The Sizewell C Project

SZC Co.’s Response to the Secretary of State’s Request for Further Information dated 18 March 2022: Appendix 5 – Updated Position Statement between SZC Co. and the Environment Agency on matters relating to the Preliminary Design and Maintenance Requirements for the Sizewell C Soft Coastal Defence Feature, with associated technical appendices

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Updated Position Statement between SZC Co. and the Environment Agency on matters relating to the Preliminary Design and Maintenance Requirements for the Sizewell C Soft Coastal Defence Feature

Signature Sheet

This Position Statement is agreed between SZC Co. and the Environment Agency the day specified below.

Signed: [redacted] Print Name: Simon Barlow Job Title: Nuclear New Build Project Manager – Sizewell C Date: 06 / 04 / 2022 Duly authorised for and on behalf of the Environment Agency
Signed: [redacted] Print Name: Carly Vince Job Title: Chief Planning Officer Date: 06 / 04 / 2022 Duly authorised for and on behalf of SZC Co.

Contents

1.0 Background

The purpose of this document is to record the current position of NNB Generation Company (SZC) Limited (SZC Co.) and the Environment Agency (EA), hereafter referred to as 'the Parties', in relation to coastal processes modelling.

During the Public Examination of the SZC DCO application, SZC Co. provided several reports that addressed the design and performance of the coastal defences:

REP8-096	Deadline 8: 9.13 Sizewell C Coastal Defences Design Report – Revision 2
REP9-020	Deadline 9: 9.31 Storm Erosion Modelling of the Sizewell C Soft Coastal Defence Feature using XBeach-2D and XBeach-G - Revision 3.0
REP10-124	Deadline 10: 9.12 Preliminary Design and Maintenance Requirements for the Sizewell C Coastal Defence Feature

Of particular relevance is REP9-020 because this used numerical modelling to assess erosion of the soft coastal defence feature (SCDF) (the "sacrificial" beach between the hard sea defences and the sea). This modelling then provides input into the Coastal Processes Monitoring and Mitigation Plan (CPMMP) to identify when the SCDF needs to be 'topped up' (recharged) with sediment as well as engineering studies to demonstrate adequacy of the sea defences against coastal flooding.

2.0 Statement of Common Ground (SoCG)

SOCG Between SZC CO and Environment Agency

While it was agreed that good progress had been made modelling and demonstrating the robustness of the sea defences during the examination, in the Deadline 10 Statement of Common Ground (SoCG) the EA remained unsatisfied that all necessary potential future and/or storm scenarios had been evaluated (REP10-094). SZC Co. held the view that sufficient scenarios had been provided to satisfy planning needs under the Development Consent Order (DCO) and it was continuing to model more extreme 'design basis' cases to satisfy the requirements for nuclear safety in conjunction with the design progression of the hard coastal defence feature (HCDF). The EA accepted that further work was being undertaken but was unable to agree Common Ground on this subject at Deadline 10. The relevant comments from the SoCG are provided in Table 1[1] for convenience.

[1] It's worth noting that several repeat the same comment and those later in the Table could not be agreed due to non-agreement in earlier elements, so in reality all comments relate to the same issue, namely adequacy of completeness of modelled scenarios.

Table 1: Matters 'Not Agreed' Between SXC Co. and the EA at Deadline 10 (Full "Ref." is MDS_CGHX)

Ref.	Matter	D10 Statement
CGH1	The overarching methodology for the assessment of impacts on Coastal Geomorphology and Hydrodynamics as detailed in **Volume 1 Appendix 6P and section 20.3** of **Volume 2 Chapter 20** of the ES	**SZC Co Comment**: Although some scenarios remain to be tested the overarching methodology used for modellig (XBeach) is agreed as appropriate and the output to date are not disputed. All modelled scenarios tested to date demonstrate that maintenance of the SCDF is viable. **EA comment** We are supportive of the overarching approach to modelling, as well as many of the conclusions of the assessment, but it is our view that there are a small number of gaps in the work done to date which affect our level of confidence in the conclusions (see other lines below for further details specific to individual elements of the assessment). We understand from discussions with the applicant that work is ongoing to address some of these areas, which we welcome, however this will not be completed until after the close of the DCO Examination.
CGH5	The proposed primary, secondary and tertiary mitigation measures to mitigate impacts as detailed in **section 20.5** and **20.12** of **Volume 2 Chapter 20**. In particular the proposed Coastal Monitoring and Mitigation Plan as defined in Condition 17 of the Marine Licence.	**SZC Co Comment:** TR544 (D2 and D3) and TR545 (D3) have been provided to the EA. The updated CPMMP was submitted at D5. Principles of mitigation agreed (mitigation by way of SCDF, its recharge and by-pass); details to be confirmed in CPMMP. SZC Co understand the Envrionment Agemcy concerns relate only to the sustainability of the SCDF. All modelled scenarios to date (including for RCP8.5) show maintenance of the SCDF is viable throughout operation and decommissioning. Even if that were not the case, other mitigation including sediment by-passing is proposed to mitigate impacts in coastal geomorphology. **EA Comment:** We are supportive of the mitigation measures proposed, namely maintenance of the SCDF via recharge, recycling or bypassing in order to maintain a longshore transport corridor across the site, as well as the use of

		the CPMMP to ensure an adaptive management approach developed in consultation with the Marine Technical Forum. However, it is our view that the modelling has not incorporated the full range of reasonable worst case scenarios (see other lines below for further details specific to individual elements of the assessment), meaning we are unable at this time to conclude that the mitigation approach will be viable for the full duration of the operational and decommissioning phases.
CGH6	The assessment of impacts associated with the hard coastal defence feature as described in section **20.6** of **Volume 2 Chapter 20** and **Appendix 20A**.	**SZC Co Comment:** 1D and 2D modelling was provided at D2 and D3, respectively, and EA provided feedback at D5. EA requested modelling to be extended to beyond 2099 and include assessment using RCP8.5 climate change scenarios. These will be provided at Deadline 7. Modelling demonstrates maintenance of SCDF is viable under all scenarios tested to date, including RCP8.5. **EA comment:** We are pleased to see that modelling has been extended to 2140 and includes the adaptive design under the RCP8.5 sea level projection and we are in agreement with a number of the conclusions in the assessment. However, at this point in time it is our view that the latest modelling work has not yet considered the full range of reasonable worst case scenarios; specifically it does not include additional more severe storm events, or further consideration of the risk posed by one or more storms occuring sequentially without a safe operating window in between for delivery of mitigation measures. We understand from discussions with the applicant that work is ongoing to address some of these areas, which we welcome, however this will not be completed until after the close of the DCO Examination. We do note however that the CPMMP represents an important mechanism to identify and address coastal changes beyond those predicted by the modelling and assessment work, and that this approach is in line with best practice for addressing uncertainty.

CGH7	The assessment of impacts associated with the soft coastal defence feature as described in section **20.7** of **Volume 2 Chapter 20** and **Appendix 20A**.	**SZC Co Comment:** 1D and 2D modelling was provided at D2 and D3, respectively, and EA provided feedback at D5. EA requested modelling to be extended to beyond 2099 and include assessment using RCP8.5 climate change scenarios. These will be provided at Deadline 7. Modelling demonstrates maintenance of SCDF is viable under all scenarios tested to date, including RCP8.5. The SCDF is intended to release material during storms, which will redistrubute along adjacent beaches. Impacts fro teh SCDF itself are considered negligible or beneficial **EA comment:** We are pleased to see that modelling has been extended to 2140 and includes the adaptive design under the RCP8.5 sea level projection and we are in agreement with a number of the conclusions in the assessment. However, at this point in time it is our view that the latest modelling work has not yet considered the full range of reasonableworst case scenarios; specifically it does not include additional more severe storm events, or further consideration of the risk posed by one or more storms occuring sequentially without a safe operating window in between for delivery of mitigation measures. We understand from discussions with the applicant that work is ongoing to address some of these areas, which we welcome, however this will not be completed until after the close of the DCO Examination.. We do note however that the CPMMP represents an important mechanism to identify and address coastal changes beyond those predicted by the modelling and assessment work, and that this approach is in line with best practice for addressing uncertainty.
CGH11	The assessment of combinations of spatially and temporally overlapping marine	**SZC Co Comment:**

	components as described in section **20.11** of **Volume 2 Chapter 20**.	1D and 2D modelling was provided at D2 and D3, respectively, and EA provided feedback at D5. EA requested modelling to be extended to beyond 2099 and include assessment using RCP8.5 climate change scenarios. These will be provided at Deadline 7. Modelling demonstrates maintenance of SCDF is viable under all scenarios tested to date, including RCP8.5. Environment Agency concerns appear to be soley based on the viability of maintaining the SCDF which is independent of any other elemnent of the project. **EA comment:** Whilst we are comfortable with the assessments relating to a number of the components of coastal and marine infrastructure (e.g. the BLFs and cooling water infrastructure), we cannot at this time agree with the full assessment of cumulative impacts owing to our residual concerns around the modelling of the coastal defences (see CGH6 & CGH7 for more detail). We recognise that further work is planned to address some of these concerns, which we welcome, however the results of this work will not be available until after the close of the DCO Examination.
	The residual effects of impacts associated with the hard coastal defence feature as described in section **20.6** of **Volume 2 Chapter 20** and **Appendix 20A**.	**SZC Co Comment:** 1D and 2D modelling was provided at D2 and D3, respectively, and EA provided feedback at D5. EA requested modelling to be extended to beyond 2099 and include assessment using RCP8.5 climate change scenarios. These will be provided at Deadline 7. Modelling demonstrates maintenance of SCDF is viable under all scenarios tested to date, including RCP8.5. **EA comment:** As described in our comments on CGH6, we are comfortable with the approach to the assessment and with a number of the conclusions presented in the latest iteration of the modelling work. However, at this point in time it is our view that the assessment has not yet considered the full range of reasonableworst case scenarios; specifically it does not include additional more severe storm events, or further consideration of the risk posed by one or more storms occuring sequentially without a safe operating window in between for delivery of mitigation

		measures. We understand from discussions with the applicant that work is ongoing to address some of these areas, which we welcome, however this will not be completed until after the close of the DCO Examination. We do note however that the CPMMP represents an important mechanism to identify and address residual effects beyond those predicted by the modelling and assessment work, and that this approach is in line with best practice for addressing uncertainty.
CGH13	The residual effects of impacts associated with the soft coastal defence feature as described in section **20.7** of **Volume 2 Chapter 20** and **Appendix 20A**.	**SZC Co Comment:** 1D and 2D modelling was provided at D2 and D3, respectively, and EA provided feedback at D5. EA requested modelling to be extended to beyond 2099 and include assessment using RCP8.5 climate change scenarios. These will be provided at Deadline 7. Modelling demonstrates maintenance of SCDF is viable under all scenarios tested to date, including RCP8.5. **EA comment:** As described in our comments on CGH7, we are comfortable with the approach to the assessment and with a number of the conclusions presented in the latest iteration of the modelling work. However, at this point in time it is our view that the assessment has not yet considered the full range of reasonableworst case scenarios; specifically it does not include additional more severe storm events, or further consideration of the risk posed by one or more storms occuring sequentially without a safe operating window in between for delivery of mitigation measures. We understand from discussions with the applicant that work is ongoing to address some of these areas, which we welcome, however this will not be completed until after the close of the DCO Examination. We do note however that the CPMMP represents an important mechanism to identify and address residual effects beyond those predicted by the modelling and assessment work, and that this approach is in line with best practice for addressing uncertainty.

3.0 Progress Update

On 8th March 2022, SZC Co. held a workshop with the EA, with ESC and ONR also in attendance, to present and discuss further numerical modelling work that assessed erodibility of the SCDF under more extreme scenarios, as requested by the EA. The accompanying technical report (BEEMS TR553: Modelling of Soft Coastal Defence Feature under Design Basis Conditions) was provided on 18th February 2022 for review in advance of the workshop. The report was not submitted as part of the DCO application or examination.

BEEMS TR553 uses the same numerical modelling approach as that used previously in Storm Erosion Modelling of the Sizewell C Soft Coastal Defence Feature using XBeach-G - Revision 3.0 (REP9-020) but uses more extreme sea level and storm conditions and a pre-eroded beach which are representative of the design basis conditions which will be used to satisfy the requirements for nuclear safety in conjunction with the design progression of the hard coastal defence feature (HCDF).

Three 1:10,000 year joint probability scenarios for waves and water levels were tested with differing surge height contributions (ranging from moderate to extreme). Climate change allowances were applied consistent with the 'reasonably foreseeable' scenario for the design basis, incorporating a 10% increase on present-day wave heights and an increase in mean sea level consistent with UKCP18 projections at the 95th percentile confidence level for Representative Concentration Pathway (RCP) 8.5 over a site lifetime timescale to 2140. Three cases were selected as they represent differing magnitudes of waves and water levels:

- **Scenario F1:**

Mean sea level (before surge)	= 1.9m AOD (approx.)
Peak surge height	= 3.5m (approx.)
Peak water level	= 6.75m AOD (one high tide cycle)
Minimum water level	= 0.75m to 1m AOD (3 low tide cycles)
Transition level (erosion (above)/deposition (below))	= 2.8m AOD (approx.)

- **Scenario E1:**

Mean sea level (before surge)	= 1.9m AOD (approx.)
Peak surge height	= 1.5m (approx.)
Peak water level	= 5.02m AOD (one high tide cycle)
Minimum water level	= 0.75m to 1m AOD (5 low tide cycles)
Transition level (erosion (above)/deposition (below))	= 1.3m AOD (approx.)

- **Scenario A1:**

  Mean sea level (before surge) = 1.9m AOD (approx.)
  Peak surge height = 0.5m (approx.)
  Peak water level = 3.74m AOD (one high tide cycle)
  Minimum water level = 0.75m to 1m AOD (5 low tide cycles)
  Transition level (erosion (above)/deposition (below)) = 1.2m AOD (approx.)

All scenarios used a pre-eroded beach (54% volumetric loss) to simulate a case with prior severe erosion without the opportunity to deliver mitigation (e.g., beach recharge) measures.

All scenarios were modelled using a grain size of D50 = 10 mm, as SZC Co has committed to a default position that the SCDF sediments will match the modal size of native beach sediments, i.e. 10 mm.

The predicted level of the beach erosion is clearly affected by sea water levels when comparing Scenario F1 (high mean sea level plus extreme surge height) with Scenarios A1, E1 (high mean sea level plus moderate to large surge height). However, there is relatively little difference in the erosion pattern and transition level when comparing Scenarios A1 and E1 where the surge height varies quite significantly but is less extreme.

All 3 scenarios demonstrated that the HCDF was not exposed.

During the meeting, the case for modelling scenarios with lower water levels was discussed in case the HCDF toe which is founded at 0m AOD could be more sensitive to erosion in these scenarios. SZC Co confirmed scenarios with lower sea water levels, as well as the range modelled in TR553, will be assessed as part of the detailed design of the permanent sea defences.

Following the meeting SZC Co circulated a short note explaining why scenarios with lower water levels would not be more onerous for exposure of the HCDF toe based on (i) the pattern of erosion observed with different water levels in the three modelled cases (above); (ii) the greater beach width at the lower level; and (iii) the much greater attenuation of wave energy at lower water levels. The note also confirmed that even if the HCDF were to be exposed, sediment by-passing would be used to mitigate any impacts on coastal processes (see Appendix B).

BEEMS TR553 has been updated to reflect discussions at the meeting, and the post meeting note, and provided to all parties. The SoCG between SZC Co and the Environment Agency has been updated accordingly (Appendix C).

4.0 Position of the Parties

SZC Co. & EA agree that:

- Modelling of all relevant potential future extreme scenarios, necessary for the SZC DCO, has now been undertaken.
- Modelling of the additional Design Basis Scenarios demonstrates that the SCDF as described should provide the necessary protection to prevent interruption of sediment supply along the SZC frontage and not significantly affect coastal processes. Recharge of the SCDF is likely to be required to ensure the SCDF has sufficient volume to withstand such events over the life of the station to 2140.
- Modelling of the additional Design Basis Scenarios demonstrates that the SCDF as described should provide the necessary protection to prevent any significant exposure or undermining of the hard sea defences (Hard Coastal Defence Feature; HCDF). Recharge of the SCDF is likely to be required to ensure the SCDF has sufficient volume to withstand such events over the life of the station to 2140.
- Should the HCDF become exposed suitable secondary mitigation is proposed to prevent any significant impacts on coastal processes.
- Further work is required to develop and approve the CPMMP, secured under DCO Requirement 12 and DML Condition 14, which will define the triggers (minimum allowable beach volumes) for when recharge is required, and will commit SZC Co. to continued dialogue with all relevant coastal authorities to identify, discuss and where necessary mitigate emerging issues.

5.0 Appendix A - BEEMS TR553; “Modelling of the SCDF under the Reasonable Foreseeable Design”

MODELLING OF SOFT COASTAL DEFENCE FEATURE UNDER DESIGN BASIS CONDITIONS

NOT PROTECTIVELY MARKED

DOCUMENT TITLE	Modelling of Soft Coastal Defence Feature under Design Basis Conditions

ISSUE REASON	P6 - Construction

CONTRACTOR DETAILS

CONTRACTOR NAME	Cefas

CONTRACTOR DOCUMENT NUMBER	TR553	**CONTRACTOR REVISION**	01

ECS CODES

REVISION HISTORY

REVISION	REVISION DATE	PREPARED BY	POSITION/TITLE	CHECKED BY	POSITION/TITLE	APPROVED BY	POSITION/TITLE
01	16/02/2022	David Haverson	BEEMS Modelling Lead	Piyali Chowdhury	Senior Coastal Scientist	Siân Limpenny	Programme Director
02	22/03/2022	David Haverson	BEEMS Modelling Lead	Siân Limpenny	Programme Director	Siân Limpenny	Programme Director

REVISION STATUS/SUMMARY OF CHANGES

Revision	Purpose	Amendment	By	Date
01	P6	Initial submission to SZC Co	Cefas	16/02/2022
02	P6	Minor text revisions to description of surge component, reflect low water scenario discussions with EA.	Cefas	22/03/2022

Cefas

Coastal Marine Applied Research

UNIVERSITY OF PLYMOUTH

Modelling of Soft Coastal Defence Feature under Design Basis Conditions

Modelling of Soft Coastal Defence Feature under Design Basis Conditions

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Version and Quality Control

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Update, Internal & Executive QC	0.14	DH, TD, SL	16/02/2022
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Submission to EDFE	2.00		22/03/2022

The modelling presented in this report was conducted by Dr Christopher Stokes and Liane Brodie, CMAR (University of Plymouth). However, the report and analysis presented was authored solely by Dr David Haverson, Cefas. Any interpretation of model results relating to engineering decisions regarding the design of the Soft Coastal Defence Feature in this report are owned by Cefas.

