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Net Zero Teesside

Main Site Foundations Optioneering Appraisal

bp (On Behalf of OGCI)

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Prepared by	Checked by	Verified by	Approved by
[redacted]	[redacted]	[redacted]	
Njemile Faustin Senior Geotechnical Engineer	Craig Carter, Associate Director	Stephen Mason, Technical Director	James Todd, Strategic Business Director

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Prepared for:

bp (On Behalf of OGCI)

Prepared by:

Craig Carter, Associate Director Ground Engineering

AECOM Infrastructure & Environment UK Limited
Unit 2, Avalon House
Marcham Road
Oxford OX14 1TZ
United Kingdom

T: +44 1235 555 025
aecom.com

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1. Executive Summary

AECOM Limited has been instructed by bp to undertake a Foundation optioneering appraisal for the Net Zero Teesside (NZT) Main Site, in the North East of England. The Main Site has a long and complex history of development and heavy industrial usage, which has left a legacy of possible contamination and geotechnical constraints across the site. It was previously occupied by the Thai-based Sahaviriya Steel Industries (SSI) Redcar Steel Works and is now owned by South Tees Development Corporation (STDC). Proposed redevelopment of the Main Site comprises construction of structures to capture, utilise and store Carbon.

Different geotechnical foundation options were reviewed to develop a foundation option strategy for the Main Site that is safe, simple and economic to construct given the ground conditions at the site. Detailed design including assessment of the performance criteria will be carried out during Front End Engineering Design (FEED). To make a preliminary qualitative assessment of foundation solutions and ground improvement measures that may be appropriate for redevelopment of the site, AECOM reviewed several reports including Geotechnical and Geo-Environmental desk studies previously prepared for the Main site (by others and prepared a technical note outlining proposed ground investigation rationale. The desk studies form the basis of the site conditions and geotechnical risks described in this report. The technical note sets out the geotechnical risks that have been identified at the site which require investigation, the preferred ground investigation techniques, geotechnical and geo-environmental sampling and testing (insitu and laboratory) and monitoring requirements.

This report details the findings of the Foundation optioneering appraisal and presents a matrix of potential foundation solutions with pros, cons and cost considerations provided for each feasible foundation option.

Conclusions of this foundation optioneering appraisal include:

- The most favourable foundation option for low threat low load structures is a raft foundation. Localised ground improvement to stiffen the formation could include excavation and replacement of soft and loose soils to depths not exceeding 3m.
- Continuous flight auger (CFA) piles and Bored cased piles are considered a favourable option for medium threat structures to reduce the risk of settlement resulting from loading the surface Made Ground and/or the underlying estuarine loose sands and soft clays and silts present at depth.
- CFA piles and Bored cased piles are considered feasible for high threat structures to reduce the risk settlement generated by loading the surface Made Ground and/or the underlying estuarine loose sands and soft clays and silts present at depth. However, Bored cased piles are most favourable as they will be able to generate a greater axial resistance (load carrying capacity) as the installation equipment is does not restrict rock socket length, and these piles can advance through ground obstructions.
- Driven cast-in-situ piles are considered a favourable option for medium threat structures to reduce the risk of settlement resulting from loading the surface Made Ground and/or the underlying estuarine loose sands and soft clays and silts present at depth. This form of construction has been used to support the existing Redcar blast furnace to the west.
- Medium threat and high threat structures could potentially be supported on raft foundations in combination with ground treatment including excavation and replacement or vibro-replacement (stone columns). However, complex soil-structure interaction analysis is required which may result in increased design and construction risk.
- It may be beneficial to adopt a single deep foundation piled solution across all medium and high threat structures on the site to realise cost savings and reduce design and construction complexity.
- All foundation options described in this report will need to be re-assessed following ground investigation works and preliminary design. All foundation options will be subject to the proposed load and serviceability criteria to be determined during FEED.

2. Introduction

On the instruction of bp, (the Client), AECOM Ltd (AECOM) has carried out a Foundation optioneering appraisal for the Net Zero Teesside Main Site redevelopment based on the ground risks that have been identified. The proposed Main Site development includes construction of structures relating to power generation, carbon capture and gas compression: a Combined Cycle Gas Turbine (CCGT) gas-fired generating station and gas, electricity and cooling water connections, with post-combustion carbon capture and compression plant, a gathering station for carbon dioxide (CO_2) from the generating station and other industrial sources, low-pressure CO_2 pipeline connections to potential industrial sources, and a high pressure CO_2 pipeline for the onward transport of CO_2 to an offshore geological storage site in the North Sea. An indicative layout is shown in Figure 1.

Figure 1 Plan view of the NZT Main Site showing proposed structures

2.1 Aim of the report

The aim of this Foundation optioneering appraisal is to carry out a risk based assessment of potential foundation solutions for the Main Site and to propose the preferred foundation approach that will inform the foundation option strategy.

2.2 Scope and Purpose

This Foundation optioneering appraisal has been prepared in general accordance with the procedures outlined in AECOM's proposal dated 25th June 2020. The overall procedure involved:

I. Initial classification of structure threat level in line with the requirements of bp (2014). Engineering Technical Practice GP04-60: Onshore and Nearshore Geotechnical Engineering, Clause 10.2.

II. Summary of ground conditions and development of the conceptual ground model based on historical exploratory hole records and available geotechnical test data.

III. Review of constraints, drivers and decision making criterion (agreed with bp on behalf of OGCI during inception meeting 28 July 2020).

IV. Review of both shallow and deep foundation solutions and ground improvement techniques. Preparation of an outline assessment of the pros and cons of each technique looking at various aspects including Health, Safety, Security & Environment (HSSE) during construction, technology readiness, constructability, risk reduction (or escalation) factor, cost and programme.

V. A high-level assessment of existing ground investigation data relating to potential expansion of slag material within the Made Ground.

VI. Preferred option selection including Level 1 programme for key development, procurement and site activities. Deliverables will include a Foundation Risk Assessment (GP04-60, Clause 10.7) including a matrix of options assessed against relevant pros/cons.

Initial proposals to engage with external contractors to discuss best practice and optimise foundation solutions have not been undertaken at this stage, as agreed with bp (which has led to impact on the scope deliverables outlined above). Therefore, some of the original objectives like technology readiness and programme have not been covered in this report. An outline rationale for initial phases of ground investigation that will inform the decision around the final foundation strategy has been reported separately (AECOM, 2021).

2.3 Sources of Information

This report has been prepared using industry best practice with reference to Eurocodes and British Standards, information provided by the Client (where available) and other sources such as published geological and hydrogeological mapping, historical borehole records and site-specific ground investigation records. All information sources are included in the References section.

For this assessment, AECOM has been granted permission to refer to the findings contained within the following third party reports:

- 6 Alpha (2020). Onshore Unexploded Ordnance Threat and Risk Assessment with Risk Mitigation Strategy: Net Zero Teesside. Project Number: 8008, Report Version: Final.
- AECOM (2020). STDC 'Main Site' *Geotechnical and Geo-Environmental Desk Study*. Project number: 60559231-CTR005-003 GEO-002. Revision P03.
- AECOM (2021). Onshore CO2 Export Pipeline Corridor Geotechnical and Geo-Environmental Desk Study. Project number: 60559231-CTR005-003 GEO-002. Revision P02.
- AECOM (2021). Technical Note: Preliminary Onshore Ground Investigation for Net Zero Teesside – *Ground Investigation Rationale*. Reference PR-60559321_ACM_TN_ENV_001_B.
- Arcadis (2018a). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A *Site: Condition Report*, dated August 2018.
- Arcadis (2018b). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A Site: *Geotechnical Risk Assessment Report*, dated November 2018.
- Arcadis (2018c). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A Site: *Ground Remediation Options Appraisal Report*, dated December 2018.
- bp (2014). Engineering Technical Practice GP04-60: Onshore and Nearshore Geotechnical Engineering
- CH2M (2017). SSI Redcar – SSI 1, *Factual Report* – Initial Trial Pitting, South Tees Site Company Ltd, dated November 2017.
- Allied Exploration & Geotechnics Ltd (2018). The Former SSI Steelworks, Redcar – Ground Investigation Contract – Priority Areas Within SSI Landholdings Contract 1 and Contract 2 (Area A), *Final Factual Report*, Contract No. 4153 & 4154 (Area A), South Tees Site Company, dated June 2018.

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3. General Description

3.1 Site Location and Layout

The Main Site is located to the north-west of Redcar, North Yorkshire at National Grid Reference NZ571255 (457100, 525500) as shown on Drawing 60559231-ACM-CTR005-002-DRG-001, included in Appendix A. The site is currently identified as Teesworks, Redcar. It is approximately 70 hectares in size, bounded to the North by the Coatham Sands and the Teesmouth and Cleveland Coast RAMSAR, Site of Special Scientific Interest (SSSI) and Special Protection Area (SPA) areas. Further details are provided in the integrated georeferenced database provided by AECOM and hosted on bp's OneMap portal and the AECOM (2020). STDC 'Main Site' *Geotechnical and Geo-Environmental Desk Study*.

An unnamed road forms the north boundary of the Main Site, north of which is land formed from early 18th century land reclamation and extensive areas of historical slag waste disposal which now include an area of marshland and ponds, beyond which are dune habitats, a beach and foreshore leading to the North Sea.

Ordnance Survey (OS) mapping indicates that the ground level at the Main Site is mainly flat. Maximum levels of 8.2m Ordnance Datum (OD) are recorded in the south reducing to 5.0m OD towards the northern boundary of the Main Site, then falling to the north across Coatham Sands down to sea level. It is noted that at the time of writing, the site is understood to be undergoing reclamation by contractors working for South Tees Development Corporation (STDC).

The Central Area Transmission System (CATS) pipeline and Breagh high pressure gas pipelines run parallel with, and approximately 50m from the east boundary of the Main Site. These sensitive service utility lines run from the North Sea making landfall to the north east of the site forming a known constraint requiring consideration during future Front End Engineering Design (FEED) studies undertaken for the proposed development.

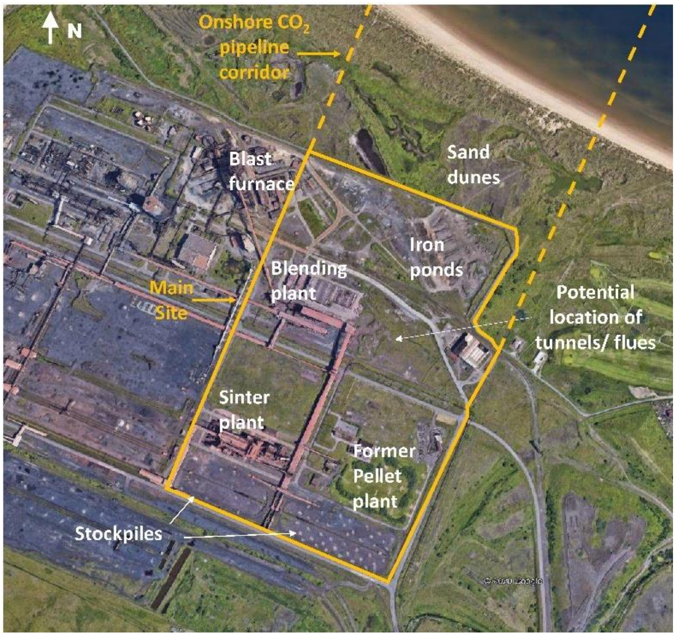


Figure 2 Location of existing industries at bp's Net Zero Teesside site

3.2 Historic Use

Ordnance Survey (OS) historical maps dated between 1856 and 2019 show that the Main Site has a long history of development and heavy industrial usage. It was initially reclaimed from the Tees Estuary in the 1800's and the reclamation work included construction of the South Gare Breakwater across the site between 1863 and 1888. Additional land covering the south west area of the Main Site, south of the breakwater, was later reclaimed in the 1970s by draining "The Marshes". Historical development of the Main Site is dominated by two phases of development; first as Redcar Iron and Steel Works, and more recently the Redcar Blast Furnace and Coking Works (Teesside Works) acquired by Sahaviriya Steel Industries (SSI) in 2012, and finally closed in 2015.

Figure 2 shows existing industrial structures on the Main Site prior to the ongoing reclamation being understood to being undertaken by South Tees Development Corporation (STDC). At the northern part of the Main Site is land formed from early 18th century land reclamation and extensive areas of historical slag waste. It includes an area of marshland and Iron Ponds. The west and southern boundaries of the Main Site are formed by the wider industrial area of the former SSI site, currently occupied by the former Blast Furnace and Power Station to the west and the Sinter Plant and Sinter Plant stockpile areas to the south. Land to the east comprises either open former industrial land associated with the former SSI site with land to the north comprising beach habitat of Coatham Sands. Appendix A shows the site location plan with some historical features namely, the Tees Estuary, South Gare Breakwater, The Marshes and areas of historic infill material. Areas of historical infill are identified by dates ranging between 1894 and the 1970's, based on a review of historical O OS mapping described in detail in the AECOM Geotechnical and Geo-Environmental Desk Studies (2020, 2021).

4. Geological Setting

4.1 Ground conditions

British Geological Survey (BGS) mapping indicates that the geology at the Main Site comprises widespread Made Ground deposits underlain by variable Superficial Deposits and mudstone Bedrock (Mercia Mudstone Group, Redcar Mudstone Formation and Penarth Group). The Mercia Mudstone Group subcrops on the north west corner of the Main Site, the Redcar Mudstone Formation covers most of the site area and the Penarth Group outcrops as a thin band between the Mercia Mudstone Group and Redcar Mudstone Formation across the north west corner of the Main Site.

Geological mapping is available in the georeferenced database provided by AECOM and now hosted on bp's OneMap portal.

4.1.1 Made Ground

Made Ground associated with the long historical industrial use of the area is widespread across the site. Its composition is highly variable predominantly comprising "Reclaimed (Made) Ground" but may also include areas of "Thick Slag". Previous ground investigations show that the Made Ground comprises various types of slag, including expansive ferrous slag and is poorly sorted and poorly compacted due to uncontrolled placement of material.

Historical Ordnance Survey (OS) mapping and anecdotal evidence suggest that the Tees Estuary was confined within training walls built of slag mostly constructed between 1859 and 1871, and adjacent areas were infilled in sections divided by slag walls with estuary dredging and industry wastes, e.g. predominantly slag.

The South Gare Breakwater was also constructed from slag and topped with a concrete wall. The land area underlying the Main Site to the north was filled using mainly blast furnace slag and smaller quantities of basic steel slag in the late nineteenth and twentieth century. The south west area of the Main Site ("The Marshes") is reported to have been drained in the 1950's and thereafter it is assumed raised with industrial wastes and/or dredging arisings.

4.1.2 Superficial Geology

British Geological Survey (BGS) 1:50,000 scale maps show that the site is underlain by variable Superficial Deposits. The distribution of individual deposits at the site from youngest to oldest is Blown Sand, Tidal Flat Deposits, Glaciolacustrine Deposits and Glacial Till.

- The Blown Sand deposits are anticipated to be present beneath the eastern part of the Main Site and across the north portion of the CO_2 Transport Corridor, south of the high water mark (H.W.M). The BGS Lexicon describes these Quaternary deposits as "sand that has been transported by wind, or sand consisting predominantly of wind-borne particles".
- The Tidal Flat Sand Deposits, previously identified by the BGS as Estuarine Alluvium, are anticipated to be present beneath the Blown Sand across most of the CO_2 Transport Corridor. Tidal Flat Clay Deposits are irregularly distributed across the south and east of Main site and are subject to rapid lateral change. The BGS describes two different layer types for these deposits; Sand and Silt and Sand or Silt and Clay.
- Glaciolacustrine Deposits comprising of clay and silt and sand are mapped around the edges of the Tees Estuary. These Glaciolacustrine Deposits subcrop south east of the site but are likely to underlie the Tidal Flat Deposits below the Main site. These fine-grained soils are considered to form part of the Tees Laminated Clay which is extensive deposit of laminated clay and silt deposited in a post glacial lake present across Teesside.
- Highly variable Glacial Till comprising clay with pebbles and lenses of gravel, may also be present at depth beneath the whole of the site. Localised deposits of Glacio-Lacustrine Clay are present in the Glacial Till.

