Ardersier Port

Ardersier Port

Spit Stability: Geotechnical Assessment

Reference: ArdPhase1-ARUP-WP3-XX-RP-C-000001 (Haventus), 294067-ARUP-Z1-XX-RP-CG-000001 (Arup)

Issue 07 | 7 February 2024

Job number 294067-00

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Document Verification

Project title	Ardersier Port
Document title	Spit Stability: Geotechnical Assessment
Job number	294067-00
Document ref	ArdPhase1-ARUP-WP3-XX-RP-C-000001 (Haventus), 294067-ARUP-Z1-XX-RP-CG-000001 (Arup)
File reference	19

Revision	**Date**	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 01.docx		
Issue 01	04/07/2023	**Description**	First issue.		
			Prepared by	**Checked by**	**Approved by**
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		Signature			
Issue 02	05/07/2023	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 02.docx		
		Description	Updated following client review.		
			Prepared by	**Checked by**	**Approved by**
		Name	Tommaso Bizzotto	Andrew Richmond	Philip Stephenson
		Signature			
Issue 03	06/07/2023	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 03.docx		
		Description	Updated following client review.		
			Prepared by	**Checked by**	**Approved by**
		Name	Tommaso Bizzotto	Andrew Richmond	Philip Stephenson
		Signature			

Revision	Date	Filename	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 04.docx		
Issue 04	15/09/2023	**Description**	Updated to include GI info available as of 08/09/2023.		
			Prepared by	**Checked by**	**Approved by**
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		Signature			
Issue 05	13/10/2023	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 05.docx		
		Description	Updated following Client review.		
			Prepared by	**Checked by**	**Approved by**
		Name	Andrew Richmond	Andrew Richmond	Philip Stephenson
		Signature			
Issue 06	06/02/2024	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 06.docx		
		Description	Updated to include latest GI info and Client comments.		
			Prepared by	**Checked by**	**Approved by**
		Name	Andrew Richmond	Andrew Richmond	Philip Stephenson
		Signature			
Issue 07	07/02/2024	**Filename**	294067-ARUP-Z1-XX-RP-CG-000001 - Spit Stability Assessment Issue 07.docx		
		Description	Updated following Client review.		
			Prepared by	**Checked by**	**Approved by**
		Name	Andrew Richmond	Andrew Richmond	Philip Stephenson
		Signature	<Redacted>	<Redacted>	<Redacted>

Issue Document Verification with Document ☑

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Executive Summary

Ardersier Port is proposing to redevelop its existing land into a new port facility. A major element of the scheme is the utilisation of the existing natural spit as a breakwater for the port. The spit will protect the proposed quay from the North Sea and provide the required conditions for safe utilisation of the quay by vessels.

Current proposals for Ardersier Port involve additional dredging works to increase the depth and width of the main channel and create berth pockets.

This report presents a detailed assessment which has been undertaken in relation to the stability of the spit following the proposed dredging works. The assessment indicates that the proposed design is robust in terms of the global geotechnical stability of the spit. A regular survey and maintenance regime could be adopted to manage the risk of local slope movements on lee side of the spit which may result from scour due to wave or vessel action.

1. Introduction

Ardersier Port is proposing to redevelop its existing land into a new port facility. A major element of the scheme is the utilisation of the existing natural spit as a breakwater for the port. The spit will protect the proposed quay from the North Sea and provide the required conditions for safe utilisation of the quay by vessels.

Current proposals for Ardersier Port involve additional dredging works to increase the depth and width of the main channel and create berth pockets.

This report presents an assessment of the geotechnical stability of the spit following dredging down to the Phase 1 dredge level of -12.9mCD. The available ground investigation information has been reviewed to derive a site-specific ground model which has been used to assess the geotechnical stability of the proposed dredge slope. This has been compared against existing submerged slopes in the area, as well as published case history data, to provide additional verification of the proposed geometry.

The proposed Phase 1 dredge profiles have been developed with particular regard for the future stability of the spit. The following measures have been adopted to minimise the risk of disturbance to this natural structure:

- the use of 1v:6h for the submerged slope angle of any dredged slope in natural materials; and
- along the lee side of the spit, a 25m buffer has been adopted between the edge of the spit (taken as Mean Low Water Springs) and the start of any submerged slope within the dredge. This provides additional space, in case of any unforeseen slope movement, without impact on the spit.

The geotechnical stability of these slopes has been assessed and the conclusion from this work is that the design is suitable and safeguards the overall stability of the spit. This is detailed further in the report.

The head of the spit is considered to represent a lower risk to the overall stability of the spit relative to the slopes that flank the narrower cross section in the north (sea) to south (lee) direction. A narrower buffer may, therefore, be appropriate in this area. The risk of instability caused by erosion due to coastal sediment transport processes at the head of the spit is understood to be low (refer to Appendix A) due to the environment being one of deposition, rather than erosion. The risk of localised instability at the head of the spit should be managed through an enhanced regular inspection regime and reinstatement, if required.

It is understood that Haventus will construct dredge slopes at a steeper angle (1v:4.5h) than proposed in this report, with the slope starting from a fixed position consistent with the Arup dredge design. This will result in a buffer which is in the order of 45 to 50m wide along the lee side of the spit, which is significantly greater than the width proposed in this report. The additional width provides confidence that, should the slopes ravel back to 1:6, as our assessments indicates would be a stable angle, the global stability of the spit would not be compromised. It will also provide more time for any ground movements associated with the ravelling process to be detected as part of the proposed monitoring regime and remedial measures to be implemented in a timely manner, should these be required.

The impact of scour from the operation of vessels in the port or wave action in the harbour basin is an important aspect of the long-term stability of the dredged slopes on the lee side of the spit. It is considered that scour due to vessel action should be anticipated due to the nature of the materials which make up the spit. This risk needs to be actively managed during operation of Phase 1 of the port through regular bathymetric surveys and, where required, reinstatement of the spit to avoid development of large-scale failures. The provision of the buffer attempts to provide some safeguard against this form of erosion between survey and maintenance cycles, the effectiveness of this should be monitored.

2. Development of the Phase 1 dredging profiles

2.1 Basis of design

The design work presented in this report is based on information available at the time of writing. A ground investigation for the proposed new quay wall construction has been completed and has been used to inform this assessment. A further investigation has also been undertaken on the spit itself. All expected draft logs and laboratory test results have been received in draft form. The information has been reviewed and incorporated into this assessment. Provided the final factual report is consistent with the draft information, no further updates to this assessment are required.

This report presents the work undertaken to assess the geotechnical stability of the spit proposed for the dredging works proposed as part of Phase 1 of the port works. This involves a proposed dredge level of -12.9mCD. A complementary assessment of scour associated with vessel operations is ongoing and will be reported separately. Work associated with sediment transport is being undertaken by others and will also be reported separately.

The scope of this report is limited to the Phase 1 of the proposed works only.

2.2 Dredge profile

The Phase 1 dredging profiles have been developed based on the bathymetric survey information provided by Ardersier Port (drawing No. 2022_004_A_P_DW_100 Rev P02). The proposed maximum dredge level is -12.9mCD through the navigation channel area up to the eastern end of Phase 1 quay.

The dredge profiles pay particular regard to the future slope stability of the spit. A series of criteria have been used when considering the layout in order to minimise the risk of disturbance to this natural structure. This includes:

- The use of 1v:6h for the submerged slope angle of any dredged slope which is compliant with the range of typical underwater slopes presented BS6349-1-3:2012. This is considered to be a safe estimate based upon observed slope angles within the existing bathymetry in the area together with slope stability calculations using assumed material parameters.
- A 25m buffer along the lee side of the spit between the edge of the spit (taken as Mean Low Water Springs) and the start of any submerged slope within the dredge. This provides a margin of safety for the spit in the following ways:
    1. to allow for any slumping in dredge slope profiles due to local variations or planes of weakness in the strength of the underlying material. Slope slumps to a reduced gradient of 1v:8h could be accommodated by the 25m buffer without disturbance of the spit.
    2. to provide a margin to prevent the existing spit being undermined by scour holes due to vessel disturbance. A scour hole of up to 4m could be accommodated by the 25m buffer zone provided.
    3. as per point 2 to allow for the potential for local over-dredge at the toe of any dredged slopes in close proximity to the spit. Normal over dredge tolerances are likely to be of the order of 1.0m and could, therefore, be comfortably accommodated by the proposed buffer zone.
    4. In areas of away from the proposed spit, 1v:6h dredge slopes have also been adopted, although this is considered to be conservative and will be reviewed in the future stages of the design.
- A narrower buffer is proposed around the head of the spit, as outlined later in Section 5.3.

In later sections of this report, geotechnical analysis will be presented to demonstrate the overall stability of the slopes defined with a 1v:6h gradient, formed with the naturally occurring soils on-site.

It is understood that Haventus will construct dredge slopes at a steeper angle (1v:4.5h) than proposed in this report, with the slope starting from a fixed position consistent with the Arup dredge design. This will result in a buffer which is in the order of 45 to 50m wide along the lee side of the spit, which is significantly greater than the width proposed in this report. The additional width provides confidence that, should the slopes ravel back to 1v:6h, as our assessments indicates would be a stable angle, the global stability of the spit would not be compromised. It will also provide more time for any ground movements associated with the ravelling process to be detected as part of the proposed monitoring regime and remedial measures to be implemented in a timely manner should these be required.

Additional considerations will be presented in the following sections on important themes reported by BS6349-1-3:2021, these being:

- Local experience – interrogation of the bathymetric survey;
- Static liquification assessment; and
- Geotechnical slope stability assessment.

2.3 Plan and Typical Cross Section of Phase 1 Concept Dredge Solution

The dredge plan and typical cross sections are given on drawing number 294067-ARUP-XX-XX-SK-CG-000002. Three cross sections are provided for illustrative purposes below. Figure 2.1, Figure 2.2 and Figure 2.3 represent the navigation channel, port entrance and main harbour basin respectively. These figures illustrate the general use of shallow dredge slopes adopted together with the buffer zones in close proximity to the spit.

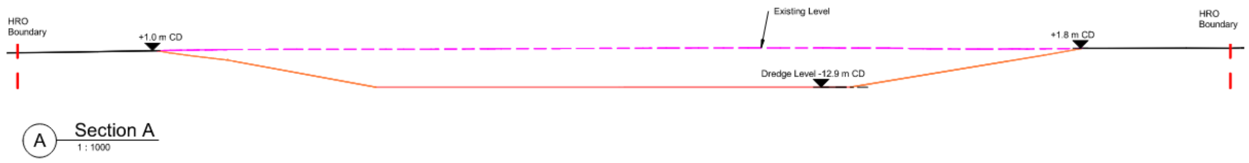


Figure 2.1: Typical Cross Section for The Navigation Channel.

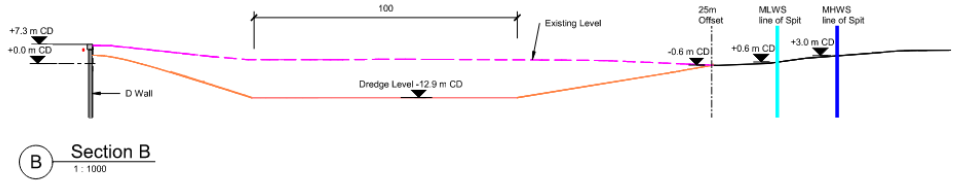


Figure 2.2: Typical Cross Section for The Port Entrance.