CMAR: Coastal Marine Applied Research

CMAR is a research-informed consultancy group based in the School of Biological and Marine Sciences at the University of Plymouth, south west UK, and contract our services through the university's wholly owned commercial subsidiary, University of Plymouth Enterprise Limited (UoPEL). We focus on coastal processes and marine physics, and aim to provide a first-class data collection, analysis, modelling, and synthesis service to help address important issues in the coastal and marine environment. We strive to understand and predict the behaviour of coastal, marine and estuarine systems to support the appropriate management of resources and activities in these environments. Our team consists of highly qualified coastal scientists and engineers, and our research on coastal dynamics is published in international, peer-reviewed journals.

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Table of contents

List of Tables and Figures

Tables

Figures

Executive Summary

At Sizewell C, construction of a Hard Coastal Defence Feature (HCDF) is proposed along the eastern (seaward) flank of the station. It is the primary defence against coastal flooding during extreme waves and water levels and is required to limit overtopping. It will be constructed in the terrestrial environment above Mean High Water Springs and will be separated from the sea by a shingle (pebble and sand-sized material) Soft Coastal Defence Feature (SCDF) using the native grain sizes. The SCDF will be a maintained and volumetrically enlarged beach seaward of the HCDF that is designed to maintain the longshore sediment transport corridor along the Sizewell coastline and prevent exposure of hard coastal defences (BEEMS Technical Report TR544).

In addition to its role for environmental compatibility with coastal processes, the SCDF performs a supporting role in the fulfilment of the hazard protection function of the HCDF for maintaining nuclear safety from overtopping in coastal flood conditions. In this respect, the SCDF is to (i) maintain beach levels and wave height limitation approaching the toe of the HCDF accounting for potential erosion in extreme events; and (ii) prevent erosive exposure or undercutting of the toe of the HCDF, which could affect its stability (in its as-constructed state or in case of future adaptation for more severe climate change).

This report provides a scoping analysis of the performance of the SCDF in its supporting role to the HCDF under sea conditions that are representative of the expected design basis for nuclear safety (i.e., conservatively defined at 10,000 year return period, with allowance for climate change and uncertainty). The results provide strong confidence in the adequacy of the SCDF concept and sizing in line with the DCO application. The formal substantiation of the combined performance of the HCDF and SCDF for erosion control and overtopping protection will follow as part of the sea defence detailed design. This report provides information to Sizewell C's design engineers that are responsible for the SCDF and HCDF designs. Specifically, the outcome of this modelling will help inform the engineering teams to consider the design of the HCDF to meet its safety requirements.

The hydrodynamic conditions applied in this report are statistically highly unlikely (1:10,000 year probability) and very extreme, meaning they are not representative of typical coastal geomorphology processes and should be considered separately from those assessments considered in BEEMS Technical Reports TR544 and TR545 which dealt with the general viability of the SCDF concept and its capacity to prevent HCDF exposure and, therefore, disruption to coastal processes.

For this report, the SCDF response was tested using conservatively defined 10,000 year return period sea conditions with allowance for climate change mainly at the 'Reasonably Foreseeable' level. Sizewell C design engineers have indicated that this is consistent with the principles on which the design basis sea conditions will be defined for the detailed design. Details of the analysis scenarios are listed below. For ease of terminology, the term 'Reasonably Foreseeable Design Basis' is used in places in this report as shorthand to denote this level of hazard challenge. The SCDF response was tested using the existing 1D XBeach gravel model used in BEEMS Technical Report TR545. The present analysis embodies several conservatisms in terms of the hydraulic input parameters and the pre-receded beach geometry (as supplied by SZC Co.) which is assumed. Three 1:10,000 year joint probability scenarios for waves and water levels (including surge) were tested with a 10% increase applied to wave heights and sea level rise (SLR) predictions for 2140 under the 95th percentile of the Representative Concentration Pathway (RCP) 8.5. Three cases were selected as they represent differing magnitudes of waves and water levels:

- Scenario A1: Peak Hs (wave height) = 8.95 m; peak still water level = 3.74 m.
- Scenario E1: Peak Hs = 8.21 m; peak still water level = 5.02 m.
- Scenario F1: Peak Hs = 4.78 m; peak still water level = 6.75 m.

The F1 scenario was modelled because it was used previously in the SZC Development Consent Order (DCO) Flood Risk Assessment (FRA). To maintain consistency with the FRA modelling, the F1 RFDB waves and water levels were extracted from the -8 m ODN contour inside of the Sizewell-Dunwich Bank (i.e, the bank is present in the input conditions for the XBeach model). The A1 and E1 scenarios, which were not used in the FRA, were also modelled as they were considered to provide a more severe test of beach erosion. To provide an additional level of conservatism, and ensure the most extreme conditions were tested, the conditions from A1 and E1 1.6 km seaward of the Sizewell-Dunwich Bank were applied to the open boundary of the Xbeach-G storm erosion model without any reduction due to the presence of the Sizewell-Dunwich sand bank, i.e. the bank is removed fully. All scenarios were modelled using a grain size of D_{50} = 10 mm, based on SZC Co's commitment to a default position that the SCDF sediments will match the modal size of native beach sediments, i.e., 10 mm. The particle size used for each model run is denoted in subscript e.g., $F1_{10mm}$ is the modelled F1 scenario with a D_{50} = 10 mm.

The RFDB conditions also specified a severely depleted beach scenario (provided by SZC Co.), rather than a fully recharged SCDF, as the start point for the modelling. That is, the SCDF profile receded landward by 20 m with its 6.5 m ODN design crest eroded to 5.2 m ODN. SZC Co has committed to maintaining the SCDF and therefore such a profile is only likely to arise following a sequence of severe storms with insufficient time between them to allow recharge.

The $F1_{10mm}$ model showed that beach material was eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. The coastal path, at an elevation of 5.2 m ODN, was eroded with a maximum vertical reduction in bed elevation of 1.4 m. The maximum horizontal translation was -10.9 m (at the 4.1 m ODN contour, negative translations are landward). The HCDF was not exposed and its 3.7 m ODN platform had 0.25 – 0.84 m of sediment thickness remaining at the end of the modelled storm. The maximum erosion at the end of $F1_{10mm}$ storm was -20.34 m^3/m, but the net change in beach volume was +0.01 m^3/m, with 104.09 m^3/m beach volume remaining.

Scenario F1 was tested as an RFDB condition for HCDF integrity as it represented a worst case for overtopping during the Flood Risk Assessment (FRA). However, whilst appropriate for the FRA more energetic wave conditions were considered to assess the worst case for beach erosion i.e., Scenarios A1 and E1. Scenarios A1 and E1 have lower water levels but higher waves (than F1) and resulted in higher levels of beach erosion, both volumetrically and horizontal retreat (see Fig ii). However, Scenarios A1 and E1 represent offshore conditions without the presence of the Sizewell-Dunwich Bank, whereas Scenario F1 includes the bank present. Therefore, more erosion is to be expected with scenarios A1 and E1 compared to F1. The degree of erosion is almost the same for A1 and E1, with Scenario E1 having slightly larger volumetric loss and horizontal beach translation despite the larger waves. However, E1 volumetric erosion and horizontal beach translation were only 0.27 m^3/m and 0.1 m, respectively, greater than A1.

Both Scenarios $A1_{10mm}$ and $E1_{10mm}$ show similar response patterns to Scenario $F1_{10mm}$ with beach material eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. For Scenarios $A1_{10mm}$ and $E1_{10mm}$ the volume eroded from the upper subaerial beach (above the point of inflection, whereby the beach material is deposited on the lower subaerial beach) is -37.95 m^3/m and -38.22 m^3/m, respectively, compared to -20.34 m^3/m for Scenario $F1_{10mm}$. The largest horizontal beach translation of the eroded upper subaerial beach is -11.1 m and -11.2 m for Scenario A1 and E1, respectively, which is similar to the F1 maximum retreat of -10.9 m.

The RFDB conditions represent 1:10,000 year events of combined wave and water levels on an initial severely eroded beach profile. The eroded beach profile used in this report represents loss of the SCDF's sacrificial layer with only parts of the inner buffer layer[1] remaining. The RFDB start profile has a volume of

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[1] As explained in BEEMS Technical Report TR544, the SCDF is notionally divided into two parts – an inner buffer layer which is not intended to be eroded and an outer sacrificial layer that would be progressively eroded and occasionally recharged (before exposure of the buffer layer).

104.08 m^3/m, which is less than half (45.7%) of the full SCDF profile. In reality, the beach would be recharged in as short a period as reasonably practical and therefore would not remain in this state for extended periods. However, should the oceanographic conditions of the RFDB occur with the beach in this state, then the modelling results show that the 10 mm D_{50} grain size would be sufficient to withstand all three 1:10,000 year events modelled without exposing the HCDF, however model uncertainty means that this statement cannot be made with complete confidence especially as some sections are almost exposed under the modelled conditions.

Whilst the HCDF toe was not exposed under the A1 and E1 1:10,000 year events, the worst erosion with respect to HCDF integrity, specifically toe undermining potential, may not in fact be a joint probability 1:10,000 scenario. Lower water levels with extreme waves could cause worse erosion at the toe level, however, there is good confidence that scenarios with lower sea water levels would not be onerous and would not threaten to undercut the toe of the hard sea defence at 0.0 m ODN. Scenarios with lower sea water levels, as well as the range modelled herein, will be assessed as part of the detailed design of the permanent sea defences by SZC Co.

In any event, from an Environmental Impact Assessment (EIA) perspective, even if in the extremely unlikely event that the HCDF were to be exposed, mitigation by way of sediment by-passing would be used to maintain sediment transport pathways until the SCDF could be recharged. There would be no significant impact on downdrift beaches which themselves would have undergone significant change during such extreme events.

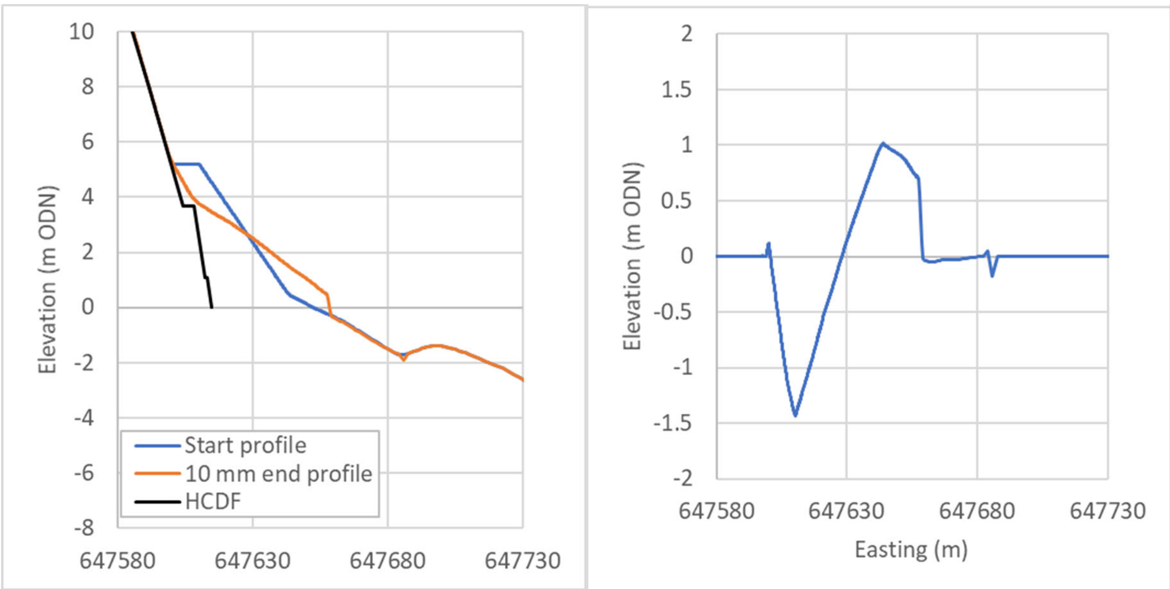

Fig i. Start and end beach profile (top) and the profile changes (bottom) for the Reasonably Foreseeable Design Basis Scenario F1 with a D_{50} = 10 mm grain size.

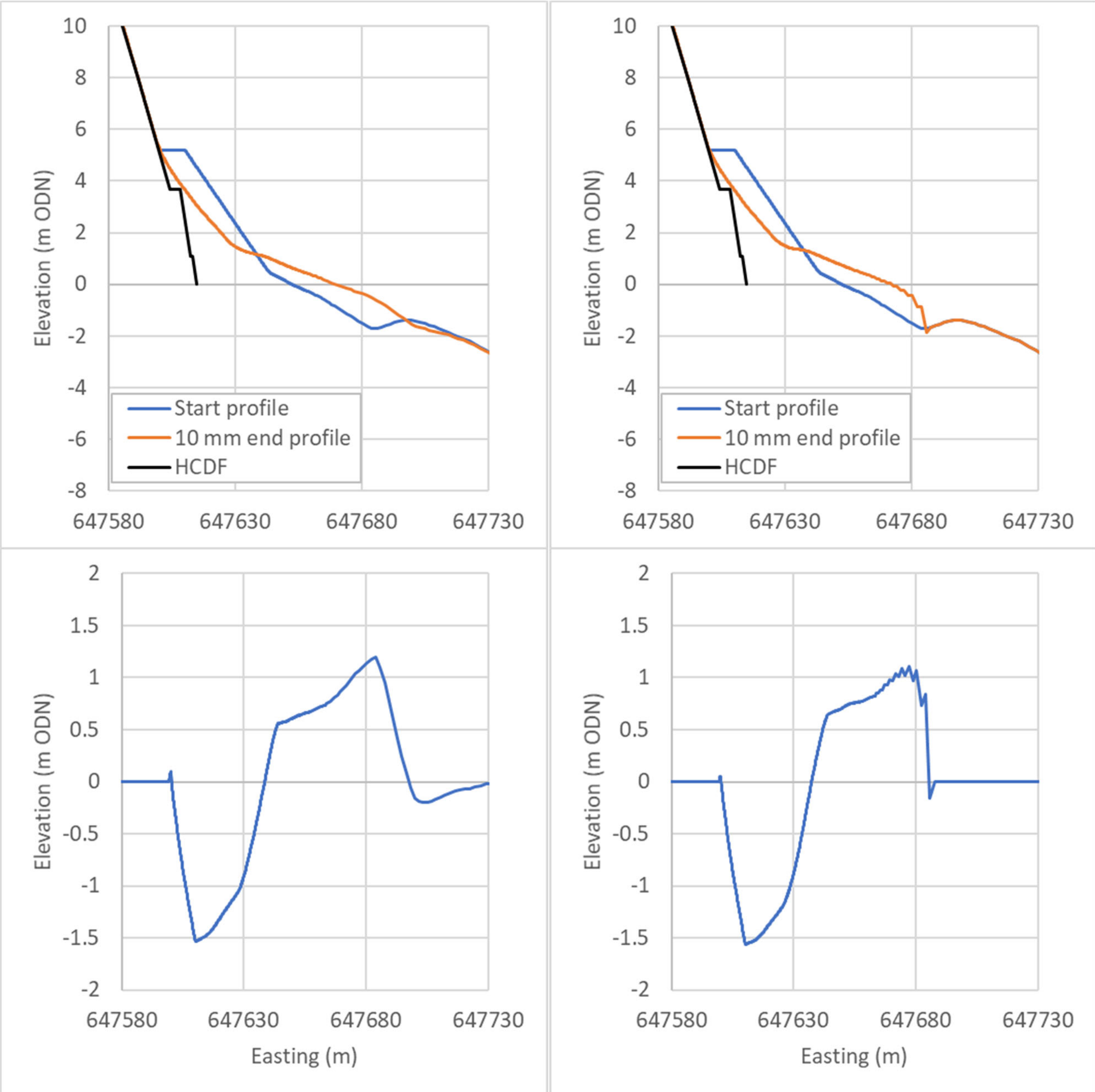

Fig ii. Start and end beach profile (top) and the profile changes (bottom) for Scenario A1 (left) and Scenario E1 (right) with a D_{50} = 10 mm grain size.

1 Introduction

1.1 Background

At Sizewell C (SZC), construction of a Hard Coastal Defence Feature (HCDF) is proposed along the eastern (seaward) flank of the station. It is the primary defence against coastal flooding during extreme waves and water levels, and is required for site integrity. It would be constructed in the terrestrial environment above Mean High Water Springs (MHWS) and would be separated from the sea by a shingle Soft Coastal Defence Feature (SCDF) using the native grain sizes. The SCDF would be constructed between the HCDF and MHWS level to increase back-beach volume.