4.1.3 Bedrock Geology

British Geological Survey (BGS) 1:50,000 scale maps show that the oldest bedrock geology subcrops (present at soil rock interface) west and north of the site with progressively younger layers subcropping to the east. This indicates a shallow regional dip towards the east. The oldest to youngest three rock formations that subcrop across the Main Site are described as follows:

- Mercia Mudstone Group - infringing on the north west corner of the Main site, The Mercia Mudstone Group is an extremely weak or weak, distinctly weathered red brown Mudstone. Thin veins of gypsum/anhydrite and sandstones are present, although there is no evidence of solution features noted.
- Redcar Mudstone Formation - is present beneath most of the Main Site. The Redcar Mudstone Formation is an extremely weak or weak, grey mudstone, locally fossiliferous. It is sometimes heavily fractured, or, recovered as non-intact rock. It is potentially aggressive to construction materials due to its pyritic nature.
- Penarth Group - outcrops as a thin band between the Mercia Mudstone Group and Redcar Mudstone Formation across the north west corner of the Main Site. The Penarth Group was recovered as weak weathered interbedded mudstones and siltstones in one historical borehole. Historical records do not confirm if the Penarth Group consists of the more deleterious carbonaceous Westbury Formation, which can be highly pyritic containing both the reactive form of pyrite and the less reactive visible form.

4.2 Groundwater conditions

Historical boreholes recorded varying groundwater strike levels at the Main Site of between 1.8m OD and 5.4m OD. It is notable that some exploratory locations in the southern portion of the Main Site were terminated due to excessive groundwater inflows. Groundwater levels are reported to be generally present at a depth of about 3.0m (3.7m OD) in the south of the Main Site and at a depth of 3.1m (2.9m OD) in the north of the Main Site. Data gathered from parts of the Main Site confirm that groundwater may be shallow and subject to some tidal influence depending on proximity to the North Sea coast and/or Tees Estuary. Groundwater depths will reduce to sea level to approximately 2.0mOD (mean high water level) trending north over the CO_2 Transport Corridor.

Within the Bedrock, the Redcar Mudstone Formation, that underlies most of the site, is classified by the Environment Agency as an undifferentiated secondary aquifer having "*previously been designated as both minor and non-aquifer in different locations due to the variable characteristics of the rock type*". The Mercia Mudstone Group and Penarth Group that subcrop below the north west corner of the site are classified as a Secondary Aquifer (B), having "*predominantly lower permeability layers which may store and yield limited amounts of groundwater due to localised features*".

4.3 Previous Assessment / Ground Investigation

There are no publicly available borehole records published on the BGS Onshore Geoindex national borehole database within the Main Site. However, several historical site investigations have been carried out with the two most relevant being:

- CH2M (2017): approximately 400 trial pits across the SSI site, with around 100 trial pits excavated within the boundary of the Main Site; and
- Allied Exploration & Geotechnics Ltd (2018): 26 boreholes, 15 trial pits and associated geotechnical and chemical testing.

Ground investigation data provided has been used to develop a preliminary ground model and summary of ground conditions proved at the STDC Main site as summarised in Table 1 below. Ground investigation data is not available across the CO_2 Transport Corridor.

Table 1. Summary of Ground Conditions

Strata	Depth (mbgl)	Description
Made Ground	4 to 9 m bgl	The Made Ground predominantly comprised granular material with a fine-grained component and low to high cobble/boulder content which included slag including fused slag, refractory brick, concrete and occasionally clinker, coke, coal and/or metal.
Tidal Flat Deposits	4 to 21 m bgl	The Tidal Flat Deposits (TFD) were predominantly medium dense comprising silty variably gravelly sand with layers/bands of gravel and shell beds. Layers of soft or loose clay and/or silt were identified.
Glacial Till	14 to 27 m bgl	Variable but predominantly comprising firm becoming stiff and very stiff slightly sandy slightly gravelly clay with gravel composed of mixed lithologies, including sandstone, limestone and rare coal. Localised deposits of glacio-lacustrine clay present.
Redcar Mudstone Formation (predominant across the site)	+22 m bgl	Weak to extremely weak weathered mudstone.

4.4 Geotechnical Laboratory Testing

It is noted that although significant ground investigations have been undertaken in the past, the laboratory data provided is of limited value as this has not been provided as an electronic database; and has only been made available in pdf format. Digitising this data would be time consuming and is outside the scope of this report. A review of in-situ SPT testing and inferred density and undrained shear strength has been undertaken as part of this report.

4.5 Standard Penetration Testing (based on existing test data)

Figure 2 shows the Standard Penetration Testing (SPT) data for the Main Site. The data is presented in terms of uncorrected SPT N value versus level. Figure 2 includes blow counts that were determined by linear extrapolation based on the penetration achieved after 50 blows to a maximum value of 100. It is noted that these extrapolated values are not likely to be accurate and are indicative only.

The SPT N values are highly variable in the Made Ground reflecting the variable composition and density of this strata. SPT N values range from 5 to >100. In the coarse (granular) Tidal Flat Deposits, SPT N values increase with depth from approximately 10 to 40. In the fine (cohesive) Tidal Flat Deposits, SPT N values do not show a trend with depth, with most values around 12. However, a small number of low SPT N values (N=5) recorded in tests undertaken at the top of the Tidal Flat Deposits may have been influenced by tidal groundwater variations, reflect imbalances in pore water pressures or the localised presence of finer grained layers during testing, for example silt. SPT N values vary between 24 and 60 in the Glacial Till but all but one range from 40 to 60.

In the Bedrock, SPT N values generally vary from 50 to >100. Three SPT tests in the Redcar Mudstone and two in the Penarth Group were terminated at a blow count of 50 based on penetration of less than 40mm. Extrapolated values were capped at 100. The material descriptions on the historic logs describe the materials as “Extremely weak mudstone”, recovered as gravel. Lower SPT N values of approximately N = 50 to 65 in the Redcar Mudstone, between -10m OD and -14m OD is indicative of its weathered status.

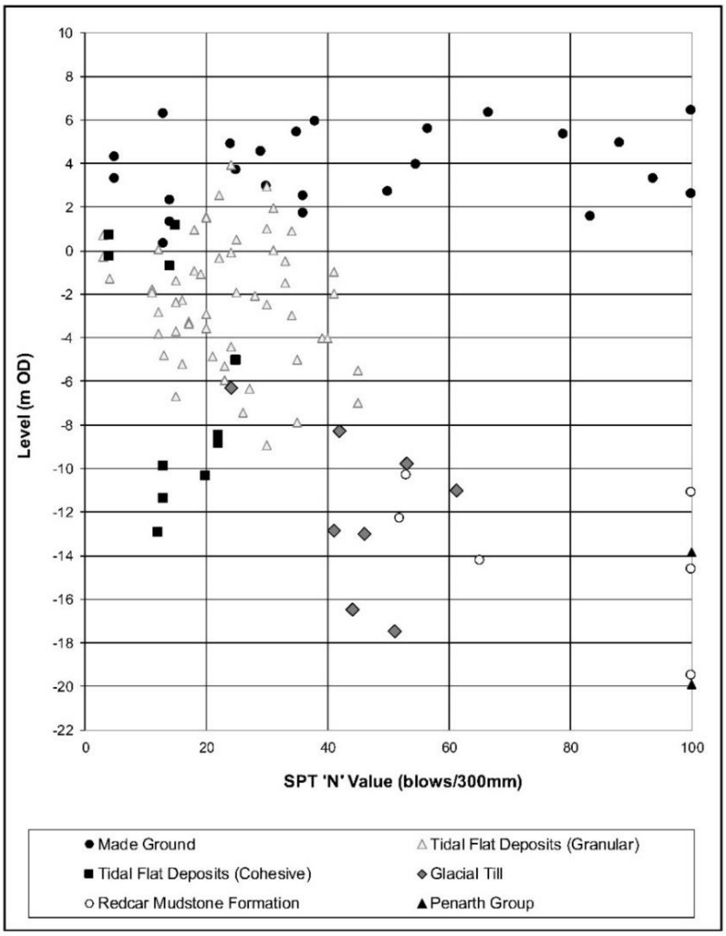


Figure 3 SPT N Value vs Depth

4.5.1 Empirical SPT N correlations

Table 2 provides a density classification for sands and gravels based on uncorrected SPT N-values. This classification was used to approximate the in-situ state of the Made Ground and coarse (granular) Tidal Flat Deposits.

Table 2 Classification based on uncorrected SPT N-values (Ref. British Standard BS 5930)

Term	Uncorrected SPT N-values
Very loose	0 - 4
Loose	4 - 10
Medium Dense	10 - 30
Dense	30- 50
Very dense	>50

For the purposes of this assessment, direct measurements have been augmented with strengths derived from correlation with in-situ SPT N test results.

A correlation reported by Stroud (1974) originally developed for overconsolidated clays which was extended to glacial soils by Stroud and Butler (1975) has been used to provide an indication of the mass undrained shear strength c_u (kPa) of the cohesive Tidal Flat Deposits and Glacial Till based on the SPT N blow count. The relationship is appropriate to overconsolidated clays and is given by:

$$c_u = f_1 N$$

where f_1 is a constant dependent on plasticity index (PI). In the absence of plasticity index data, some f_1 values have been assumed based on the anticipated high plasticity of the cohesive Tidal Flat Deposits, Glacial Till and Bedrock. Values typically used for 'f_1' generally range between 4 and 6, depending on soil plasticity. A f_1 value of 4.5 and 5.5 has been assumed for the cohesive Tidal Flat Deposits and Glacial Till respectively. However, it is noted that the Stroud and Butler correlation is not strictly applicable to organic rich alluvial soils which tend to be normally or lightly overconsolidated such as Tidal Flat Deposits present at the site.

BS 5930:2015+A1:2020 Code of practice for ground investigations indicates unconfined compressive strength for rock described as extremely weak to be in the range of 0.6 to 1.0 MPa.

4.5.2 Inferred Density and Consistency (strength) values

Inferred soil density and strength values based on available ground investigation information for the Main Site is summarised in Table 3.

Table 3 Indicative Ground Conditions

Anticipated Strata	Thickness (m)	Depth (m bgl)	Indicative density	Indicative c_u (kPa)
Made Ground, including expansive ferrous slag	Up to 9m	4.0 – 9.0	Loose to Very Dense	-
Tidal Flat Deposits	3.0 – 15.0	4.0 – 21.0	Medium dense to dense (granular)	20[1] - 55 (cohesive)
Glacial Till	2.5 – 9.0	14.0 – 27.0	-	220 - 330
Redcar Mudstone Formation (extremely weak)	Depth not proven	>22.0	-	300 – 500[2]

[1] Lower strength recorded at the top of the Tidal Flat deposits possibly due to influence of tidal groundwater variations, imbalances in pore water pressures or the localised presence of finer soils.

[2] Equivalent to an unconfined compressive strength range of 0.6 to 1MPa.

5. Geotechnical Constraints

A number of ground risks that may have material impact on the development if not properly mitigated through design prior to construction have been identified (AECOM, 2020 & 2021). The key risks that have been identified are listed below:

- Inadequate bearing due to poorly compacted, loose and soft underlying material.
- Heave and collapse settlement of Made Ground subject to loading or changes in the groundwater regime.
- Obstructions and voids in the Made Ground and underlying natural deposits.
- Presence of Unexploded Ordnance (UXO).
- Shallow groundwater.
- Soil contamination.

It is noted that the CO_2 Transport Corridor is within the Teesmouth and Cleveland Coast RAMSAR, SSSI and SPA areas. Ecological constraints are outside the scope of this report and are described in the AECOM Geotechnical and Geo-Environmental Desk Studies (AECOM, 2020 & 2021).

5.1 Inadequate bearing capacity

Historical ground investigations have shown that areas of the Main Site are underlain by soft/loose Tidal Flat deposits and Blown Sand deposits. These materials are likely to exhibit poor strength and compressibility, potentially giving rise to ultimate limit state (ULS) bearing capacity failure and serviceability limit state (SLS) performance issues on footings founded on these soils without remediation or engineering control.

5.2 Heave and collapse settlement of Made Ground

Heave and collapse of soils may occur due to the Made Ground and underlying natural strata. Previous ground investigations have shown that the Made Ground is poorly sorted and compacted. Therefore, collapse settlement may occur due to a change in loading (for example, caused by vibrations from plant) and changes to the groundwater regime through surface water infiltration or groundwater movement.

Chemical testing from previous ground investigations has identified iron and steel slag in the Made Ground. Arcadis (2018b) report highlights that ‘based on the petrology testing, the majority of the slag deposits at the site are considered to be dominated blast furnace slags but with a significant minor component of steel slag containing minerals with future expansion (heave) potential’.

Observations made during a site walkover by AECOM and BP on 18 March 2020 highlighted the potential risk to structures from heave and collapse of underlying soils, with several structures exhibiting signs of deformation and cracking. It was suspected that the observed structural damage was caused by ground heave, most likely from the expansion of slag.

5.3 Obstructions and voids

Potential ground obstructions are anticipated as a result of the long history of infilling that has occurred, particularly across the southern portion of the site. This includes infilling from early land reclamation works (1857) followed by infilling of slag and other waste materials from Coatham Ironworks (1872), Redcar Steel Works (1917) and Redcar Blast Furnace & Coking Works, Teesside Works (1973), see Appendix A. Obstructions are anticipated to include fused slag, steel slag boulders and concrete from former foundations and construction. Several trial pits from previous investigations terminated on obstructions. The most significant ground obstructions are expected trending north west south east below the former Steel Plant, Coke Processing Plant and the location of former travelling cranes present across the Site.

5.4 Presence of unexploded ordnance

Unexploded ordnance (UXO) from the Second World War (WWII) can present a risk to modern construction activity. Bombs often penetrated the ground by several metres on impact and, if they failed to explode, may continue to exist in a live state. The site has been identified by 6 Alpha Associates as a high risk with regards to UXO. The high metallic content of the Made Ground is identified as a potential hindrance to reliable UXO surveys

5.5 Shallow groundwater

Shallow groundwater levels are to be expected that may pose a risk to intrusive works at the Main Site. Arcadis (2018b) reported that groundwater entered approximately half of the trial pits were terminated due to water ingress.

Data suggests that that the groundwater direction is flowing north northeast (i.e. towards the coast). Groundwater is likely to be tidally influenced and shallow towards the north boundary of the site and the coastline. Perched groundwater within the marshy areas and ponds within the Teesmouth and Cleveland Coast RAMSAR, SSSI and SPA areas present across the CO_2 Transport Corridor. Groundwater levels are reported to be generally present at a depth of about 3.0m (3.7m OD) in the south of the Main Site and at a depth of 3.1m (2.9 mOD) in the north and may be tidally influenced.

5.6 Soil contamination

Previous ground investigation by others, and related chemical testing, has demonstrated that soil contamination may exist on site, e.g. sulfate, sulphide, high pH, cyanide and Asbestos Containing Materials. Elevated levels of sulfate, primarily within the Made Ground, is considered to have the potential to leach to groundwater.

The presence of soil contamination can present a risk to human health and groundwater, amongst other receptors, if not properly mitigated. Sulfates can be aggressive to concrete substructures.

5.7 Groundwater contamination

Groundwater sampling and monitoring by others indicates that there is a potential for groundwater contamination in the underlying soils. However, the monitoring data to date is insufficient to confirm seasonal trends or reliability/repeatability of the measured concentrations. Disturbance of the ground may release contaminated leachate into groundwater by creating new pathways. This might occur for example during excavation or piling or during open cut excavation unless suitable construction methods or mitigation are employed.

5.8 Conceptual Site Model

A conceptual site model based on the ground and groundwater conditions anticipated at the Main Site combined with the key geotechnical risks identified is provided in Appendix B.