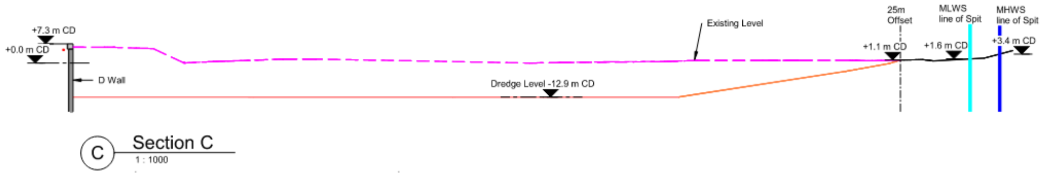


Figure 2.3: Typical Cross Section for The Harbour Basin.

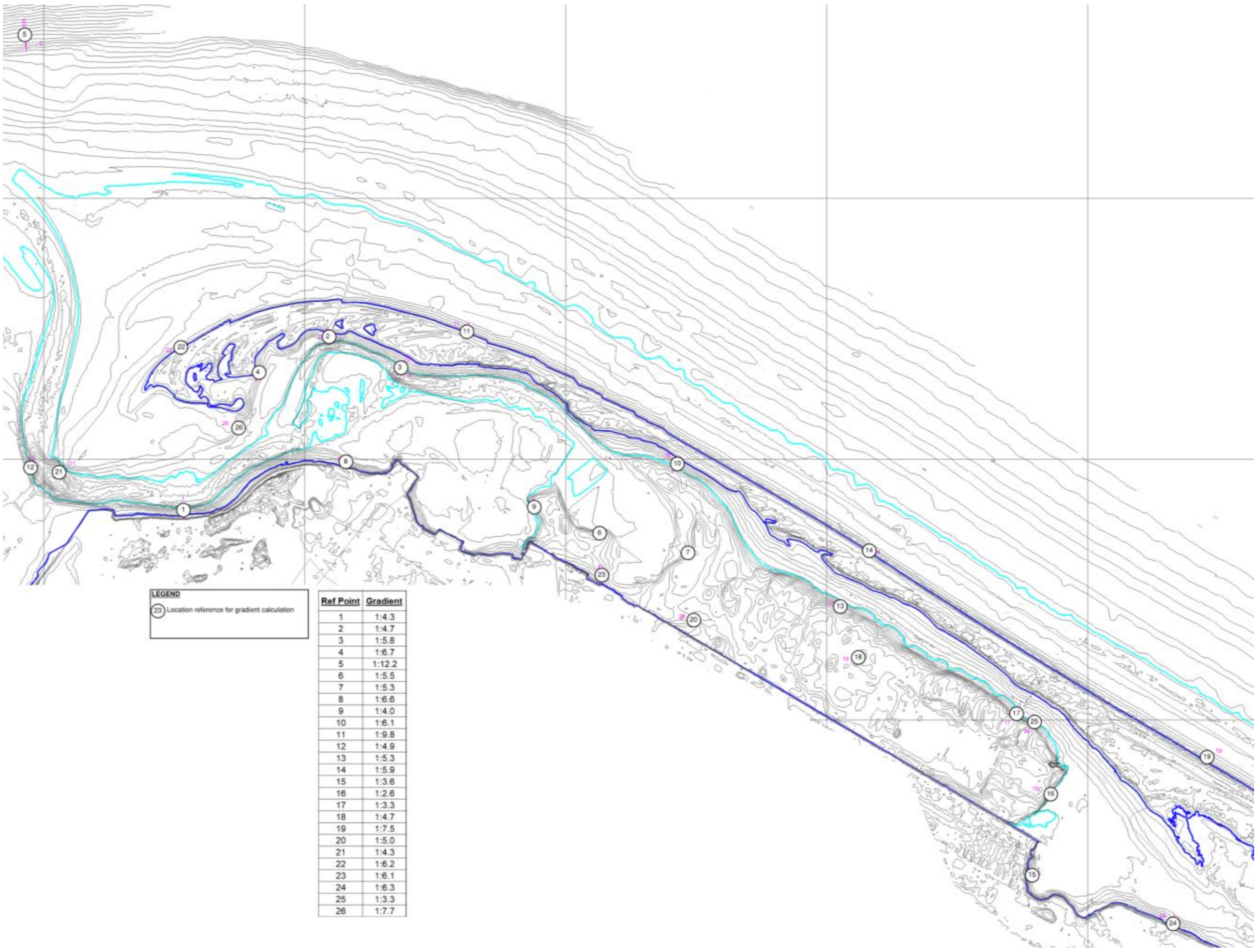
3. Local experience: Bathymetric survey

A bathymetry survey was undertaken by Aspect Surveys in 2018. An excerpt of this survey is presented in Figure 3.1, focusing on the spit. As outlined in BS6349, this information is important to provide evidence of the slope geometries which exist in similar ground and water conditions.

Using the elevation contours, gradients were calculated around the spit area (Figure 3.1). As an approximate guide, the observations of the measurements can be made:

- slope angles vary across the area, ranging from 1:2.6 to 1:12.
- 16 of the 26 values are steeper than or equal to 1:6, 10 are less steep than 1:6;
- the numerical mean of the slope angles calculated is 1:5.7; and
- the median value of the slope angles calculated is 1:5.4.

The review of the existing slopes indicates that a slope of 1:6 is within the range of angles observed at the site, it is a significantly lower angle than the steepest slopes observed and is on the safer side of the average values observed.



Ref Point	Gradient
1	1:4.3
2	1:4.7
3	1:5.8
4	1:6.7
5	1:12.2
6	1:5.5
7	1:5.3
8	1:6.6
9	1:4.0
10	1:6.1
11	1:9.8
12	1:4.9
13	1:5.3
14	1:5.9
15	1:3.6
16	1:2.6
17	1:3.3
18	1:4.7
19	1:7.5
20	1:5.0
21	1:4.3
22	1:6.2
23	1:6.1
24	1:6.3
25	1:3.3
26	1:7.7

Figure 3.1: Bathymetry survey, with gradient annotations

4. Ground Conditions

4.1 Ground Investigation Information

Two phases of ground investigation have been undertaken for the site as part of Phase 1 of the project. The first phase of ground investigation works was located on the quay side of the port. The site works and reporting are complete, as described in Section 4.1.1.

A second phase of investigation works has also been completed on the spit itself, as described in Section 4.1.2.

4.1.1 Quay side investigation information

A ground investigation was undertaken by Solmek for the Phase 1 works between 21st November 2022 and 19th January 2023. This comprised 15 cable percussive boreholes and 23 CPT's along the length of the quay wall and anchor pile wall to depths of up to 50m. The investigation included the installation of groundwater monitoring, tidal monitoring and insitu permeability testing together with a programme of laboratory testing.

The consolidated borehole logs, laboratory test results and CPT data can be found in the following report issued by Solmek via email dated 3rd October 2023.

- Phase 2: Site Investigation. Quay Wall Phase 1, Ardersier Port, Inverness. Haventus Ardersier Port. S221111 – Final Report, dated June 2023.

4.1.2 Spit investigation works

Ground investigation works were undertaken on the spit between May and July 2023. The aim was to confirm the ground conditions at the spit and undertake in-situ and laboratory testing to provide material properties to enable detailed design of the submerged slopes to be formed as part of the dredging works. The scope of the proposed works comprised nine boreholes, five of which were undertaken as part of the current Phase 1 of the port development and four are to be completed at a later date, for a later phase of development. The investigation works include cable percussion boreholes drilled to a minimum level of -35mCD, with associated sampling and insitu and laboratory testing.

This report is based on the information received from Solmek by email to date. All of the information requested has been received in draft form and will be formalised in a final factual report by Solmek. Provided the final reported information is consistent with the draft information received to date, no further updates would be required to this report.

- 7th June 2023, Subject: Fwd: S–pit BH Log - BHSP09
  - BH-SP09 Log typed.pdf
- 16th June 2023, Subject: RE: Ardersier
  - BH-SP08 Log typed.pdf
  - Spit BHSP08 Schedule.xlsm
- 27th June 2023, Subject: Ardersier Spit Boreholes
  - BH-SP08 Log typed.pdf
  - BH-SP09 Log typed.pdf
  - S230503 Geotech Report SP08 & 09.pdf
  - S230503 SP08 & 09.ags
- 30th June 2023, Subject: RE: Ardersier Boreholes
  - BH-SP06 Log typed.pdf
  - BHSP07 Log typed.pdf
  - S230503 Geotech Report.pdf
  - S230503.ags
  - Spit BHSP07 Schedule 4.xlsm
- 8th September 2023
  - S230503 Geotech Report SP05.pdf
  - S230503 SP05.ags
  - S230503 Geotech Report SP06.pdf

  - S230503 SP06.ags
  - S230503 SP07.ags
  - S230503 Geotech Report SP07.pdf
  - S230503 Geotech Report SP08 & 09.pdf
  - S230503 SP08 & 09.ags
  - S230503 Geotech Report Additional.pdf
  - S230503 Additional.ags
  - BH-SP05 Log typed.pdf
  - BH-SP06 Log typed.pdf
  - BH-SP07 Log typed.pdf
  - BH-SP08 Log typed.pdf
  - BH-SP09 Log typed.pdf
  - S230503 Ardersier Spit BH Logs 05 – 09.ags
  - 1742 - SSBX BHSP09 06.00 B - 38342-490775.PDF
  - 1742 - SSBX BHSP09 15.00 B - 38342-490773.PDF
  - 1742 - SSBX BHSP09 23.00 B - 38342-490776.PDF
  - S23053 - Ardersier Port - Schedule S221111_4 GEO-38343 01.PDF
  - S230503 - Ardersier Port - Schedule S221111_4 GEO-38342 01.PDF
- 1st February 2024 the following new information was received.
  - S23053 - Ardersier Port - Schedule S221111_4 GEO-38551 01.PDF
  - S23053 - Ardersier Port - Schedule S221111_4 GEO-38552 01.PDF
  - S23053 - Ardersier Port - Schedule S221111_4 GEO-38553 01.PDF
  - BHSPO07 (153mm).pdf
  - BHSPO07 (203mm).pdf
  - BHSPO07 (254mm).pdf
  - BHSPO08 (203mm).pdf
  - BHSPO08 (254mm).pdf

A summary of the current understanding of the ground conditions is provided in the following section.

4.2 Ground model

The “Whiteness Head”, situated on the north side of the quay, is a shingle spit complex formed by active westerly longshore drift processes. It is understood that the shallower layers of the spit comprise coastal erosion deposits resulting from longshore drift action.

Ground investigations have been undertaken on the quay side of the port and on the spit itself. The information is reasonably consistent between the two ground investigations. Available information indicates that the upper strata of the spit are formed by sandy gravel. Below this, strata comprise fine sands, of Holocene age, with locally increasing silt content at depth.

The Holocene strata predominantly comprise silty sands, however, a layer of clayey silt has been typically encountered between approximately -30m CD and -40mCD in the CPTs on the quay side but not encountered in the boreholes. It is considered that, in reality, this stratum is likely to comprise silty or very silty sand and the clay classification is spurious and due to the penetration rate of the CPT’s.