The SCDF is a maintained and volumetrically enlarged beach seaward of the HCDF that is designed to maintain the longshore sediment transport corridor along the Sizewell coastline and prevent exposure of the HCDF (BEEMS Technical Report TR544). It uses a “working with nature” approach where the release and transport of SCDF sediment in the coastal system is determined by natural coastal processes (erosion by storm waves), some of which would deposit on adjacent shorelines (and potentially reduce erosion rates there). To prevent HCDF exposure by progressive, unmitigated, natural erosion, the SCDF would be maintained or ‘topped up’ (primarily by recharge) once the beach volume reduces to a threshold value which will be set in the Coastal Processes Monitoring and Mitigation Plan (CPMMP) (BEEMS Technical Report TR523).

Using a 2D calibrated XBeach-sand model of the SCDF and surrounding shoreline along with a semi-calibrated[2] 1D XBeach-gravel model, BEEMS Technical Reports TR544 and TR545 demonstrated that the SCDF was viable and would serve its intended function over the life of the station, including during the decommissioning phase of the power station (to 2140).

Whilst BEEMS Technical Reports TR544 and TR545 dealt with the viability of the SCDF and its capacity to prevent HCDF exposure and disruption to coastal processes, the SCDF performs a supporting role in the fulfilment of the hazard protection function of the HCDF for maintaining nuclear safety from overtopping in coastal flood conditions. In this respect, the SCDF is to (i) maintain beach levels and wave height limitation approaching the toe of the HCDF accounting for potential erosion in extreme events; (ii) prevent erosive exposure or undercut of the toe of the HCDF, which could affect its stability (in its as-constructed state or in case of future adaptation for more severe climate change).

This report provides a scoping analysis of the performance of the SCDF in its supporting role to the HCDF under sea conditions which are representative of the expected design basis for nuclear safety (i.e., conservatively defined at 10,000 year return period, with allowance for climate change and uncertainty). The results provide strong confidence in the adequacy of the SCDF concept and sizing in line with the DCO application. The formal substantiation of the combined performance of the HCDF and SCDF for erosion control and overtopping protection will follow as part of the sea defence detailed design.

The hydrodynamic conditions applied in this report are statistically highly unlikely and very extreme, meaning they are not representative of typical coastal geomorphology processes and should be considered separately from those assessments considered in BEEMS Technical Reports TR544 and TR545.

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[2] XBeach-G is a 1D model for gravel sized sediments (2 – 80 mm) that includes wave swash infiltration and exfiltration processes, which are important to the erosive behaviour of gravel beaches. Whilst the XBeach-S model is calibrated to observations of the existing beach at Sizewell, the XBeach-G model is not strictly calibrated to Sizewell or the SCDF as data does not exist, for example for hydraulic conductivity (the ability of water to infiltrate and exfiltrate through the gravel beach). However, the model is parameterised based on suitable published calibration studies.

The purpose of the modelling within this report will be to provide information to SZC's design engineers that are responsible for the SCDF and HCDF designs. Specifically, the outcome of this modelling will inform the engineering teams to consider the design of the HCDF to meet its safety requirements for nuclear.

In its feedback during the SZC public examination, the Environment Agency (2021) queried whether the range of scenarios tested was sufficient. In the Statement of Common Ground between SZC Co. and the Environment Agency (SZC Co, 2021), the Environment Agency made the following comment:

> *"However, at this point in time it is our opinion that the assessment has not yet considered the full range of reasonable worst case scenarios; specifically it does not include additional more severe storm events, or further consideration of the risk posed by one of more storms occurring sequentially without a safe operating window in between for delivery of mitigation measures."*

This report now addresses the full range of reasonable worst-case scenarios across the 1:10,000 year joint probability spectrum. It also specifically considers storm sequencing by running the 1:10,000 year conditions on a severely depleted profile that represents a severely eroded beach without the proposed mitigation to restore its volume.

1.2 Modelling approach

To understand the SCDF response under design conditions, the SCDF response was tested using conservatively defined 10,000 year return period sea conditions with allowance for climate change mainly at the 'Reasonably Foreseeable' level. Sizewell C design engineers have indicated that this is consistent with the principles on which the design basis sea conditions will be defined for the detailed design. Details of the analysis scenarios are listed below. For ease of terminology, the term 'Reasonably Foreseeable Design Basis' is used in places in this report as shorthand to denote this level of hazard challenge. The SCDF response was tested using an existing 1D XBeach gravel model (see BEEMS Technical Report TR545).

Three 1:10,000 year joint probability scenarios for waves and water levels (including surge) were tested with a 10% increase applied to wave heights due to climate change and sea level rise (SLR) predictions for 2140 under the 95th percentile of the Representative Concentration Pathway (RCP) 8.5. For each scenario the surge component varies according to the peak water level. SLR is first applied to the astronomical tide with the surge component then scaled to raise the peak water level to that of the required 1:10,000 year joint probability water level. The shape of the surge curve was based on the template curve predicted by the Environment Agency for Lowestoft and applicable between Winterton-on-Sea to Aldeburgh (McMillan et al., 2011). This is in line with the Coastal Flood Boundary recommendations for design tide and storm surge in this location.

Three cases were selected as they represent differing magnitudes of waves and water levels:

- Scenario A1: Peak wave height (Hs) = 8.95 m; peak still water level = 3.74 m.
- Scenario E1: Peak Hs = 8.21 m; peak still water level = 5.02 m.
- Scenario F1: Peak Hs = 4.78 m; peak still water level = 6.75 m.

For the three cases considered, a grain size of D_{50} = 10 mm was used, as SZC Co has committed to a default position that the SCDF sediments will match the modal size of native beach sediments, i.e. 10 mm.

Scenario F1 was chosen as it was used as the RFDB conditions for the FRA. To maintain consistency with the FRA the RFDB conditions of Scenario F1 represent conditions inside of the Sizewell-Dunwich bank at the -8 m ODN contour, with the bank present. Whilst scenario F1 produced the worst case for the FRA, it does not necessarily translate to the worst case with respect to the HCDF integrity and potential for toe exposure. Therefore, it was appropriate to also test Scenario A1 and E1, due to their larger wave heights and lower water levels, which may induce larger erosion at the elevation of the HCDF toe (0 m ODN).

To provide another level of conservatism and ensure the most extreme conditions are tested, the offshore conditions of Scenarios A1 and E1, which have the largest waves, were applied to the open boundary of the Xbeach-G storm erosion model without any reduction due to the presence of the Sizewell-Dunwich sand bank, i.e. the bank is fully removed.

To identify which model scenario is being discussed in the results and discussion sections, the notation used in this report identifies the joint probability scenario followed by the particle size. That is:

- $F1_{10mm}$ refers to the F1 joint probability model with a D_{50} of 10 mm;
- $A1_{10mm}$ refers to the A1 joint probability models with a D_{50} of 10 mm;
- $E1_{10mm}$ refers to the E1 joint probability models with a D_{50} of 10 mm.

Based on scientific literature, BEEMS Technical Report TR544 considered an additional option of a modified cobble berm embedded within the SCDF’s inner buffer layer to significantly lower the risk of HCDF exposure and potential damage that could lead to the need to construct the Adapted HCDF. In addition, if it *were* to become exposed it would also lessen the impacts that it would have to coastal processes and the designated Minsmere sites. Fine cobbles are known to be resistant to erosion (from natural examples, full-scale physical models and constructed cobble berms) but are still dynamic and absorb wave energy, unlike hard engineering concrete or rock armour features. Therefore, Scenario F1 was also run with a grain size of D_{50} = 80 mm to simulate the behaviour of fine cobbles. The ancillary results of the 80 mm model runs are presented in Appendix A as they may prove useful for engineering design.

- The F1 scenario using the cobble layer is identified as $F1_{80mm}$ where the D_{50} of 10 mm was $F1_{10mm}$.

2 Methods

2.1 XBeach model

The XBeach-G model was chosen to test the RFDB conditions as it includes groundwater effects (groundwater level, infiltration, exfiltration) since water exchange with the beach face plays an important role in influencing wave uprush and backwash velocities at gravel beaches as well as the sediment transport and morphological response (McCall, 2015). Furthermore, Xbeach-G runs in non-hydrostatic mode which resolves individual wave crests and troughs, as incident wave motion dominates the wave signal at the shore of steep sloping beaches. Therefore, XBeach-G provides a more accurate prediction of wave run-up.

The 1D XBeach-G model, developed and tested in BEEMS Technical Report TR545 has been used for this study. For specific model parameters and description of the XBeach model, see Section 2 of BEEMS Technical Report TR545.

2.2 Model domain

For the 1D simulations, a single cross-shore profile was used at British National Grid Northing 264105 m, which lies at the centre of the Sizewell C frontage. The 1D XBeach-G simulations were performed on the optimised cross-shore resolution as used in BEEMS Technical Report TR545 with a minimum resolution of 0.1 m at the coast, and maximum of 6.3 m at the offshore boundary. This resolution was required for the non-hydrostatic computations[3]. The 1D domain has a cross-shore extent of 1.6 km (which is inshore of the Sizewell-Dunwich Bank) and contains the same artificial slope at the offshore boundary down to 20 m depth for model stability as applied in BEEMS Technical Report TR545[4]. Figure 1 shows the full model domain extent.

The RFDB conditions also specified a severely depleted beach (provided by SZC Co.), rather than a fully recharged SCDF, as the start point for the modelling. That is, the SCDF profile receded landward by 20 m with its 6.5 m ODN design crest eroded and lowered by 1.3 m to 5.2 m ODN. SZC Co have committed to maintaining the SCDF and therefore such a profile is only likely to arise following a sequence of severe storms with insufficient time between them to allow recharge. Therefore, the safety case profile represents a depleted beach following storms without recharge (more depleted than the Beast from the East modelling – a 1:107 year event for cumulative wave energy - in BEEMS Technical Report TR544) and then a subsequent 1:10,000 year storm.

The position of the inner and outer longshore bars was kept the same, which is a conservative assumption. Whilst under natural conditions with sufficient sand supply the longshore bars would be expected to keep pace with the shoreline movement and sea level rise (SLR), it has been assumed under such extreme conditions that the bars would not keep pace i.e., they would temporarily be further offshore relative to the shoreline and in deeper water (owing to SLR), which reduces their dissipative capabilities.

Figure 2 shows the comparison of the RFDB beach profile (blue) with the non-eroded SCDF (orange) and the natural beach profile[5] (yellow). The HCDF structure below the beach is also shown (black). Whilst Figure 2 shows the HCDF toe down to a depth of 0 m ODN, within the model domain the HCDF is set as non-erodible.

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[3] Non-hydrostatic computations require a fine resolution between computational nodes to fully discretise the individual wave forms.
[4] XBeach applies an artificial slope at the offshore boundary to ensure wave breaking does not occur immediately at the offshore boundary.
[5] Natural beach profile was provided by multibeam bathymetry for the marine component and lidar data for the terrestrial topography, collected in 2017.

As the finer sediment (sand) contained in the subtidal bars and offshore region at Sizewell cannot be reliably modelled in the gravel version of XBeach[6], the seabed at Sizewell was made non-erodible within the 1D XBeach model runs seaward of the inner trough of the inner bar (x < 1400, Figure 3). This same approach was used in the XBeach-G runs shown in BEEMS Technical Report TR545. The effect is that the movement of the finer sediment contained in the bars and offshore region is not simulated, meaning that only the dynamics of the subaerial beach/SCDF (pebbles/cobbles) were modelled (x > 1400, Figure 3). This is a reasonable assumption as gravel is not found in the subtidal region and modelling the inner and outer longshore bars as gravel features could lead to unrealistic onshore transport.

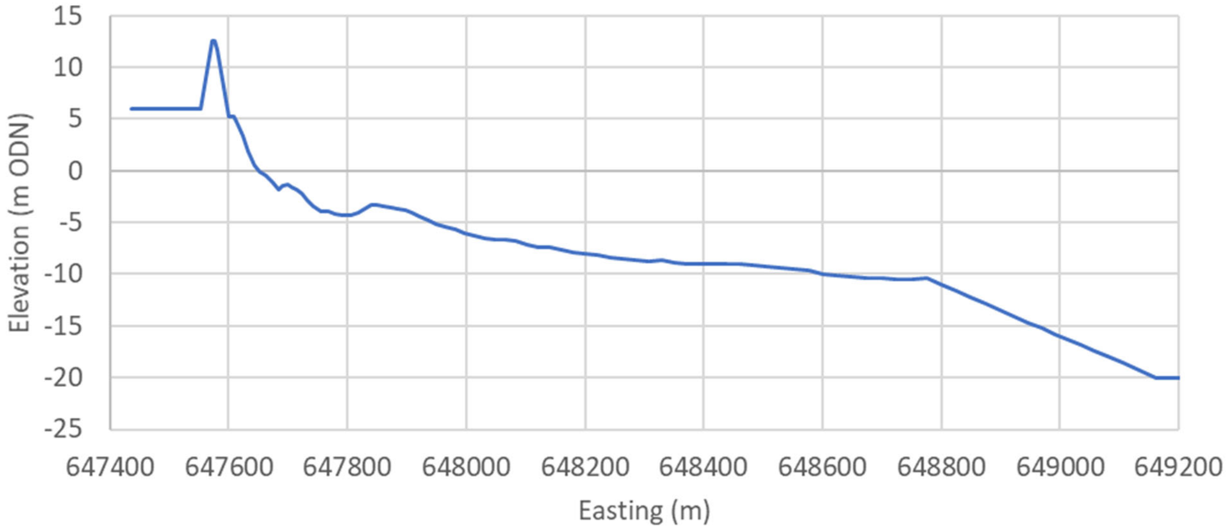


Figure 1 Full model domain extent.

[6] The sand fraction is below the gravel size range (2-80 mm) for which the XBeach-G model was developed.

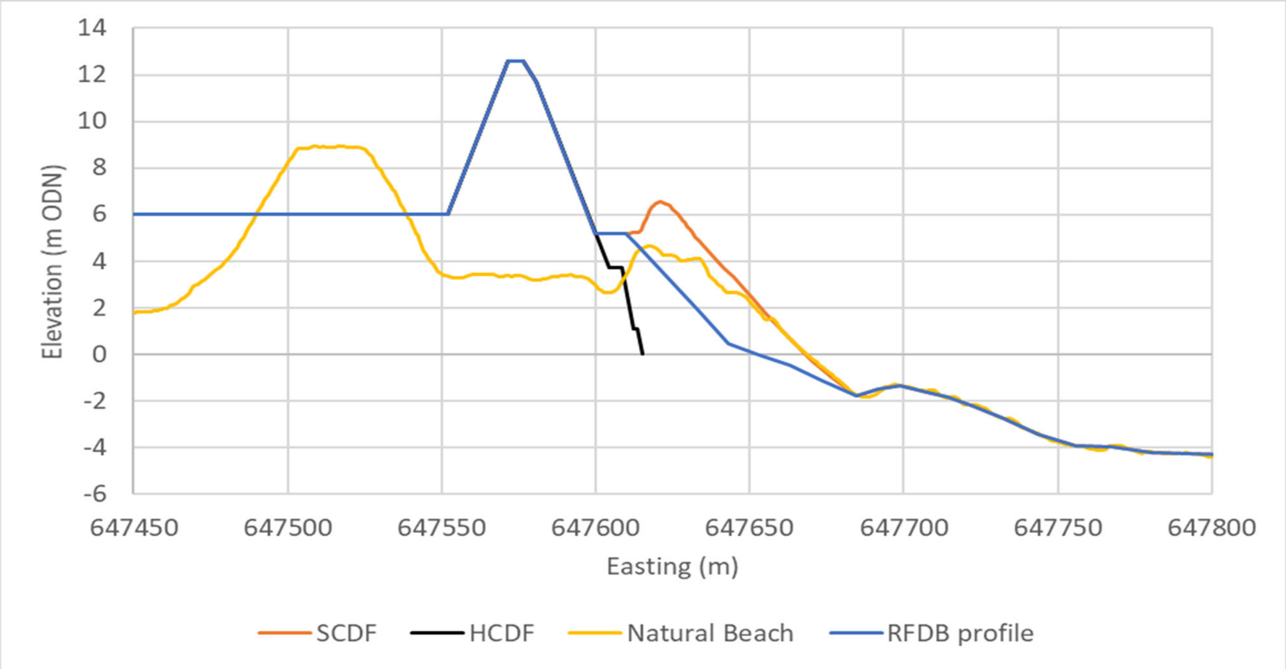


Figure 2 Comparison of the Reasonably Foreseeable Design Basis (RFDB) beach profile with the non-eroded SCDF and the natural beach profile. The HCDF structure below the beach is also shown.