6. Heave (based on existing test data)

6.1 Introduction

As discussed in Section 4, the Made Ground at the Main Site is highly variable both in nature and compaction. The Made Ground contains a significant proportion of slag material with the potential to cause heave. In addition, the slag material, Bedrock and possibly the Superficial Deposits contain Sulfates that are aggressive to concrete. Both these factors create adverse conditions for both ground improvement and foundations to transfer structural loads to greater depths. It is significant to note that ground movements have already occurred at the Main Site. Field observations have recorded differential levels across areas of hard standing and directionally tapered cracking in structures.

Available historic ground investigation records show that slag testing was carried out on samples from eleven trial pit locations clustered in the north and south parts of the site (Allied Exploration & Geotechnics Ltd, 2018). However, it is considered that the volume of material tested may not be fully representative of the Main Site conditions and potentially insufficient to fully evaluate the slag in terms of aggressivity and heave potential. Further investigation is recommended to determine the distribution and variability of the slag within the Made Ground and to identify pockets of slag that may have a higher potential reactivity. Some observations based on information provided in the AECOM Desk Study Reports (AECOM 2020,2021), the three project reports prepared by ARCADIS (Arcadis, 2018a, 2018b & 2018c) and the Allied Exploration & Geotechnics Ltd (2018) factual report are given below:

- There is great variability in the Made Ground and it is difficult to determine an effective distribution of slag types.
- The samples are described as a mixture dominated by blast furnace slag and refractory slags and waste, with subordinate basic steel slags, and with other variable constituents including iron, mudstone, coke, coal and brick etc.
- Historical expansion of the slag is confirmed with the presence of gypsum, ettringite and possibly thaumasite, and the presence of calcium carbonate. However, the high potential for further expansion is confirmed by the presence of basic steel slag and only partial reaction of this material. Future expansion of the slag material and consequential ground heave may be instigated by site redevelopment activities. In particular, it may be brought about by ground improvement processes causing break up of existing slag fragments and exposure of unreacted material.
- Small quantities of lime (CaO) and magnesia (MgO) have been recorded from the samples examined, which present potential for expansion through hydration.
- All the slag samples tested have significant sulfate speciation, with Design Sulfate classes ranging generally between DS3-DS5, but the volume of samples tested is not considered to be representative of the site and the highly variable nature of the ground.
- The accelerated swelling tests conducted on the 11 slag samples record a range of volumetric expansion of between 0.8 and 2% determined over a 28-day test period. This indicates the potential for slag expansion, which could be brought about by interaction with water. With variability of material, the effects of differential movement become more significant, as often the solution and precipitation of the material may occur through transportation by groundwater or capillary migration and nucleation occurs away from the site of dissolution. Therefore, the limited number of samples tested may not be representative of the volume of variable material present.

7. Foundation optioneering appraisal

7.1 Structure Classification

Preliminary proposals for redevelopment of the Main Site show construction of five new plant structures for U&O, cooling, High Pressure (HP) compression, carbon capture and power. The structures can be classified into three categories of low, medium and high threat as guided by Section 10 of GP 04-60 (bp, 2014). The Use and Occupancy (U&O) building was classified as a medium threat structure and the other four structures were classified as high threat structures (cooling, HP Compression, Carbon Capture and Power). The sterile and laydown areas can be classified as low threat (assuming low threat ancillary structures may be constructed in these areas together with environmental screening bunds, fencing and lighting). An illustrative layout of the position of the five main structures and their threat category are shown in Figure 4.

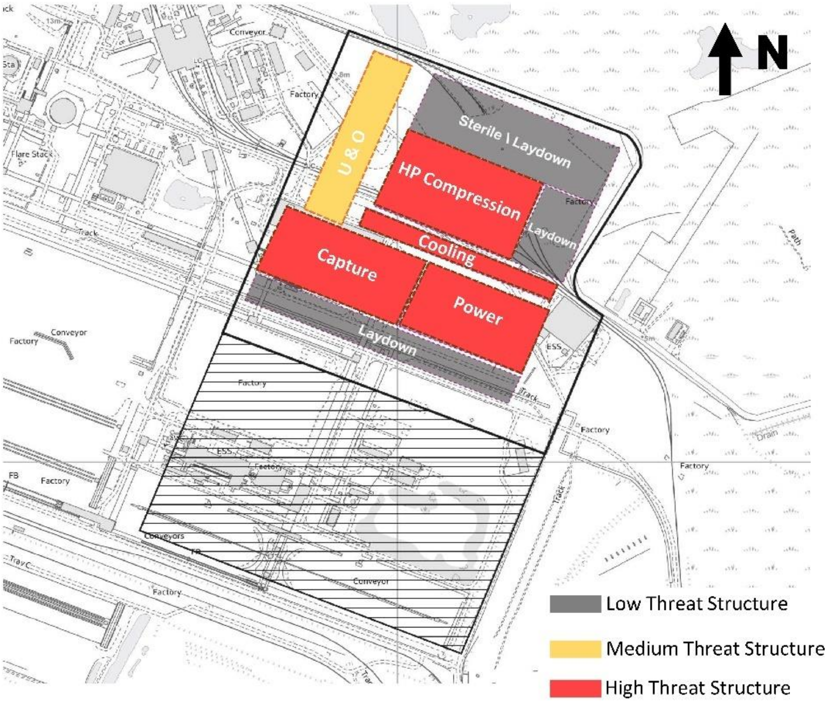


Figure 4 Proposed layout of proposed NZT structures

7.2 Foundation Assessment Procedure

The selection of an appropriate foundation for the proposed structures at the Main Site is anticipated to be greatly influenced by a number of factors and variables including the size of the proposed structures (dimensions and height), composition of the structures, layout of structural supports, load conditions (type, magnitude and direction), structure serviceability limits, strength and stiffness of the supporting ground and the groundwater conditions. At the time of writing this report, limited details are available for the proposed structures and a detailed ground investigation is being planned for both the Main Site and CO_2 Transport Corridor.

AECOM's foundation strategy for the proposed structures has been developed in accordance with the requirements of GP 04-60 (bp(2014). A range of foundation options, shown in Figure 5, have been identified as potentially suitable to safely transmit loads onto an adequate bearing stratum below ground level.

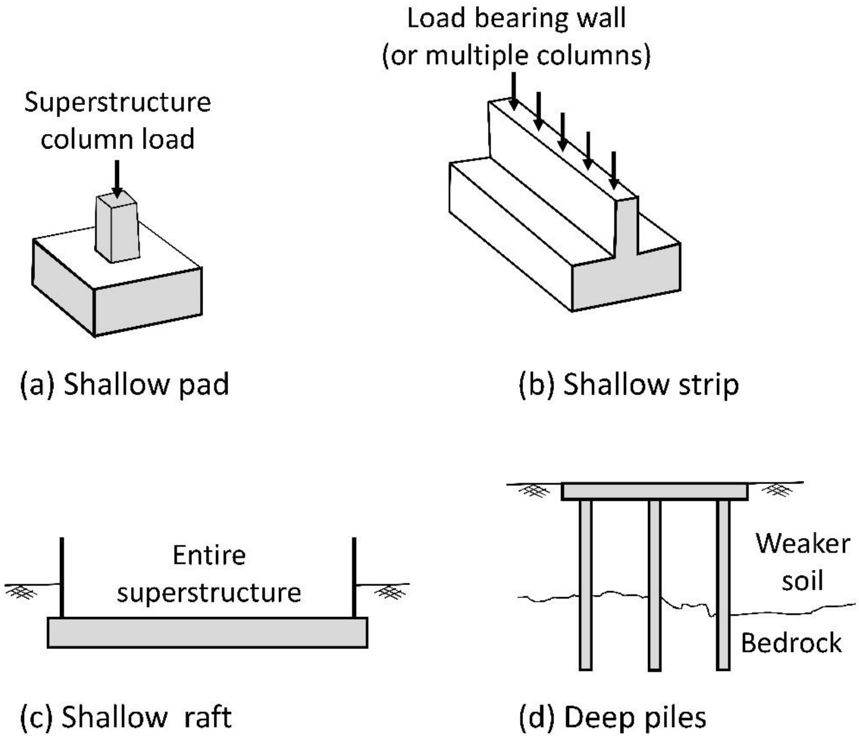


Figure 5 Shallow and deep foundation options

A two phase assessment was used to identify the most appropriate foundation type for structures in each threat category, considering the anticipated ground conditions and the magnitude of allowable foundation movement. The assessment criteria and procedure adopted is summarised in Figure 6.

In the first stage, different shallow and deep foundation and ground improvement options were assessed to determine if the bearing capacity of the ground and settlement under working loads may be adequate under different load conditions and criteria, as defined in GP 04-60:

- initial loading conditions (primary consolidation)
- longer term creep (secondary consolidation)
- dynamic loading due to equipment vibration and seismic events
- transient loading (due to wind / thermal / snow / other operational effects)
- cost

At this preliminary stage, the magnitude and direction of the loads as well as operational effects and serviceability limits are not known, so the assessment assumes that the structure is either heavily or lightly loaded. Foundation options were also evaluated for different ground characteristics that may be problematic including the presence of hard layers, presence of soft/compressible layers and natural ground chemistry and mineralogy. This first phase of the assessment identified the foundation options as being either suitable or not suitable as an absolute value based on criteria provided in GP 04-60:

As part of the second phase assessment, foundation options that were not eliminated based on the generic criteria above, were then evaluated against seven key geotechnical risks identified in the desk studies AECOM (2020, 2021) as outlined in Section 5. Based on this second assessment, foundation options were classified as being not suitable, suitable or potentially suitable with adequate mitigation. Mitigation measures identified may include:

- Adoption of raft foundations in lieu of pad or strip footings to reduce the potential for differential settlement that may occur within the loose and/or variable density made ground across the site;
- Excavation and replacement of soft or loose soils to increase the bearing capacity and/or reduce the compressibility of soils below the structure;
- Ground improvement techniques to increase the bearing capacity and/or reduce the compressibility of soils below the structure;
- Deep foundations to transfer structure loads through the made ground and soft or loose density Tidal Flat deposits down to more competent higher strength glacial till or competent bedrock present below the site.

It is important to note that the ground conditions may vary considerably over very short distances, both vertically and laterally, as well as over separate areas of the site as a result of the varying age of historical infilling and industrial development. The strength and stiffness of the ground and foundation option suitability is also heavily influenced by the presence of shallow groundwater. Therefore, a thorough ground investigation is required for all the foundation options considered, to gain a good understanding of the ground and groundwater conditions.

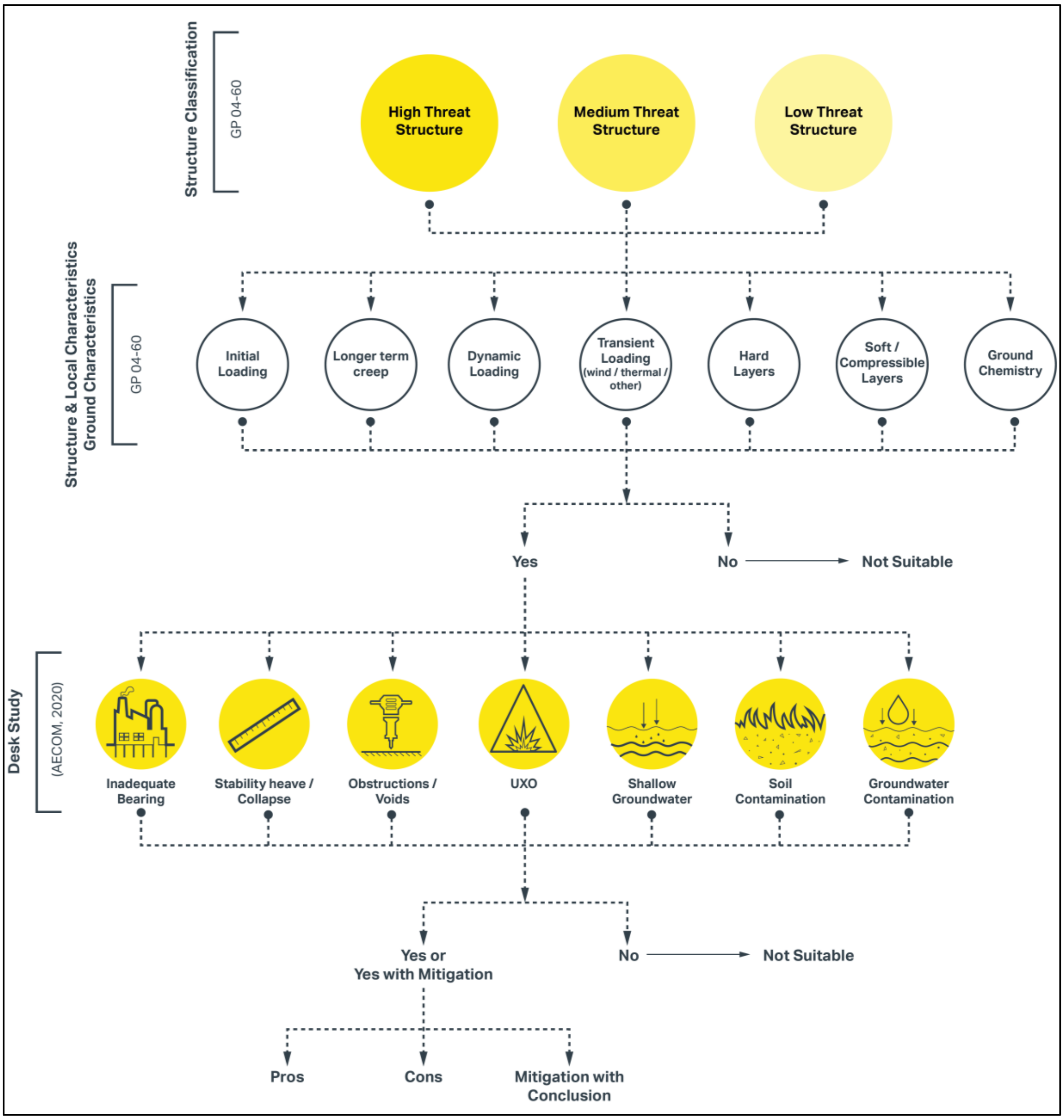


Figure 6 Foundation optioneering appraisal - decision matrix

7.3 Foundation Option Suitability

The results of the foundation option assessment for the three structure categories (low, medium and high threat) are summarised in Figure 7 to Figure 9. The figures indicate acceptability of the different foundation options considered against each criterion, focussed on load conditions, ground conditions and geotechnical risks. A 'traffic light' system of red (not suitable), orange (suitable with mitigation) and green (suitable) has been adopted. The full assessment undertaken including a summary of pros, cons and mitigation measures considered for each structure category is also provided in Appendices C.1 to C.3 and described in Section 7.4.

