Dublin Docklands, to the east of the city centre, is undergoing a major brownfield regeneration programme to transform a massive 520 ha (1,300 acres) site into a world-class mixed use development. The Dublin Docklands Development Authority (DDDDA) is a public body created in 1997 to drive the regeneration process forward. Fundamental to the start of this rejuvenation was the clean-up of an important 8.9 ha (22 acres) anchor site fronting the south side of the River Liffey.

Located between the river and the historic Grand Canal Dock, the Sir John Rogerson’s Quay gasworks had been used as the main source of gas production for Dublin since the 1820s. The DDDDA acquired the site from Bord Gais Eireann, the statutory body responsible for the transmission, distribution and supply of natural gas in Ireland, in 1998.

The remediation of this site was a major undertaking. From the detailed site investigation to the surrender of the second of two waste licences took over 5 years at a cost of some €40M including infrastructure improvements. The lack of landfill capacity in Ireland to take contaminated soils forced the investigation and use of alternative treatment technologies in a country where there had previously been little or no market for such technologies.

This paper outlines the various hurdles, which had to be overcome including:

- Site characterisation
- Quantified risk assessments and remediation strategy
- A novel contractor-designed hybrid perimeter cut-off/retaining wall
- Accommodation of a large existing preserved chimney.
- Waste Management Licences: application, management and surrender
- Use of remediation technologies including gravel jet washing, thermal treatment and soil washing
- On site water treatment
- Odour controls and air quality monitoring
- Site records and validation

A major concern at the outset of the project was the fact that it would require two Waste Management Licences. None had previously been issued in the context of contaminated land in Ireland and it was realised that it would probably be the first application for surrender of a licence since the introduction of the legislation. All of the parties; Client, Engineer, Contractor and Regulator (The Environmental Protection Agency) thus became focused on the importance of the latter in the interests of successful regeneration of the site. Only by all embracing the need, for effective communication of the rules, for anticipation of potential areas of difficulty and for compliance throughout, was success achieved.

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1. INTRODUCTION

The former Sir John Rogerson’s Quay gasworks site, located approximately 1.0km to the east of Dublin City centre, was acquired by Dublin Docklands Development Authority (DDDA) from Bord Gais Eireann in 1998. The 8.9 hectare site is divided into five areas; Sites 1-4 are identified on Plate 1 with Site 5 being located on the eastern end of the Grand Canal Dock. The River Liffey flows from west to east immediately to the north of the site. DDDA intend to transform the site into a mixed development of residential, commercial, amenity and retail uses. Mouchel Parkman was commissioned to advise DDDA on the remediation works.

The new development comprises large areas of underground car parking which required excavation to depths down to at least -1.0mOD (Malin); site ground levels prior to remediation works varied between around 1.5 and 4.0mOD. Groundwater is located generally around 0.0mOD across the site, near to mean tide level governed by the adjacent River Liffey. An old brick chimney, 54m in height was retained as a feature in the new development.

For nearly 200 years, almost without exception, every town and even some villages in Ireland satisfied their energy needs by the manufacture of gas from coal (perhaps later from oil) at the local gasworks. At the peak of the industry, it is estimated that there were some 114 gasworks throughout the country. It comes as no surprise that the largest of these undertakings was in Dublin.

Gas production commenced at Sir John Rogerson’s Quay gasworks circa 1830; coal being delivered to site from overseas by barge and off-loaded onto Site 4 (See Plate 1). Coal was heated in retorts located on Site 1 and stored on Sites 1 and 2. One of the largest gasometers was a fixed height waterless type located at the corner of Sir John Rogerson’s Quay and Cardiff Lane and was for many years a well known Dublin landmark.

Mouchel Parkman carried out a detailed study of the site’s historical development including the evolution and layout of processes to allow a targeted ground investigation to be undertaken.
By-products of the manufacture of gas included coal tars, spent oxide, coke and ammoniacal liquor; the first two in this list are commonly found in appreciable quantities on former gasworks sites. Spent oxide is a residue from iron oxide used in the purification of coal gas to remove sulphur, cyanide and other harmful constituents. This material consists of a deep blue friable solid ("blue billy"), the blue colouration resulting from the presence of ferric ferrocyanide. Coal tar is an extremely complex mixture of substances such as benzene, toluene, xylene, tar acids, naphtha, anthracene and phenanthrene. The coal tar was generally stored in underground tanks; several of which have been identified from historical plans located across Sites 1 and 2; these were sometimes poorly constructed and allowed large quantities of tar to seep into the ground. Initially the tar was unwanted, but it soon spawned a chemical industry in much the same way as oil has today. A chemical works located on Site 3 was identified from historical maps. These works converted the by-products of gas manufacture into marketable materials; everything from road tar and creosote to aspirin and fruit sprays!
The production of gas was enhanced in the 1960's by a process involving the catalytic cracking and reforming of a particular fraction from the distillation of crude oil. These plants were known as oil-gas plants. Feedstocks included light distillate spirit, naphtha and liquid petroleum gas (LPG) and were stored in large volumes on Site 2. Leakage from these tanks and associated pipelines caused further contamination of the ground.