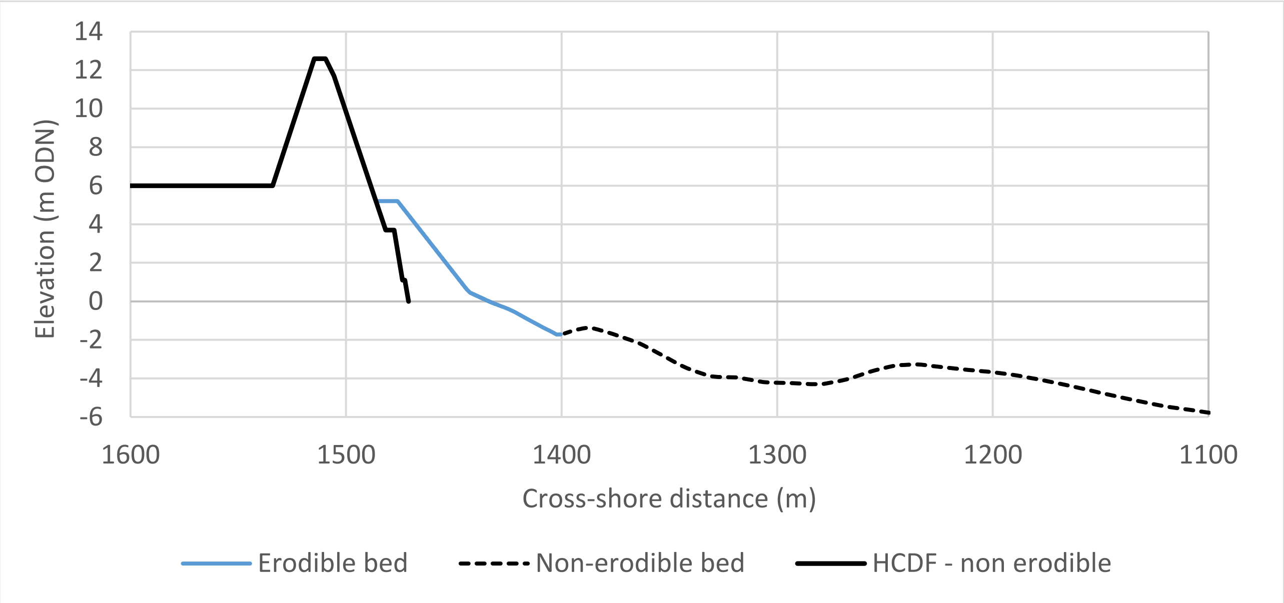


Figure 3 The solid blue line indicates the mobile seabed within the model, while the dotted black line shows the seabed that was made non-erodible in the model. The HCDF profile is also non erodible.

2.3 Boundary conditions

2.3.1 Reasonably Foreseeable Design Basis – Scenario F1

The response of the SCDF for the RFDB is tested against the boundary forcing parameters (wave height and water levels) relating to the joint probability Scenario F1, since it is the most critical joint probability pair in terms of overtopping (see Table 2-7 (Atkins, 2021)).

The joint probability scenarios of waves and tides were originally calculated in BEEMS Technical Report TR319 using UK Climate Projections (UKCP) from 2009. These conditions were then updated following UKCP18 (Lowe et al, 2018) and used for the Basis of Design for the FRA. For this study, SLR for 2140 (with respect to a baseline of 2008) has been taken from the UKCP18 climate scenario RCP8.5 95th percentile. SLR predictions at 2140 (which represents the end of the decommissioning phase of SZC) is +1.82 m. The original assumption of a 10% increase in the wave height/period due to climate change used in BEEMS Technical Report TR319 (from UKCP09) used in the HCDF design to date has been retained for the RFDB modelling. However, it is noted that the long term trends of UKCP18 does in fact suggest a decrease in wave height in this region.

The joint probability conditions presented in BEEMS Technical Report TR319 are for the offshore conditions outside of the Sizewell-Dunwich Bank. Depending on the combination of wave heights and water levels, wave heights can reduce as they pass over the sand banks due to bathymetric wave breaking, but with very extreme water levels, this effect can reduce. The wave and water levels for Scenario F1 applied for the RFDB represent conditions inside of the Sizewell-Dunwich Bank at the -8 m ODN contour. The boundary forcing conditions are applied as a JONSWAP spectrum associated with the respective wave height and period.

For Scenario F1, the peak water level is +6.75 m ODN, peak significant wave height is Hs = 4.78 m and the wave direction is 70° clockwise from North. The modelled storm is 99-hours long and peak wave and water levels (including storm surge) are coincident (see Figure 4). The mean sea level, before storm surge is applied, is c. 1.9 m ODN. A peak surge height of c. 3.5 m is applied to reach the desired peak water level. The lowest water level in the tidal time series is 0.6 m ODN. The wave storm shape has been taken as triangular. A constant mean wave period of Tm = 7.2 seconds has been applied.

2.3.2 Scenarios A1 and E1

Scenario F1 is an extreme 1:10,000 year event for combined waves and water levels, but the wave height is only mid-way on the joint probability curve of possible wave height/water level combinations (Figure 5; BEEMS Technical Report TR319). As the energy levels are lower than the A1 and E1 scenarios, it was considered that whilst F1 is a worst case for flood risk assessment, A1 and E1 are likely to result in higher levels of SCDF erosion and present greater risk of HCDF exposure. Note that the joint probability curves are for offshore conditions seaward of Sizewell-Dunwich Bank and do not include storm surge or SLR. Scenarios A1 and E1 were chosen to test the sensitivity of the RFDB beach profile to the larger waves of these scenarios (compared to the F1 peak Hs = 4.78 m). From Figure 5 it can be seen that Scenario A1 represents the combined conditions with the highest wave heights (Hs = 8.95 m), but the lowest water levels, which is most likely to cause the largest beach change on the lowest portions of the beach profile. Scenario E1, has marginally smaller waves (Hs = 8.21 m) but over 1 m higher water levels.

To provide another level of conservatism for storm erosion modelling, the offshore combined wave and water levels of Scenario A1 and E1 are applied to the open boundary of the Xbeach-G model without any reduction due to the presence of the Sizewell-Dunwich Bank, i.e. wave dissipation due to the bank is excluded.

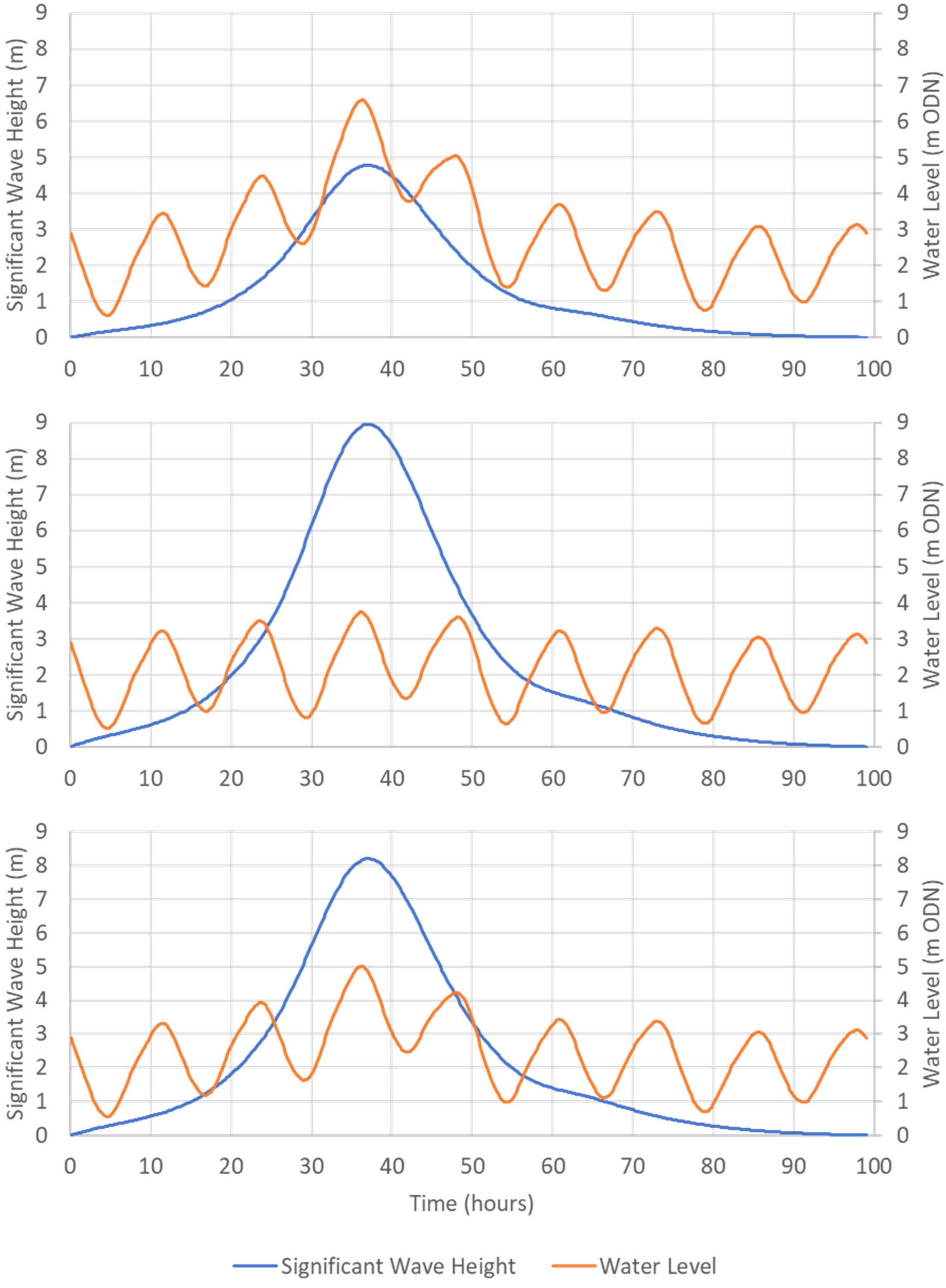


Figure 4 Water level and significant wave height boundary conditions for the RFDB Scenario F1 (top), A1 (middle) and E1 (bottom).

For Scenario A1, the peak water level is +3.74 m ODN with a peak significant wave height, Hs, of 8.95 m. For Scenario E1, the peak water level is +5.02 m ODN with a peak Hs is 8.21 m. For both scenarios A1 and E1, the wave direction is 70° clockwise from North. The storms are 99-hours long and peak wave and water levels are coincident (see Figure 4). As with Scenario F1, the time series of water levels includes a storm surge. For Scenario A and E, the peak surge component is c. 0.5 m and c. 1.5 m, respectively. For both storms the mean sea level before surge is the same as Scenario F1, i.e., c. 1.9 m ODN. The lowest water level is 0.51 m ODN and 0.56 m ODN, for Scenario A1 and E1, respectively. The wave storm shape has been taken as triangular. A constant mean wave period of Tm = 12.61 seconds has been applied for Scenario A1 and a constant mean wave period of Tm = 12.1 seconds for Scenario E1. The wave period is that associated with the return interval wave height. As the Scenarios A1 and E1 represent conditions outside of the bank, the wave height is larger and hence the period is longer, but also the wave period has not been shortened due to energy dissipation over the bank.

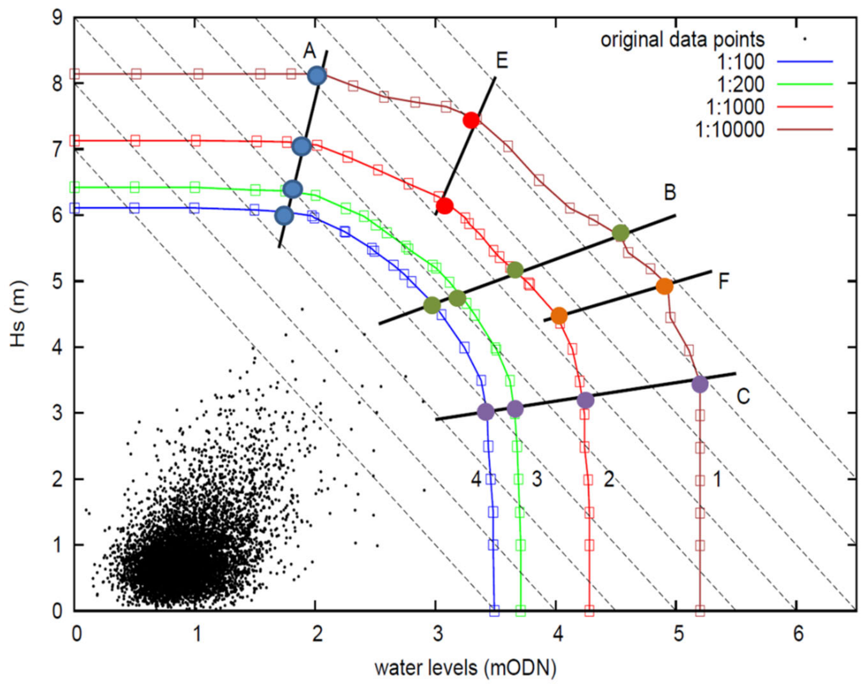


Figure 5 Joint probability curves of combined waves and water levels. Dashed lines mark where the water level is half that of Hs. Different joint probability scenarios were assigned a unique letter in BEEMS Technical Report TR319 (A, E, B, F, C) and a numeral representing the return periods as shown on the plot e.g., 1 is the 1:10,000 year joint probability. Water levels are relative to the 2008 baseline. Figure originally produced in BEEMS Technical Report TR319.

3 Results

3.1 Reasonably Foreseeable Design Basis - Scenario F1

Figure 6 shows the resulting change in the depleted RFDB beach profile with a D_{50} = 10 mm grain size under the combined 1:10,000-year joint probability wave and water levels of Scenario F1, with storm surge and RCP8.5 95th percentile 2140 SLR. Results showed that beach material was eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. The coastal path, at an elevation of 5.2 m ODN, was eroded with a maximum reduction in bed elevation of 1.4 m, with a maximum increase of ~ 1.0 m in bed elevation in the intertidal zone above the 0 m ODN mark. The HCDF was not exposed and there was still beach volume above the 3.7 m ODN platform level with a depth of 0.25 m. However, given the model is a gravel only model and does not include the finer grain sizes, it is likely this edge of the HCDF would be exposed. However, this portion of the HCDF is able to withstand exposure. Below the 0 m ODN mark, there was minimal change in bed elevation. Over the length of the RFDB conditions, the net change in beach volume is +0.01 m^3/m, with 104.09 m^3/m beach volume remaining. The beach volume is calculated with respect to a seaward boundary of 0 m ODN (the depth of the HCDF toe), which is consistent with the volumetric calculations in BEEMS Technical Reports TR544 and TR545.

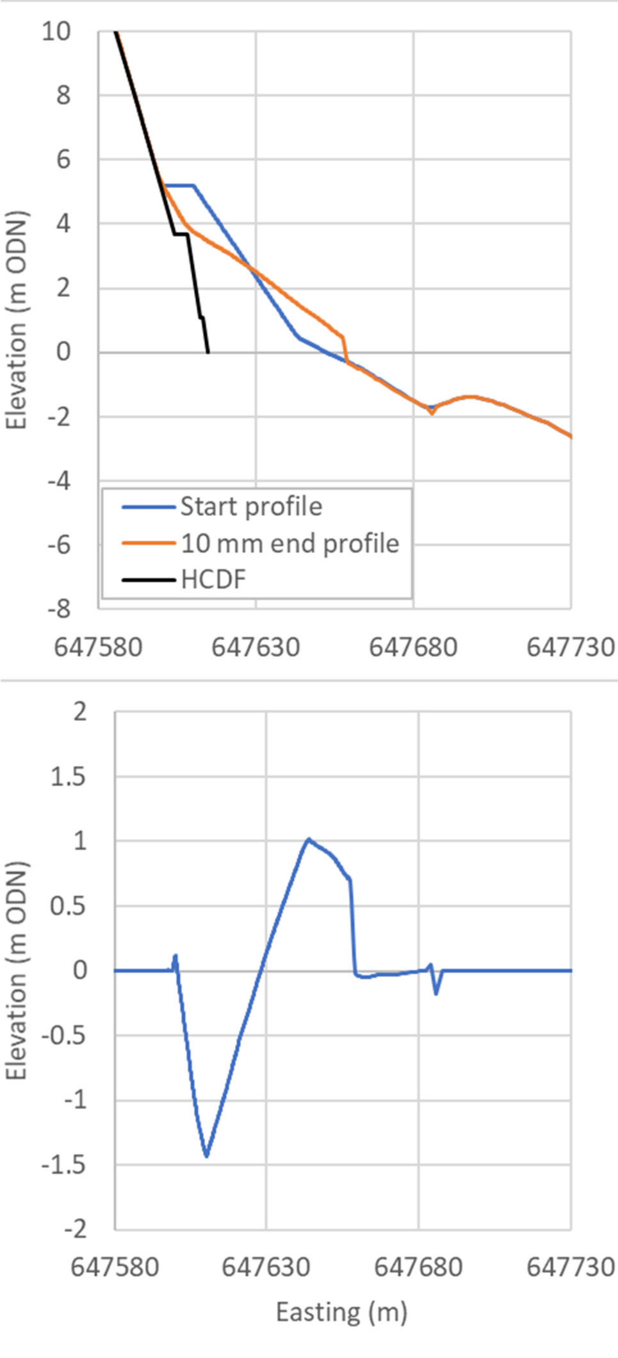


Figure 6 Start and end beach profile (top) and the profile changes (bottom) for the RFDB profile under Scenario F1 conditions with D_{50} = 10 mm grain size.

3.2 Reasonably Foreseeable Design Basis - Scenario A1

During the running of Scenario A1, a scour pit began forming at the landward edge of the subtidal non-erodible layer, as shown in Figure 3, where the low water levels and waves were leading to erosion of the lower intertidal zone. As this scour pit is an unrealistic artefact (due to the non-erodible layer inhibiting bed evolution that would occur in reality), the landward end of the non-erodible layer was moved 60 m seaward to the outside of the inner longshore bar (for Scenario A1 only, as the higher water levels of Scenario E1 lead to minimal effect). Whilst this allowed for more realistic evolution of the lower beach, the effect on the subaerial beach is minimal as the beach material from the upper subaerial beach is mainly deposited landward of the inner longshore bar with only small changes to the inner longshore bar itself (see Figure 7; left panel).

Figure 7 (left panel) shows the resulting change in the depleted RFDB beach profile with a D_{50} = 10 mm grain size under the combined 1:10,000-year joint probability wave and water levels: Scenario A1, with storm surge and RCP8.5 95th percentile 2140 SLR. Results showed that beach material was eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. The coastal path, at an elevation of 5.2 m ODN, was eroded with a maximum reduction in bed elevation of 1.5 m, with a maximum increase of ~ 1.2 m in bed elevation in the intertidal zone below the 0 m ODN mark. The end profile showed that the HCDF was not exposed and there was still beach volume above the 3.7 m ODN platform level with a depth of 0.2 m. However, given the model is a gravel only model and does not include the finer grain sizes, it is likely this edge of the HCDF would be exposed. However, this portion of the HCDF is able to withstand exposure, whereas the toe is assumed not to be able to withstand exposure. Over the length of the RFDB conditions, the net change in beach volume is -25.55 m^3/m, with 78.53 m^3/m beach volume remaining. The beach volume is calculated with respect to a seaward boundary of 0 m ODN (the depth of the HCDF toe).