Figure 7 Foundation optioneering appraisal - Low threat structures

Figure 8 Foundation optioneering appraisal - Medium threat structures

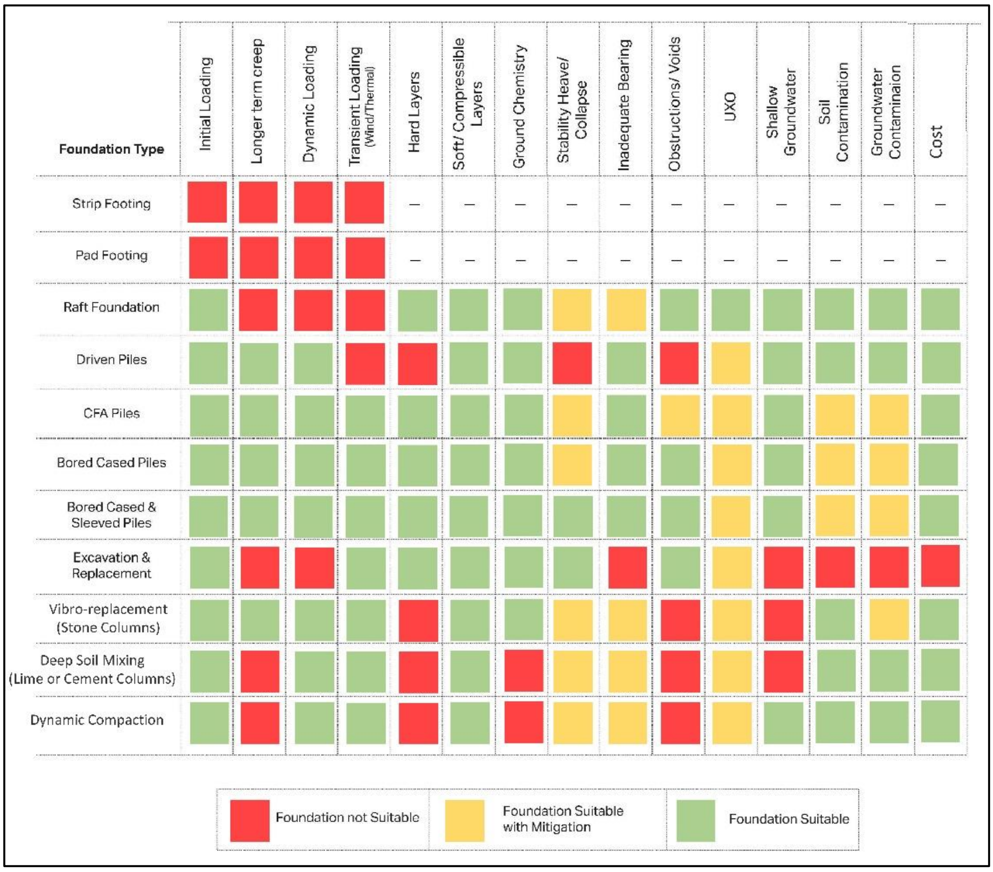


Figure 9 Foundation optioneering appraisal - High threat structures

7.4 Foundation Options

This section describes the foundation options for the proposed structures based on the foundation appraisal results. Selected foundation systems will need to be designed to accommodate the proposed load and serviceability criteria, to be determined during Front End Engineering Design (FEED).

The site has been identified by 6 Alpha Associates as a high unexploded ordnance (UXO) risk (6 Alpha, 2020). There is great uncertainty in the appropriate management of the UXO risk as the high metallic content of the Made Ground is identified as a potential hindrance to reliable UXO surveys. The UXO risk will need to be carefully managed before construction of foundations for the proposed structures.

Prior to foundation construction, in-situ plate load test on foundation formation is recommended to identify the creep and dynamic load conditions of the Made Ground and the natural strata. A comprehensive programme of integrity testing and monitoring is recommended during all phases of excavation and construction of the proposed structures to verify the performance of the foundation solution. Fibre optic sensors may also be embedded in the foundations to monitor performance over the intended design life.

Site trialling of different foundation options against specified load and performance criteria could be considered as part of early phases of detailed design or as part of any early contractor involvement enabling works.

7.4.1 Shallow foundations

Shallow foundations, commonly known as pad, strip or spread foundations, are used to transmit structural loads onto a suitable bearing stratum at a shallow depth, where groundwater is absent or can be readily controlled. Shallow foundations may comprise individual pad foundations supporting a single column; strip foundations supporting a wall or multiple columns or a raft foundation supporting the entire structure. Table 4 summarises the advantages and disadvantages of shallow foundations.

The design of shallow foundations should conform to the requirements of BS *EN 1997-1:2004+A1:2013* and *BS 8004:2015+A1:2020.* Section 4.1.2 of BS 8004:2015+A1:2020 states that shallow foundations are "*generally suitable in, but not limited to, the following design situations:*

- *where an adequate bearing stratum occurs at shallow depth (typically less than 2m deep);*
- *on dense (or denser) coarse soils above the water table;*
- *on medium strength (or stronger) fine soils.*

Spread foundations should not be placed on non-engineered fill unless such use can be justified on the basis of a thorough ground investigation and detailed design. Spread foundations should generally not be placed on engineered fill unless that fill is designed for the use of spread foundations."

Table 4 Shallow foundations - advantages and disadvantages (Ref. ICE Manual of Geotechnical Engineering, Table 52.1, 2012) and Appendices C.1 to C.3

	Pad / strip footings	Raft Foundation
Pros	Minimal cost	Can be a cost effective solution to support lightly loaded structures not subject to dynamic loading; Significantly reduces differential settlement if sufficiently rigid, which reduces the potential for structure distress or cracking; Can span localised areas of soft or loose density ground; Removes risk posed by obstructions within Made Ground at shallow depth when compared to deep foundations;
Cons	Competent soils need to be reasonably close to ground surface, typically less than 1 or 2m; Groundwater control and temporary construction support measures needed if water is above base of the footing and permeable soils are present; Only suitable for lightly loaded structures not subject to dynamic loading; Not suitable for structures subject to long term creep movements or stringent serviceability limits; Limited application if applied loads include large horizontal forces or overturning moments; Vulnerable to large differential movements if applied loads vary significantly across the structure or if ground conditions are not heterogeneous; Possible adverse interaction between adjacent footings, if closely spaced.	Competent soils need to be reasonably close to ground surface, typically less than 3 or 4m; Groundwater control and temporary construction support measures needed if water is above base of the footing and permeable soils are present; Large volumes of soil may be excavated during construction which could be a problem if the soil is contaminated; increased costs for soil treatment and disposal; Loading will lead to a significant increase in stress to considerable depth. Risks posed if weak layers are present at depth. The potential influence of loading on any proposed underground infrastructure will need to be reviewed; Raft deformation needs to be checked to ensure the movement is acceptable; Adjacent construction activities may undermine raft;
Construction	Simple to construct; Specialist equipment and subcontractors not required.	Simple to construct; Specialist equipment and subcontractors not required.
Cost	Cost effective option for simple structures.	Foundation movements (settlement and heave) may be anticipated. Serviceability and maintenance costs over the design life of the proposed structures may be higher than those anticipated from deep foundation options.

The Foundation optioneering appraisal indicates that conventional pad or shallow strip foundations are generally suitable for lightly loaded low threat structures that are not susceptible to creep or dynamic loading, for example lighting columns, fencing, cable trays and unoccupied buildings. This foundation option is not suitable for medium or high threat structures at the Main Site. Shallow pad or strip foundations may not provide sufficient bearing resistance if soft compressible layers are present within the Made Ground or underlying Tidal Flat Deposits. Historical ground information indicates that the Made Ground at the Main Site is highly variable and potentially subject to heave due to its significant slag content (see Sections 4.1 and 6). Therefore, pad or strip foundations may not be sufficiently rigid to mitigate ground instability from heave or collapse. The presence of ground obstructions or voids will present additional problems.

The Foundation optioneering appraisal indicates that shallow raft foundations spanning the entire footprint of a structure is potentially suitable for low and medium threat structures at the Main Site. Raft foundations may also be suitable for high threat structures not subject to long term creep, dynamic or transient loading conditions. For all structures, a detailed UXO risk strategy will be needed to reduce the significant risk of encountering UXO. Strip or raft foundations may increase the likelihood of encountering UXO in comparison to deep foundations described below. However, mitigation measures for making safe and removal of UXO within open excavations can be undertaken under controlled conditions. Flexible joints may be incorporated through both the superstructure and the raft foundation to help accommodate heave or collapse ground movements. Mitigation measures to lessen the risk of ground movement or to provide adequate bearing resistance may include excavation of the existing Made Ground and replacement with chemically inert Engineered Fill. Additional mitigation in the form of ground treatment of the Made Ground may be employed if the raft foundation cannot satisfy the required loads, settlement tolerances and serviceability limits to be defined at FEED.

Adoption of raft foundations is likely to provide reduced construction costs in comparison to deep pile foundations and/or ground improvement described below. However, larger foundation movements (settlement and heave) would be anticipated and may result in longer term serviceability and maintenance costs over the design life of the proposed structures. This would need to be allowed for in the design, construction and operation risk registers for the scheme.

7.4.2 Deep pile foundations

Pile foundations are used to transmit structural loads through weaker near-surface soils onto a more competent bearing stratum at greater depth. The piles may be constructed as either as a single pile supporting a load bearing column or as a group of piles supporting either the entire superstructure or heavily loaded parts of the structure. There are several different types of piles varying on the method of construction. The choice of pile will depend on the ground conditions, pile performance requirements (working load and settlement tolerances), environmental requirements (noise, vibration, spoil disposal, contamination and carbon efficiency) and site constraints. This report refers to the three classifications reported by BS EN 1997-1:2004+A1:2013; driven piles, continuous flight auger (CFA) piles and bored / bored cased piles. Table 5 summarises the advantages and disadvantages of these pile categories.

The design of deep pile foundations should conform to the requirements of BS *EN 1997-1:2004+A1:2013* and *BS 8004:2015+A1:2020.* Section 4.1.3 of BS 8004:2015+A1:2020 states that deep pile foundations are "*generally suitable in, but not limited to, the following design situations:*

- *on compressible strata overlying bedrock;*
- *on compressible strata overlying coarse soils of adequate density, there being no other beds of greater compressibility below the coarse soils;*
- *where the strata consist of fine soils of great thickness capable of supporting the piles by friction;*
- *where there is a need to minimise movements of a structure owing to swelling or shrinkage of surface soils; and*
- *where the addition of a foundation load would cause instability of the existing ground (e.g. at the crest of an existing slope).*"

The presence of thick deposits of slag at the Main Site may have potential to generate ground displacements (heave and / or lateral expansion) as a result of chemical changes and / or variations in groundwater level. Expansion of ferrous slag proved by historical ground investigations to be present at the SSI Redcar Steelworks (Main Site) could result in unpredictable additional uplift and lateral loading on piles after installation. Piled foundations will need to be designed to accommodate additional loading.

The foundation optioneering appraisal indicates that a deep piled foundation is not a cost effective foundation solution for low threat structures, but it may be appropriate for medium and high threat structures.

The risk of encountering UXO poses additional hazards for all pile solutions and one option is not favoured specifically for the risk of encountering UXO.

The foundation optioneering appraisal showed that driven piles may be appropriate for the proposed structures. The presence of obstructions within the Made Ground or hard layers within the natural strata is problematic for pile driving. These may result in unacceptable structural damage (cracking / spalling) to driven concrete or steel piles or loss of plan position and verticality tolerances. Vibrations generated during the pile driving process may also cause damage to existing utility services. Driven steel piles may be susceptible to high chloride concentrations present with the groundwater that may be tidally influenced. However, corrosion protection to buried steel could be provided as part of the design.

Small diameter (600mm) driven-cast in situ piles may provide a viable foundation option for medium and high threat structures. It is understood that the existing blast furnace to the west is constructed on a 4m thick concrete slab supported by 576, 600mm diameter special heavy 'Frankipiles' installed on a 1.6m^2 grid (Jorden & Dobie, 1976). Franki refers to a proprietary product design which is understood to have comprised driven cast-in-situ concrete piles with an enlarged base.

CFA piles or bored piles were identified as a suitable pile foundation for both medium and high threat structures. However, both options require mitigation to prevent potential ground instability from heave or collapse, soil contamination, groundwater contamination, and a detailed UXO risk strategy to reduce the significant risk of encountering UXO.

CFA piles may be installed to a maximum depth of around 30m to be founded within Glacial Till or the underlying Bedrock. These piles may accommodate all the load cases, i.e. initial loading, longer term creep, dynamic loading and transient loading. This solution will transfer loads to competent strata at depth and limit settlement. However, the presence of obstructions in the Made Ground including buried foundations may prevent pile toe levels and construction tolerances (plan position and/or verticality) from being achieved. If the required toe penetration is not achieved CFA piles may not be able to resist predicted heave movements in the Made Ground or achieve the total bearing resistance assumed in design.

The Foundation optioneering appraisal showed that bored cased piles may also be suitable to support the proposed structures. Bored cased piles have a larger load capacity than CFA piles as they can be constructed at larger diameters, provide deeper rock sockets and may be advanced through hard obstructions in the Made Ground or underlying natural strata by the use of specialist boring tools where temporary / permanent casing is installed. The casing will provide support to the pile through the variable Made Ground, Tidal Flat Deposits and Glacial Till, while also reducing the risk of contaminated groundwater migrating from the Made Ground to the underlying aquifer.

There are a few options for bored piles to reduce the risk of heave from potentially swelling slag materials in the Made Ground. Firstly, pile embedment can be extended deeper into the bedrock in order to ensure that skin friction generated by the rock socket is greater than the potential uplift likely to be generated on the pile shaft over the depth of expansive soils. Unlike CFA piles, bored cased piles can achieve greater depths and restrictions to achieve an adequately long rock socket are not limited by the method of construction. Alternatively, a wider pile shaft can be constructed at the bottom of the pile (i.e. under-reamed pile toes) to provide additional skin friction. A final option that may be considered is the provision of permanent sleeving (e.g. bentonite / vermiculite) around the bored piles over the zone expected to be vulnerable to movements caused by volumetric changes (e.g. swelling) in order to resist uplift generated by heave. However, this form of construction may be more expensive than conventional piled foundations, although a cost benefit assessment could be undertaken to determine whether savings could be realised if shorter rock socket lengths could be formed using this option, in comparison to bored cased piles.

Adoption of deep foundations is likely to result in increased construction costs in comparison to shallow raft foundations described above. However, deep foundations reduce the risk of unacceptable ground movements (settlement and heave) which may result in reduced serviceability and maintenance costs over the design life of the proposed structures.

7.4.3 Piled rafts

Piled rafts are a hybrid type of foundation where the structural load is transmitted to the ground via both a raft (as for a shallow foundation) and a relatively small number of widely spaced piles. This technique can reduce the number of piles, raft thickness, reinforcement grade and density if adopted in appropriate ground conditions. It may also lead a simplification of foundation construction and time needed may be minimised. The adoption of piled rafts can therefore lead to safety and sustainability improvements.

The system can be designed as a raft-enhanced pile group or a pile-enhanced raft. In a raft-enhanced pile group, both the piles and raft are designed to work in a pseudo-elastic manner. The pile group bearing resistance will not be fully mobilised at working load. Behaviour of this system is governed by the relative stiffness of the pile group to the raft. The piles are usually stiffer than the raft and therefore will attract most of the load; the relative proportions can be determined during design. In a pile-enhanced raft, piles are designed to mobilise their ultimate bearing resistance with the raft carrying most of the design loads. In this arrangement piles can be located below heavily loaded columns. The design is dependent on careful assessment of lower and upper bound pile bearing resistance and the pile load-settlement behaviour must be ductile (i.e. the pile resistance must be maintained at relatively large settlements).

Piled rafts may be more economic than conventionally designed pile groups and can significantly reduce structural forces in the raft, providing there are competent soils at reasonable depth. However, complex soil-structure interaction analysis is required, and adjacent construction activity may adversely affect their performance. Due to the complexities involved with piled rafts the viability of this technique is not considered in this report but could be assessed at FEED when structure loads and serviceability limits have been defined.

7.4.4 Structure floor slabs

Structure floor slabs and connecting services / infrastructure may also need to be piled to reduce differential movements, particularly for settlement sensitive structures with tight serviceability limit requirements.

For medium and high threat structures, suspended ground floor slabs may be required to mitigate against heave that may still occur due to movements resulting from expansion of the most reactive slag in the Made Ground.