Fig 1 is a plan of Site 1 that shows the large number of former storage tanks identified from a study of historical maps and records of the works. Sites 2 and 3 show similar findings.

2. GEOLOGY, HYDROLOGY AND HYDROGEOLOGY

Historically the site was reclaimed from the southern flank of the Liffey Estuary in Dublin Bay in the mid-1700's. A substantial amount of uncontrolled filling was required to reclaim the site from the estuary, resulting in the layers of fill now present. The near surface geology underlying the fill is made up of alluvial deposits consisting of interbedded silts, sands and gravels (with a large proportion of cobbles in places) underlain by glacially deposited boulder clays with sands and gravels over a limestone bedrock. The hydrogeological conditions pertaining to the site are best considered in terms of the two principal water bearing horizons, as discussed in the following paragraphs.

Shallow Aquifer (Superficial Deposits)

The superficial deposits comprise: Fill of low to moderate permeability, overlying Estuarine Alluvium consisting of clays, silts and sands that have a limited permeability. These in turn overlie the glacio-fluvio-glacial gravels (with significant amount of cobbles in some locations) that have a moderate to high permeability. It is reasonable to consider the fill, alluvium and gravels as a single unit, comprising an aquifer that is in hydraulic continuity with the river.

Boulder Clay underlies the glacial gravels and in general serves as a groundwater partition, but glacial gravel lenses may form windows in the Boulder Clay that allow groundwater mixing between the gravel aquifer and limestone aquifer beneath.

Deep Aquifer (Bedrock)

The Carboniferous 'Calp' Limestone, which underlies the site at depth, is informally considered a "Minor Aquifer" by the Geological Survey of Ireland, and there are no well abstractions within the vicinity of the site.

It is considered that hydraulic continuity exists between the two water bodies.

Groundwater flow would tend to be towards the River Liffey in a north westerly direction.

Distribution of Contamination

After investigating the site it was clear that the general fill was often contaminated with some or all of the contaminants mentioned above, whilst the natural strata beneath were only effected by the mobile components. Ammonia, polycyclic aromatic hydrocarbons (PAHs), phenols and sulphates are the mobile components that have impregnated the natural strata. Natural groundwater flow provided the mechanism by which the contamination was able to spread to the gravels and other permeable strata. As the gravel was the stratum with the highest permeability, mobile contaminants tended to be concentrated there. Some gravels were so saturated with oil and tar, particularly at the gravel / clay interface that they were, themselves considered a contamination source.

3. REMEDIATION STRATEGY

Risk Assessment

Quantified Risk Assessment (QRA) is now the preferred method for assessing the risk to human health and to the surrounding groundwater / rivers. The assessment was made using internationally accepted methods (predominantly USEPA guidelines) and defined the remediation standards to which the site has been cleaned. Site Action Values (SAV's) based on the risks to groundwater and human health were derived. As there were two assessments (groundwater and human health) two sets of SAVs were produced. For each parameter assessed the lower of the two SAVs was incorporated into the remediation strategy in order to be health/environment conservative. For soils encountered below -1.5m OD (Malin Head) the values derived from the groundwater risk assessment were adopted as SAVs, as the soil at this depth would pose an insignificant risk to the developed site's end users.

The groundwater risk assessment assumed that the water beneath the site would remain in continuity with the gravel aquifer and the rivers. In reality, the groundwater is sealed off by an underground cut-off wall and this is another intrinsic conservatism of the QRA.

Hybrid Perimeter Wall

In order to remove contaminated gravels for treatment the excavations extended down to 6 metres below the existing ground level and 4 metres below the mean water table in places. To facilitate the excavations an underground cut-off wall was constructed around the perimeter of the main site. The wall around the perimeter of the main site was 1020m in length with depths ranging from -3m AOD to -8.5mAOD. The most significant risk associated with this containment retaining wall was the potential for contaminated ground water and leachates re-entering the site following remediation. The chosen solution had to have a continuous low permeability (1x10⁻⁶ m/sec), a high degree of construction certainty and be capable of withstanding the bending moments and shear forces associated with cantilever retained heights of up to 5.0m. The chosen hybrid solution consisted of a slurry trench with CFA piles to provide the structural capacity.