Available information does not confirm the level of rockhead at the site, however, recent investigation works suggests that it is at least greater than 50m below ground level. The rockhead has been shown to be sufficiently deep that it is not a significant factor in the stability of the spit.

A schematic geological cross-section through the proposed port is shown in Figure 4.1.

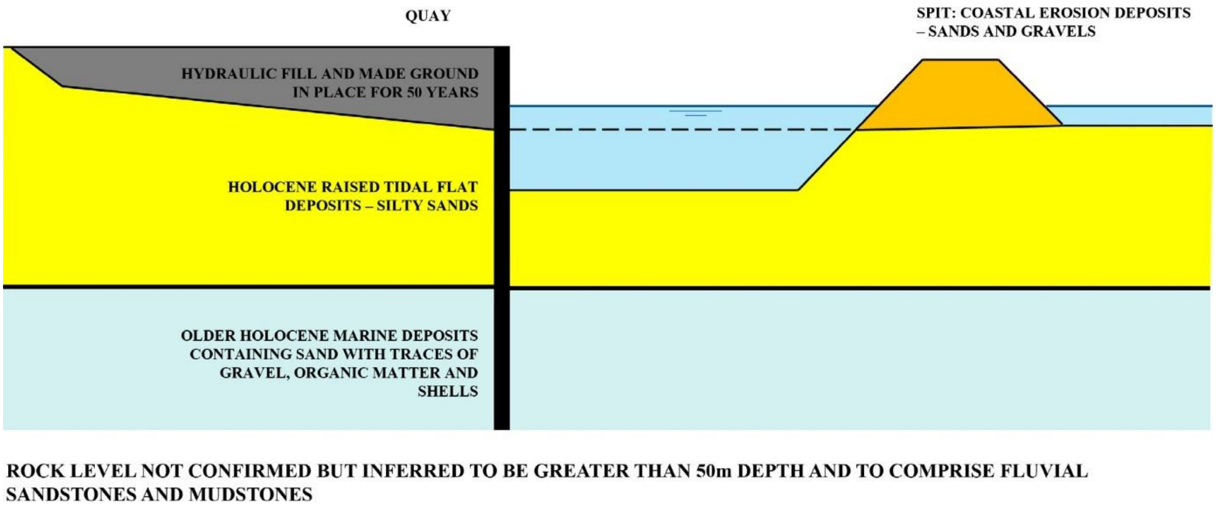


Figure 4.1: indicative geological cross section through Ardersier Port.

4.3 Ground conditions based on the quay side GI

The material properties for the subsequent slope stability assessments have been derived from CPT and SPT data and laboratory testing. The CPTs are located ‘landside’ i.e. south-west of the main quay wall, however, the ground investigation information available at the time of writing indicates that the conditions are consistent across the site. The adoption of parameters based on testing from the quay side of the port is, therefore, considered appropriate for the spit stability assessment.

Pertinent results from the ground investigation are included below.

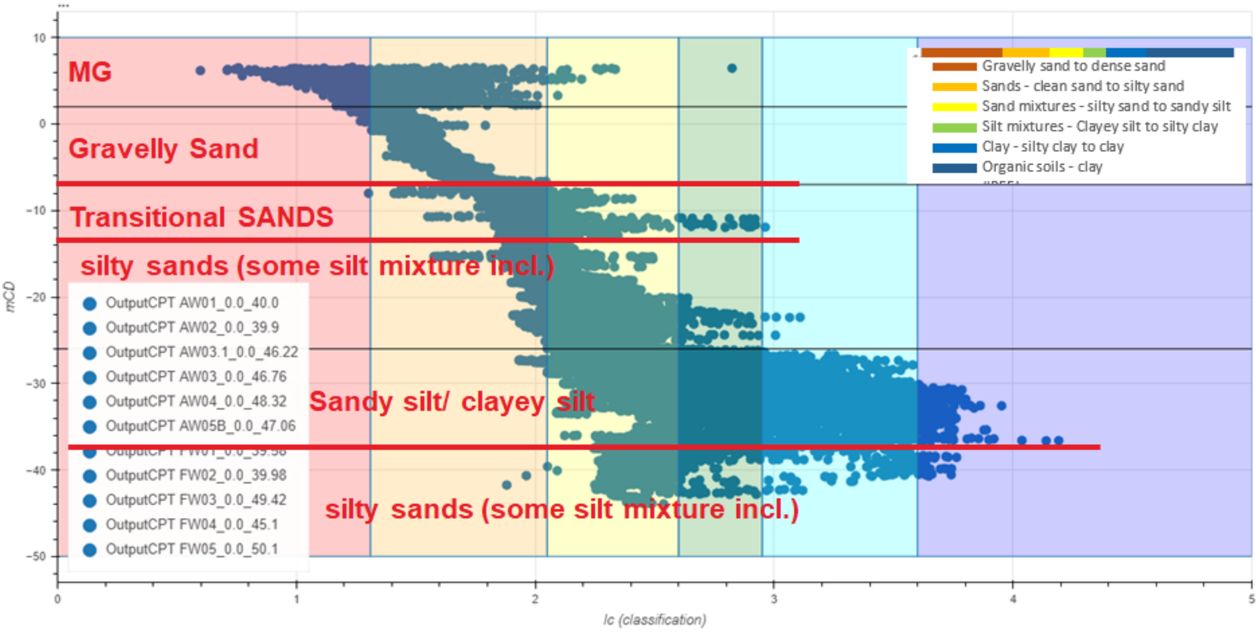


Figure 4.2. Soil Classification based on CPT’s.

Figure 4.2 indicates the soil behaviour type index against reduced level calculated using the Robertson [10] method which accounts for overburden, as described in Robertson & Cabal [9]. The plot is based on CPT’s and indicates the strata pertinent to the stability of the spit are gravelly sands/sands overlying transitional sands and silty sands.

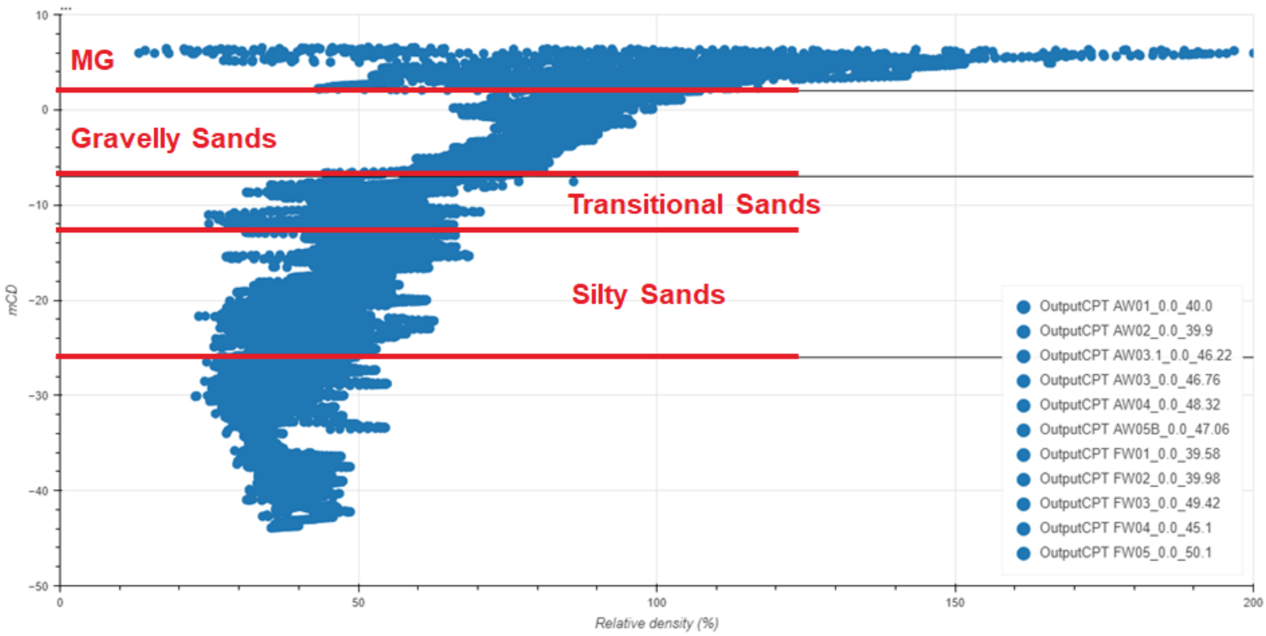


Figure 4.3. Relative Density based on CPT's.

Figure 4.3 shows relative density data for the strata at the site based on CPT results. The data indicates relative densities as follows:

- Gravelly sands: generally 65% to 85% with a reducing trend with depth;
- Transitional sands: between 40% and 60% with no clear trend with depth; and
- Silty sands: generally 35% to 60% with a reducing trend with depth.

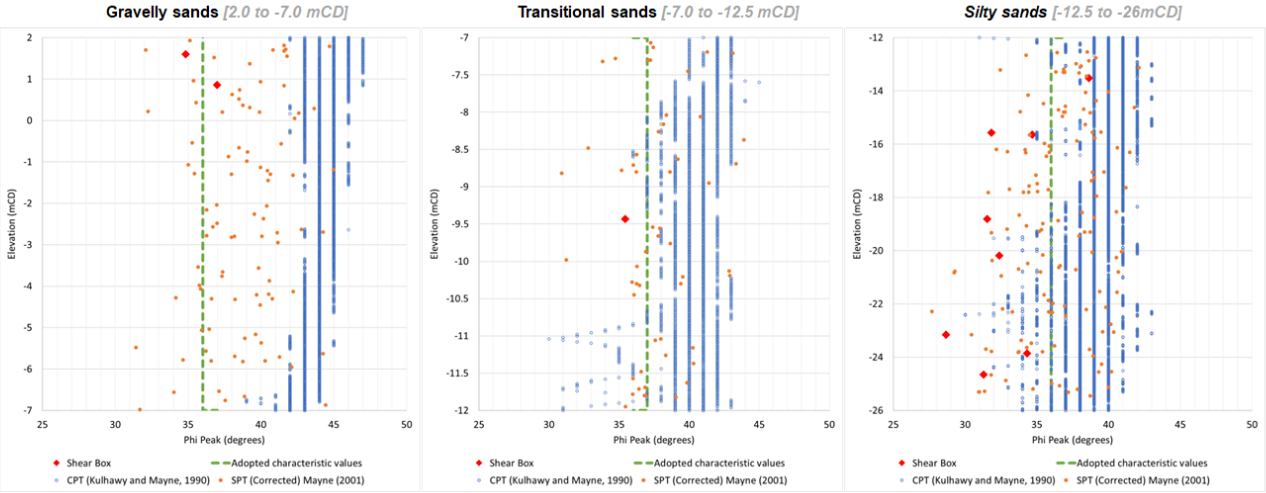


Figure 4.4. Strength (friction angle) data based on CPT's, SPT's and shear box tests.

Available soil shear strength data is plotted in terms of friction angle, from CPT's, SPT's and shear box tests, against elevation in Figure 4.4. The friction angles based on CPTs were calculated using the method described by Kulhawy and Mayne [12]. The friction angles based on SPTs were calculated using the Mayne [13] method using depth corrections outlined in BS EN ISO 22476-3:2005+A1:2011.