Table 5 Deep pile foundations – advantages and disadvantages

	Driven piles	Continuous Flight Auger (CFA) piles	Bored piles / Bored Cased piles
Pros	Quality and soundness of pile can be inspected before driving; Not liable to 'squeezing' or 'necking' during construction; Installation not affected by groundwater; Can be installed in long lengths: (jointed precast concrete piles up to 40m) Can be re-driven if affected by ground heave; Displacement pile so spoil is not brought to the surface, so no need for off-site spoil disposal. Useful if contaminated soils are present; Can be designed to withstand high bending and tensile stresses. Piles with a solid concrete core may carry up to 15MN; Stabilising fluids used to support pile bores through unstable soils at depths beyond the economical use of temporary casing; Driven cast-in-situ piles with enlarged bases have been successfully installed below the existing blast furnace to the west.	Suitable for constructing piles through sands, gravels, silts and clays and limited penetration of weak rocks; Suitable for water bearing ground where deep casings or bentonite support would be otherwise required; Relatively quiet piling with little or no vibration; Automated instrumentation of piling rigs allows monitoring of pile construction and performance reporting producing real time QA/QC records; Wider pile spacing may be possible in comparison to driven piles. Instrumented piles can be installed to measure load and settlement performance.	Bored piles can offer higher capacities with potentially better economies than driven piles. Soil or rock removed during boring can be inspected for comparison with ground investigation data; A variety of drilling tools can be used to penetrate boulders or other obstructions which cannot be penetrated by any form of displacement pile; Bored cased piles may allow for advancement through obstructions by the use of specialist boring tools where temporary / permanent casing is installed; Installed without appreciable noise or vibration (i.e. minimal environmental impact); Length can be varied to intersect a bearing stratum of variable elevation; such as variable competent rock head level which may be present due to weathering; No limitation on the construction of longer rock sockets or under-reamed pile toes to provide additional skin friction to reduce the risk of heave and uplift resulting from potentially swelling slag materials within the made ground; Casing between potentially contaminated groundwater and underlying aquifer reduces the risk to groundwater contamination. The installation of temporary casing through water bearing coarse granular soils or soft soils will enable control of integrity problems which may occur during construction by balancing water pressures within and outside pile bores. In situ strength tests can be made in large-diameter pile boreholes; Very large diameter bases (under reams) can be formed in favourable ground; Installation does not cause ground heave; Pile lengths of up to 50m and over 3m in diameter are feasible to carry pile loads up to 30MN; Wider pile spacing may be possible in comparison to driven piles. Instrumented piles can be installed to measure load and settlement performance.

	Driven piles	Continuous Flight Auger (CFA) piles	Bored piles / Bored Cased piles
Cons	Noise and vibration due to driving may be unacceptable; Difficult to correct deviations once pile driving commences; The length of unjointed pile types cannot be readily varied to intersect a bearing stratum of variable elevation; Must be properly reinforced to withstand stresses due to handling; May suffer unseen damage which reduces load carrying capacity; Piles may break during driving, necessitating the installation of replacement piles; Displacement of soil during driving may lift adjacent piles or damage adjacent structures; Cannot be driven with very large diameters / sections; End enlargements, if provided, destroy or reduce shaft friction over shaft length; Jointed precast piles may not be suitable for tension and lateral loads; Zone of soil immediately adjacent to the pile will be disturbed and remoulded by construction process. Presence of obstructions will prevent the use of driven piles unless they can be economically removed prior to piling or the ground loosened by pre-boring. Installation may induce excess pore water pressures in soft clays and silts within the Tidal Flat Deposits. The dissipation of these pressures will cause the soil to consolidate and induce an additional downdrag load. Without rock shoes, driven piles are likely to only achieve a limited penetration into rock. Susceptible to 'false sets' which can occur where there are obstructions or boulders in the ground, or where thin rock bands overlie weaker layers. False sets can also occur in dense silts and weathered mudstones. Ultimate compressive resistance generated may be limited due to the inability of forming long rock sockets using this technique. Low ultimate moment resistance, therefore unable to accommodate bending moments induced by lateral soil movements induced in the ground from for example by loading of adjacent areas. Closer pile spacing may be required in comparison to CFA or bored / bored cased piles.	Risk of flighting causing ground instability during pile construction (flighting is the upward displacement of spoil along the auger flights to ground surface); Not appropriate in ground containing frequent and substantial obstructions; Careful control of concrete delivery and extraction of auger needed to prevent pile integrity problems; Potential for pile 'squeezing' through soft soils and/or water bearing coarse (granular) soils. Pile integrity problems may occur where installed through water bearing coarse (granular) soils. Ultimate compressive resistance generated may be limited due to the inability to form long rock sockets using this technique; Pile may not be able to resist heave due to limited potential to extend rock socket length to depth;	Concrete in shaft is susceptible to squeezing or necking in soft soils due to poor control of extraction rate and concrete injection; Temporary casing and/or support fluid required in cohesionless soils, weak fractured rocks, low plasticity silts or clays below the water table; Lateral pressure on soft soil from fresh concrete can lead to bulges in the pile section i.e. sections of enlarged pile shafts; Local slumping of open unsupported pile bores may occur due to groundwater seepage; Enlarged bases cannot be formed in coarse-grained soils; Possibility of low end-bearing resistance in coarse-grained soils due to loosening by conventional drilling operations; Drilling a number of piles in a group can cause a loss of ground and lead to settlement affecting adjacent structures and/or services; Zone of soil immediately adjacent to the pile may be disturbed and remoulded by construction. If bores are left open too long clays can soften leading to lower skin friction being mobilised. Generates spoil arisings at surface which if contaminated can lead to increased cost due to soil treatment and/or disposal offsite.

	Driven piles	Continuous Flight Auger (CFA) piles	Bored piles / Bored Cased piles
Construction and Programme	A pre-formed or cast in place pile that displaces the soil, predominantly in a lateral direction, during construction. Fast construction if piles are manufactured in advance.	Drilled and concreted in one continuous operation enabling much faster installation time than for bored piles; Economical and rapid pile construction in water-bearing strata - no temporary casings or stabilising fluid needed;	Constructed with or without casing, by excavating or boring a hole in the ground and filling with plain or reinforced concrete, Quick and efficient installation Often larger diameter and greater capacity than CFA piles. Can overcome underground obstructions or penetrate ground too hard to bore using a CFA.
Cost	Cost effective in comparison to bored, cased or sleeved piles.	Cost effective in comparison to bored, cased or sleeved piles.	Bored cased piles may be prohibitively expensive. Sleeved piles may be more expensive than conventional piled foundations, although a cost benefit assessment could be undertaken to determine whether savings could be realised if shorter rock socket lengths were formed.

7.4.5 Ground improvement

As previously described the Made Ground presents significant risk of heave and collapse ground movements to the proposed redevelopment due to its highly variable composition, slag content and substantial thickness of up to 9m (Sections 4.1 and 6). These characteristics make it difficult to predict the engineering behaviour of the Made Ground and it is likely to provide inadequate and/or variable support to the proposed structures. Where shallow foundations cannot provide the required settlement performance, ground improvement may be an economical alternative to a deep piled solution. Such techniques may increase the strength and stiffness of the Made Ground and underlying natural strata, to improve bearing resistance and potentially reduce total and differential settlements.

The design of ground improvement by deep vibration should conform to the requirements of *BS EN 14731:2005,* Clause 7. The design of ground improvement by deep mixing should conform to the requirements of *BS EN 14679:2005, Clause 7.* Further guidance is given in the CIRIA C573 (2002) A Guide to Ground Treatment.

The Foundation optioneering appraisal showed that ground treatment was not economically feasible for proposed low threat structures at the Main Site. It may be more appropriate for medium and high threat structures, as described below. It is important to note that field trials, in-situ testing and monitoring are highly recommended to verify the performance and effectiveness of any ground improvement solutions that may be implemented

7.4.5.1 Excavation and Replacement

Excavation and replacement ground treatment involves excavating the Made Ground typically to a maximum depth of about 6m and replacing it with processed or imported, compacted Engineered Fill. This is done under a controlled construction process and is primarily targeted at reducing total and differential settlement but may also increase the bearing resistance of the Made Ground.

Excavation and replacement ground treatment is typically only suitable for soils above the water table. Existing records show the presence of shallow, tidally influenced groundwater at approximately 3m depth below the Main Site. This adversely impacts the stability of excavations and also restricts working conditions. As a result, without groundwater control by dewatering or sheet pile cut-off walls the excavation and replacement ground treatment will not be cost effective where the Made Ground is greater than 3m thick and may not be feasible at the Main site between depths of 3 and 5m.

Results of the Foundation optioneering appraisal showed that excavation and replacement may be suitable in combination with raft foundations and a suspended floor slab for medium threat structures. However, there may be additional costs associated with disposal of large volumes of excavated Made Ground, particularly if it is found to be contaminated. It is notable that excavation and replacement will not remove the risk of significant residual settlements occurring due to compression of untreated Tidal Flat Deposits at depth.

The Foundation optioneering appraisal concludes that excavation and replacement may not provide adequate bearing resistance for high threat structures, particularly due to the ongoing potential for long term creep movements or settlement induced by dynamic loading to occur.

Given that the Made Ground encountered at the site is predominantly granular and extends to depth (maximum 9m), it is considered unlikely that adequate cut-off to allow for dewatering will be feasible. This option also has wider implications in that this type of construction is likely to extend below the proposed development platform currently being developed separately by Teesworks (understood to be a successor to STDC). Therefore, although this option may be technically feasible it is not considered a favourable foundation solution.

Localised excavation and replacement may be considered to stiffen formation soils to allow for construction of low load intensity ground bearing floor slabs.

7.4.5.2 Vibro-compaction and vibro-replacement

Vibro-compaction is a densification process that may be used up to depths of approximately 20m in granular soils. A vibrating closed-ended steel tube, typically 300 mm to 500 mm diameter, is inserted into the ground and the vibrations cause the surrounding soil particles to be rearranged reducing air voids and increasing soil density. This results in stiffening the ground and reduces foundation settlement (total and/or differential) when loaded.

Vibro-replacement, commonly also known as vibro-stone columns, is another densification process that may be used up to depths of approximately 20m in both cohesive and granular soils. It may be used in both the Made Ground and underlying Tidal Flat Deposits. This technique creates 600mm to 800mm diameter columns of compacted stone to transmit load or resist shear. The stone may be introduced at the top of the hole, and similar to vibro-compaction, it is compacted using a vibrating steel tube. Alternatively, the stone may be introduced from the bottom of the hole if the Made Ground or underlying natural strata is weak or the water table is high.

The shallow groundwater conditions at the Main Site may compromise the integrity of the stone columns via washout or displacement. The long term integrity / serviceability of stone columns installed through thick deposits of underlying soft clays and silts / loose sands (Tidal Flat Deposits), under high and/or dynamic load conditions would need to be determined.

The Foundation optioneering appraisal showed that vibro-replacement may be adopted for both medium and high threat structures in conjunction with raft foundations to reduce total and differential settlement.

The existing ground investigation data has proved the presence of organic materials, obstructions, expansive slag and chemicals in the Made Ground which may hinder the effectiveness of this ground improvement technique. Obstructions may prevent penetration of the equipment through areas of dense and or fused slag materials. Long term settlement may also occur if the silt or clay content of the underlying Tidal Flat Deposits is high preventing construction of a continuous stone column. Furthermore, vibro-replacement ground treatment may not be effective to improve the properties of fines rich Tidal Flat Deposits. The soils are of relatively low strength and may not generate sufficient lateral/passive resistance to prevent bulging of the stone columns during or after installation. In addition, the depth at which these soils are present across site may mean it is not possible to fully treat them, leaving a zone of soft clays and silts / loose sands below the columns in which significant residual movements could still occur.

Vibro-compaction and vibro-replacement techniques may be considered to stiffen formation soils to allow for construction of ground bearing floor slabs for medium threat structures, depending on load and serviceability limits. However, complex soil-structure interaction analysis is required which may result in increased design time and cost and a residual construction risk.

7.4.5.3 Deep soil mixing (lime or cement columns)

Deep soil mixing is a ground treatment technique for soft fine grained soils in which quicklime or cement is introduced at depth via a hollow stem auger. The auger has a special blade to mix the quicklime/cement as the auger is rotated (in the reverse direction) and withdrawn from the hole. The soil-lime columns, typically 500mm in diameter and up to 15m deep, are designed to act as a composite with the surrounding soil and are individually capable of individually bearing loads of 50-100kN. However, the columns can sometimes act as drains, and their bearing resistance can decrease over time due to leaching by slightly acidic groundwater.

This technique is best suited for the stabilisation of thick deposits of soft clays found at or close to ground surface. As these conditions are not present, the Foundations optioneering appraisal has concluded that deep soil mixing is not a suitable technique for use on this site.

Additionally, the introduction of lime in potentially expansive Made Ground may result in post construction heave of treated soils, over and above the heave anticipated from expansive slag materials across the site.

7.4.5.4 Dynamic Compaction

Dynamic compaction is used to increase the ground stiffness by repetitive dropping of heavy weights (high energy impacts) at fixed grid points. Dynamic compaction is carried out in a series of phases or passes and the maximum depth of treatment depends both on the weight of tamper and height of drop. This compaction process is more effective in granular soils but has also been used successfully in finer soils. The Foundations optioneering appraisal showed that Dynamic compaction was not suitable to improve ground at the Main site because expansive slag material in the Made Ground and underlying layers of loose estuarine sands and soft clays and silts of the Tidal Flat Deposits mean that the characteristics of the ground are only likely to be marginally improved.

In addition, the location of the Central Area Transmission System (CATS) pipeline and Breagh high pressure gas pipelines which run parallel with, and approximately 50m from the east boundary of the Main Site form a known constraint for the development. High energy, high impact compaction techniques which are likely to result in significant ground vibrations are therefore not recommended.

7.5 Summary of appraisal findings

The Foundation optioneering appraisal indicates that shallow strip or pad foundations are expected to be suitable for low load intensity low risk structures, for example, such as lighting columns, fencing, cable trays and unoccupied buildings.

Shallow raft foundations spanning the entire footprint of a structure may be considered a potentially suitable option for low and medium threat structures at the Main Site. This option is favoured as it limits the potential for differential movements from settlement or heave. Mitigation measures such as local excavation and compaction beneath and in conjunction with raft foundations could be considered.

Deep pile foundations were found to be most appropriate for medium and high risk structures. Appropriate construction techniques may comprise driven cast-in-situ concrete piles, continuous flight auger (CFA) piles, bored cased piles or bored cased and sleeved piles. Additional mitigation measures such as a detailed UXO risk strategy and probing for obstructions in the Made Ground before piling commences should be considered.

It may be beneficial to adopt a single pile foundation installation technique across all medium and high threat structures to be constructed on site to maximise cost savings and reduce design and construction complexity.

All foundation options described in this report will need to be re-assessed following ground investigation works and preliminary design. All foundation options will be subject to the proposed load and serviceability criteria (to be determined during Front End Engineering Design (FEED)).

A summary of the foundation appraisal assessment for high, medium and low threat structures is given in Table 6. An assessment of different structure, load and ground risk criteria for each structure threat level is shown in Figure 7 to Figure 9. The full foundation appraisal is presented in Appendices C.1 to C.3. Foundation option conclusions are provided in Section 8 below.

Table 6 Summary of foundation optioneering appraisal findings

		Foundation suitable based on assessment [1]		
Category	**Foundation type**	**Low Threat**	**Medium Threat**	**High Threat**
Shallow Foundations	Strip Footing	Yes, with mitigation, if no long term creep or dynamic loading.	No	No
	Pad Footing	Yes, with mitigation, if no long term creep or dynamic loading.	No	No
	Raft Foundation	Yes, with mitigation: -	Yes, with mitigation	No
Deep Foundations	Driven Piles	No	Yes, with mitigation	Yes, with mitigation
	CFA Piles	No	Yes, with mitigation	Yes, with mitigation
	Bored Cased Piles	No	Yes, with mitigation	Yes, with mitigation
	Bored Cased & Sleeved Piles	No	Yes	Yes
Ground improvement	Excavation and replacement	No	Yes, in conjunction with raft foundation	No
	Vibro-replacement - stone columns	No	Yes, in conjunction with raft foundation. Considered an option to support ground bearing floor slabs	Yes, in conjunction with raft foundation. No Considered an option to support ground bearing floor slabs
	Deep mixing - lime or cement columns	No	No	No
	Dynamic compaction	No	No	No

[1]. For all foundation options, a detailed UXO strategy is required to minimise UXO risks.

8. Foundation Options Conclusions

8.1 Low Threat Structures

Suitable foundation options for low threat structures included:

1. Pad footing (if not susceptible to creep or dynamic loading)
2. Strip footing (if not susceptible to creep or dynamic loading)
3. Raft foundation

Option 3 (raft foundation) is considered most favourable as pad or strip foundations may not be sufficiently rigid to mitigate ground instability from heave or collapse of the Made Ground.