Remediation Technology Options

In selecting the most effective solution, consideration had to be given to the fact that an underground car park was to be constructed across large areas of the site, necessitating removal of large volumes of soil.
**Removal to Landfill**

Many similar sites in Northern Ireland and in Great Britain have been remediated by simply excavating the contaminated soil and removing it to landfill. The benefits of this approach include relatively low costs (landfill tax exemptions are often applicable), speedy delivery of a clean site and simple execution. However, land filling of potentially treatable soil is not sustainable and the many lorry movements required to transfer material to the tip would have an adverse environmental impact on local residents. Specifically removal to local landfill was not an option for the Dublin project as there were no facilities able to accept the contaminated soil in the Republic of Ireland. Therefore, a 'dig and dump' approach was rejected.

**Bioremediation**

Bioremediation refers to the use of microbes to breakdown contamination into inert waste products (e.g. CO₂ and H₂O). These microorganisms are sometimes introduced to the contaminated soil, but more commonly air and nutrients are added to encourage the proliferation of microbes already present. These techniques are relatively inexpensive, sustainable, and have proven successful on many remediation projects.

The main disadvantage of bioremediation techniques, when applied to gasworks, is the microbes suitable for breaking down the hydrocarbons associated with coal tar do not thrive in the presence of cyanides. The complex mixture of contaminants (heavy metals, hydrocarbons and cyanides) encountered on the gasworks precludes the successful use of biological remediation techniques. Bioremediation is also a relatively slow process and would not have been able to achieve the remediation goals in the timescale required by the client.

**In-situ Stabilisation / Containment**

This technology isolates contamination from the surrounding environment by stabilising or 'freezing' it in place, often by mixing the soil with cement. The benefits include its suitability for all soil and contamination types as well as minimal local environmental impact during execution as little earth is exported from the site. There was a concern about the validation and long term durability about this form of treatment.

**Thermal Desorption**

Thermal desorption is an ex-situ soil treatment involving the removal of contaminants unstable at high temperatures by heating the soil in a closed furnace. Fumes arising from the oven are then rigorously treated in order to meet stringent air emission criteria. The method is well suited to the granular soils encountered and is capable of successfully treating the tar-saturated soils associated with former tar tanks.

Disadvantages of this method are the relatively high costs (soil was transported to Holland as no such facilities exist in Ireland), and limitations based on sulphate and heavy metal concentrations (discussed below). Thermal desorption was chosen as one of the treatment methods as it would be able to treat soil too contaminated with heavy tars for soilwashing.

**Physio-chemical Soilwashing**

Soilwashing is an ex-situ technique born out of the mineral extraction industry. The method assumes contamination is concentrated in a certain soil fraction and endeavours to extract this 'dirty' fraction from an otherwise 'clean' soil matrix. Once extracted, the dirty fraction is normally disposed to landfill while the clean fraction is recycled in construction projects. The method only becomes economic when the recovered clean material significantly outweighs the contaminated material extracted. It is not possible to wash clay soils successfully, whereas gravel washes very well.

In the soils excavated at Sir John Rogerson's Quay, contamination was generally confined to the particles less than 5mm and as the majority of the made ground and contaminated natural deposits were granular, the soil lent itself to this type of treatment. As this was an ex-situ treatment, remediation would be possible in the timescale required and soilwashing was adopted as the main treatment method.

It was envisaged that mobile plant (soil washing and / or thermal desorption) would be used to remediate the gravels and other suitable materials from the gasworks on site. However, it became clear that a long public consultation period would have been necessary before the plant could be licensed and commercial pressures to develop the site precluded this kind of delay.

### 4. WASTE LICENCING

**General**

Under the Waste Management Act, 1996, Section 39 the recovery of waste at a facility is not permitted save under a Waste Licence. Various recovery processes were employed on the gasworks to ensure that clean material was not exported for treatment and therefore it was necessary to operate the site under a Waste Licence. Two applications were made to the Environmental Protection Agency (EPA) one relating to Sites 1, 2, 4 and 5 and another for Site 3. This allowed development to proceed on Sites 1, 2, 4 & 5 (after surrender of the Licence) while remediation works progressed on Site 3. These were the first applications for Waste Management Licences relating to contaminated land in Ireland.

The licensed activities, in accordance with the Fourth Schedule of the Waste Management Act, 1996 were:

- **Class 2: Recycling or reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes).**
- **Class 4: Recycling or reclamation of other inorganic materials.**

Before waste activities could begin a detailed Environmental Management System (EMS) was submitted to the EPA. The EMS included method...
statements for all aspects of the works, and these were agreed by the EPA.