The plots indicate a greater degree of spread from the SPT and shear box results compared to the CPT results. The shear box and SPT results generally form a lower bound to the CPT data. This may be due to difficulty in achieving relative densities which are consistent with the material insitu in the shear box tests or an imbalance of water pressures in the boreholes when undertaking SPTs. Most reliance has been placed on the CPT data.

For the gravelly Sands, the CPT's consistently indicate higher friction angles than the SPT and shear box results. A characteristic friction angle of 36º was selected, predominantly based on the SPT data.

In the case of transitional Sands, the CPT's generally indicate higher friction angles than the SPT and shear box results. A characteristic friction angle of 37º was selected based on the CPT and SPT data.

The shear strengths based on shear box results in the silty sands are consistently lower than the general SPT and CPT data. A characteristic friction angle of 36º was selected, predominantly based on the CPT and SPT data.

Based on a review of the available ground investigation information, a summary of the adopted ground model and characteristic shear strength parameters is shown in Table 4.1.

Table 4.1. Material properties adopted for OASYS Slope analyses

Stratum	Unit weight (kN/m^3)	Friction angle (º)	Cohesion (kPa)	Top level (mCD)	Bottom level (mCD)
Gravelly sands	20	36	0	n/a	-7
Transitional sands	20	37	0	-7	-12.5
Silty sands	20	36	0	-12.5	-26

Conservatively, in-line with BS6349-1-3:2012, no cohesion is assumed for the slope analyses.

4.4 Ground conditions based on the spit GI

The ground investigation completed on the spit has provided some preliminary laboratory testing including PSD testing, shear box tests and consolidated drained triaxial compression tests.

Particle Size Distribution (PSD) results are shown in Figure 4.5. These have been used to determine the uniformity coefficient (C_u) values shown in Figure 4.6

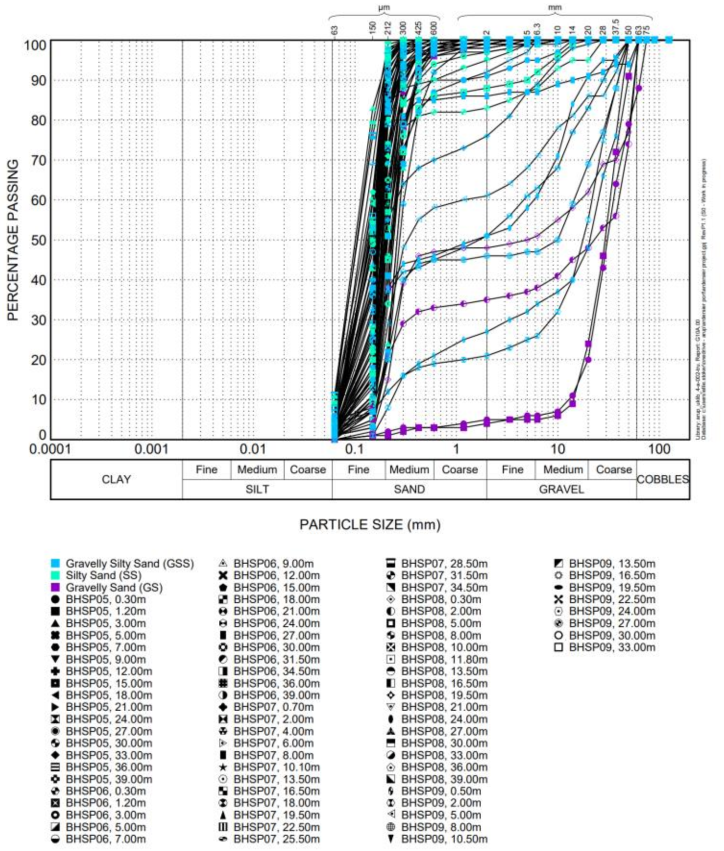


Figure 4.5: Particle size distribution test results from spit GI.

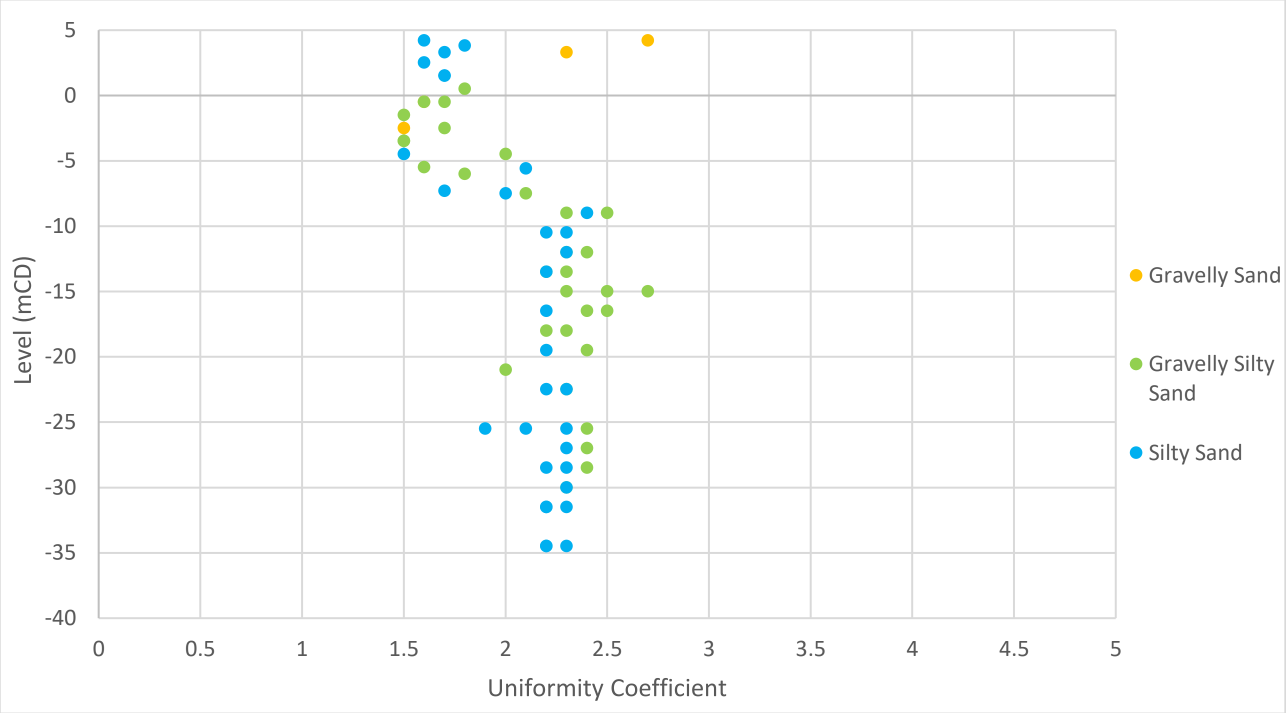


Figure 4.6. Uniformity Coefficients for samples obtained from the spit GI. Note 6 values between 50 and 250 have been omitted for clarity.

Between ground level and -5mCD the C_u value is ≤ 2. Below -5mCD, the C_u value increases slightly to between 2 and 3. The PSD results indicate that the materials are generally a uniformly graded fine sand. This is consistent with the quay side ground conditions.

The Standard Penetration Test (SPT) results are shown in Figure 4.7. Values were corrected for overburden pressure as detailed in BS EN ISO 22476-3:2005+A1:2011. The results indicate the ground conditions to be dense above approximately -5.0mCD and medium dense below -5.0mCD.

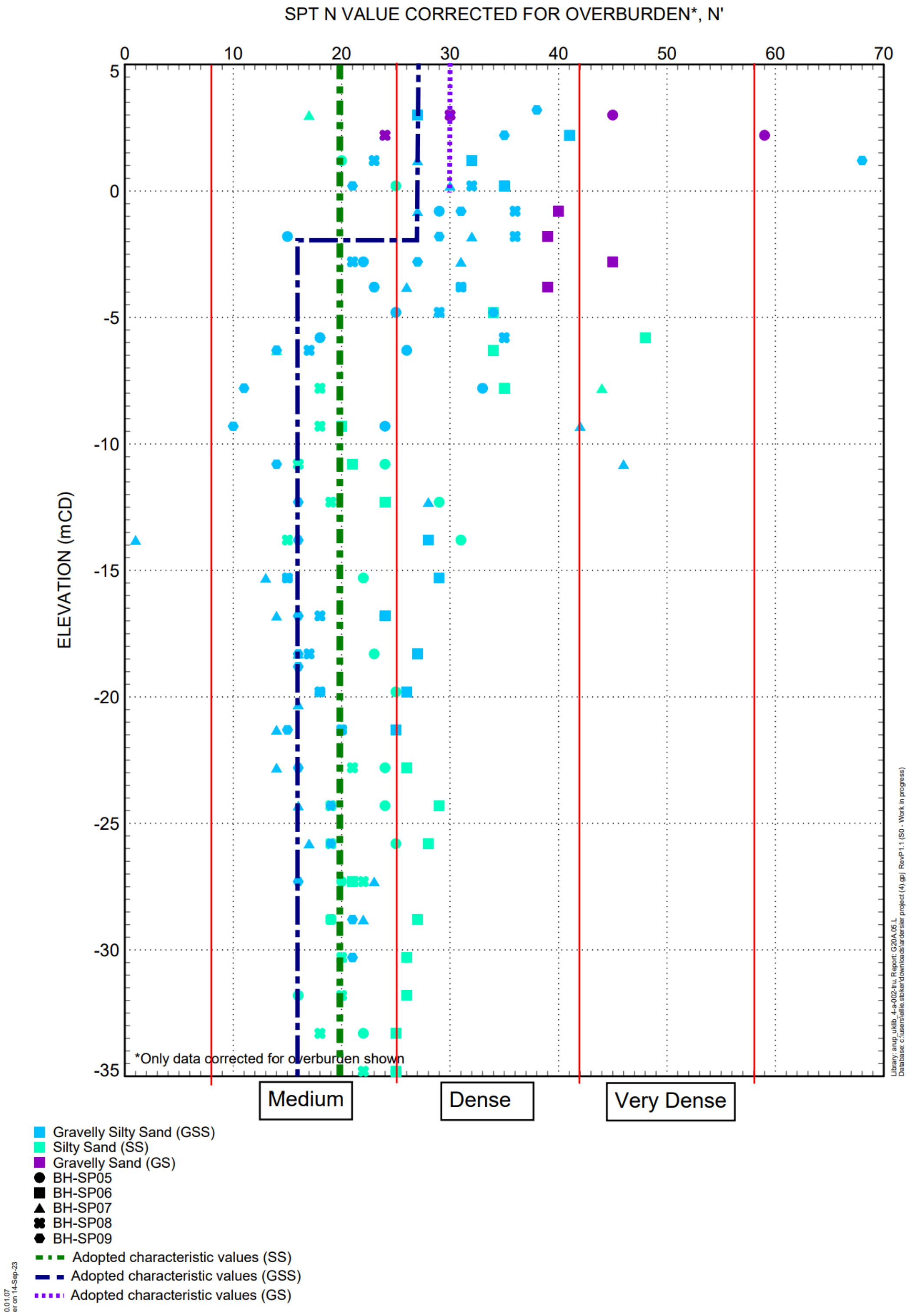


Figure 4.7. SPT N Value for boreholes undertaken on the spit. Corrected for Overburden

Using the corrected SPT N-values, friction angles have been determined in accordance with Mayne [13] and are shown in Figure 4.8. The plot also shows friction angles measured in shearbox and triaxial tests. The friction angles have been interpreted from the raw laboratory data assuming cohesion is zero in all cases.

