East Anglia THREE

# Appendix 7.3

## Scour Assessments

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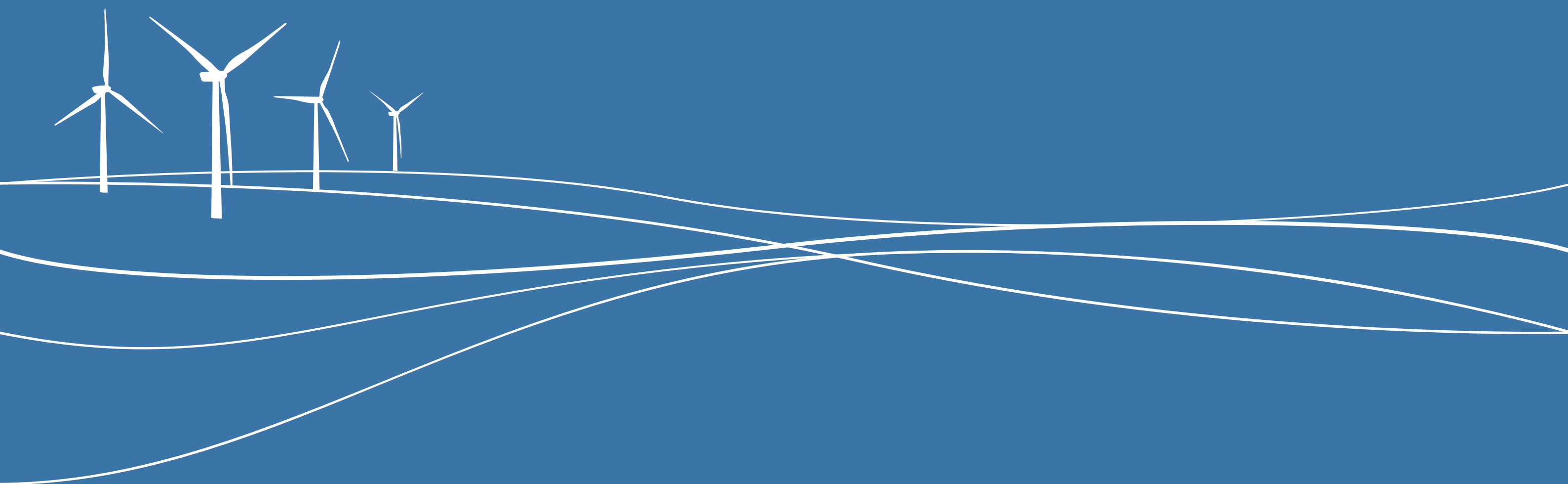

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# 7.3 MARINE GEOLOGY, OCEANOGRAPHY AND PHYSICAL PROCESSES - SCOUR ASSESSMENT

## 7.3.1 Introduction

1. This appendix provides detailed information concerning the assessment methods and predictions of scour development in the sea bed around the various types of foundation structures being considered for use in the proposed East Anglia THREE project.

2. The document reviews the assumed environmental input parameters and their provenance, followed by a description of the predicted scour depths and volumes. A number of technical references are provided which describe the techniques used to predict the scour around the various foundation types considered. Several of these references include verifications of predictions against observed data.

3. Historically, investigations into the development of scour have concentrated mainly upon the scour of granular sand, rather than that of complex soil media. The reasons for this are obvious; the material properties and the hydrodynamic behaviour of granular materials are, for the most part, quite well understood, and there are theoretical underpinnings supporting a significant number of the available predictive methods. On the other hand, complex soil media, such as mixtures of granular and cohesive sediments, are far harder to quantify for scour in mathematical terms.

4. *Table 7.3.1* lists the references applying to the various techniques that have been used in this study to predict foundation scour.

5. With the exception of the soil material strength methods developed by Annandale (1995; 2006) and Annandale and Smith (2001), as listed in *Table 7.3.1*, (hereafter collected terms ‘the Annandale solutions’), all of the predictive methods apply to a granular material.

6. The Annandale solutions cover all types of soil media, but still use as their starting point an initial granular calculation, to define a vertical domain over which the scour prediction will be undertaken.

7. In situations where a non-erodible sub layer lies underneath an upper granular stratum, then the scour depth prediction will be truncated at the resistant layer. A small amount of survey data for monopile structures at offshore windfarms such as Barrow, reported by Whitehouse et al (2011), can be used to provide information regarding the shape of such a truncated scour hole.