**Movement of Materials**

The classification, identification and control of excavated soil was paramount to the success of the project. Visual assessment of contaminated soils is unreliable and in all cases, soil was assessed using chemical analysis. The site was split into 20m by 20m by 1m cells and each cell was assessed separately, with the exception of buried tanks, which were considered individually. In order to characterise each cell, samples were taken and dispatched for laboratory analysis.

The Waste Licence conditions stipulated that all wastes leaving the facility were weighed and the destination, waste description and carrier details noted. Waste was removed from the facility either by road or by ship via an overhead conveyor. The conditions were met using a calibrated weighbridge for road transport and a weigh-cell incorporated into the conveyor. All waste exported to mainland Europe for treatment was subject to a Transfrontier Shipment Notice and a financial bond was required to cover treatment of the soil in the event that it was not accepted abroad.

**Environmental Monitoring**

The waste licence required that the remediation works were undertaken without significant impact on the local environment and emissions to air, sewers and groundwater were monitored to ensure compliance.

Monitoring of all emissions to the atmosphere (dust, vapours and noise) was undertaken during the works in order to ensure compliance with occupational exposure levels. Any excavation in dry weather has the potential to produce dusty conditions. Monitoring dust concentrations was, therefore, particularly important.

The potential for the generation of odours was recognised and procedures were implemented to ensure that these were controlled during the works. Regular meetings were held with local residents representatives and our monitoring results displayed daily.

Groundwater quality in both the gravel and limestone aquifers beneath the site monitored after the remediation earthworks were complete. The purpose of the monitoring was to demonstrate that the facility no longer represents a risk to the environment.

**Surrender of the Licence**

The waste licences could only be surrendered once the waste activities have been completed and the EPA satisfied that the site is no longer having an impact on the local environment. In order to demonstrate this, a comprehensive Validation Report was submitted to the EPA describing the works carried out, including the results of all environmental monitoring and soil analysis.

The two Licences were successfully surrendered; the first in Ireland!

5. **REMEDIATION PROCESSES**

**Introduction**

The main objectives of this project were to remove contamination sources from above and within the gravel aquifer and protect the cleaned site in order that it could be developed without risk to the end users and surrounding environment. In order to achieve this economically, gravel was excavated and much of it was treated at Sir John Rogerson’s Quay. The gravels are ideal for recovery as a large proportion (60 to 80%, see Fig 2) comprises the >6mm fraction. In the contaminated gravels, this coarse fraction is intrinsically clean with oily/tarry residues only adhering to the surface. The washing process was designed to remove this surface contamination. Due to their small surface area to volume ratio the coarse gravel particles (40-100mm) are the cleanest, while the finer fraction (<6mm), with the larger surface area to volume ratio is the most contaminated (see Fig 3). In order to recover the coarse and intermediate gravel fractions various processes were used, both domestically on site in Ireland and overseas in Belgium and Holland. The following sections describe the two on-site methods used: Gravel washing and vibration screening, together with the two off-site methods, physio-chemical washing and thermal desorption.

In addition, a water treatment plant was constructed on-site and details are provided below.
On-Site Waste Minimisation Processes

Gravel Washing

The washing plant comprises a loading hopper, 150mm screen, delivery conveyor, rotating drum with high-pressure water jets, silt/water collection hopper and sedimentation lagoons. Contaminated gravel was placed into the hopper and cobbles greater than 150mm were rejected by the screen. The particle fraction <150mm was then transported up an inclined conveyor and delivered into the wash drum. The drum was perforated to allow silt, sand and gravel <5mm to be washed out whilst the >5mm gravel and cobbles are retained inside. Gravels are moved through the rotating drum by spiral flights using the same principle as an Archimedes Screw. During its residence in the drum, the gravel is sprayed by high-pressure water jets and agitated by the drum's rotation. It is the action of the water and attrition of the gravel particles against each other that removes the surface contamination. Essentially contamination is taken from the soil phase and suspended/dissolved in the water phase.

Water, sand and silt were collected by a hopper positioned below the drum and this drained to a series of settlement lagoons. Once the sediments had settled out the wash water was pumped to a treatment installation on-site. The water was then discharged to foul sewer under licence, but could potentially be recycled back into the gravel washing plant. Clean gravel was discharged from the end of the drum.

It was found that between 60 to 80% of the gravel could be re-cycled as backfill on the site. However, as there was a surplus of backfill on the site alternative destinations were sought in conjunction with the Contractor and the EPA. Washed gravels were tested and it was found that the contamination had reduced to below Dutch Intervention Values. It was found that material of this standard was readily marketable and a number of local outlets were found.