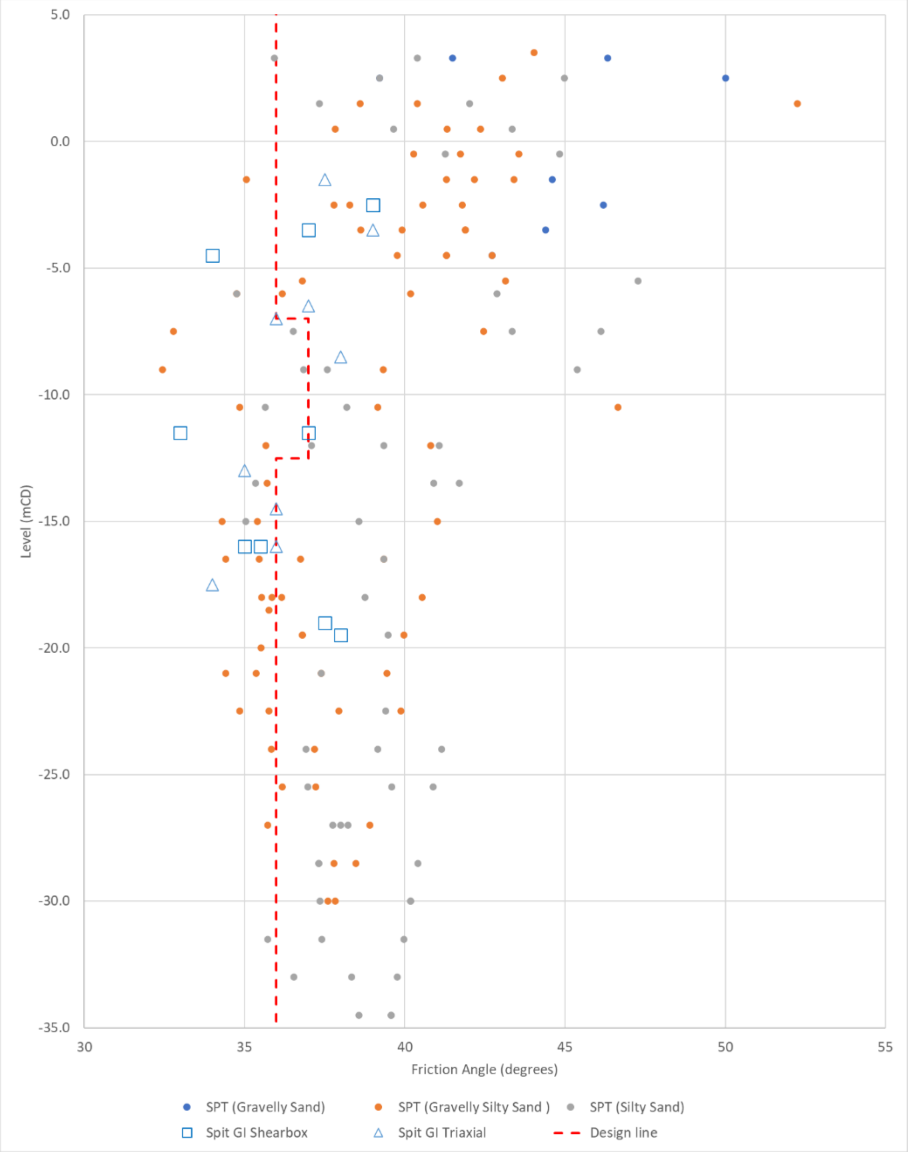


Figure 4.8. Friction angles based on SPT tests (Mayne, 2001) and laboratory testing.

The plot indicates that the friction angle is generally higher in the upper strata and reduces slightly at depth. Above a level of -5mCD, the gravelly sand strata generally have a friction angle of between 37° and >45°. Strata below -5mCD typically have friction angles between 35° and 40°.

The shearbox and triaxial test data generally form a lower bound to the SPT data. This is considered to be due to difficulty in achieving the insitu density of the material in the laboratory tests, particularly when the material has a significant silt content. The trend of higher friction angles above -5mCD is consistent between the SPT and laboratory testing data. It is considered that the higher strengths in the upper strata reflect a higher gravel content.

The results above are generally in line with the ground conditions derived from the quay side GI, however, the friction angles determined from the laboratory testing indicate a lower characteristic strength for the transitional and silty sands with friction angles of approximately 34 to 35°. The sensitivity of the slope stability analysis to this assumption has been tested and is reported later.

The material properties based on the spit GI are outlined in Table 4.2.

Table 4.2. Material properties based on spit GI.

Stratum	Unit Weight (kN/m^3)	Friction angle (°)	Cohesion (kPa)	Top level (mCD)	Bottom level (mCD)
Gravelly sands	20	36	0	n/a	-5
Transitional sands	20	34	0	-5	-12.5
Silty sands	20	35	0	-12.5	-35

5. Spit slope stability assessment

As noted previously, the Spit is a natural geomorphological feature resulting from ongoing coastal processes. Its geometry and composition have evolved over recent geological time and will continue to do so over the life of the port. As a result, the physical interaction between the proposed dredging, port operations and the stability of the spit need to be assessed. The following section provide a description of the geotechnical slope stability analyses undertaken. Impacts of scour due to vessel movements and sediment transportation are not within the scope of this report and will be covered elsewhere.

5.1 Flow slide slope instability assessment

Static liquefaction potential, as mentioned in BS6349-1-3:2021 in section 15.2.3, needs to be assessed and, where necessary, remediated on marine structures. The assessment can also be used as an indicator of how mobile the material is and susceptible to transportation. Static liquefaction can be assessed via a number of approaches which have to be considered holistically.

For this study, firstly the available Particle Size Distribution (PSD) lab results were assessed from the boreholes performed on the spit. This exercise was used to assess the level of sand/silt content, which affects the susceptibility of the material to static liquefaction. The PSD results are shown in Figure 5.1. 77 tests were undertaken in total. approximately 64 of the samples indicate the material to be ‘particularly’ susceptible to liquefaction. The PSD data suggest that the material is less susceptible at shallow depth within the sandy gravel but becomes more susceptible with depth.

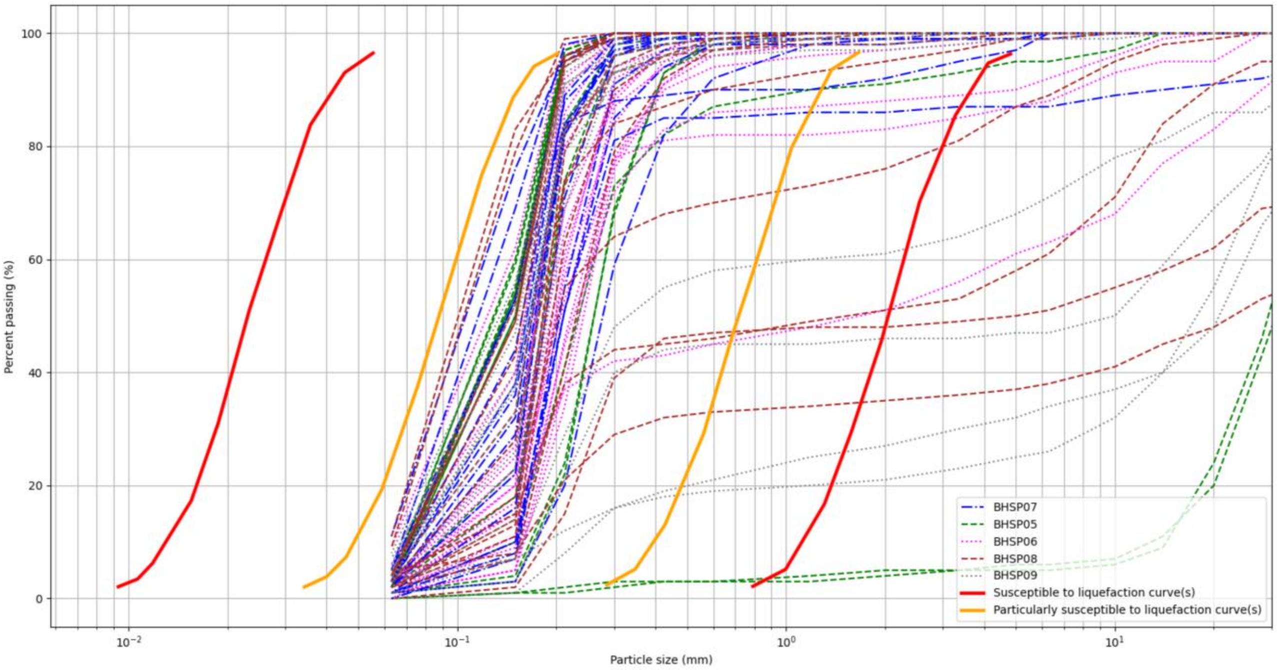


Figure 5.1. PSD grading curves for the spit GI, with susceptibility to liquefaction curves overlaying liquefaction curves from the Japanese Geotechnical Society (1998)

Static liquefaction can also be investigated using SPT and CPT results. SPT N values and CPT tip resistance can be correlated to contractive/dilative behaviours of materials. Flow slide slope instability is a behaviour linked to contractive soils.

Olson and Stark (2003) propose that the first step of liquefaction analysis for sloping ground is determining whether the soils in question are contractive on shearing, i.e. susceptible to liquefaction (flow slide) failure. Based on back-analysis of liquefaction failure case studies, a relationship between corrected SPT blow count (N_{60}) and in-situ effective stress has been proposed by Olson and Stark (2003) to identify contractive soils susceptible to liquification. SPT data collected from both the quay side ground investigation and the spit ground investigation have been plotted against this relationship and is presented in Figure 5.2. Similarly, Olson and Stark (2003) identified a relationship between CPT tip resistance and in-situ effective stress to identify contractive soils susceptible to liquification. The CPT data collected on the site has been plotted on Figure 5.3.