3.3 Reasonably Foreseeable Design Basis - Scenario E1

Figure 7 (right panel) shows the resulting change in the depleted RFDB beach profile with a D_{50} = 10 mm grain size under the combined 1:10,000-year joint probability wave and water levels Scenario E1, with storm surge and RCP8.5 95th percentile 2140 SLR. Results showed that beach material was eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. The coastal path, at an elevation of 5.2 m ODN, was eroded with a maximum reduction in bed elevation of 1.6 m, with a maximum increase of ~ 1.1 m in bed elevation in the intertidal zone below the 0 m ODN mark. The end profile showed that the HCDF was not exposed and there was still beach volume above the 3.7 m ODN platform level with a depth of 0.2 m. However, given the model is a gravel only model and does not include the finer grain sizes, it is likely this edge of the HCDF would be exposed. Over the length of the RFDB conditions, the net change in beach volume is -22.51 m^3/m, with 81.57 m^3/m beach volume remaining. The beach volume is calculated with respect to a seaward boundary of 0 m ODN (the depth of the HCDF toe).

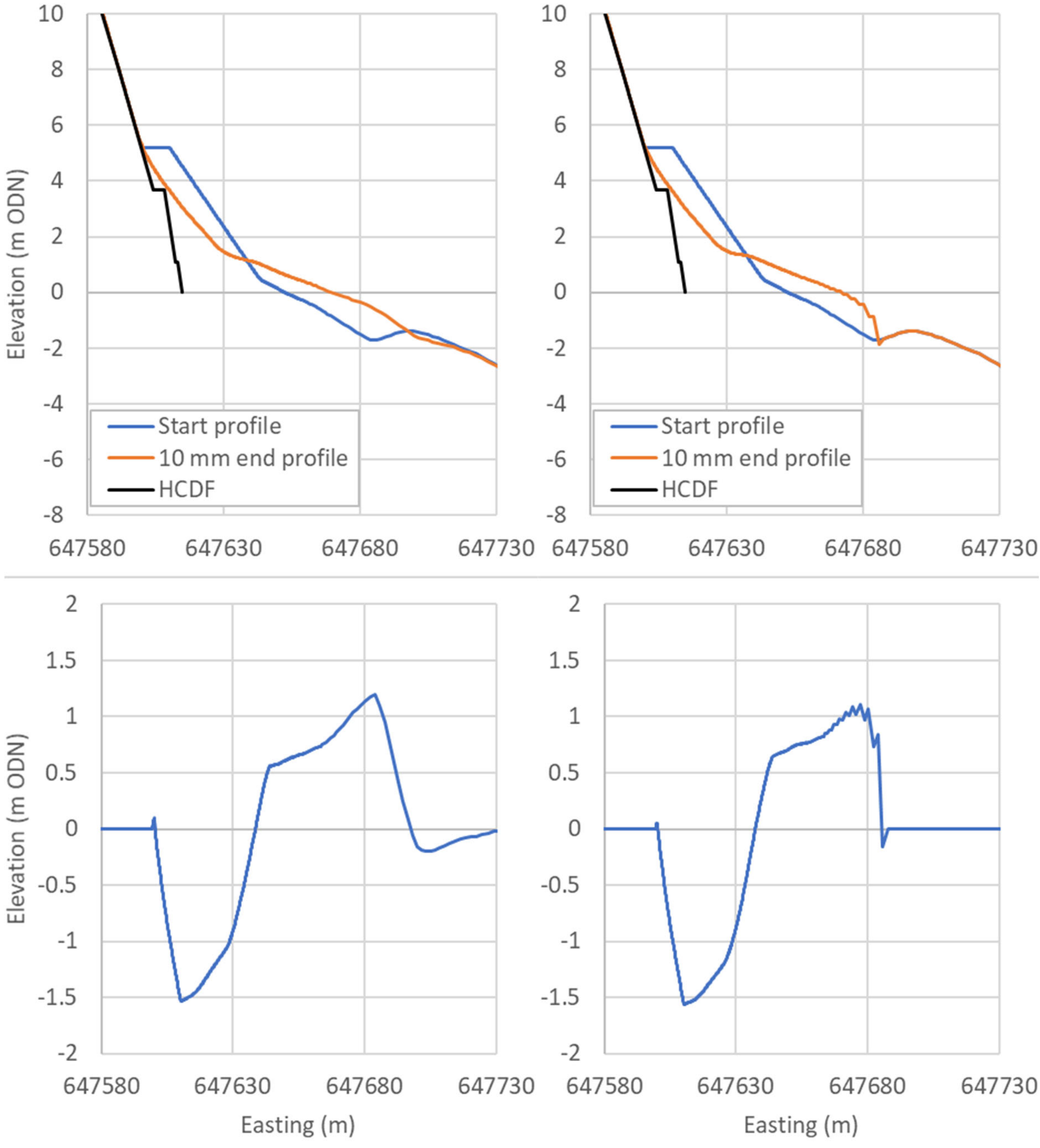


Figure 7 Start and end beach profile (top) and the profile changes (bottom) for the RFDB profile under Scenario A1 (left) and E1 (right) with a D_{50} = 10 mm grain size.

3.4 Beach width and depth

Whilst the change in beach volume is an important metric to understanding the beach evolution under storm conditions, there are other metrics. Beach width and the depth of sediment above the buried section of the HCDF also provide useful information to the engineers that are responsible for the SCDF and HCDF designs.

Figure 8 shows the start and end profiles of all scenarios along with full SCDF profile for reference. Additionally, it also shows the horizonal beach width seaward of the HCDF for all elevations above the elevation of the HCDF toe (0 m ODN).

In all the horizontal beach width lines, there are two notable notches at the 1.1 m ODN and 3.7 m ODN contours. These are the elevations of the two horizontal platforms of the HCDF profile (shown in the top plot of Figure 8) and the notches represent where the beach width grows momentarily between the seaward and landward edges of those elevations.

For all three scenarios with a grain size of D_{50} = 10 mm ($A1_{10mm}$, $E1_{10mm}$ and $F1_{10mm}$), the beach width at the 3.7 m ODN contour is almost fully eroded with only a small amount of beach material vertically above this point (0.19-0.25 m). Equally for the same scenarios, the beach width grows at the elevation of the HCDF toe (0 m ODN). Vertically above the HCDF toe, the depth of sediment reduces from 4.53 m at the start of the RFDB profile to a minimum (for all scenarios) of 3.02 m representing a 1.51 m vertical reduction in sediment depth above the HCDF.

Table 1 summaries the beach width seaward of the HCDF, at different elevations between the HCDF toe (0 m ODN) and coastal path behind the SCDF (5.2 m ODN) for the different scenarios tested. Table 2 summarises depth of sediment above the buried HCDF profile at the HCDF toe and the leading edge of the 3.7 m ODN platform.

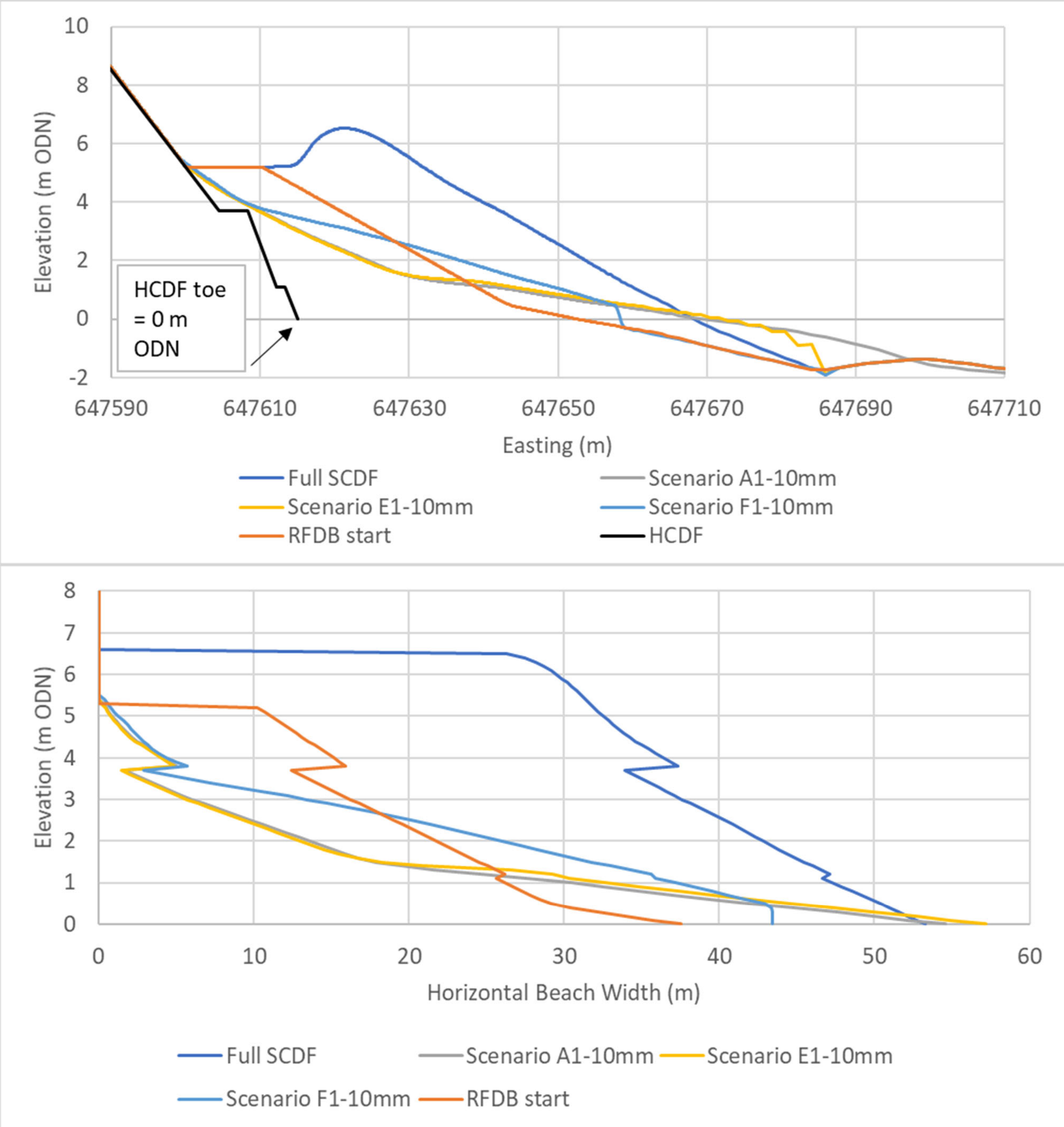


Figure 8 Start and end profiles of all scenarios (top) and the horizonal beach width seaward of the HCDF above the elevation of the HCDF toe (bottom), along with full SCDF profile for reference.

Table 1 Summary of the beach width seaward of the HCDF, at different elevations between the HCDF toe (0 m ODN) and coastal path behind the SCDF (5.2 m ODN).

Contour (m ODN)	Beach Width (m)				
	Full SCDF start profile	RFDB start profile	Scenario $A1_{10}$mm end profile	Scenario $E1_{10}$mm end profile	Scenario $F1_{10}$mm end profile
5.2	31.90	10.20	0.48	0.40	0.77
3.7	33.94	12.42	1.60	1.43	2.87
1.16 (MHWS)	47.15	26.17	24.69	29.26	35.66
0.71 (MHWN)	49.16	27.82	37.07	39.69	40.58
0 (HCDF toe)	53.29	37.56	54.60	57.21	43.40

Table 2 Depth of sediment above the buried HCDF profile at the HCDF toe and the leading edge of the 3.7 m ODN platform.

Profile	Depth of sediment above HCDF toe (0 m ODN)	Depth of sediment above 3.7 m ODN platform (leading edge)
Full SCDF	5.33	1.50
RFDB start	4.53	1.50
Scenario $A1_{10mm}$	3.06	0.21
Scenario $E1_{10mm}$	3.02	0.19
Scenario $F1_{10mm}$	3.47	0.25

4 Discussion

4.1 Beach response

The RFDB beach profile represents a severely eroded beach profile acted upon by both extreme wave and water levels. It is representative of a beach profile whereby the SCDF's sacrificial layer has been fully eroded and only part of the inner buffer layer remains– 45.7% of the full 104.08 m^3/m SCDF (as shown in Figure 10). In practice, the beach would be recharged as soon as possible after the recharge trigger volume had been reached, meaning that the RFDB profile is unlikely to occur, and if it did it would not remain in this state for extended periods. However, were a storm to attack the severely depleted RFDB beach profile, the modelling results showed that the HCDF would not be exposed (for all the 10 mm grain size scenarios). Figure 9 shows a schematic cross section of the HCDF and SCDF, as shown in BEEMS Technical Report TR544. The red line shows the indicative position of the recharge threshold (yet to be agreed in the CPMMP, BEEMS Technical Report TR523). Whereas the dark line shows the RFDB start profile, which is likely to be well behind the SCDF recharge threshold.

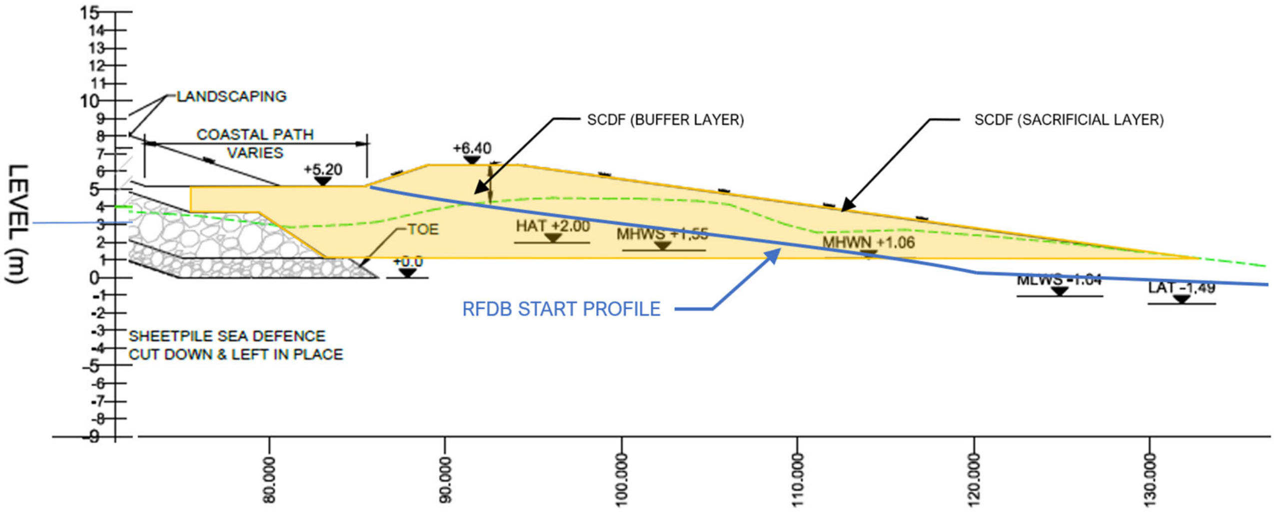


Figure 9 Schematic cross-sections of the hard and soft coastal defence features (HCDF and SCDF) taken from BEEMS Technical Report TR544. The SCDF (yellow) is conceptually divided into two volumes, separated by the SCDF recharge threshold $V_{recharge}$ (yet to be defined). The SCDF *buffer* layer (whose volume is V_{buffer}) is not intended to be exposed, whilst the SCDF sediment to seaward is *sacrificial* (V_{sac}) and would be replenished once $V = V_{rechange}$.

Three 1:10,000 year joint probability cases were investigated. The F1 scenario was first selected as it was the worst case for overtopping and Flood Risk Assessment, however the A1 and E1 scenarios provided worse cases for storm erosion because their wave power is substantially higher than F1. For example, the peak Hs for A1 is almost double that of F1, although the A1 water levels are substantially lower (3.75 m ODN) than F1 (6.75 m ODN). The higher rates of erosion (beach translation and volumetric loss) are shown in Figure 10. It is worth noting that the combined waves and water levels of Scenario A1 and E1 are representative of offshore conditions applied directly to the XBeach-G model boundary, which is landward of Sizewell-Dunwich Bank –this means that the natural energy dissipating effects of the bank are not included in the A1 and E1 models, but are included in the XBeach-G F1 model. For Scenario $A1_{10mm}$, $E1_{10mm}$ and $F1_{10mm}$ the volume eroded from the upper subaerial beach (above the point of inflection, whereby the beach material is deposited on the lower subaerial beach) is much higher (-37.95 m^3/m and -38.22 m^3/m, respectively) than $F1_{10mm}$ (-20.34 m^3/m) as a result of the differences in wave energy.

The model results for the $F1_{10mm}$ scenario showed a low net volumetric gain, 0.01 m^3/m. Whilst this contrasts with the results of the NE 1:20 year return interval for wave height with 2140 RCP4.5 SLR and a D_{50} =10 mm grain size used with XBeach-G with in BEEMS Technical Report TR545, which showed net volumetric losses of up to -16 m^3/m, the results are not unexpected. The volumetric calculations are provided for the beach volume above the 0 m ODN mark (the depth of the HCDF toe), as undertaken in BEEMS Technical Reports TR544 and TR545. Due to the F1 water levels (peak of 6.75 m ODN), there is very little change below the 0 m ODN mark. The lowest water level in the model boundary conditions for Scenario F1 is 0.6 m ODN (excluding waves). The highest water levels submerged the entire beach profile and reshaped the upper subaerial beach (Figure 11). The $F1_{10mm}$ model erodes the highest portions of the subaerial beach above the 2.8 m ODN contour. However, this eroded material during the $F1_{10mm}$ run is deposited lower on the intertidal beach but above the 0 m ODN mark, resulting in minimal net change but with a reprofiled beach.