Contaminated sand and silts from the settlement lagoons were dried and exported for treatment by either thermal desorption or physio-chemical washing depending on the grading and concentration of hydrocarbon contamination.

Vibration Screening

The settlement stage of the on-site gravels washing was time-consuming and trials were conducted to establish whether the contaminated fine fraction could be removed from the gravels using screening plant. A ‘Viper’ 4-way screening plant was employed to split the gravels into four size fractions using one static (100mm) and 2 vibrating meshes (5mm and 40mm). The gravels were predominantly contaminated with PAHs and Fig 3 summarises the results of the gravel screening trials. The initial objective was to improve the quality of the gravels so that they met Site Action Values and could be used for backfilling.
Physio-chemical Washing and Thermal Treatment in Europe

Soilwashing in Belgium

The soil suitable for soilwashing was shipped to a facility in Antwerp. The criteria for ensuring the soil was suitable for soil washing were both chemical and physical. The particle size distribution had to be such that no more than 15% of the particles are less than 63 µm otherwise to comply with licensing restrictions. The process was successful in extracting heavy metal, cyanide, sulphate and other inorganic contamination from the soil. It was also efficient at removing light hydrocarbons, but less successful with viscous tars. In general soilwashing removes 85% of the PAH loading from sands and gravels. If the residual PAH loading in the washed gravel or sand exceeds generic Belgian soil guidelines the material cannot be recycled. If there was a risk that any individual PAH would exceed these guidelines after washing, the soil was sent for thermal treatment instead. PAH species were assessed individually, but in general if total PAH exceeded 1250 mg/kg the soil was thermally treated.
The soilwashing plant was the most sophisticated in Europe and combines many extraction techniques. Figure 4 outlines the main elements of the soilwashing process applied to the gravels in Belgium.

The soilwashing process produces three main outputs: Clean gravel, clean sand and a filter cake/silt containing all the contamination. The two clean products are used in Belgian construction projects (e.g. roads) and the filter cake is dried and eventually removed to an engineered landfill.

**Thermal Desorption in Holland**

Gravels that were too saturated with tar for soilwashing (Total PAH >1250 mg/kg) were shipped to Rotterdam for treatment. Thermal desorption operates at lower temperatures than incineration which has two advantages:

1. The product is still marketable as a soil rather than the ash produced by high temperature incineration.
2. Emissions from the furnace are less noxious (and hence treated more economically) than those from incineration.

The process also uses considerably less energy than incineration and is consequently less expensive to operate.

Once the soil arrived at the thermal desorption facility it was assessed based on soil chemistry and structure to establish whether the material would need improvement before entering the furnace. The gravels did not require improvement like the more cohesive alluvial silt and clay, which was mixed with granular material prior to treatment. This mixing was necessary to expose more soil particle surface area.

The thermal desorption of contaminants from the Dublin gravels took place at 800 to 900°C depending on the exact chemistry, moisture content and soil structure of the batch. The process essentially transfers the contaminants from the soil to the air phase. The soil was discharged from the furnace and allowed to cool, whilst the air was drawn off into a series of filters and purification measures to remove dust, sulphur, organic contaminants and other fumes. The majority of the plant is devoted to purifying the air in order to meet Dutch air emission standards. The product is a black sand or gravel that still resembles a soil, but has no organic content and is therefore incapable of sustaining plant life. This soil is assessed against generic Dutch soil standards and recycled in civil construction works. The gravels are usually used in road construction, as there is a high demand for aggregates in the Netherlands.

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We would like to acknowledge the other parties who contributed to the success of this project:

**Client : Dublin Docklands Development Agency**

**Main Contractor : Pierse - DEC NV Joint Venture**

**Hybrid Wall Sub-Contractor : Bachy Soletanche Ltd**

**Regulator : Environmental Protection Agency**

**CONCLUSIONS**

- Remediation of this site has enabled the recycling of prime development land in the heart of Dublin and redevelopment has progressed in its wake at an impressive pace.

- Waste Licensing imposed onerous duties on all parties but the reward is a Surrender Certificate from the EPA which is a major demonstration of confidence to investors.

- The lack of readily useable mobile plant licences in Ireland hindered the establishment of mobile treatment plant on site and therefore treatment within Ireland.

- Be proactive towards public perceptions.

- 'Unforeseen ground conditions' takes on a new meaning in the context of complex soil treatment processes.

- The perimeter hybrid wall proved very effective in fulfilling its purposes. Water levels outside the wall were virtually unaffected.