8.2 Medium Threat Structures

Suitable foundation options for low threat structures included:

1. Raft foundation with or without ground treatment (if not subject to long term creep, dynamic or transient loading conditions)
2. CFA piles. Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination.
3. Bored cased piles (with or without sleeves). Mitigation may be required for ground instability from heave or collapse, UXO, soil contamination and groundwater contamination.
4. Driven cast-in-situ piles, Mitigation may be required for obstructions, for example by making allowance for the installation of replacement / additional piles during construction.

Options 2 (CFA piles), 3 (Bored cased piles) and 4 (Driven cast-situ piles) are considered most favourable as these accommodate all the load cases, i.e. initial loading, longer term creep, dynamic loading and transient loading. This solution will transfer loads to competent strata at depth and limit settlement. CFA piles are faster to install and cheaper to construct in comparison to bored cased piles, however bored cased piles have greater bearing resistance and can advance through obstructions.

Ground treatment below raft foundations could comprise excavation and replacement or vibro-replacement (stone columns).

8.3 High Threat Structures

Suitable foundation options for low threat structures included:

1. Raft foundation with or without ground treatment (if not subject to long term creep, dynamic or transient loading conditions).
2. CFA piles. Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination.
3. Bored cased piles (with or without sleeves). Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination.
4. Driven cast-in-situ piles, Mitigation may be required for obstructions, for example by making allowance for the installation of replacement / additional piles during construction.

Options 2 (CFA piles), 3 (Bored cased piles) are and 4 (Driven cast-situ piles) are considered favourable as these accommodate all the load cases, i.e. initial loading, longer term creep, dynamic loading and transient loading. This solution will transfer loads to competent strata at depth and limit settlement. However, bored cased piles are considered to be more favourable over CFA piles as they have greater bearing resistance, rock socket length is not limited by installation technique and this form of construction can advance through obstructions. Option 4 (Driven cast-in-situ piles) with enlarged bases have been successfully installed below the existing blast furnace to the west.

Ground treatment below raft foundations may comprise excavation and replacement or vibro-replacement (stone columns).

Consideration could also be given to the feasibility of adopting piled rafts once load and settlement criteria are defined following completion of FEED.

9. References

6 Alpha (2020). Onshore Unexploded Ordnance Threat and Risk Assessment with Risk Mitigation Strategy: Net Zero Teesside. Project Number: 8008, Report Version: Final.

AECOM (2020). STDC 'Main Site' Geotechnical and Geo-Environmental Desk Study. Project number: 60559231-CTR005-003 GEO-002. Revision P03

AECOM (2021). Onshore CO2 Export Pipeline Corridor Geotechnical and Geo-Environmental Desk Study. Project number: 60559231-CTR005-003 GEO-002. Revision P02

AECOM (2021). Technical Note: Preliminary Onshore Ground Investigation for Net Zero Teesside – Ground Investigation Rationale. Reference PR-60559321_ACM_TN_ENV_001_B.

AEG (2018). Ground Investigation, 'The Former SSI Steelworks, Redcar – Ground Investigation Contract – Priority Areas Within SSI Landholdings Contract 1 and Contract 2 (Area A)".

Arcadis (2018a). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A Site: Condition Report, dated August 2018

Arcadis (2018b). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A Site: Geotechnical Risk Assessment Report, dated November 2018

Arcadis (2018c). The Former SSI Steelworks Redcar: Priority Areas within SSI Landholdings Contract 1 and 2A: Contract 1 and 2A Site: Ground Remediation Options Appraisal Report, dated December 2018

bp (2014). Engineering Technical Practice GP04-60: Onshore and Nearshore Geotechnical Engineering

British Standard Institution (2015). BS 5930:2015+A1:2020 Code of practice for ground investigations

British Standards Institution (2014). BS EN 1997-1:2004+A1:2013 Incorporating corrigendum February 2009 Eurocode 7 – Geotechnical Design – Part 1: General Rules, Incorporating corrigendum No. 1 February 2009 Implementation of CEN amendment July 2014.

British Standard Institution (2015). BS8004:2015 +A1:2020: Code of practice for foundations.

BRE (2015). FB 75 Building on fill: Geotechnical Aspects. 3rd Edition.

British Standard Institution (2013). BS EN 1997-1:2004+A1:2013 - Eurocode 7: Geotechnical Design

British Standard Institution (2005). BS EN 14731 - Execution of special geotechnical works - Ground treatment by deep vibration

British Standard Institution (2005). BS EN 14731 - Execution of special geotechnical works - Deep mixing

CIRIA C573, Guide to ground treatment, 2002

CH2M (2017). Factual Report – Initial Trial Pitting - SSI Redcar – SSI2.

Eric E. Jorden & M. Dobie, Tests on piles in Keuper Marl for the foundations of a blast furnace at Redcar, Geotechniquie, Volume 26 Issue 1, March 1976, pg 105 - 113).

ICE Manuals (2012). ICE Manual of Geotechnical Engineering Volume II. ICE Publishing. Editors: Burland John, Chapman Tim, Skinner Hilary, and Brown Michael.

Mitchell, J. M. and Jardine, F. M. (2002). A Guide to Ground Treatment, CIRIA Report C573. London, UK: CIRIA.

Piling and Penetrative Ground Improvement Methods on Land Affected by Contamination: Guidance on BS EN 1997-1:2004 + A1: 2013 Eurocode 7: Geotechnical design – Part 1: General Rules, UK National Annex: 2014 to BS EN 1997-1:2004 + A1: 2013 Eurocode 7,

Pollution Prevention, Environment Agency National Groundwater & Contaminated Land Centre Report NC/99/7.

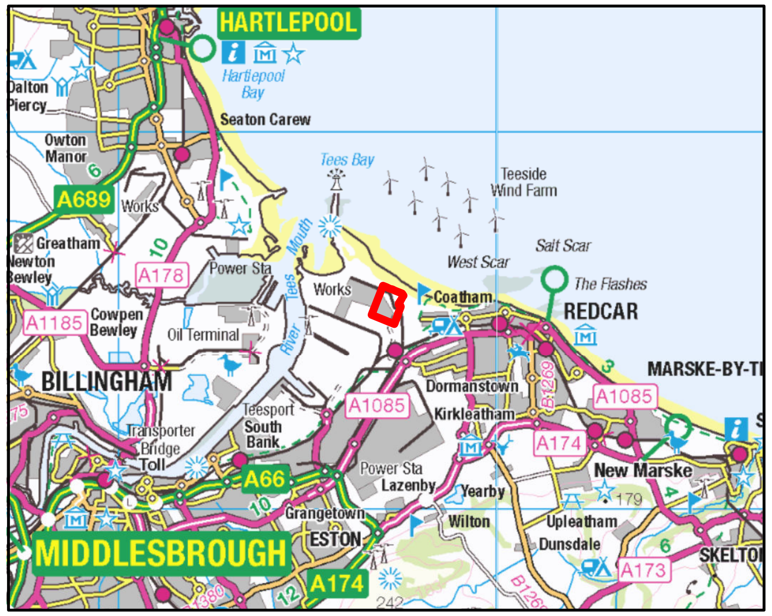
Stroud, M.A and Butler, FG. (1975). The Standard Penetration Test and the Engineering Properties of Glacial Materials, University of Birmingham, 1975

Stroud, M. A. 1989. The Standard Penetration Test – Its Application and Interpretation. Proceedings of the Geotechnology Conference on Penetration Testing in the UK, Thomas Telford.

Appendix A Main Site Geotechnical Constraints

Drawn: RPA

ISO A3 420mm X 297mm



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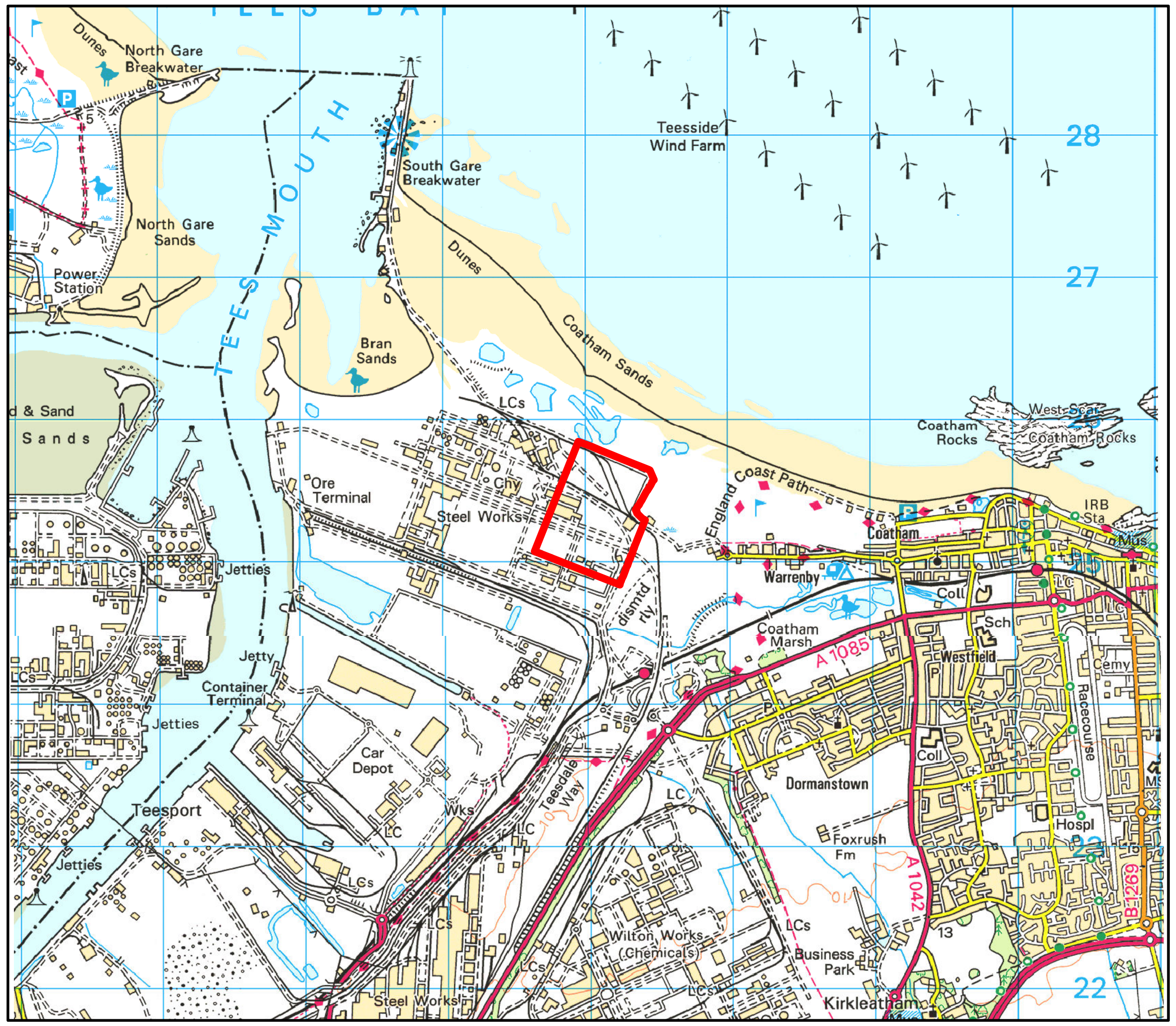

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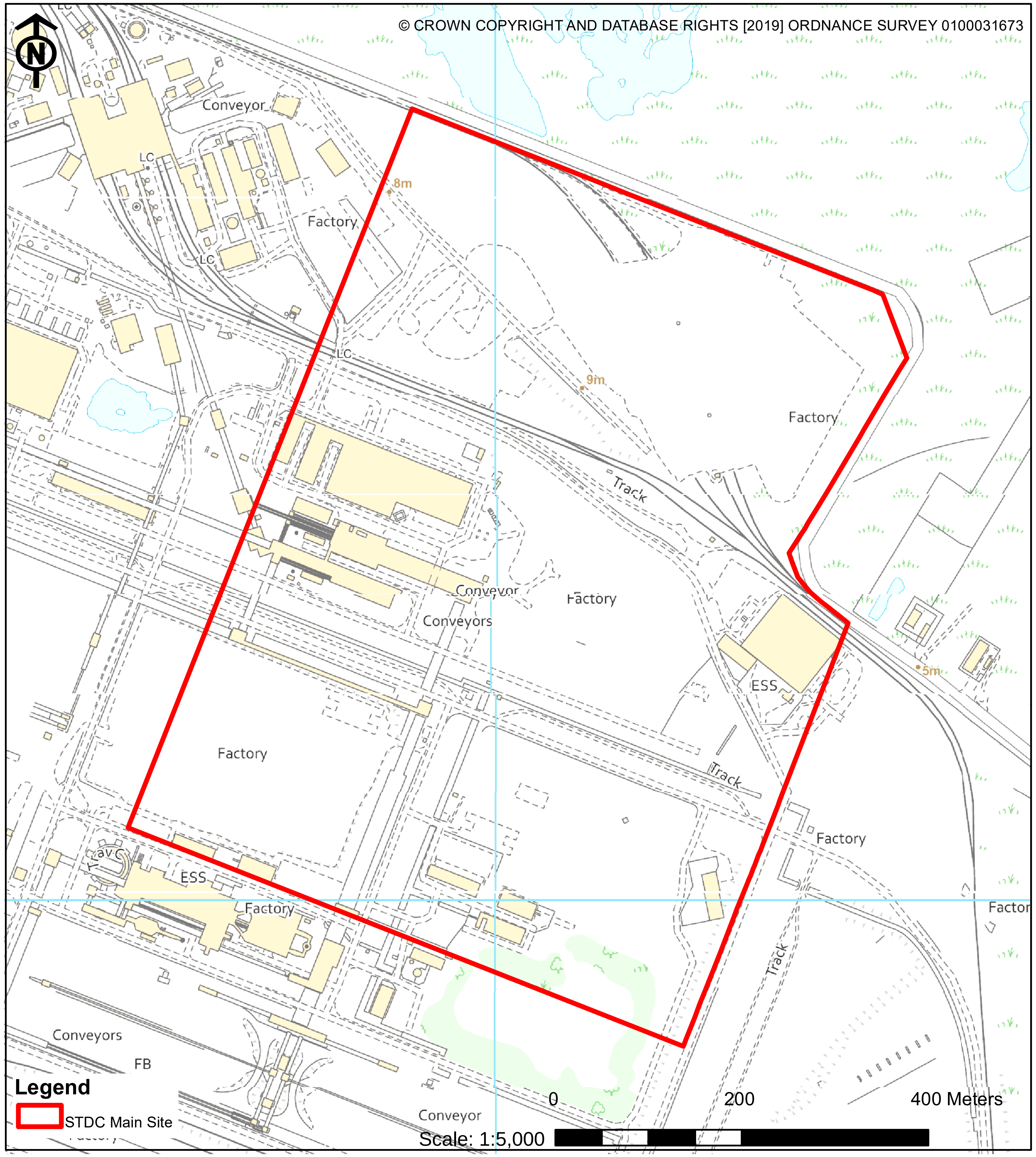


NET ZERO TEESSIDE

OGCI CLIMATE INVESTMENTS HOLDINGS LLP

Site Boundary Plan (STDC)