Figure 11 shows the start and end beach profiles of the $F1_{10mm}$ results, alongside the horizontal beach profile change. For the D_{50} = 10 mm grain size runs, the cut and fill beach response removes a large portion of the upper subaerial beach and deposits the eroded material on the lower subaerial beach. The largest horizontal beach translations of the eroded upper subaerial beach are -11.1 m and -11.2 m (both at the 4.2 m ODN contour, negative translations are landward) for Scenarios $A1_{10mm}$ and $E1_{10mm}$, respectively, compared to -10.9 m (at the 4.1 m ODN contour) for $F1_{10mm}$. By comparison, the largest horizontal beach translation of the eroded subaerial beach, under the NE 1:20 year return interval (modelled in BEEMS Technical Report TR545), is -7.9 m (at the 3 m ODN contour, Figure 12). At the 5.2 m contour (the approximate height of the coastal path behind the SCDF), the beach under all three scenarios with a grain size of D_{50} = 10 mm is almost fully eroded back to the HCDF with only 0.4 - 0.77 m of beach width remaining (Table 1).

The A1 and E1 scenarios were specifically tested due to their higher wave energy levels and erosion potential. The choice to feed offshore waves directly into the model, effectively removing the dissipative effects of Sizewell-Dunwich Bank, adds a further layer of extremism into this safety case modelling. There is no evidence to suggest that the bank would be lost over the life of the station. At the end of the simulations, over 3 m of beach material covered the HCDF toe and the beach width at the 0 m ODN contour (the depth of the toe) the beach width grew by 17.0 m and 19.7 m, for Scenario $A1_{10mm}$ and $E1_{10mm}$ respectively (see Table 1 and Table 2).

The degree of erosion is almost the same for A1 and E1, with Scenario E1 having slightly larger volumetric loss and horizontal beach translation despite the larger waves. However, E1 volumetric erosion and horizontal beach translation were only 0.27 m^3/m and 0.1 m, respectively, greater than A1.

Under these extreme A1 and E1 scenarios the beach volume is sufficient to avoid exposing the HCDF, however the remaining volumes are low in some places and model uncertainty means exposure could occur under real world equivalent scenarios. Therefore, SCDF maintenance is key to avoiding an RFDB profile (or similar) arising, which is the start point of this modelling. This would be avoided by ensuring that beach recharge occurs promptly when triggered. Note that long-term progressive erosion is not considered in this report, however this would not change the presented modelling results as this report is only considering the short-term storm response. Further HCDF exposure risk reduction from rising sea levels and sequences of severe storms without the opportunity to recharge, can be gained though the inclusion of a layer of fine cobbles in the design (see Appendix A).

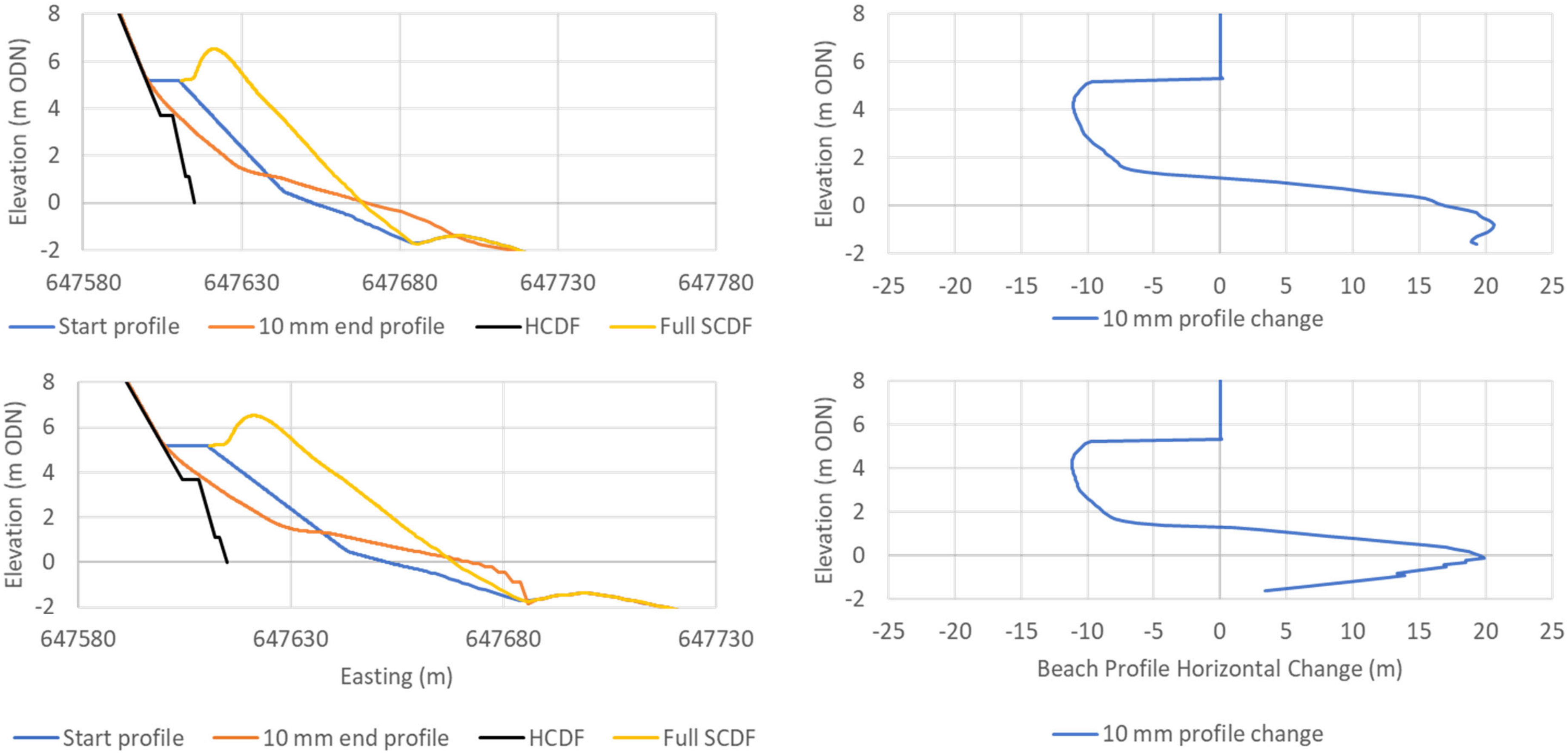
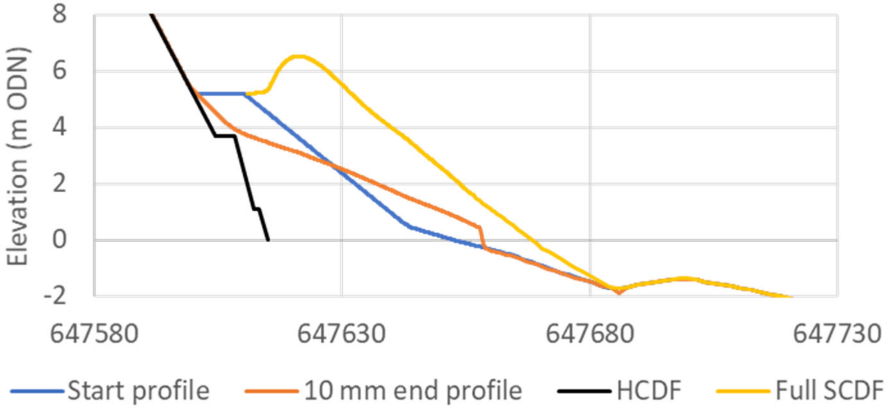


Figure 10 Start and end beach profile (left) and the horizontal profile changes (right) for the RFDB Scenario A1 (top) and E1 (bottom) with a D_{50} = 10 mm grain size.



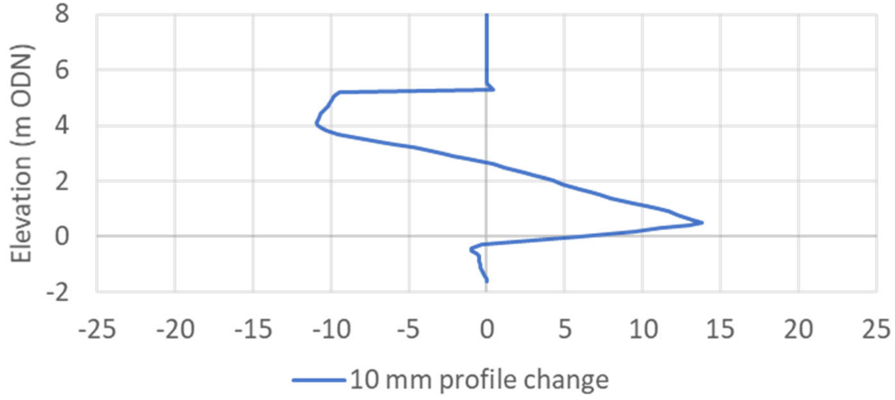


Figure 11 Start and end beach profile (left) and the horizontal profile changes (right) for the RFDB Scenario F1 with a D_{50} = 10 mm grain size.

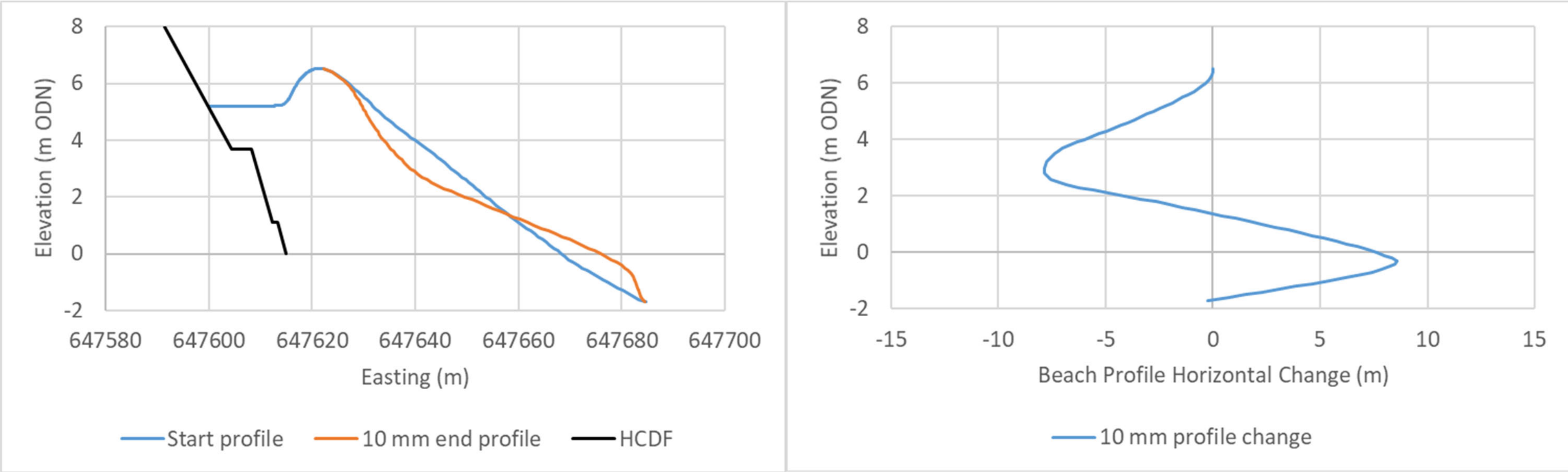


Figure 12 Start (full SCDF profile) and end beach profile (left) and the horizontal profile changes (right) for the NE 1:20 year return interval for wave height and RCP4.5 2140 SLR with a D_{50} = 10 mm grain sizes.

Whilst the HCDF toe was not exposed under the A1 and E1 1:10,000 year events, the worst erosion with respect to HCDF integrity, specifically toe undermining potential, may not in fact be a joint probability 1:10,000 scenario. Lower water levels with extreme waves could cause worse erosion at the toe level. The reasons for having confidence at this stage that scenarios with lower sea water levels would not be onerous and would not threaten to undercut the toe of the hard sea defence at 0.0 m ODN are as follows:

- The maximum horizontal erosion observed for the three modelled cases was 10.9 -11.2m. As the pre-eroded beach at the HCDF toe elevation is 37.5m wide, a similar degree of erosion would not threaten HCDF exposure.
- From the distribution of results over the modelled cases, the sensitivity of the erosion pattern to sea water level appears to be reducing for lower sea water levels. That is, the erosion patterns shown in Scenario A1 and E1 (Hs = 8.95 m and 8.21 m respectively) are almost identical despite the difference in peak water level, showing the cut and fill pattern for such large waves is insensitive to the A1 – E1 water level.
- Waves at the beach face would be much smaller under lower water levels due to extensive wave breaking and dissipation. Similarly, the extent of horizontal erosion would be reduced (i.e. < 11m). Large waves (e.g. Scenario A1) at present day mean sea levels (~0m ODN) will start to break in approximately 11–12 m of water depth on the seaward side of Sizewell-Dunwich Bank , effectively creating a 2800m-wide surf zone to the shoreline that would significantly reduce wave height and energy at the beach face.
- In any event, the SCDF has a large volume and would be maintained, and the modelled conditions are for design basis and highly unlikely to occur.

Scenarios with lower sea water levels, as well as the range modelled in this report (BEEMS Technical Report TR553), will be assessed as part of the detailed design of the permanent sea defences by SZC Co.

5 Conclusions

For this report, the SCDF response was tested using conservatively defined 10,000 year return period sea conditions with allowance for climate change mainly at the 'Reasonably Foreseeable' level. Sizewell C design engineers have indicated that this is consistent with the principles on which the design basis sea conditions will be defined for the detailed design. Details of the analysis scenarios are listed below. For ease of terminology, the term 'Reasonably Foreseeable Design Basis' is used in places in this report as shorthand to denote this level of hazard challenge. The present analysis embodies several conservatisms in terms of the hydraulic input parameters and the pre-receded beach geometry (as supplied by SZC Co.) which is assumed. Three 1:10,000 year joint probability scenarios for waves and water levels (including surge) were tested with a 10% increase applied to wave heights and sea level rise (SLR) predictions for 2140 under the 95th percentile of the Representative Concentration Pathway (RCP) 8.5. Three cases were selected as they represent differing magnitudes of waves and water levels:

- Scenario A1: Peak Hs (wave height) = 8.95 m; peak still water level = 3.74 m.
- Scenario E1: Peak Hs = 8.21 m; peak still water level = 5.02 m.
- Scenario F1: Peak Hs = 4.78 m; peak still water level = 6.75 m.

The RFDB was tested using the existing 1D XBeach gravel model used in BEEMS Technical Report TR545. The RFDB conditions also specified a severely depleted beach (provided by SZC Co.), rather than a fully recharged SCDF, as the start point for the modelling. That is, the SCDF profile receded landward by 20 m with its 6.5 m ODN design crest eroded to 5.2 m ODN. SZC Co have committed to maintaining the SCDF and therefore such a profile is only likely to arise following a sequence of severe storms with insufficient time between them to allow recharge.

All scenarios were modelled using a grain size of D_{50} = 10 mm, as SZC Co has committed to a default position that the SCDF sediments will match the modal size of native beach sediments, i.e. 10 mm.

The $F1_{10mm}$ model showed that beach material was eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. The coastal path, at an elevation of 5.2 m ODN, was eroded with a maximum vertical reduction in bed elevation of 1.4 m. The maximum horizontal translation was -10.9 m (at the 4.1 m ODN contour, negative translations are landward). The HCDF was not exposed and its 3.7 m ODN platform had 0.25 – 0.84 m of sediment thickness remaining at the end of the modelled storm. The maximum erosion at the end of $F1_{10mm}$ storm was -20.34 m^3/m, but the net change in beach volume was +0.01 m^3/m, with 104.09 m^3/m beach volume remaining.

Scenario F1 was tested as an RFDB condition for HCDF integrity as it represented a worst case for overtopping during the Flood Risk Assessment (FRA). However, whilst appropriate for the FRA more energetic wave conditions were considered to assess the worst case for beach erosion i.e., Scenarios A1 and E1. Scenarios A1 and E1 have lower water levels but higher waves (than F1) and resulted in higher levels of beach erosion, both volumetrically and horizontal retreat. However, Scenarios A1 and E1 represent offshore conditions without the presence of the Sizewell-Dunwich Bank, whereas Scenario F1 includes the bank present. Therefore, more erosion is to be expected with scenarios A1 and E1 compared to F1. The degree of erosion is almost the same for A1 and E1, with Scenario E1 having slightly larger volumetric loss and horizontal beach translation despite the larger waves. However, E1 volumetric erosion and horizontal beach translation were only 0.27 m^3/m and 0.1 m, respectively, greater than A1.

Both Scenarios $A1_{10mm}$ and $E1_{10mm}$ show similar response patterns to Scenario $F1_{10mm}$ with beach material eroded from the upper supratidal beach and deposited lower on the subaerial beach and intertidal zone. For Scenarios $A1_{10mm}$ and $E1_{10mm}$ the volume eroded from the upper subaerial beach (above the point of inflection, whereby the beach material is deposited on the lower subaerial beach) is -37.95 m^3/m and -38.22

m^3/m, respectively, compared to -20.34 m^3/m for Scenario $F1_{10mm}$. The largest horizontal beach translation of the eroded upper subaerial beach is -11.1 m and -11.2 m for Scenario A1 and E1, respectively, which is similar to the F1 maximum retreat of -10.9 m.