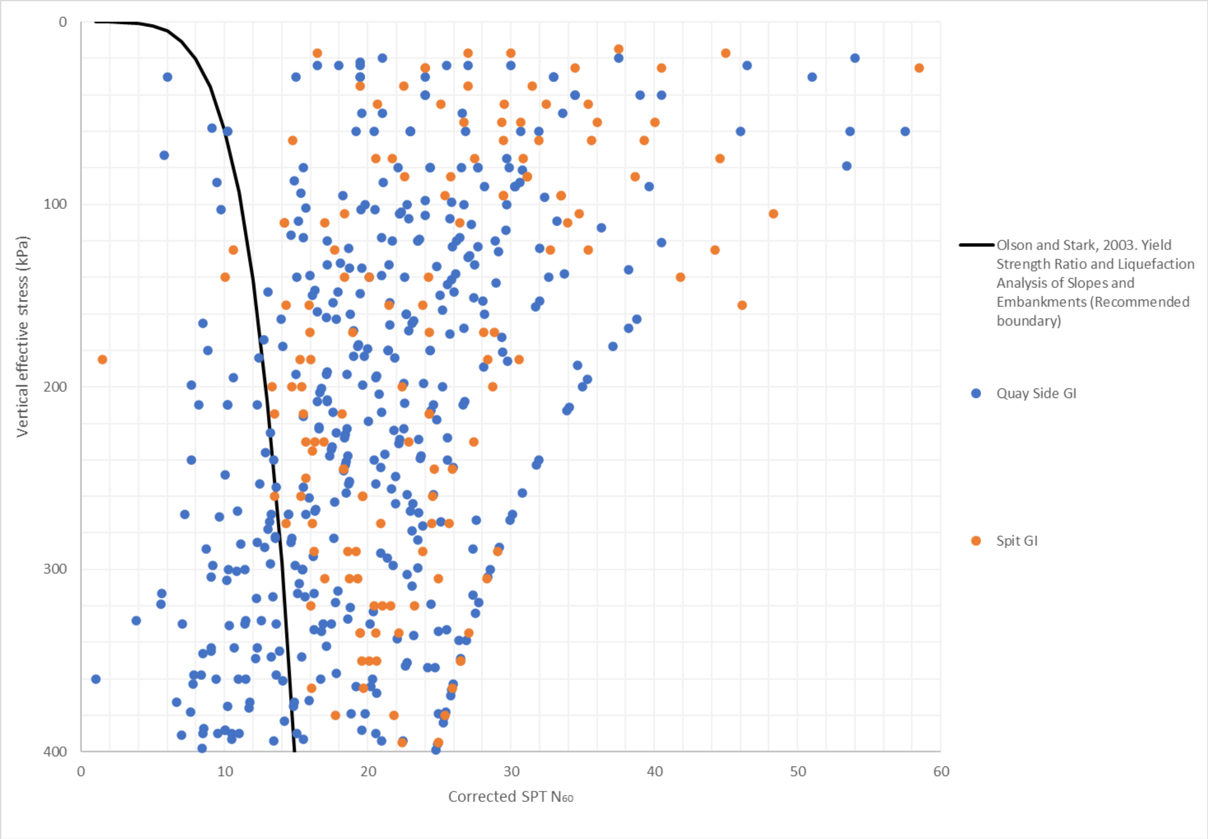


Figure 5.2. SPT N versus vertical effective stress – with Olson and Stark's [1] 'behaviour' curve

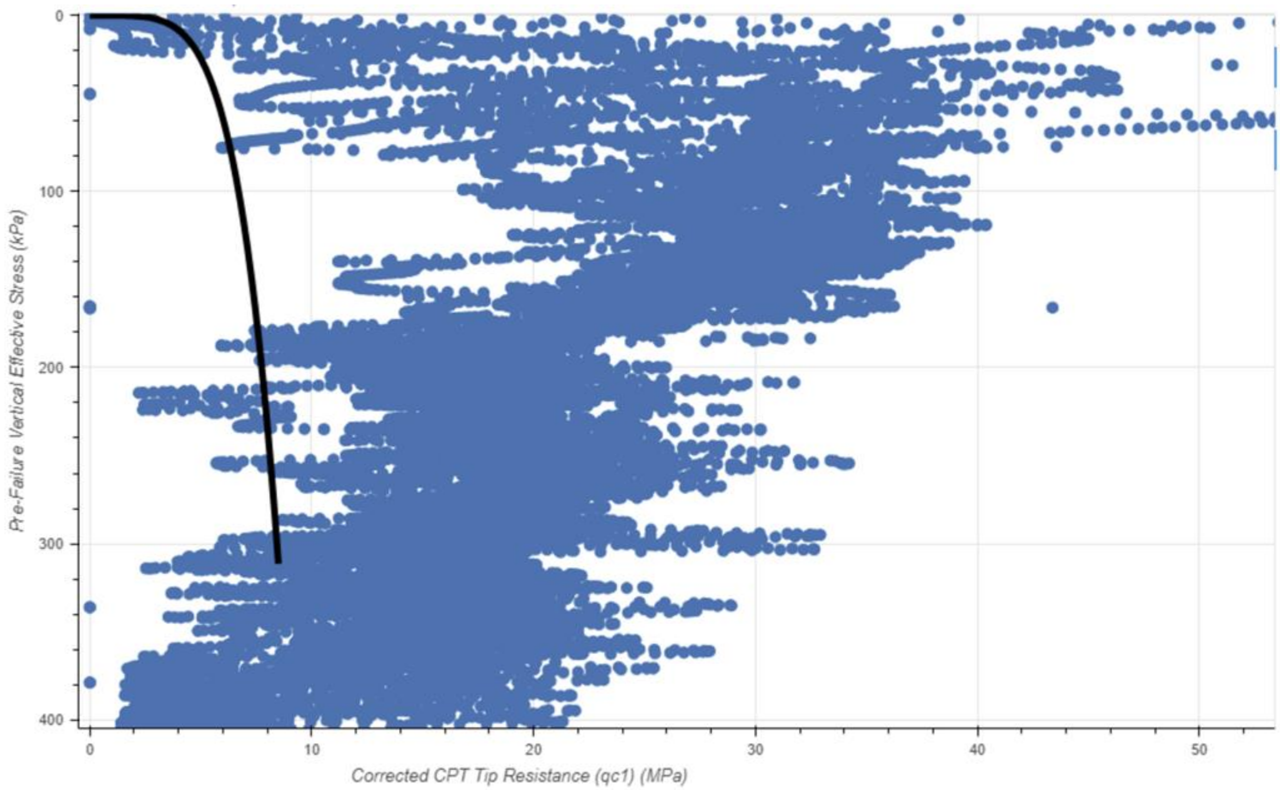


Figure 5.3. CPT tip resistance versus vertical effective stress – with Olson and Stark's [1] 'behaviour' curve

From the SPT data in Figure 5.2, only a small number of data points are within the liquefiable (contractive) region. The majority of the points indicate the ground to be in a dilative state. A similar conclusion can be drawn from the CPT data (Figure 5.3). The majority of the points indicate dilative behaviour, however, liquifiable (contractive) behaviour is indicated to be more likely at vertical effective stresses of greater than 300kPa (equating to levels lower than approximately -21mCD*). This level is beneath the dredge level and is, therefore, not relevant to the stability of the spit slope.

*assuming constant unit weight of 20kN/m^3, ground level at +6.0mCD (spit level) and groundwater level at +3mCD:

3*20 = 60kPa,

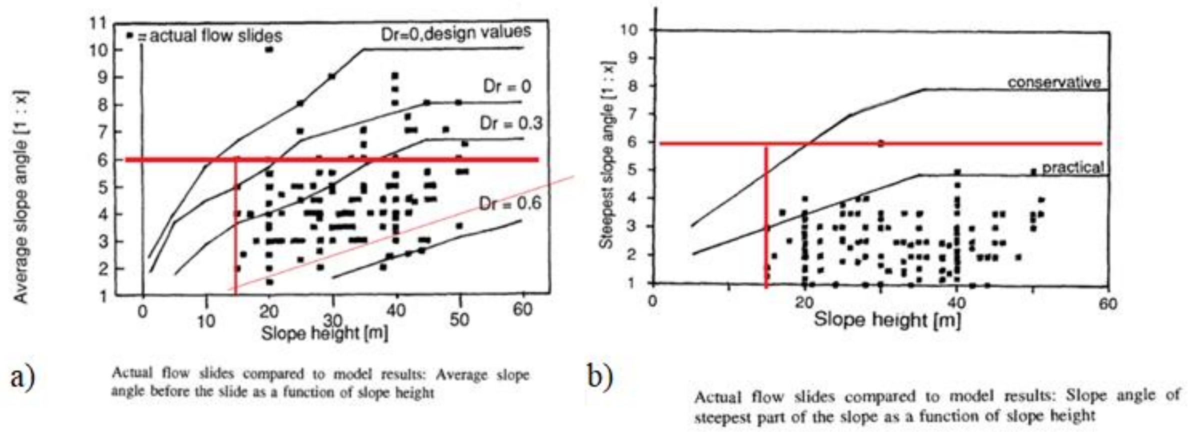
300-60 = 240kPa,

240kPa / (20-10) = 24m,

3+24=27m,

+6mCD – 27m = -21mCD

Additionally, Stoutjesdijk et al. (1994) reports 100 case studies where flow-slides occurred on shoreline structures, such as dykes. The geometry of the structures was typically similar to the ground profile across the spit and, therefore, provides useful data for comparison. Figure 5.4a shows slope height versus average slope angle, with design lines for the relative density of the material. From the CPT data shown in Figure 4.3, the in-situ relative density (Dr) over the levels applicable to the spit slope (+6mCD down to -12.9mCD) are generally greater than 40% (Dr>0.4) and mostly significantly greater than this. It can be seen that there are no flow slides recorded for slopes that had 1 in 6 slope angles and slope height of between 15m and 18m for relative densities of greater than 40%.



a) Actual flow slides compared to model results: Average slope angle before the slide as a function of slope height

b) Actual flow slides compared to model results: Slope angle of steepest part of the slope as a function of slope height

Figure 5.4. Flow Slide case studies [4]. a) Average slope angle b) Steepest slope angle

Based on the case studies reported above, and the results of the static liquefaction potential, it is considered that the risk of flow-slide is low and that the proposed slope design angles are appropriate.

5.2 Slope stability assessment

An assessment to evaluate the slope stability of the gradient chosen (1v:6h) was performed using limit equilibrium and numerical methods and is presented in this section of the report. The assumptions and methodology used will be introduced before presenting the results.

5.2.1 Model geometry

Figure 5.5 shows a plan view of the dredge drawing (294067-ARUP-XX-XX-DR-CG-002001). Cut sections A, B and C have been used for verification of the slope stability.