**Table 7.3.1. Schedule of prediction methods used in the study**

| Type of structure and environmental loading | Method reference |
|---|---|
| Conical gravity base: in waves | Khalfin (2007) with diameter expressed as base of cone value (on the assumption that the top of the base plate is at or below seabed level) |
| Conical gravity base: in currents | Khalfin (1983) modified by Bos et al (2002a) with diameter expressed as base of cone value |
| Conical gravity base: in waves & currents combined | Khalfin (2007) with the sea bed friction velocity increased to cover effects of wave-current interaction by using Soulbsy and Clarke (2005) |
| Suction bucket: in currents alone | Khalfin (1983) modified by Bos et al (2002a) |
| Suction bucket: in waves | Bos et al (2002b) and informed by Yeow and Cheng (2003) for contribution from upper tower |
| Suction bucket: in waves and currents combined | Bos et al (2002b) and informed by Yeow and Cheng (2003) for contribution from upper tower |
| Monopile: in currents | Harris et al (2010) |
| Monopile: in waves | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Monopile: in waves and currents | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Jacket: main piled columns | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Jacket: suction caissons in currents alone | Khalfin (1983) modified by Bos et al (2002a) |
| Jacket: suction caissons in waves | Bos et al (2002b) followed by Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Jacket: suction caissons in waves and currents | Bos et al (2002b) followed by Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Jacket: horizontal bracing elements | Sumer and Fredsϕe (2002) |
| Tripod: in currents | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Tripod: in waves | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Tripod: in currents and waves | Harris et al (2010), Sumer and Fredsϕe (2002) and Raaijmakers and Rudolph (2008) |
| Scour including seabed material strength | Annandale (1995); Annandale and Smith (2001); Annandale (2006) soil strength methods |
| Plan form of scour holes | Harris et al (2010) |
| Effects of soil type upon scour development | Analysis of $D_{50}$ grain sizes from grab samples |

8. Diagram 7.3.1 compares observed equilibrium scour depths in the field and the laboratory, against the corresponding values predicted by the methods used in the present study. In all cases, the sea bed material was granular and no account could be taken of any additional soil strength. Whilst Diagram 7.3.1 indicates the inevitable volume of scatter that will occur in such a comparison, it does also confirm that the

predictive methods used in the present study provide realistic results for scour depths.

9. The scour predictions shown in this appendix apply throughout to a situation where there is no scour protection provided. This is deemed a worst case in terms of the yield of sediment into the marine environment from scour formation around the wind turbine foundation. Given that the full requirements (or otherwise) for scour protection material will not be made until after the Development Consent Order application, this is deemed a sensible worst case for these assessments of sediment yield.

10. Consideration is also given in Chapter 7 Marine Geology, Oceanography and Physical Processes to a situation where, for various foundation types, scour protection material is used to prevent scour from occurring. In such situations, the sediment yield from scour processes will be zero, although there would be some requirement for sea bed preparation prior to installation of scour protection material and the scour protection itself would occupy a footprint on the sea bed.