Scale: As Shown

Drawing Number: 60559231-ACM-CTR005-002-DRG-001

AECOM

Project No: 60559231

Date: March 2020

Scale @ A3 1:5,000

AECOM

PROJECT
NET ZERO TEESSIDE

CLIENT
NZT POWER AND NZNS STORAGE

KEY
- The Main Site

Historical Features
- Breakwaters
- H.W.M.O.S.T 1856
- Tees Estuary 1856

Infill

Date
- Infill 1894
- Infill 1915
- Infill 1952
- Infill 1970s / The Marshes

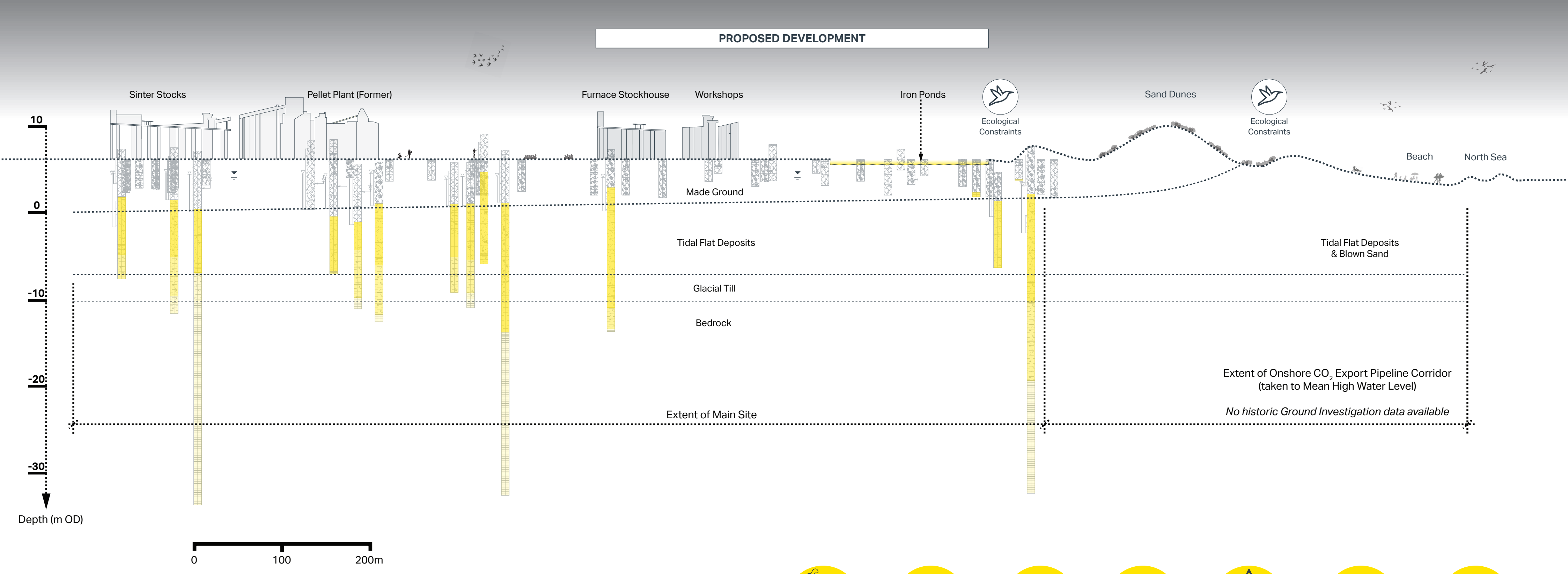
TITLE
FOUNDATIONS OPTIONS REPORT
GEOTECHNICAL CONSTRAINTS

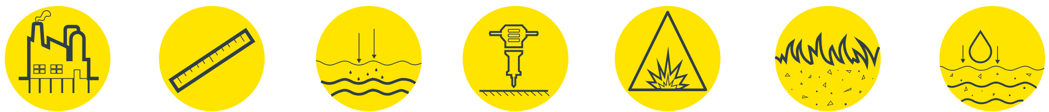
REFERENCE
NZT_210216_ STDC_CONSTRAINTS_1

SHEET NUMBER 1 of 1

DATE 16/02/2021

Appendix B Conceptual Site Model





MADE GROUND	Granular material with a fine-grained component and low to high cobble/boulder content which included slag including fused slag, refractory brick, concrete and occasionally clinker, coke, coal and/or metal. **Expected thickness: Up to 9m** **Expected Depth: 4 - 9m bgl**	Inadequate Bearing	Heave & collapse settlement of Made ground	Shallow Groundwater	Obstructions / Voids	Presence of Unexploded Ordnance	Soil Contamination	Groundwater Contamination
TIDAL FLAT DEPOSITS	Medium dense comprising silty variably gravelly sand with layers/bands of gravel and shell beds. Layers of soft or loose clay and/or silt were identified. **Expected thickness: 3 - 15m** **Expected Depth: 4 - 21m bgl**	Inadequate Bearing		Shallow Groundwater	Obstructions / Voids	Presence of Unexploded Ordnance	Soil Contamination	Groundwater Contamination
GLACIAL TILL	Variable but predominantly comprising firm becoming stiff and very stiff slightly sandy slightly gravelly clay with gravel composed of mixed lithologies, including sandstone, limestone and rare coal. Localised deposits of glacio-lacustrine clay present. **Expected thickness: 2.5 - 9m** **Expected Depth: 14 - 27m bgl**				Obstructions / Voids		Soil Contamination	Groundwater Contamination
REDCAR MUDSTONE FORMATION	Weak to extremely weak weathered mudstone **Expected thickness:** Depth not proven **Expected Depth: >22 m bgl**	Inadequate Bearing					Soil Contamination	Groundwater Contamination

m bgl = metres below ground level

Appendix C Foundation Appraisal

C.1 Low Threat structures

Threat Level	LOW THREAT																		
	← GP 04-60 →							← Desk Study →							Cost	Automated Summary	Pros	Cons	Mitigation and Conclusion
Condition / Foundation Type	Initial Loading	Longer term creep	Dynamic Loading	Transient Loading (wind / thermal / other)	Hard Layers	Soft/Compressible Layers	Ground Chemistry	Stability Heave / Collapse	Inadequate Bearing	Obstructions & Voids	UXO	Shallow Groundwater	Soil Contamination	Groundwater Contamination					
Strip Footing	✓	✗	✗	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	✓	✓	Unsuitable for conditions of long term creep or dynamic loading. May be unsuitable due to soft/compressible Layers, ground instability from heave or collapse, inadequate bearing capacity and ground obstructions or voids.	Minimal cost Easy to construct	Only suitable for lightly loaded structures not subject to dynamic loading	Suitable for lightly loaded structures not subject to creep or dynamic loading.
Pad Footing	✓	✓	✓	✓	✓	✗	✓	M	M	M	✓	✓	✓	✓	✓	Suitable for all load cases. May be unsuitable due to soft/compressible Layers. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and ground obstructions or voids.	Economical foundation option for medium threat low load structures. More cost effective when compared to raft foundations.	Not suitable for not structures subject to long term creep movements or dynamic loading.	Suitable for Medium Threat low structures not subject to dynamic loading.
Raft Foundation	✓	✓	✓	✓	✓	✓	✓	M	M	✓	✓	✓	✓	✓	✓	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse and inadequate bearing capacity.	Suitable for Low Threat low load structures.		Suitable with mitigation.
Driven Piles	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	M	✓	✓	✓	✗	Suitable for all load cases. May be unsuitable due to hard layers, ground instability from heave or collapse and ground obstructions or voids. Mitigation may be required for UXO. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
CFA Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✓	M	M	✗	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Bored Cased Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	✓	M	✓	M	M	✗	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, UXO, soil contamination and groundwater contamination. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Bored Cased & Sleeved Piles	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✗	Suitable for all load cases. Mitigation may be required for UXO, soil contamination and groundwater contamination. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Excavation and Replacement	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	M	✗	✗	✗	✗	Suitable for all load cases. May be unsuitable due to inadequate bearing capacity, shallow groundwater, soil contamination and groundwater contamination. Mitigation may be required for UXO. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Vibro-replacement - stone columns	✓	✓	✓	✓	✗	✓	✓	M	M	✗	M	✗	✓	M	✗	Suitable for all load cases. May be unsuitable due to hard layers, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity, UXO and groundwater contamination. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Deep Soil Mixing - lime or cement columns	✓	✓	✓	✓	✗	✓	✗	M	M	✗	M	✗	✓	✓	✗	Suitable for all load cases. May be unsuitable due to hard layers, aggressive ground chemistry, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**
Dynamic Compaction	✓	✓	✓	✓	✗	✓	✗	M	M	✗	M	✓	✓	✓	✗	Suitable for all load cases. May be unsuitable due to hard layers, aggressive ground chemistry and ground obstructions or voids. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO. May be prohibitively expensive			**Not suitable as not expected to be cost effective.**

C.2 Medium Threat structures

Threat Level	MEDIUM THREAT														
	← GP 04-60 →							← Desk Study →							Cost
Condition / Foundation Type	Initial Loading	Longer term creep	Dynamic Loading	Transient Loading (wind / thermal / othe	Hard Layers	Soft/Compressible Layers	Ground Chemistry	Stability Heave / Collapse	Inadequate Bearing	Obstructions & Voids	UXO	Shallow Groundwater	Soil Contamination	Groundwater Contamination	
Strip Footing	✗	✗	✗	✗	-	-	-	-	-	-	-	-	-	-	-
Pad Footing	✓	✗	✗	✗	✓	✗	✓	M	M	M	✓	✓	✓	✓	✓
Raft Foundation	✓	✓	✓	✓	✓	✓	✓	M	M	✓	✓	✓	✓	✓	✓
Driven Piles	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	M	✓	✓	✓	✓
CFA Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✓	M	M	✓
Bored Cased Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	✓	M	✓	M	M	✓
Bored Cased & Sleeved Piles	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✗
Excavation and Replacement	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	M	✗	✗	✗	✗
Vibro-replacement - stone columns	✓	✓	✓	✓	✗	✓	✓	M	M	✗	M	✗	✓	M	✓
Deep Soil Mixing - lime or cement columns	✓	✓	✓	✓	✗	✓	✗	M	M	✗	M	✗	✓	✓	✓

Foundation Type	Automated Summary	Pros	Cons	Mitigation and Conclusion
Strip Footing	Unsuitable for loading of Medium threat structures.			Not suitable
Pad Footing	Unsuitable for conditions of long term creep, dynamic or transient loading. May be unsuitable due to soft/compressible Layers. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and ground obstructions or voids.	Economical foundation option for medium threat low load structures. More economical when considered against raft foundations.	Not suitable for not structures subject to long term creep movements or dynamic loading.	Ground Investigation. Adequate Design. Suitable for Medium Threat low structures not subject to dynamic loading.
Raft Foundation	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse and inadequate bearing capacity.	Removes risk posed by obstructions within the made ground at shallow depth. Shallow obstructions and foundations may be excavated / ripped out where required. Large raft foundations reduces the risk of differential settlement due to obstructions and voids. If UXO is encountered this foundation solution allows identification and decommissioning. Removal off site possible through contractor RAMS and construction management plans. Risk posed from/to groundwater is reduced as this foundation solution is only likely to intercept shallow surface water that may be controlled by localised pumping or cut-off.	Does not address the potential issues from expansive slag. May not be suitable for long term creep and dynamic loading. Increases the likelihood of UXO being encountered due to volume of disturbed surface soils excavated during construction. Relatively large volume required to be excavated, moved and potentially disposed during construction of raft foundations increases the likelihood and cost of disposal of contaminated soils **(TBC based on STDC site remediation proposals).**	Ground Investigation. Adequate Design. Feasibility of this solution is dependant on the proposed load intensity and the serviceability limits performance criteria (to be determined during FEED). Long term large scale instrumented plate load test on foundation formation may be considered to demonstrate creep and dynamic load conditions. Ground improvement may be required to provide adequate bearing and mitigate risk of collapse. Expected ground movements and heave may be mitigated by inclusion of adjustable expansion joints in construction.
Driven Piles	Suitable for all load cases. May be unsuitable due to hard layers, ground instability from heave or collapse and ground obstructions or voids. Mitigation may be required for UXO.	Have been adopted successfully on the Redcar blast furnace to the west. Expected to be cost effective when compared to other piling techniques. Delivered in bespoke lengths to site. Different shapes and sizes available. Prefabricated sections are delivered and assembled during installation via locking of male & female jointed sections. Displacement pile so removes costs associated with disposal of potentially contaminated soils.	Low ultimate moment resistance, therefore, unable to accommodate bending moments induced by lateral soil movements induced in the ground from for example by loading of adjacent areas. Can be susceptible to "false set" when driven into certain types of mudstone due to excess pore pressures generated during installation. This can be partly mitigated by restriking all/proportion of piles a few days after installation to determine driving resistance once pore pressures induced during construction have dissipated. Potential for UXO strike - risk cannot be fully eliminated. Susceptible to damage from obstructions present in the made ground including buried foundations (TBC based on STDC site remediation proposals) which may prevent toe levels and / or construction specification tolerances (plan position and/or verticality) being achieved. Integrity of installed piles may be confirmed by post installation non destructive testing (NDT), eg CASE/CAPWAP. Allowance should be made for damage/installation of additional replacement piles. Damage to slender pile sections possible. This may be partly mitigated by advanced probing/pre-boring undertaken before installation. Ultimate compressive resistance generated may be limited due to the inability of forming long rock sockets using this technique. Working loads ~50 to ~70Te for a 270mm square section but the higher value is unlikely to be achieved unless piles end bear on hard rock such as sandstone (which is only likely to be encountered locally below the site). Inadequate bearing due to limited potential for extending the pile into the underlying solid strata for extended rock socket. Driven piles may result in fracturing of the rock potentially increasing the risk of creating preferential pathway between the made ground soils and ground water and underlying bedrock aquifer. Adverse environmental impacts caused by noise and ground vibration generated during installation. Noise is unlikely to be a significant constraint/restriction on the adoption of this technique due to the industrial/post-industrial setting of the site. Use is likely to be restricted by ground vibrations in areas close to sensitive structures and/or service corridors.	UXO risk to be established through detailed risk assessment and probability assessment. Driven cast-in-situ piles have been used in constrction of the redcar balst furnace to the west. Mitigation required for the following: - risk of structural damage/loss of integrity caused by damage due to encountering obstructions - relatively low load carrying (capacity) expected to be generated - low ultimate moment resistance - risk of damage caused by ground vibrations to services
CFA Piles	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination.	Cost effective in comparison to bored cased or bored sleeved piles. Reduces the risk of long term creep settlement on loading in made ground and/or loose / soft estuarine sands, clays and silts at depth.	Obstructions in the made ground including buried foundations **(TBC based on STDC site remediation proposals)** may prevent toe levels and / or specification construction tolerances (plan position and / or verticality) being achieved. Ultimate compressive resistance may be limited due to the inability to form long rock sockets using this technique. Pile may not be able to resist heave due to limited potential to extend rock socket length to depth. Potential for pile 'squeezing' through soft soils and/or water bearing coarse (granular) soils. Pile integrity problems may occur where installed through water bearing coarse (granular) soils.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Probing for obstructions in the made ground in advance of pile construction could be considered. Considered feasible but carries risk that pile toe levels and construction specification tolerances (plan position and / or verticality) may not be achieved.
Bored Cased Piles	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, UXO, soil contamination and groundwater contamination.	Reduces the risk of long term creep settlement on loading in made ground and/or loose / soft estuarine sands, clays and silts at depth. Bored cased piles may allow for advance through obstructions by pre-boring. No limitation on the construction of longer rock sockets or under-reamed pile toes to provide additional skin friction to reduce the risk of heave and uplift resulting from potentially swelling slag materials within the made ground. Casing between potentially contaminated groundwater and underlying aquifer reduces the risk to groundwater contamination. The installation of temporary casing through water bearing coarse granular soils or soft soils enables the control of any integrity problems which may occur during construction by balancing of water pressures within and outside pile bores.	Bored piles generate arisings at surface which may include potentially contaminated soils. Increased cost due to soil treatment and/or disposal offsite is possible.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Suitable foundation option.
Bored Cased & Sleeved Piles	Suitable for all load cases. Mitigation may be required for UXO, soil contamination and groundwater contamination. May be prohibitively expensive	As bored piles above. Sleeved piles are designed to resist heave from potentially swelling slag within the made ground. The sleeving may allow formation of shorter rock socket lengths in comparison to bored cased bored piles.	As bored piles above. Increased cost in comparison to bored cased piles.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Suitable foundation option.
Excavation and Replacement	Suitable for all load cases. May be unsuitable due to inadequate bearing capacity, shallow groundwater, soil contamination and groundwater contamination. Mitigation may be required for UXO. May be prohibitively expensive	Provides engineered fill over the depth of excavation and replacement producing a substantial increase in near surface foundation bearing resistance (capacity). Could be adopted in conjunction with raft foundations and / or ground bearing slabs. This treatement is expected to reduce total and differential settlements below raft foundations.	Significant volume of soil treatment and / or disposal of potentially contaminated soils. Groundwater is shallow across the site ~ 3m depth and may be tidally influenced, this solution is therefore only suitable for soils above groundwater, but will have a limited impact where made ground > 5m depth. Groundwater is shallow across the site ~ 3m depth and may be tidally influenced, may result in significant constraints for stability of excavations during construction. This may also restrict working. Does not remove the risk of long term settlement on loading occurring in both the made ground and/or loose / soft estuarine sands, clays and silts at depth.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. May be suitable in combination with raft foundations but does not remove the risk of significant residual settlements occurring due to compression of untreated strata at depth.
Vibro-replacement - stone columns	Suitable for all load cases. May be unsuitable due to hard layers, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity, UXO and groundwater contamination.	Cost effective option in comparison to piling. Could be adopted with raft foundations and / or suspended floor slabs. Reduces total and differential settlement. Speeds up consolidation settlement. Mitigates risk of soil liquefaction.	Does not address the potential issues from expansive slag. Advancing stone columns through significant depths of made ground may be problematic. Pre-boring may mitigate risk of obstructions. Shallow groundwater may result in the potential for integrity problems caused by stone washout or displacementwashout , and result in difficult construction conditions. Concern over long term integrity / serviceability of ~~the~~ columns installed through thick deposits of underlying soft / loose estuarine sands, clays and silts, especially under high and / or dynamic load conditions. Not suitable for soft clays, organic soils and peats because of their lack of lateral confinement.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. May be an option for medium threat medium load structures in combination with raft foundations. Early specialist contractor involvement would be recommended possibly in combination with site trials.
Deep Soil Mixing - lime or cement columns	Suitable for all load cases. May be unsuitable due to hard layers, aggressive ground chemistry, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO.	As vibro compaction stone columns. Best suited to the stabilisation of deep soft clays (not found near surface at this site).	As vibro compaction stone columns. Introduction of lime in potentially expansive soils may result in post construction heave of treated soils, over and above the heave anticipated from expansive slag materials across the site. Potential for integrity problems when constructed below groundwater. Can act as drains. May lose strength over time because of leaching by slightly acidic groundwater. Post treatment plate load tests required to confirm performance.	Not suitable