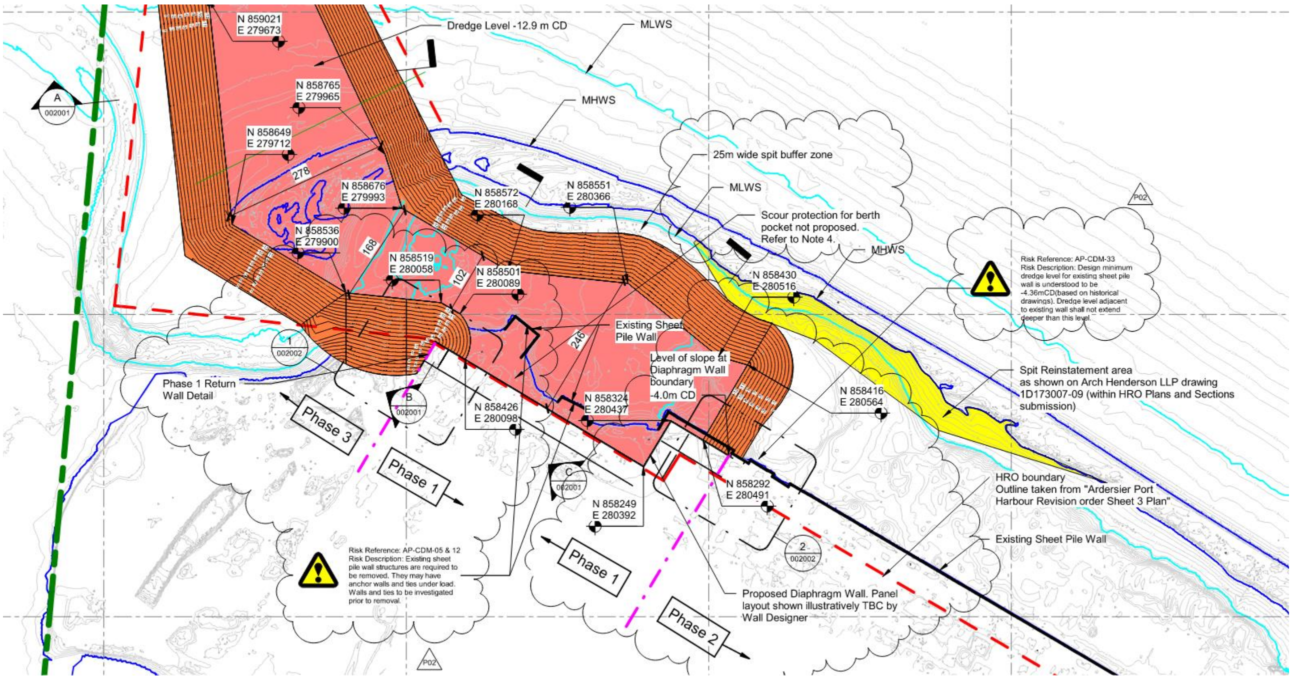


Figure 5.5. Plan view of the proposed dredging works

Orange regions of Figure 5.5 show slopes with an angle of 1:6.

The assumption of an over-dredge allowance of 1m has been adopted for the slope analyses herein, which is consistent with experience from similar projects. An additional allowance was considered for the potential effects of scour, where an additional 2m localized lowering of the toe of the slope has been assumed.

The slope analyses considered two cases (Figure 5.6), those being:

- Case A: The over-dredge + scour occur at the same angle as the main slope (1:6); and
- Case B: The over-dredge + scour with increased slope angle of 1:5.

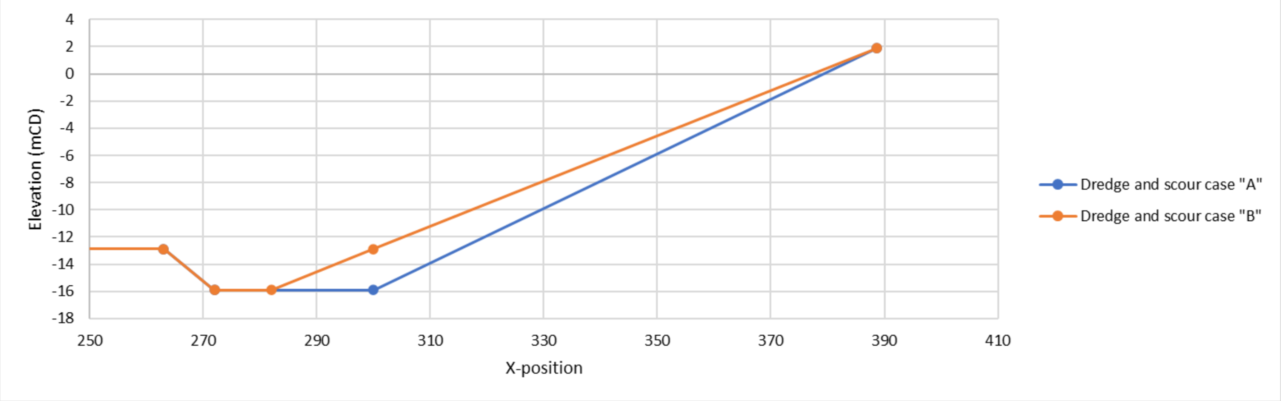


Figure 5.6. Dredge / scour cases visually depicted.

5.2.2 Methodology

OASYS Slope (limit equilibrium method) has been used primarily for slope analyses, with an additional study using Plaxis finite element analysis software to validate its results.

5.2.2.1 OASYS Slope

OASYS Slope (V22) is a limit equilibrium method (LEM) software, which has been used to check the factor of safety / over-design factor (ODF) of circular slip failures. Bishop's method, with variably inclined interslice forces, has been used to derive the ODF.

A minimum slip weight equating to 1.5m^3 of material has been adopted (i.e. 30kN/m), and the two most extreme water scenarios have been checked – those being the Lowest and Highest Astronomical Tide (+0.2mCD and +4.8mCD, respectively).

5.2.2.2 Plaxis 2D

Plaxis 2D (V22), a finite element analysis software, has also been used in conjunction to verify the slope stability. The Plaxis model has been used to ensure that non-circular or complex slip failures are not of concern. The Plaxis model was initialised as flat, with subsequent stages digging down to the proposed slope profile. Subsequently, a C-Phi reduction (safety phase) was used to determine the critical slip geometry and ODF.

5.2.3 Material properties

Material properties for this slope assessment have been presented in Section 0. Partial factors have been applied to the material strength properties, as prescribed by the BS EN 1997-1:2004+A1:2013 (EC7) for approach DA1C2 that is considered the most critical for slope stability.

5.2.4 Load information

The spit is not anticipated to undergo any active loading, and if it were, this would be sufficiently far away from the proposed slopes to be ignored. On this basis, verification using EC7 DA1C1 is not required.

5.2.5 Results

This section summarises the OASYS Slope and Plaxis results.

5.2.5.1 OASYS Slope Results

Table 5.1 presents the DA1 C2 results for the 1:6 slope angle models assuming the Case A geometry (Figure 5.6) allowing for over-dredge and scour.

Table 5.1. OASYS Slope, Design Approach 1 Combination 2 results

Section	**Overdesign factor (DA1 C2)**	
	LAT	**HAT**
A	2.898	3.506
B	3.515	3.515
C	2.961	3.509

Sections A and C gave very similar results and were both considered to represent critical sections. The ODF was generally lower for the LAT case. This was because the water level generally intersected the ground surface on the slope and led to localised critical slip surfaces near the crest of the slope. In the case of Section B, the ODF was the same in the LAT and HAT cases because the slope was submerged in both cases.

Section A was analysed for Case B (Figure 5.6) with a revised geometry to incorporate an allowance for over-dredge and scour. The revised geometry results in a slope gradient of 1v:5h (a 20% steepening of the slope angle).

Comparing the ODF’s (DA1 C2) for the LAT scenario, for the critical section A (as in Table 5.1), there is a reduction of ODF from 2.898 to 2.482.

The analyses were recalculated using the ground model based on the spit GI. The results were found to be consistent. This is because the analyses were governed by potential failures in the upper slope, where the parameters were not reduced.

5.2.5.2 Plaxis Results

Section C has been used for the Plaxis analysis in order to investigate the presence of failure mechanisms that might not be captured by a limit equilibrium analysis. Sections A and C were found to give very similar results in the OASYS Slope analyses reported above. The LAT scenario was considered.

Using characteristic soil properties and a C-Phi reduction in Plaxis, the safety phase obtains an implied factor of safety of 3.606.

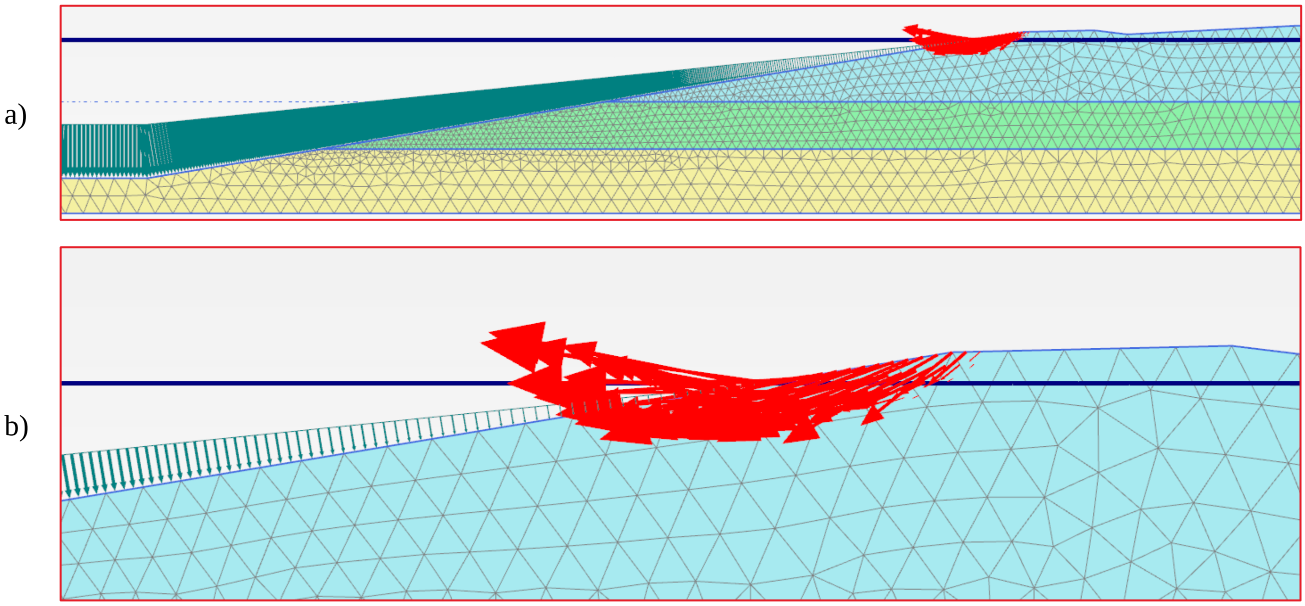


Figure 5.7. Plaxis, Incremental displacements for C-Phi reduction stage. A) Overview image B) Zoomed in

The result of the C-Phi reduction in Plaxis equates to factoring down the tangent of the friction angle by 3.606. This indicates a friction angle of 11.4° once factored. Using this back-calculated friction angle in the slope analyses confirms that the slip identified in Plaxis is in good agreement, with an ODF of approximately unity. Therefore, OASYS Slope analyses and Plaxis indicate consistent critical failure mechanisms and ODF values.

In cases where the LAT is below the ground surface, i.e. where the spit is exposed above water level, both the OASYS Slope and Plaxis analyses indicate the critical failure mechanism to be located around the water level, in the intertidal zone. The ODF against failures lower down the slope is greater and similar to the ODF for the HAT case.

5.2.6 Slope stability results discussion

BS6349-1-3:2012 details typical slope angles for still and active water conditions. The port is considered as an active water condition, whilst analysis presented above consider a still ground water condition. In order to apply the results of this study to the active water conditions, a comparison of the still and active water typical side slopes, reported in BS6349-1-3:2012, is presented in Table 5.2 .

Table 5.2. Excerpt from BS6349:2012 [3] with additional interpretation regarding the ODF required to for active waters conditions.