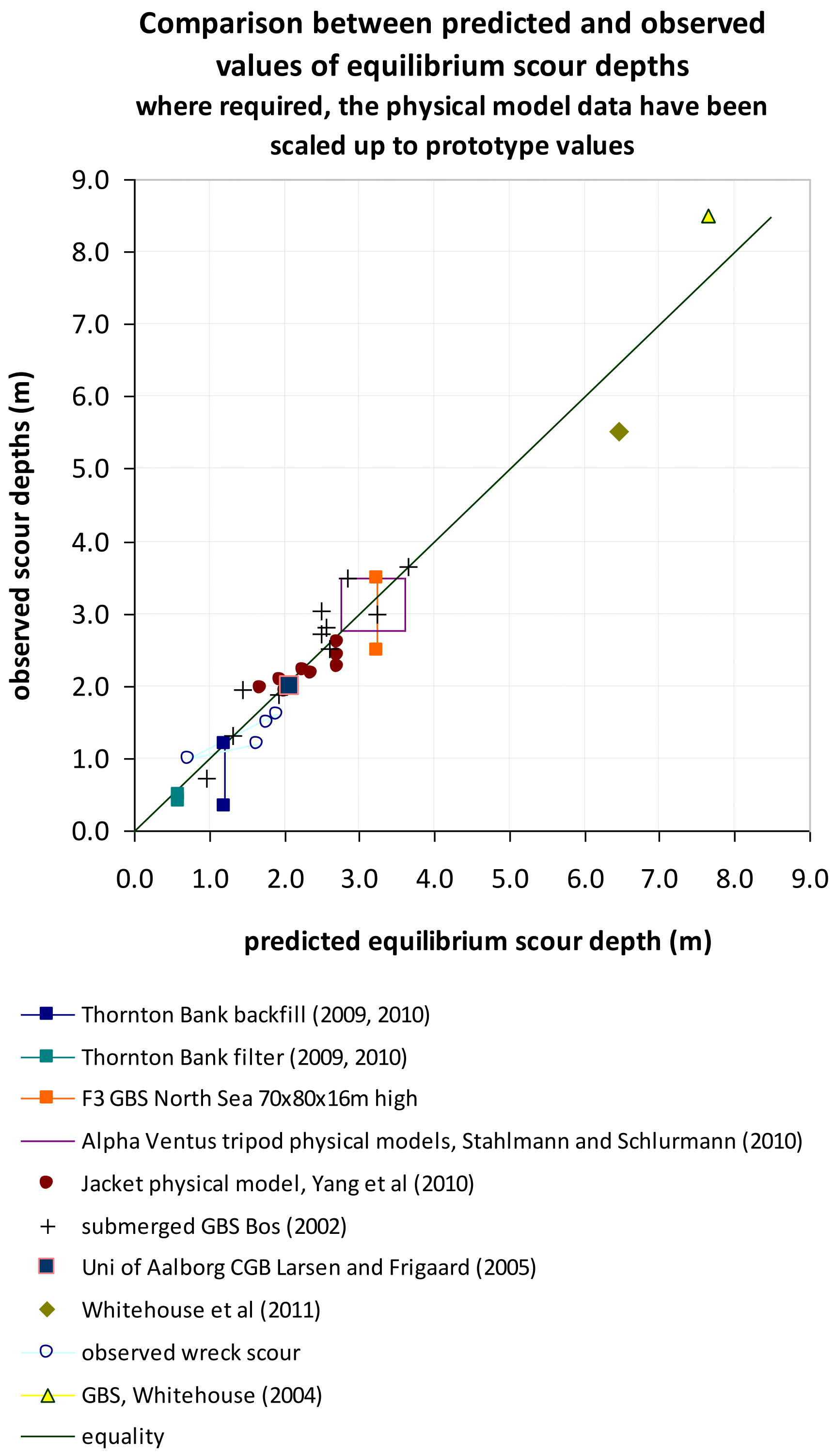


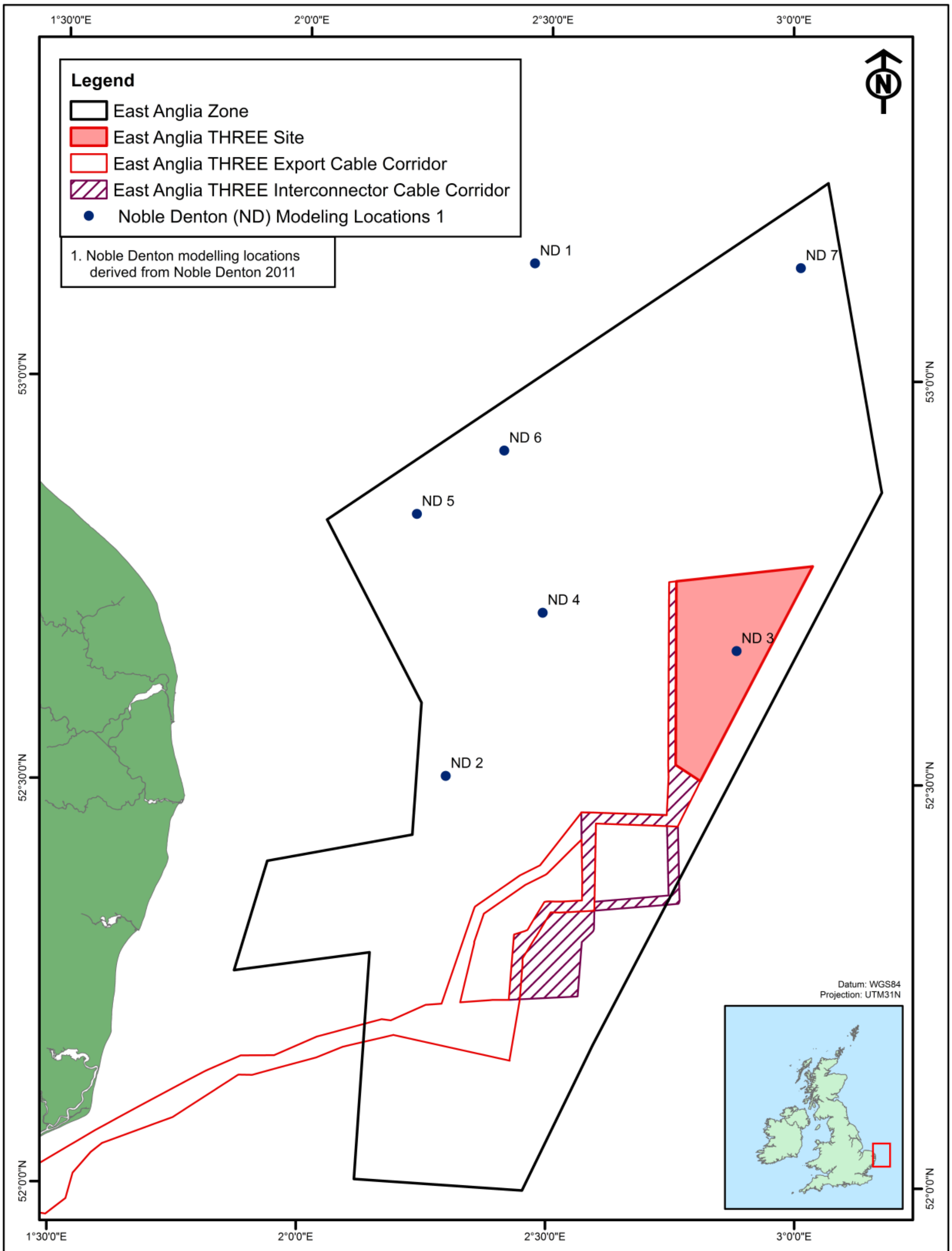
**Diagram 7.3.1. Comparison between observed equilibrium scour depths**

### 7.3.2 Return Period Metocean Input Conditions

11. The metocean input parameters used in this document derive from the report on the Metocean Conditions Study for the Norfolk Wind Farm, undertaken by Noble Denton (2011) and the predictions were undertaken at seven locations within the East Anglia Zone, shown in *Figure 7.3.1*.

12. Point 3 is located directly within the East Anglia THREE site and provides a useful dataset for the basis of scour predictions in the present study.  Data from Point 3 are therefore highlighted in light blue in all relevant tables within this appendix for ease of reference.

13. *Table 7.3.2* presents the return-period metocean conditions advised in the Noble Denton (2011) report.  Data from Point 3 are approximately representative of the 'average' predicted extreme conditions over the East Anglia Zone.



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## East Anglia THREE Limited

Locations of the Noble Denton
Metocean Prediction Points

| Rev | Date | By | Comment |
|---|---|---|---|
| 2 | 22/10/15 | DT | Second Draft |
| 1 | 21/10/15 | DT | First Issue. |

Original
A4
Plot Scale
1:700,000

0 5 10 km
0 2 4 6 nm

**Volume 3** **Figure 7.3.1**

| Layout | Date | Rev | Dwg No. |
|---|---|---|---|
| N/A | 22/10/2015 | 2 | EA3-L-138 |

Ref:

Table7.3.2. Schedule of return-period metocean conditions (Noble Denton, 2011)