The RFDB conditions represent 1:10,000 year events of combined wave and water levels on an initial severely eroded beach profile. The eroded beach profile used in this report represents loss of the SCDF's sacrificial layer with only parts of the inner buffer layer remaining. The RFDB start profile has a volume of 104.08 m^3/m, which is less than half (45.7%) of the full SCDF profile. In reality, the beach would be recharged in as short a period as reasonably practical and therefore would not remain in this state for extended periods. However, should the oceanographic conditions of the RFDB occur with the beach in this state, then the modelling results show that the 10 mm D_{50} grain size would be sufficient to withstand all three 1:10,000 year events modelled without exposing the HCDF, however model uncertainty means that this statement cannot be made with complete confidence especially as some sections are almost exposed under the modelled conditions.

Whilst the HCDF toe was not exposed under the A1 and E1 1:10,000 year events, the worst erosion with respect to HCDF integrity, specifically toe undermining potential, may not in fact be a joint probability 1:10,000 scenario.

Whilst the HCDF toe was not exposed under the A1 and E1 1:10,000 year events, the worst erosion with respect to HCDF integrity, specifically toe undermining potential, may not in fact be a joint probability 1:10,000 scenario. Lower water levels with extreme waves could cause worse erosion at the toe level, however, there is good confidence that scenarios with lower sea water levels would not be onerous and would not threaten to undercut the toe of the hard sea defence at 0.0m AOD. Scenarios with lower sea water levels, as well as the range modelled herein, will be assessed as part of the detailed design of the permanent sea defences by SZC Co.

In any event, from an Environmental Impact Assessment (EIA) perspective, even if in the extremely unlikely event that the HCDF were to be exposed, mitigation by way of sediment by-passing would be used to maintain sediment transport pathways until the SCDF could be recharged. There would be no significant impact on downdrift beaches which themselves would have undergone significant change during such extreme events.

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Appendix A Modelling D_{50} = 80 mm grain size

A.1 Background

A D_{50} = 80 mm model run was chosen to simulate the behaviour of fine cobbles, which are known in nature, full-scale physical models and constructed cobble berms to be resistant to erosion but still dynamic and absorptive of wave energy, unlike hard engineering concrete or rock armour features. Based on scientific literature, BEEMS Technical Report TR544 proposed a modified cobble berm embedded within the SCDF's inner buffer layer to significantly lower the risk of HCDF exposure. In addition, this element of the design would also lessen the impacts that it would have to coastal processes and the designated Minsmere sites and reduce the need to construct the Adapted HCDF (owing to risks of the HCDF toe becoming undermined).

A.2 Results

A.2.1 Reasonably Foreseeable Design Basis - Scenario F1 80 mm grain size

Figure 13 (right panels) shows the resulting change in the depleted RFDB beach profile with an D_{50} = 80 mm grain size under the combined 1:10,000-year joint probability wave and water levels of Scenario F1, with storm surge and RCP8.5 95th percentile 2140 SLR. The results are shown alongside Scenario F1 with a D_{50} = 10 mm grain size (left panels) for comparison. Results showed that beach material was eroded from the lower subaerial beach and deposited higher up the subaerial beach. The coastal path, at an elevation of 5.2 m ODN, was built up further with a maximum increase in bed elevation of ~1.5 m, with a maximum decrease of ~0.9 m in bed elevation in the intertidal zone above the 0 m ODN mark. The HCDF was not exposed and there was an increase in beach volume above the 3.7 m ODN platform level with a depth of 1.85 m. Below the 0 m ODN mark, there was minimal change in bed elevation. Over the length of the RFDB conditions, the net change in beach volume is +3.32 m^3/m, with 107.40 m^3/m beach volume remaining. The beach volume is calculated with respect to a seaward boundary of 0 m ODN (the depth of the HCDF toe).

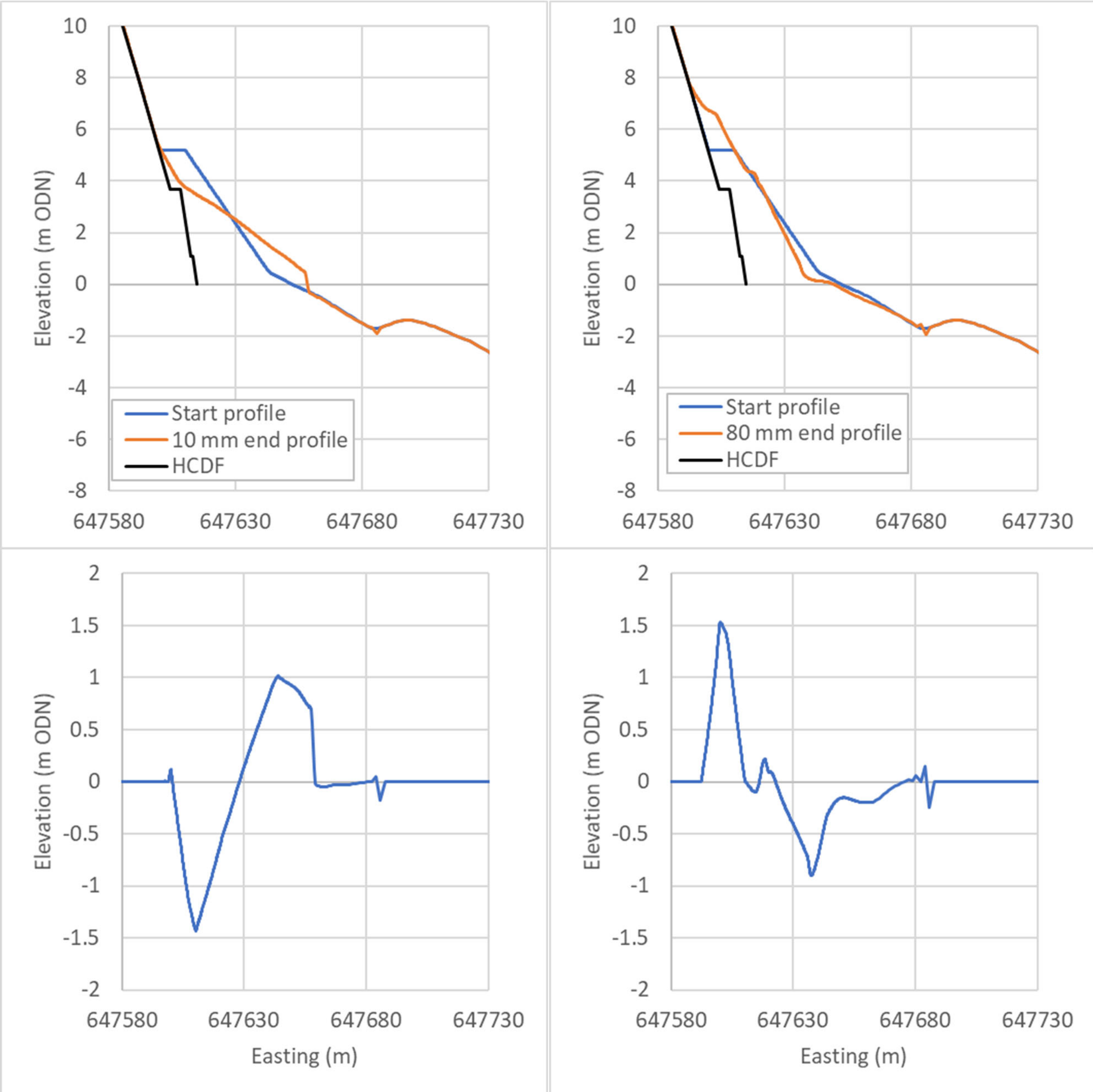

Figure 13 Start and end beach profile (top) and the profile changes (bottom) for the RFDB profile under Scenario F1 conditions with D_{50} = 10 mm (left) and D_{50} = 80 mm (right) grain sizes.

A.2.2 Beach width and depth

Whilst the change in beach volume is an important metric to understanding the beach evolution under storm conditions, there are other metrics. Beach width and the depth of sediment above the buried section of the HCDF also provide useful information to the engineers that are responsible for the SCDF and HCDF designs.

Figure 14 shows the start and end profiles of all scenarios along with full SCDF profile for reference. Additionally, it also shows the horizonal beach width seaward of the HCDF for all elevations above the elevation of the HCDF toe (0 m ODN).

In all the horizontal beach width lines, there are two notable notches at the 1.1 m ODN and 3.7 m ODN contours. These correspond to the elevations of the two horizontal platforms of the HCDF profile (shown in the top plot of Figure 14) and the notches represent where the beach width grows momentarily between the seaward and landward edges of those elevations.

For the $F1_{80mm}$ scenario the depth of sediment at the leading edge of the 3.7 m ODN platform grows (from 1.5 m to 1.85 m). Whereas, in comparison with the $F1_{10mm}$ scenario, the beach width at the 3.7 m ODN contour is almost fully eroded with only a small amount of beach material vertically above this point (0.25 m). For the $F1_{80mm}$ scenario the largest horizontal beach translation was a reduction of 8.3 m in beach width at the 0.2 m ODN contour, just above the elevation of the HCDF toe (0 m ODN). Vertically above the HCDF toe, the depth of sediment reduces slightly by 9 cm, leaving 4.44 m of sediment depth above the HCDF.

Table 3 summaries the beach width seaward of the HCDF, at different elevations between the HCDF toe (0 m ODN) and coastal path behind the SCDF (5.2 m ODN) for the different scenarios tested. Table 4 summarises depth of sediment above the buried HCDF profile at the HCDF toe and the leading edge of the 3.7 m ODN platform.

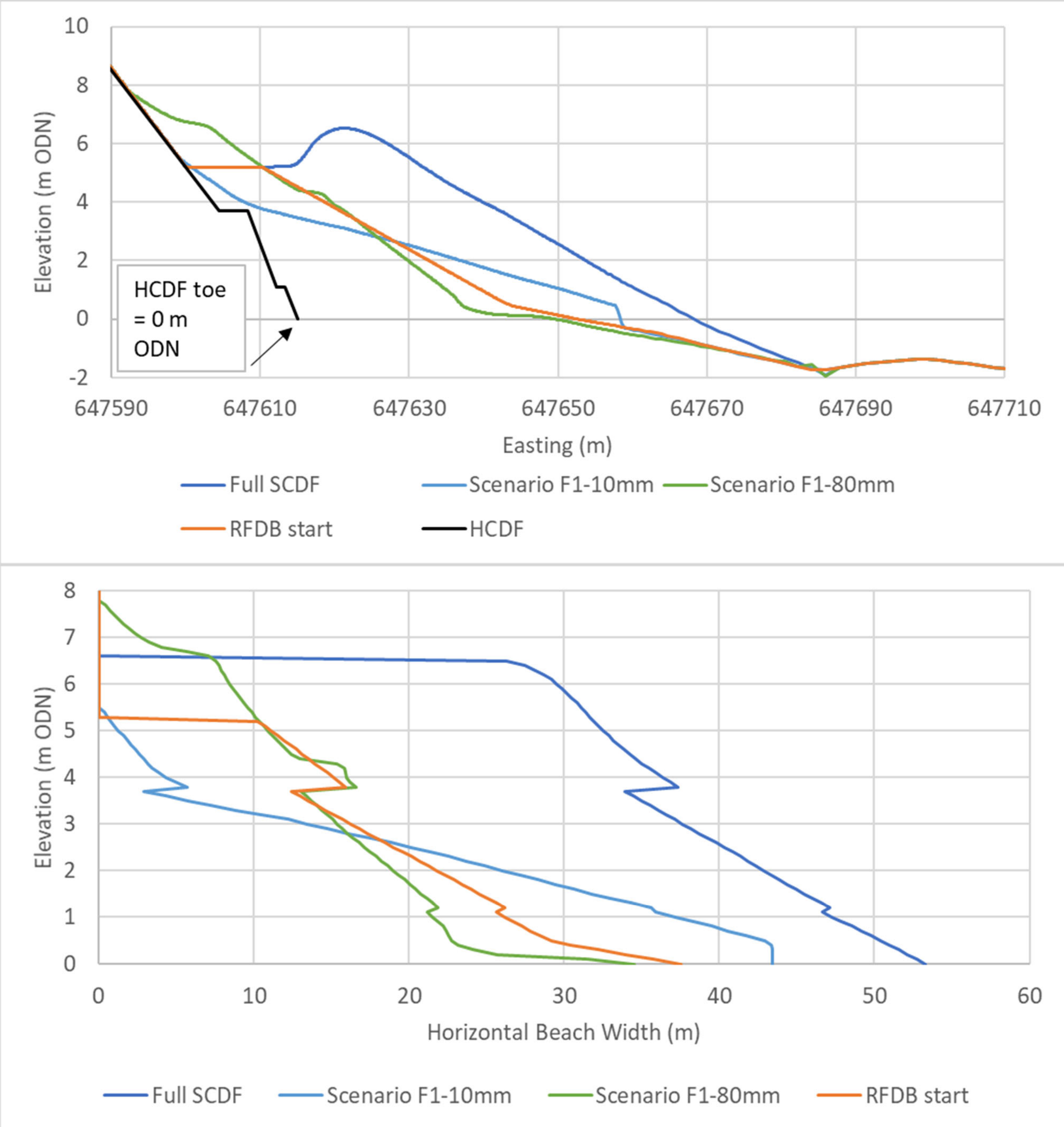

Figure 14 Start and end profiles of Scenario F1 with a D_{50} = 10 mm and 80 mm (top) and the horizonal beach width seaward of the HCDF above the elevation of the HCDF toe (bottom), along with full SCDF profile for reference.

Table 3 Summary of the beach width seaward of the HCDF, at different elevations between the HCDF toe (0 m ODN) and coastal path behind the SCDF (5.2 m ODN).

Contour (m ODN)	Beach Width (m)			
	Full SCDF start profile	RFDB start profile	Scenario $F1_{10mm}$ end profile	Scenario $F1_{80mm}$ end profile
5.2	31.90	10.20	0.77	10.37
3.7	33.94	12.42	2.87	13.00
1.16 (MHWS)	47.15	26.17	35.66	21.89
0.71 (MHWN)	49.16	27.82	40.58	22.38
0 (HCDF toe)	53.29	37.56	43.40	34.53

Table 4 Depth of sediment above the buried HCDF profile at the HCDF toe and the leading edge of the 3.7 m ODN platform.

Profile	Depth of sediment above HCDF toe (0 m ODN)	Depth of sediment above 3.7 m ODN platform (leading edge)
Full SCDF	5.33	1.50
RFDB start	4.53	1.50
Scenario $F1_{10mm}$	3.47	0.25
Scenario $F1_{80mm}$	4.44	1.85

A.3 Discussion

A.3.1 Grain size sensitivity

As outlined in BEEMS Technical Report TR544, the HCDF is fronted by the SCDF as primary mitigation which is designed to maintain the longshore sediment transport corridor along Sizewell and prevent exposure of the HCDF. The beach will be allowed to naturally erode to a threshold (yet to be agreed in the CPMMP, BEEMS Technical Report TR523) whereby beach maintenance would be undertaken. The beach would therefore consist of a sacrificial buffer layer and an inner buffer layer. Two options for the inner SCDF buffer layer were outlined in BEEMS Technical Report TR544: a pebble dominant layer matching the native grain size (the default position is 10 mm[7]) or pebbles with a recessed cobble layer, which would not be expected to be exposed because beach mitigation would be undertaken to prevent erosion of the outer buffer layer. The grain size sensitivity is investigated within this Appendix to test the efficacy of the 80 mm D_{50} grain size under the RFDB conditions.

[7] The pebble dominant subaerial beach at Sizewell has a median size of around 10 mm, including larger particles up to 50 – 60 mm diameter. The fine cobble grade has a diameter of 64 – 128 mm.

BEEMS Technical Report TR544 established that SCDF viability could be achieved across the life of the station using 10 mm diameter sediment, which is equivalent to the native modal particle size. Subject to further testing, the 10 mm size has been taken as the default size for the bulk of the SCDF. However, BEEMS Technical Report TR545 and this report demonstrate that the use of a fine cobble layer, within the buffer layer (and therefore not expected to be exposed) would significantly reduce the risk of HCDF exposure.

As a starting point, the modelling of fine cobbles uses the pre-eroded RFDB profile[8] and the degree of erosion allows, alongside the literature, early evidence for how large it would need to be to avoid exposure. The results of the grain size sensitivity (D_{50} = 10mm and 80 mm) for Scenario F1, further supports the idea of a recessed cobble layer, as detailed in BEEMS Technical Report TR544. By using an outer layer of pebbles with a D_{50} = 10 mm grain size, the beach is allowed to evolve and maintain the longshore transport corridor by drawing material down from the upper subaerial beach into the intertidal zone. In contrast, if the beach were eroded very close to the HCDF, the D_{50} = 80 mm grain size would allow the beach to evolve to prevent (or reduce the risk of) any exposure of the HCDF. Figure 15 shows, that with a D_{50} = 80 mm grain size, the maximum horizontal beach translation (-8.3 m) occurred on the lower portion of the beach, at a contour of 0.2 m ODN. Therefore, a cobble layer with a thickness of 10 m at the HCDF toe elevation (0 m ODN) would provide a higher level of protection than for pebbles alone but still allowing around 43 m (horizontal) of pebble sediment for a full SCDF. For the RFDB profile (which is unlikely to be exposed if the SCDF is well-maintained), the starting beach width at 0 m ODN is 37.6 m. Therefore, with a 10 m cobble layer, there would be 27.6 m of pebbles and 10 m of fine cobbles seaward of the HCDF (for example).

However, as the cobble layer erosion reduces with elevation, a uniform width is not necessary and a tapered profile might be more appropriate as eroding cobble beaches tend to promote onshore transport, as shown in Figure 15 (lower panels). An exposed cobble layer would also reduce the wave runup elevation, owing to larger particles and interstitial spaces, by increasing infiltration and exfiltration of water from the beach face. Wave run-up analysis was not considered in this report as the water levels exceed the beach levels.