Threat Level	MEDIUM THREAT																		
	← GP 04-60 →							← Desk Study →							*Cost*	*Automated Summary*	*Pros*	*Cons*	*Mitigation and Conclusion*
Condition Foundation Type	Initial Loading	Longer term creep	Dynamic Loading	Transient Loading (wind / thermal / othe	Hard Layers	Soft/Compressible Layers	Ground Chemistry	Stability Heave / Collapse	Inadequate Bearing	Obstructions & Voids	UXO	Shallow Groundwater	Soil Contamination	Groundwater Contamination					
Dynamic Compaction	✓	✓	✓	✓	✗	✓	✗	M	M	✗	M	✓	✓	✓	✓	Suitable for all load cases. May be unsuitable due to hard layers, aggressive ground chemistry and ground obstructions or voids. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO.	Cost effective option in comparison to piling. Technique generally effective in the densification of coarse (granular) soils, non homogenous fills, reclaimed areas with variable characteristics, where underground obstructions and large voids are present. Appropriate for use in both unsaturated and unsaturated soils.	Does not address the potential issues from expansive slag. Not an effective technique for the treatment of fine (cohesive) soils. Significant adverse environmental impact from noise and vibrations induced in the ground. Technique should not be undertaken within 15m of existing services and within 30m of existing buildings. Does not limit/remove the issue of potential risk of substantial settlement in the deep underlying loose / soft estuarine sands, clay and silts. Potential risk of ground vibrations causing damage to sensitive structures such as the CATS / BREAGH high pressure pipelines.	Not suitable

C.3 High Threat structures

Threat Level: HIGH THREAT

Foundation Type	Initial Loading	Longer term creep	Dynamic Loading	Transient Loading (wind / therm	Hard Layers	Soft/Compressible Layers	Ground Chemistry	Stability Heave / Collapse	Inadequate Bearing	Obstructions & Voids	UXO	Shallow Groundwater	Soil Contamination	Groundwater Contamination	Cost
	← GP 04-60 →							← Desk Study →							Cost
Strip Footing	✗	✗	✗	✗	-	-	-	-	-	-	-	-	-	-	-
Pad Footing	✗	✗	✗	✗	-	-	-	-	-	-	-	-	-	-	-
Raft Foundation	✓	✗	✗	✗	✓	✓	✓	M	M	✓	✓	✓	✓	✓	✓
Driven Piles	✓	✓	✓	✗	✗	✓	✓	✗	✓	✗	M	✓	✓	✓	✓
CFA Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✓	M	M	✓
Bored Cased Piles	✓	✓	✓	✓	✓	✓	✓	M	✓	✓	M	✓	M	M	✓
Bored Cased & Sleeved Piles	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	M	✓	M	M	✓
Excavation and Replacement	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	M	✗	✗	✗	✗

Foundation Type	Automated Summary	Pros	Cons	Mitigation and Conclusion
Strip Footing	Unsuitable for loading of High threat structures.			Not suitable
Pad Footing	Unsuitable for loading of High threat structures.			Not suitable
Raft Foundation	Unsuitable for conditions of long term creep, dynamic or transient loading. Mitigation may be required for ground instability from heave or collapse and inadequate bearing capacity.	Removes risk posed by obstructions within Made Ground at shallow depth. Provides partial mitigation posed by large obstructions at depth within the Made Ground. Shallow obstructions and foundations may be excavated / ripped out where required. Large raft foundations reduces the risk of differential settlement due to obstructions and voids. If UXO is encountered this foundation solution allows identification and decommissioning to be controlled. Removal off site possible through contractor RAMS and construction management plans. Risk posed from/to groundwater is reduced as this foundation solution is only likely to intercept shallow surface water that may be controlled by localised pumping or cut-off.	Does not address the potential issues from expansive slag. May not be suitable for long term creep and dynamic loading. Increases the likelihood of UXO being encountered due to the volume of disturbed surface soils excavated during construction. Relatively large volume of material required to be excavated, moved and potentially disposed during construction of raft foundations increases the likelihood and cost of disposal of contaminated soils **(TBC based on STDC site remediation proposals).**	Ground Investigation. Adequate Design. **Feasibility of this solution is dependant on the proposed load intensity and the serviceability limits performance criteria (to be determined during FEED studies).** Long term large scale instrumented plate load test on foundation formation may be considered to demonstrate creep and dynamic load conditions. Ground improvement may be required to provide adequate bearing and mitigate risk of collapse. Expected ground movements and heave may by mitigated by inclusion of adjustable expansion joints in construction.
Driven Piles	Unsuitable for transient loading. May be unsuitable due to hard layers, ground instability from heave or collapse and ground obstructions or voids. Mitigation may be required for UXO.	Have been adopted successfully on the Redcar blast furnace to the west. Delivered in bespoke lengths to site. Different shapes and sizes available. Prefabricated sections are delivered and assembled during installation via locking of male & female jointed sections. Expected to be cost effective when compared to other piling techniques. Reduces the risk of long term creep settlement on loading in made ground and/or loose / soft estuarine sands, clays and silts at depth when compared to shallow foundation options. Displacement pile so removes costs associated with disposal of potentially contaminated soils.	Low ultimate moment resistance, therefore, unable to accommodate bending moments induced by lateral soil movements induced in the ground from for example by loading of adjacent areas. Can be susceptible to "false set" when driven into certain types of mudstone due to excess pore pressures generated during installation. This can be partly mitigated by restriking all/proportion of piles a few days after installation to determine driving resistance once pore pressures induced during construction have dissipated. Potential for UXO strike - risk cannot be fully eliminated. Susceptible to damage from obstructions present in the made ground including buried foundations **(TBC based on STDC site remediation proposals) which** may prevent toe levels and / or construction specification tolerances (plan position and/or verticality) being achieved. Integrity of installed piles may be confirmed by post installation non destructive testing (NDT), eg CASE/CAPWAP. Allowance should be made for damage/installation of additional replacement piles. Damage to slender pile sections possible. This may be partly mitigated by advanced probing before installation. Ultimate compressive resistance generated may be limited due to the inability of forming long rock sockets using this technique. Working loads ~50 to ~70Te for a 270mm square section but the higher value is unlikely to be achieved unless piles end bear on hard rock such as sandstone (which is only likely to be encountered locally below the site). Driven piles may result in fracturing of the rock potentially increasing the risk of creating preferential pathway between the made ground soils and groundwater and underlying bedrock aquifer. Adverse environmental impacts caused by noise and ground vibration generated during installation. Noise is unlikely to be a significant constraint/restriction on the adoption of this technique due to the industrial/post-industrial setting of the site. Use is likely to be restricted by ground vibrations in areas	UXO risk to be established through detailed risk assessment and probability assessment. Driven cast-in-situ piles have been used in constrction of the redcar balst furnace to the west. Mitigation required for the following: - risk of structural damage/loss of integrity caused by damage due to encountering obstructions - relatively low load carrying (capacity) expected to be generated - low ultimate moment resistance - risk of damage caused by ground vibrations to services
CFA Piles	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, ground obstructions or voids, UXO, soil contamination and groundwater contamination.	Cost effective in comparison to bored cased or bored sleeved piles. Reduces the risk of long term creep settlement on loading in made ground and/or loose / soft estuarine sands, clays and silts at depth when compared to shallow foundation options.	Obstructions in the made ground including buried foundations **(TBC based on STDC site remediation proposals)** may prevent toe levels and / or specification construction tolerances (plan position and/or verticality) being achieved. Ultimate compressive resistance generated may be limited due to the inability to form long rock sockets using this technique. Pile may not be able to resist heave due to limited potential to extend rock socket length to depth. Potential for pile 'squeezing' through soft soils and/or water bearing coarse (granular) soils. Pile integrity problems may occur where installed through water bearing coarse (granular) soils.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Probing for obstructions within the made ground in advance of pile construction could be considered. Considered feasible but carries risk that pile toe levels and construction specification tolerances (plan position and/or verticality) may not be achieved.
Bored Cased Piles	Suitable for all load cases. Mitigation may be required for ground instability from heave or collapse, UXO, soil contamination and groundwater contamination.	Reduces the risk of long term creep settlement on loading in made ground and/or loose / soft estuarine sands, clays and silts at depth. Bored cased piles may allow for advancement through obstructions by pre-boring. No limitation on the ~~c~~onstruction of longer rock sockets or under-reamed pile toes to provide additional skin friction to reduce the risk of heave and uplift resulting from potentially swelling slag materials within the made ground. Casing between potentially contaminated groundwater and underlying aquifer reduces the risk to groundwater contamination. The installation of temporary casing through water bearing coarse granular soils or soft soils will enable control of integrity problems which may occur during construction by balancing water pressures within and outside pile bores.	Bored piles generate arisings from pile bores at surface which may include potentially contaminated soils. Increased cost due to soil treatment and/or disposal offsite is possible.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Suitable foundation option.
Bored Cased & Sleeved Piles	Suitable for all load cases. Mitigation may be required for UXO, soil contamination and groundwater contamination.	As bored piles above. Sleeved piles are designed to resist heave from potentially swelling slag within the made ground. The sleeving may allow formation of shorter rock socket lengths in comparison to bored cased bored piles.	As bored piles above. Increased cost in comparison to bored cased piles.	Ground Investigation. Adequate Design. UXO risk to be established through detailed risk assessment and probability assessment. Suitable foundation option.
Excavation and Replacement	Unsuitable for conditions of long term creep or dynamic loading. May be unsuitable due to inadequate bearing capacity, shallow groundwater, soil contamination and groundwater contamination. Mitigation may be required for UXO. May be prohibitively expensive	Provides engineered fill over the depth of excavation and replacement producing a substantial increase in near surface foundation bearing resistance (capacity).	Significant volume of soil treatment and / or disposal of potentially contaminated soils. Groundwater is shallow across the site ~ 3m depth and may be tidally influenced, this solution is therefore suitable for soils above groundwater, but will only have a limited impact where made ground > 5m depth. Groundwater is shallow across the site ~ 3m depth and may be tidally influenced, may result in significant constraints for stability of excavations during construction. This may also restrict working. Does not remove the risk of long term settlement on loading occurring in both the made ground and/or loose / soft estuarine sands, clays and silts at depth.	Not suitable

Threat Level	HIGH THREAT																		
	← GP 04-60 →							← Desk Study →							Cost	Automated Summary	Pros	Cons	Mitigation and Conclusion
Foundation Type	Initial Loading	Longer term creep	Dynamic Loading	Transient Loading (wind / therm	Hard Layers	Soft/Compressible Layers	Ground Chemistry	Stability Heave / Collapse	Inadequate Bearing	Obstructions & Voids	UXO	Shallow Groundwater	Soil Contamination	Groundwater Contamination					
Vibro-replacement - stone columns	✓	✓	✓	✓	✗	✓	✓	M	M	✗	M	✗	✓	M	✓	Suitable for all load cases. May be unsuitable due to hard layers, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity, UXO and groundwater contamination.	Cost effective option in comparison to piling. Could be adopted in conjunction with raft foundations. Reduces total and differential settlement. Speeds up consolidation settlement. Mitigates risk of soil liquefaction.	Does not address the potential issues from expansive slag. Advancing stone columns through significant depths of made ground may be problematic. Pre-boring may mitigate risk of obstructions. Shallow groundwater may result in the potential for integrity problems caused by stone washout or displacement, and result in difficult construction conditions. Concern over long term integrity / serviceability of columns installed through thick deposits of underlying soft / loose estuarine sands, clays and silts, especially under high and / or dynamic load conditions. Not suitable for soft clays, organic soils and peats because of their lack of lateral confinement.	May be suitable for high threat high load structures when used in conjunction with other solutions such as ground bearing floor slabs or raft foundations. Early specialist contractor involvement would be recommended possibly in combination with site trials.
Deep Soil Mixing - lime or cement columns	✓	✗	✓	✓	✗	✓	✗	M	M	✗	M	✗	✓	✓	✓	Unsuitable for long term settlement (creep). May be unsuitable due to hard layers, aggressive ground chemistry, ground obstructions or voids and shallow groundwater. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO.	As vibro compaction stone columns. Best suited to the stabilisation of deep soft clays (not found near surface at this site).	As vibro compaction stone columns. Introduction of lime in potentially expansive soils may result in post construction heave of treated soils, over and above the heave anticipated from expansive slag materials across the site. Potential for integrity problems when constructed below groundwater. Can act as drains. May lose strength over time because of leaching by slightly acidic groundwater. Post treatment plate load tests required to confirm performance.	Not suitable.
Dynamic Compaction	✓	✗	✓	✓	✗	✓	✗	M	M	✗	M	✓	✓	✓	✓	Unsuitable for long term settlement (creep). May be unsuitable due to hard layers, aggressive ground chemistry and ground obstructions or voids. Mitigation may be required for ground instability from heave or collapse, inadequate bearing capacity and UXO.	Cost effective option in comparison to piling. Technique generally effective in the densification of coarse (granular) soils, non homogenous fills, reclaimed areas with variable characteristics, where underground obstructions and large voids are present. Appropriate for use in both unsaturated and unsaturated soils.	Does not address the potential issues from expansive slag. Not an effective technique for the treatment of fine (cohesive) soils. Significant adverse environmental impact from noise and vibrations induced in the ground. Technique should not be undertaken within 15m of existing services and within 30m of existing buildings. Does not limit/remove the potential risk of substantial settlements occurring under loading in the deep underlying loose / soft estuarine sands, clay and silts. Potential risk of ground vibrations causing damage to sensitive services such as the CATS / BREAGH high pressure pipelines.	Not suitable