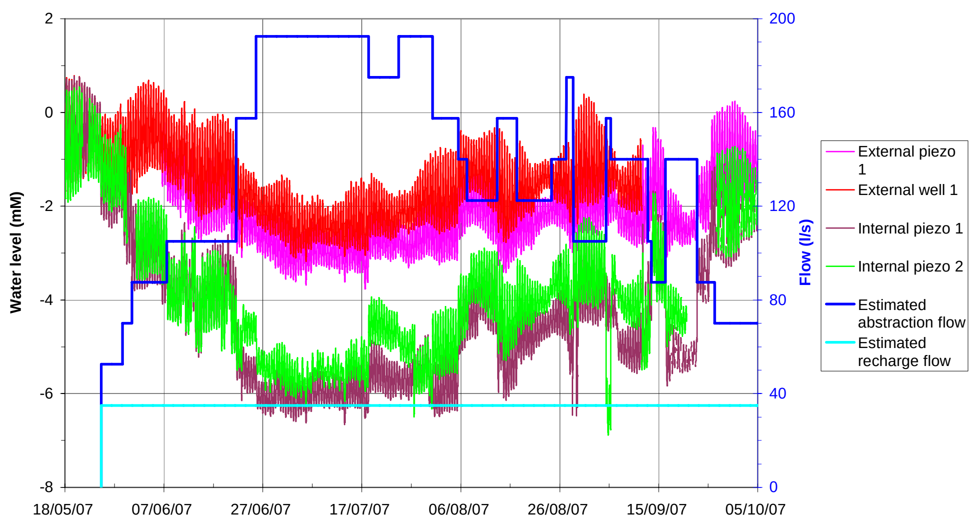


Figure 20. Data from operating phase of dewatering system at Beasley St

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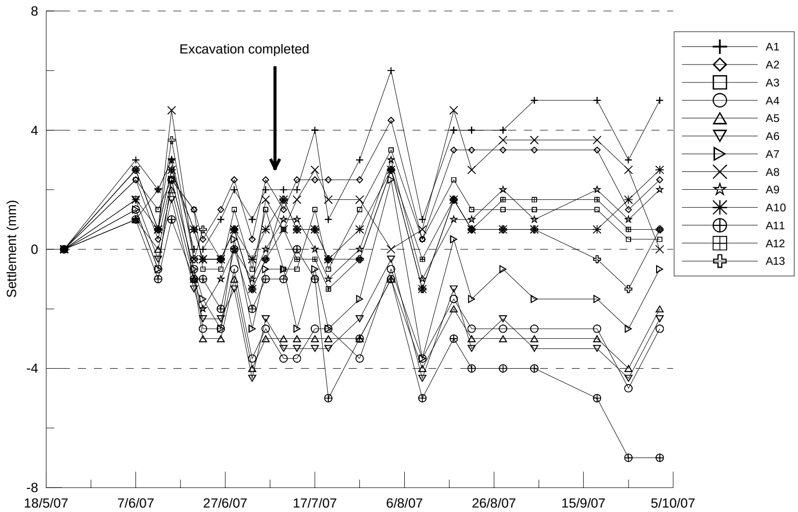

Figure 21. Settlements of adjacent buildings at Beasley St.

Clearly the behaviour of the retention system was very good. The settlements of the adjacent buildings are also significantly less than would be expected from conventional soil mechanics calculations. In the author's opinion this is due to the alluvial deposits having a small degree of overconsolidation.

Therefore as the loading due to dewatering remains in this overconsolidated range, settlements are modest. Further work on good quality samples is required to verify this.

5.3 Open cut site – UCC OCS

This site is located at the western end of the Central Island adjacent to the South Channel. These works involved an excavation in open cut over a plan area of 100 m by 60 m. The site investigation data indicated that no Alluvium was present so that Made Ground directly over laid the sand/gravel aquifer. The borehole data suggested that boulder clay was present below the sand / gravel at between 8 and 18 m depth. A drawdown of approximately 2 m was required. This was achieved using an array of shallow wells and open sumps with a total discharge flow estimated to be approximately 200 l/s.