The $F1_{80mm}$ model showed near-zero beach retreat over elevations 3 – 5.2 m ODN, above which there was accretion. In comparison, with a D_{50} = 10 mm grain size, all three scenarios (A1, E1 and F1) showed the beach narrowed over the same range and was nearly fully stripped at the 3.7 m ODN contour, which would have exposed the HCDF – only c. 20 cm of sediment remained vertically on top of the leading edge of the HCDF's 3.7 m ODN platform. At that same elevation, the remaining beach width before HCDF exposure was just 2.9 m (for the $F1_{10mm}$ model). Therefore, a cobble layer may be sufficient to provide protection from exposure at this hard point but allow the beach above this depth contour to still evolve and draw material down onto the lower subaerial beach. This could be achieved by using a horizontal beach thickness of 3 m at a contour height of 3.7 m with a vertical beach thickness of 0.5 m above the leading edge of the 3.7 m platform. It is important to note that the case modelled has very high-water levels (+6.75 m ODN), and it is expected that the cobble layer will show increased effectiveness for severe storms at less extreme water levels. Such cases have not been tested.

Based on the modelled observations, an initial cobble layer is drafted in Figure 15, along with the full SCDF, the RFDB start profile and the $A1_{10mm}$, $E1_{10mm}$ and $F1_{10mm}$ results.

As can be seen in Figure 15, the erosion associated with each scenario only has very limited intersection with the proposed cobble layer, around the 3.7 -5.2 m ODN elevation. There is minimal difference between the three end profiles and the cobble layer profile: -1.44 and 2.28 m^3/m.

The maximum slope angle of the proposed cobble layer (with a maximum base width of 10 m) is 15.2°, which is slightly steeper than the natural range measured at Sizewell, ~5-13° (BEEMS Technical Report

[8] The pre-eroded profile is considered to be well within the SCDF's buffer layer. It represents a profile that has been eroded by previous storms without interim recharge – that is a sequence of severe storms in which the second storm has a 1:10,000 joint probability.

TR544). Natural cobble beaches typically hold a similar range to that observed for Sizewell's composite beach (e.g., Jennings and Shulmeister, 2002).

The exceptional resistance to storm erosion and runup predicted for the fine cobbles (D_{50} = 80 mm) has also recently been reported from a laboratory scale physical modelling study where a cobble berm revetment was tested under storm wave conditions (Bayle et al., 2020). While the cobbles in the laboratory study were found to be dynamic, and exchanged readily from the front to the back of the feature being tested, the net change in the revetment volume was minimal and it maintained a consistent overall shape. The study also found that using cobbles allowed roll over and adjustment to SLR as the revetment moved upward and landward under water level rise. This pattern of upward and landward movement of the beach profile was replicated by the XBeach-G model with the D_{50} = 80 mm grain size.

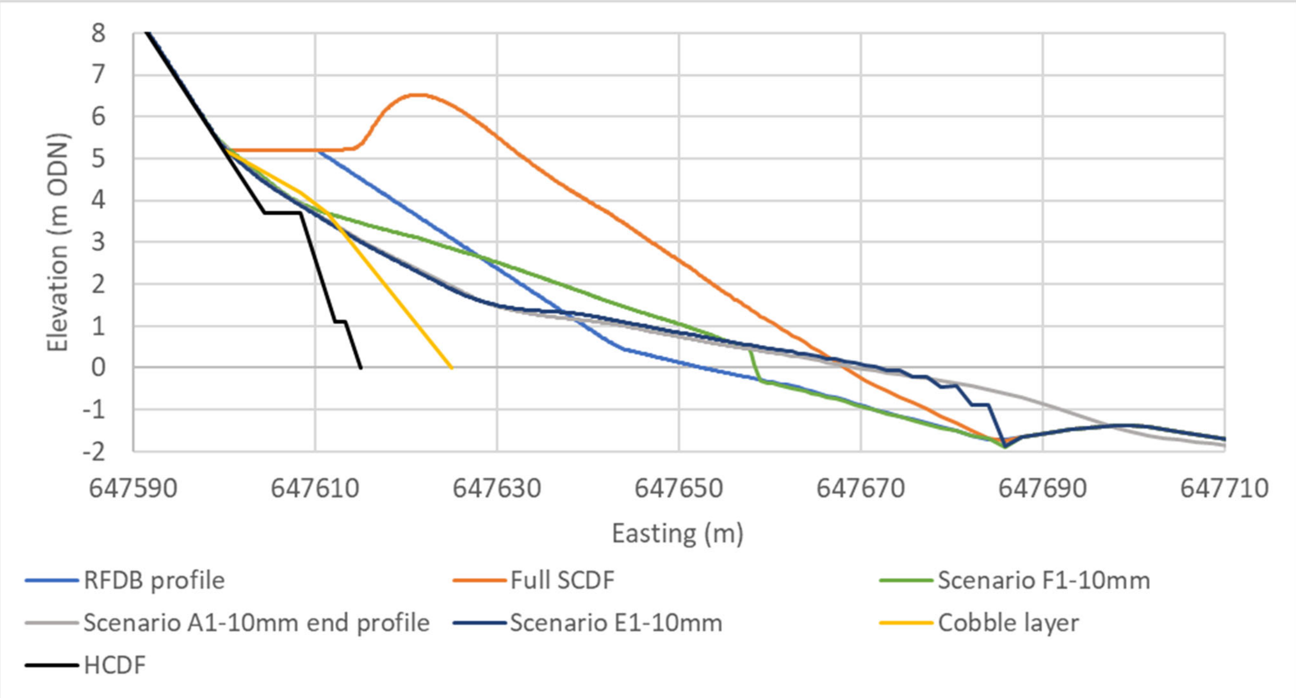

Figure 15 Summary profiles for a fully recharged SCDF, the severely eroded RFDB profile, the $A1_{10mm}$, $E1_{10mm}$ and $F1_{10mm}$ storm erosion and the potential profile for a cobble layer.

The XBeach-G model in BEEMS Technical Report TR545 was only semi-calibrated[9] by aligning tuning parameters as closely as possible with settings from the literature. It is recommended that XBeach-G is calibrated, and that full-scale physical modelling is undertaken to characterise beach response and suitably design the SCDF and its notional and physical (fine cobbles) layers.

A.4 Conclusions

The D_{50} = 80 mm simulations highlight that a recessed cobble layer (buried deep within the SCDF) would provide a highly effective form of coastal defence, making the prospects of HCDF exposure and the need to construct the Adapted HCDF much less likely. In a relative sense, the risks of HCDF exposure are much higher without the cobble layer. To allow natural beach function as far as possible, the modelling suggests that the beach should be maintained with shingle, so that the cobble layer is unlikely to be exposed in the first instance. As highlighted in BEEMS Technical Report TR544, design parameters based on natural beaches, cobble berms, whilst underpinned using numerical modelling and full-scale physical modelling should be used to set the design. For example, an indicative cobble layer could be 10 m wide at 0 m ODN, 3 m wide at 3.7 m, have a vertical beach thickness of 0.5 m above the leading edge of the 3.7 m platform and taper just below the surface where the coastal path meets the edge of the HCDF at a 5.2 m ODN.

[9] XBeach-G is a 1D model for gravel sized sediments, ranging from 2 – 80 mm. Whilst the XBeach-S model presented in BEEMS Technical Report TR545 is calibrated to observations of the existing beach at Sizewell, the XBeach-G model is not strictly calibrated to Sizewell or the SCDF as data does not exist, for example for hydraulic conductivity (the ability of water to infiltrate and exfiltrate through the gravel beach). However, the model is parameterised based on suitable published calibration studies.

6.0 Appendix B- Technical note on lower water levels

BEACH RESPONSE AT LOWER WATER LEVELS

The three 'design basis' scenarios modelled in BEEMS Technical Report TR553 had elevated sea levels, incorporating allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). For each case, the peak significant wave heights were taken from the 1:10,000 year joint probability (JP) curves (developed in BEEMS Technical Report TR319). The model results (for a D_{50} = 10 mm particle size), summarised here, show an upper beach cut and lower beach fill pattern.

Scenario F1:

Mean sea level (before surge)	= 1.9m AOD (approx.)
Peak surge height	= 3.5m (approx.)
Peak water level	= 6.75m AOD (one high tide cycle)
Minimum water level	= 0.75m to 1m AOD (3 low tide cycles)
Transition level (erosion (above) / deposition (below))	= 2.8m AOD (approx.)

Scenario E1:

Mean sea level (before surge)	= 1.9m AOD (approx.)
Peak surge height	= 1.5m (approx.)
Peak water level	= 5.02m AOD (one high tide cycle)
Minimum water level	= 0.75m to 1m AOD (5 low tide cycles)
Transition level (erosion (above) / deposition (below))	= 1.3m AOD (approx.)

Scenario A1:

Mean sea level (before surge)	= 1.9m AOD (approx.)
Peak surge height	= 0.5m (approx.)
Peak water level	= 3.74m AOD (one high tide cycle)
Minimum water level	= 0.75m to 1m AOD (5 low tide cycles)
Transition level (erosion (above) / deposition (below))	= 1.2m AOD (approx.)

The predicted level of the beach erosion is clearly affected by sea water levels when comparing Scenario F1 (high mean sea level plus extreme surge height) with Scenarios A1, E1 (high mean sea level plus moderate to large surge height). However, there is relatively little difference in the erosion pattern and transition level when comparing Scenarios A1 and E1 where the surge height varies quite significantly but is less extreme.

Scenarios with lower sea water levels, as well as the range modelled in TR553, will be assessed as part of the detailed design of the permanent sea defences. The reasons for having confidence at this stage that scenarios with lower sea water levels would not be onerous and would not threaten to undercut the toe of the hard sea defence at 0.0m AOD are as follows:

- The maximum horizontal erosion observed for the three modelled cases was 10.9 -11.2m.
  As the pre-eroded beach at the HCDF toe elevation is 37.5m wide, a similar degree of erosion would not threaten HCDF exposure.
- From the distribution of results over the modelled cases, the sensitivity of the erosion pattern to sea water level appears to be reducing for lower sea water levels.
- Waves at the beach face would be much smaller under lower water levels due to extensive wave breaking and dissipation. Similarly, the extent of horizontal erosion would be reduced (i.e. < 11m). Large waves (e.g. Scenario A1) at present day mean sea levels (~0m AOD) will start to break in approximately 11–12 m of water depth on the seaward side of Sizewell-Dunwich Bank , effectively creating a 2800m-wide surf zone to the shoreline that would significantly reduce wave height and energy at the beach face.
- In any event, the SCDF has a large volume and would be maintained, and the modelled conditions are for design basis and highly unlikely to occur.

IMPACT ON COASTAL PROCESSES

The modelling presented in BEEMS TR545 and TR553 demonstrate that even under very extreme, incredibly unlikely, conditions there is negligible chance of exposure of the HCDF. The SCDF is retained, albeit heavily eroded and, therefore, maintains the sediment transport pathway (i.e. mitigates any impact on coastal processes). Given that the SCDF will be recharged after such severe events there should be no requirement for any secondary mitigation.

However, an regardless, the SZC Environmental Statement on Coastal Processes and Hydrodynamics (APP-311) allows for temporary exposure of the HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged.

It is worth noting also that the SZC frontage is not a single entity but part of a continuum and although, the Design Basis modelling does not require it, it must be remembered that up- and downdrift beaches would also be severely affected by any such storm. In fact, downdrift beaches may well benefit from SCDF erosion providing extra material. Coastal processes for the wider region would be affected in the short term anyway: the system is not static and impacts of a severely eroded SCDF must be considered with the knowledge that adjacent beaches are also likely to have undergone severe changes.

7.0 Appendix C – Updated Table 2.4 from SZC Co. and EA SOCG

Table 4: Position of the Parties - SZC Co. and Environment Agency: Coastal Geomorphology & Hydrodynamics (08 April 2022)

Ref.	Matter	Book ref.	Position of Parties in SOCG at relevant Deadlines				SZC Co Comment	Agreed / Not Agreed
			D2	D7	D10	08 April 2022 (present)		
MDS_CGH1	The overarching methodology for the assessment of impacts on Coastal Geomorphology and Hydrodynamics as detailed in **Volume 1 Appendix 6P and section 20.3** of **Volume 2 Chapter 20** of the ES.	6.3					Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF.	Agreed
MDS_CGH2	The construction mitigation, management and monitoring measures detailed in **Part B** section 12 of the **Code of Construction Practice.**	8.11(E)					**As at D10** No areas of disagreement.	Agreed
MDS_CGH3	The securing mechanisms to control impacts on coastal geomorphology and hydrodynamics as detailed in the **Mitigation Route Map** including: - DCO Article 3 (Scheme design) - Requirement 2 (PW: CoCP) - Deemed Marine Licence Conditions, in particular Conditions 11, 17, 37, 40, 41, 42, 43, 44 and 49.	8.12(F) 3.1(J) 9.31(B) 9.12 (C)					EA are named consultees on DML Conditions 17, 40 and 41 as requested.	Agreed
MDS_ CGH4	The baseline characterisation of the Greater Sizewell Bay's (GSB) coastal geomorphology and hydrodynamics relevant to the proposed Sizewell C marine infrastructure as detailed in **section 20.4** of **Volume 2 Chapter 20** and **Appendix 20A** section 3 of the ES.	6.3					**As at D10** No areas of disagreement.	Agreed
MDS_ CGH5	The proposed primary, secondary and tertiary mitigation measures to mitigate impacts as detailed in **section 20.5** and **20.12** of **Volume 2 Chapter 20**. In particular the proposed Coastal Monitoring and Mitigation Plan as defined in Condition 17 of the Marine Licence.	6.3 9.31(B) 9.12 (C) 10.5					Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. The assessment in the ES allows for temporary exposure of the	Agreed

Ref.	Matter	Book ref.	Position of Parties in SOCG at relevant Deadlines				SZC Co Comment	Agreed / Not Agreed
			D2	D7	D10	08 April 2022 (present)		
							HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged. Thje CPMMP will monitor for such impacts and trigger mitigation as required.	
MDS_ CGH6	The assessment of impacts associated with the hard coastal defence feature as described in section **20.6** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3 9.31(B) 9.12 (C)					**SZC Co Comment:** Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. The assessment in the ES allows for temporary exposure of the HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged. Thje CPMMP will monitor for such impacts and trigger mitigation as required.	Agreed
MDS_ CGH7	The assessment of impacts associated with the soft coastal defence feature as described in section **20.7** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3 9.31(B) 9.12 (C)					**SZC Co Comment:** Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. The assessment in the ES allows for temporary exposure of the HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged. Thje CPMMP will monitor for such impacts and trigger mitigation as required.	Agreed

Ref.	Matter	Book ref.	Position of Parties in SOCG at relevant Deadlines				SZC Co Comment	Agreed / Not Agreed
			D2	D7	D10	08 April 2022 (present)		
MDS_ CGH8	The assessment of impacts associated with the beach landing facility as described in section **20.8** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3					**As at D10** No areas of disagreement	Agreed
MDS_ CGH9	The assessment of impacts associated with the nearshore outfalls as described in section **20.9** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3					**As at D10** No areas of disagreement	Agreed
MDS_ CGH10	The assessment of impacts associated with the offshore cooling water infrastructure as described in section **20.10** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3					**As at D10** No areas of disagreement	Agreed
MDS_ CGH11	The assessment of combinations of spatially and temporally overlapping marine components as described in section **20.11** of **Volume 2 Chapter 20**.	6.3 9.31(B) 9.12 (C)					Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. All marine infrastructure impacts are now agreed by the Environment Agency allowing in-combination assessment to be made.	Agreed
MDS_ CGH12	The residual effects of impacts associated with the hard coastal defence feature as described in section **20.6** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3 9.31(B) 9.12 (C)					**SZC Co Comment:** Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. The assessment in the ES allows for temporary exposure of the HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged.	Agreed

Ref.	Matter	Book ref.	Position of Parties in SOCG at relevant Deadlines				SZC Co Comment	Agreed / Not Agreed
			D2	D7	D10	08 April 2022 (present)		
							The CPMMP will monitor for such impacts and trigger mitigation as required.	
MDS_ CGH13	The residual effects of impacts associated with the soft coastal defence feature as described in section **20.7** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3 9.31(B) 9.12 (C)					**SZC Co Comment:** Further, more extreme scenarios have been modelled in BEEMS TR553 " Modelling of Soft Coastal Defence Feature under Design Basis Conditions". These three 'design basis' scenarios incorporated allowance for sea level rise and different magnitudes of surge overlayed on the astronomical tidal cycle (around mean spring tide magnitude). Even under these scenarios there is negligible chance of exposure of the HCDF. The assessment in the ES allows for temporary exposure of the HCDF anyway, with any blockage to the southerly transport of sediment material along the frontage mitigated with manual by-passing. Therefore, even if the HCDF was exposed following an extreme storm, by-passing would be used to maintain sediment transport pathways until the SCDF was recharged. Thje CPMMP will monitor for such impacts and trigger mitigation as required.	Agreed
MDS_ CGH14	The residual effects of impacts associated with the beach landing facility as described in section **20.8** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3					**As at D10** No areas of disagreement	Agreed
MDS_ CGH15	The residual effects of impacts associated with the nearshore outfalls as described in section **20.9** of **Volume 2 Chapter 20** and **Appendix 20A.**	6.3					**As at D10** No areas of disagreement	Agreed
MDS_ CGH16	The residual effects of impacts associated with the offshore cooling water infrastructure as described in section **20.10** of **Volume 2 Chapter 20** and **Appendix 20A**.	6.3					**As at D10** No areas of disagreement	Agreed