Material type	Typical side slope: Still water*	Typical side slope: Active water*	Safe slope angle ratio (active conditions: still conditions)
Coarse sand	20° (1:2.75)	10 ° (1:5.67)	2.06:1
Fine sand	15 ° (1:3.7)	5 ° (1:11.4)	3.06:1

*From Table 1 of BS6349-1-3:2012)

Table 5.2 also shows the "safe slope angle ratio", defined as the ratio of safe slope angle for active conditions to the angle for still conditions for the cases presented in BS6349-1-3:2012. This factor could then be applied to the safe angles determined for still conditions at the site to estimate a reasonable slope angle for active conditions.

OASYS Slope analyses were undertaken to derive the slope angle which would provide an ODF of 1.0 in still conditions (Table 5.3). The table also shows the equivalent slope angle that would be considered stable assuming active conditions for fine sand and coarse sand.

Table 5.3. Deriving active water slope angles using BS6349

Slope section	ODF (DA1 C2, slope angle 1:2)	Approximate estimated slope gradient for ODF = 1.0 in still conditions at LAT	Required slope gradients for COARSE SAND in active water conditions (conversion factor= 2.06)	Required slope gradients for FINE SAND in active water conditions (conversion factor= 3.06)
A	0.969	1:2.1	1:4.3	1:6.4
B	1.157	1:1.9	1:3.9	1:5.8
C	1.141	1:1.9	1:3.9	1:5.8

Whilst for section B and C the 1:6 slope gradient selected for the dredged slopes is shallower than the required ones both for fine and coarse sand (Table 5.3), for section A the gradient 1:6 is shallower than the angle required for coarse sand, but it is steeper than the angle required for fine sand. Despite this, 1:6 is believed to be a reasonable basis for the design even for active water at all the sections analysed as the material on site is indicated to be variable and a combination of fine sand and some coarser sands (Figure 5.1).

These stable slope angles tie in with the observed slope angles measured within the bathometric data for the site, refer to Section 3. Finally, it is noted that the adoption of a buffer zone of 25m along the lea side of the spit allows the slope angle to ravel back to 1 in 8 before the material within the spit would be affected. This slope is much shallower than any of those determined in the table above and shows that this is an appropriate step to allow for potential variation in materials or erosion effects caused by vessel movements in the harbour basin.

5.3 Considerations of Stability Around the Head of the Spit

The global stability of the spit is considered to be most critical in the north-south direction through the cross-section of the spit. This is because it represents the narrowest cross-section of the feature with submerged slopes on both sides. The lee side slope in particular may be exposed to scour due to vessels and wave action due to operations in the harbour basin and, therefore, additional measures such as buffer zones, as outlined in previous sections of this report are considered appropriate.

The head of the spit is considered to represent a lower risk to the overall stability of the spit for the following reasons:

- The east-west section through the head of the spit has a submerged slope only on the west flank and relatively level ground on the east side.
- As outlined in Appendix A, the head of the spit is considered to represent a depositional environment, rather than erosional. Therefore, it is more likely that sediment will build up in the area, rather than erode, due to ongoing coastal processes.

In view of the considerations above, it is considered that a narrower buffer zone may be adopted in this area. This should be done in conjunction with an enhanced monitoring and inspection regime, with timely maintenance, if required.

The monitoring strategy should be enhanced in this area to reflect the scientific and environmental importance of the head of the spit. It may involve installation of visible survey points (such as embedded stakes) along the boundary of the spit which can be surveyed and visually inspected more regularly to provide early warning of any unexpected movement. Should slope movement be observed, the disturbed ground should be reinstated, and the localised slope geometry reviewed to ensure the ongoing stability of the area.

6. Conclusions

Ardersier Port is proposing to redevelop its existing land into a new port facility. A major element of the scheme is the utilisation of the existing natural spit as breakwater for the port to protect the proposed quay from the North Sea and provide the required conditions for safe utilisation of the quay by vessels.

Current proposals for Ardersier Port involve additional dredging works to increase the depth and width of the main channel. Work presented in this report demonstrates that the proposed dredge profiles on the south side of the spit have adequate geotechnical stability based on the information available to date.

Several considerations were highlighted throughout the document and are summarised below:

- Dredge profiles have been developed for Phase 1 and a slope of 1v:6h has been selected, leaving a 25m buffer between the lee edge of the spit (taken as Mean Low Water Springs) and the start of any submerged slope within the dredge profile. The geotechnical stability of these slopes has been assessed and the conclusion from this work is that the design is suitable and safeguards the overall stability of the spit. It is considered that a narrower buffer can be adopted around the head of the spit due to lower risks of overall spit instability associated with these slopes. This should be done in conjunction with an enhanced monitoring and inspection regime, with timely maintenance, if required.

- It is understood that Haventus will construct dredge slopes at a steeper angle (1v:4.5h) than proposed in this report, with the slope starting from a fixed position consistent with the Arup dredge design. This will result in a buffer which is in the order of 45 to 50m wide along the lee side of the spit, which is significantly greater than the width proposed in this report. The additional width provides confidence that, should the slopes ravel back to 1:6, as our assessments indicates would be a stable angle, the global stability of the spit would not be compromised. It will also provide more time for any ground movements associated with the ravelling process to be detected as part of the proposed monitoring regime and remedial measures to be implemented in a timely manner should these be required.

- A review of existing submerged slope angles on, and in close proximity to, the site was carried out using the bathymetry survey. The bathymetry survey indicated a range of maximum slope angles exist within the area of the spit. Within the range of angles recorded it can be seen that a number of slopes are steeper than the proposed dredge slope angle of 1 in 6. This provides observational data that the chosen slope angle is appropriate.

- Based on preliminary results of ground investigations performed on the Spit (borehole factual logs, shear box tests, triaxial tests and particle size distribution tests) it is believed that the material underlying the superficial material on the spit are the same Holocene deposits that were identified on the quay area investigations. A holistic review of all the data collected to date has therefore been undertaken to develop a ground model and geotechnical material parameters for the assessment of the stability of the spit.

- The laboratory strength test results from the spit GI indicate potentially slightly lower strengths at depth than the field testing or quay side ground investigation. It is considered that this is most likely due to problems with recreating the insitu density of the material in the lab. Sensitivity analyses using these lower strengths have been performed in any case. The slope stability analysis results were found to be unaffected by the lower strengths at depths because the stability of the slope is governed by the upper slope in the intertidal zone, where the strengths may be higher than assumed in the calculations. The final factual report for the ground investigation is outstanding, however, provided the information is consistent with the draft information received to date, the conclusions of this report would not change.

- The potential for flow-slide instability of the spit was assessed. It was concluded that the risk of that this failure mechanism occurs for the proposed dredged slopes is low. This is based on the outcome of the case studies analysed considering the proposed slope height and angle together with a site-specific liquefaction potential assessment performed using the available SPT and CPT data.

- Limit equilibrium geotechnical analysis of the spit slope has shown that the dredge slope gradient of 1v:6h will be a stable configuration both for active and still water conditions. These analyses were based on the ground conditions encountered on site and supplemented by investigation and engineering properties derived from laboratory and field testing.

- The impact of scour from the operation of vessels in the port and wave action within the harbour basin is an important aspect of the long-term stability of the dredged slopes. It is considered that scour due to vessel action should be anticipated due to the nature of the materials which make up the spit. This could be managed during operation of Phase 1 of the port through regular bathymetric surveys and, where required, reinstatement of the spit to avoid the development of large-scale failures. The provision of the 25m buffer is considered to provide a reasonable safeguard against this form of erosion between survey and maintenance cycles. A narrower buffer is considered reasonable around the head of the spit, as outlined above.
- Work associated with coastal sediment transport is being undertaken by others and will also be reported separately.

7. References

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Appendix A – Whiteness Spit Morphology

The email in this appendix provides a technical explanation of the coastal sedimentation processes and environment affecting the spit.

Andrew Richmond

From: <Redacted> >
Sent: 06 February 2024 10:16
To: <Redacted>
Cc: <Redacted>
Subject: 678420: Ardersier Port - Whiteness Spit Morphology
Attachments: image005.wmz

Good morning Gregor,

There have been a number of previous investigations undertaken into the coastal processes around Whiteness Head that are relevant to the proposed dredge activities, and the geomorphology of the spit, these include:

- Geological Conservation Review: Whiteness Head, J.D. Hansom © JNCC 1980–2007. Volume 28: Coastal Geomorphology of Great Britain, Chapter 6: Gravel and 'shingle' beaches – GCR site reports (GCR ID: 1442) (http://www.jncc.gov.uk/page-2731);
- Port of Ardersier: Whiteness Head Coastal Assessment, May 2013. EnviroCentre Report No 5474 to Port of Ardersier;
- Coastal Processes Assessment, September 2018. EnviroCentre Report No 8364 to Ardersier Port Ltd;
- The coastline at Whiteness Head is also included in the National Coastal Change Assessment (NCCA) led by the Scottish Government (Hansom, Rennie & Fitton, 2017; The Scottish Government, 2017); and
- Ardersier Port – Deeper Dredge; Coastal Model and Assessment Update, January 2024. EnviroCentre Report No 13845 to Ardersier Port (Scotland) Ltd.

The 2018 EnviroCentre coastal assessment built upon the 2013 assessment through continued assessment of bathymetry change in the period between assessments and adoption of more detailed sediment modelling techniques. Most recently the January 2024 Assessment Update has revisited this subject in relation to the proposed variation in dredge design. A conceptual understanding of sediment transport and coastal morphology within the local coastal system has been developed through review of observed and historic changes, supplemented by hydraulic modelling. The conceptual model includes the wave driven longshore transport of sand and gravel along the eastern shore of Whiteness Head spit resulting in continued spit extension to the north-west, with recurves to the west/south-west. A continuity of this north-western transport pathway is highlighted, both offshore to the deeper waters of the main channel, and further west to the north-eastern intertidal and subtidal margin of Whiteness Sands.

The head of the spit continues to accumulate in both a north-westerly and westerly direction. Previous comparison (EnviroCentre Report No 8364, 2018) between the 2007 and 2012 bathymetric and topographic survey data showed movement in this direction of MHWS between 80 - 120 metres. Movement between 2012 and 2018 was observed to be between 35 – 55 metres. Estimated rates of MHWS movement have therefore historically been between 10 – 24 metres per year. Below MHWS significant accumulation within the intertidal and subtidal zone was also observed between 2012 and 2018. Recent comparison between 2023 and 2018 survey datasets (EnviroCentre Report No 13845, 2024) highlighted the areas dredged since 2018 within the outer harbour, and through the spit recurve, and also areas of deposition within the harbour and previous navigation channel. Also noticeable are areas of intertidal spit extension, highlighting the ongoing north-westward extension of the spit, and the recurve of the spit head towards the west.

At present in the area of the spit head the intertidal and terrestrial sediment typology is primarily gravel, and the dominant sediment transport process continues to be storm-driven transport of gravel. The processes of north-westward spit extension, and westward spit head recurve, are ongoing and it is considered that these processes will continue in the future. This north-westward feed of sediment can be anticipated to result in a future maintenance dredge requirement following reinstatement of the dredged navigation channel.

Kind regards

Martin

Martin Nichols BSc (Hons) MSc C.WEM MCIWEM
Principal Consultant

Direct dial <Redacted>
Mobile <Redacted>
Email: <Redacted>

2023 UK River Prize Winner
Project Partner
Rottal Burn Restoration