5.4 Influence of retaining wall depth on dewatering

The two case studies which did not have a cut-off (The UCC sites in Table 1) required much greater pumping per meter of drawdown than the two sites which had deep perimeter cut-offs.

From this it is apparent that the perimeter cut-off appreciably reduced the required dewatering flows. What is not so obvious is that the reduction in flow is disproportionate to the depth of the piles (if the permeability of the sand / gravel is assumed to be uniform with depth with the same horizontal and vertical permeability). Analysis of a number of pumping tests undertaken in the City has indicated an average bulk horizontal permeability for the sand/gravel of in excess of 10^{-3} m/s, Long et al. (2007). This contrasts with back analysis of projects with a perimeter cut-off which indicates that the permeability of the sand / gravel must reduce by approximately an order of magnitude at a level above the base of the installed cut-offs. It would clearly be useful if there was a way to identify horizons which represent a change in permeability since this would allow optimisation (and possibly reduction) in the depth of the perimeter cut-off. These varying permeability horizons might be explained by the changes in sand content identified at some sites but the elevation for this seems to vary appreciably and to date there is no consistent correlation apparent with permeability.

5.5 Choice of retaining wall system

Designers and contractors involved in deep excavation schemes in Cork have to choose between various forms of retaining wall system. All have advantages and disadvantages.

Sheet piles are possibly cheaper. They are easy and quick to install. However the pile driving may damage adjacent buildings and they may be more flexible resulting in larger lateral wall movements during excavation. Noise and vibration may also be an issue and props are usually required.

Secant bored piled walls will be stiffer and propping requirements may be reduced. However they will be more expensive and slower to install. Choices have to be made between continuous flight auger piles (cfa) and conventionally bored piles with full depth casing.

Until recently cfa rigs had limited depth penetration and torque capacity. However large rigs with 30 tm torque capacity are now readily available in Ireland allowing deep cfa piles to be formed in the Cork gravels. However it may be more difficult to maintain good verticality with cfa rigs.

In turn conventional bored piling rigs may provide better verticality but are also likely to cause more vibration and could potentially cause more damage to adjacent buildings.

When assessing settlement a distinction needs to be made between that caused by lateral movement of the retaining wall system (local with high risk of differential movement) and settlement caused by dewatering (potentially extensive with lower risk of differential settlement). To date all settlement monitoring has been carried out within the zone of influence of the retaining system.

6. CONCLUSIONS

1. There is significant variation in density of the gravels across the area. For the most part the average SPT N value is in the low 20's and shows only slight increase with depth.
2. In the limited study carried out here there appears to be stiffer sub-strata with higher N values present at the western fringe of the central island and markedly just south of the central island
3. Particle size distribution analyses suggest that the composition of material is very similar across the area, particularly in the upper part of the sand and gravel stratum.
4. There is evidence for some sites that there is an either a significant increase in sand content or sand layers with depth. This may have implications for engineering works, particularly for dewatering.
5. Simple desk study surveys of available information such as old maps can be very useful.
6. Currently SPT testing dominates site investigation. The results may be questionable due to the size of the particles in the gravel deposits.

7. Consideration needs to be given to other techniques such as CPTU, LPT and geophysics in particular MASW surface waves and resistivity. Geophysical techniques may be difficult in city centre areas due to ambient noise.
8. Various techniques are available for retaining wall construction and all have advantages and disadvantages.
9. However extensive dewatering and pumping effort is required to dewater excavations. Experience suggests permeability decreases with depth. However work is required to define this finding more precisely and to link it to material type.
10. Settlements of adjacent buildings due to under-drainage of alluvial soils, overlying the gravels, are of significant concern. However experience to date has shown low movement, possibly because the alluvium possesses a slight degree of overconsolidation or that older foundations are more substantial than originally thought.

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