| Point | Lat °N | Lon °E | Depth (m LAT) | Return period (years) | Surge (m) | $H_s$ (m) | $T_p$ (s) | $U_c$ (m/s) |
|---|---|---|---|---|---|---|---|---|
| 01 | 53.143 | 2.468 | 37.4 | 1 | 1.7 | 5.1 | 10.2 | 1.4 |
| 02 | 52.500 | 2.289 | 34.3 | 1 | 1.6 | 4.9 | 10.0 | 1.5 |
| **03** | **52.665** | **2.884** | **30.8** | **1** | **1.6** | **6.0** | **11.1** | **1.3** |
| 04 | 52.721 | 2.490 | 39.6 | 1 | 1.6 | 5.7 | 10.8 | 1.4 |
| 05 | 52.830 | 2.228 | 23.2 | 1 | 1.5 | 5.2 | 10.3 | 1.5 |
| 06 | 52.905 | 2.420 | 32.7 | 1 | 1.6 | 5.6 | 10.7 | 1.4 |
| 07 | 53.138 | 3.013 | 26.7 | 1 | 1.5 | 6.7 | 11.7 | 1.2 |
| | | | | | | | | |
| 01 | 53.143 | 2.468 | 37.4 | 10 | 2.1 | 5.7 | 10.8 | 1.5 |
| 02 | 52.500 | 2.289 | 34.3 | 10 | 2.0 | 5.5 | 10.6 | 1.6 |
| **03** | **52.665** | **2.884** | **30.8** | **10** | **2.0** | **6.8** | **11.8** | **1.4** |
| 04 | 52.721 | 2.490 | 39.6 | 10 | 2.0 | 6.5 | 11.6 | 1.5 |
| 05 | 52.830 | 2.228 | 23.2 | 10 | 2.0 | 5.8 | 10.9 | 1.6 |
| 06 | 52.905 | 2.420 | 32.7 | 10 | 1.9 | 6.4 | 11.4 | 1.5 |
| 07 | 53.138 | 3.013 | 26.7 | 10 | 1.9 | 7.6 | 12.6 | 1.3 |
| | | | | | | | | |
| 01 | 53.143 | 2.468 | 37.4 | 50 | 2.4 | 6.2 | 11.3 | 1.6 |
| 02 | 52.500 | 2.289 | 34.3 | 50 | 2.3 | 6.0 | 11.1 | 1.7 |
| **03** | **52.665** | **2.884** | **30.8** | **50** | **2.3** | **7.3** | **12.3** | **1.4** |
| 04 | 52.721 | 2.490 | 39.6 | 50 | 2.3 | 7.1 | 12.1 | 1.5 |
| 05 | 52.830 | 2.228 | 23.2 | 50 | 2.3 | 6.2 | 11.3 | 1.6 |
| 06 | 52.905 | 2.420 | 32.7 | 50 | 2.2 | 6.9 | 11.9 | 1.6 |
| 07 | 53.138 | 3.013 | 26.7 | 50 | 2.2 | 8.3 | 13.3 | 1.4 |
| | | | | | | | | |
| 01 | 53.143 | 2.468 | 37.4 | 100 | 2.5 | 6.4 | 11.5 | 1.6 |
| 02 | 52.500 | 2.289 | 34.3 | 100 | 2.4 | 6.2 | 11.3 | 1.7 |
| **03** | **52.665** | **2.884** | **30.8** | **100** | **2.4** | **7.5** | **12.5** | **1.5** |
| 04 | 52.721 | 2.490 | 39.6 | 100 | 2.4 | 7.3 | 12.3 | 1.6 |
| 05 | 52.830 | 2.228 | 23.2 | 100 | 2.4 | 6.4 | 11.5 | 1.7 |
| 06 | 52.905 | 2.420 | 32.7 | 100 | 2.3 | 7.1 | 12.1 | 1.6 |
| 07 | 53.138 | 3.013 | 26.7 | 100 | 2.3 | 8.6 | 13.6 | 1.5 |

Where:
$H_s$ = significant wave height (m)
$T_p$ = peak wave period (s)
$U_c$ = depth-averaged current speed over the top 20m of water depth

## 7.3.3 Scour Predictions under Granular Sea Bed Conditions

### 7.3.3.1 Conical Gravity Base Structure under Granular Sea Bed Conditions

14. For the conical gravity base structure (GBS), scour depth predictions were made using the method derived by Khalfin (2007), with a modification to the sea bed shear velocity to account for the interaction between the waves and the currents, using the solution derived by Soulsby and Clarke (2005).

15. *Table 7.3.3* summarises the expected minimum and maximum diameters for the base of the cone of the GBS, where it interfaces with the base plate. These dimensions were applied to the prediction of the scour depths for the granular sea bed assumption.

**Table7.3.3. Minimum and maximum GBS footprint diameters**

| Water depth (m) | Minimum footprint | Maximum footprint |
|---|---|---|
| Up to 35 | 20m diameter | 50m diameter |
| 35 to 45 | 25m diameter | 55m diameter |
| Greater than 45 | 30m diameter | 60m diameter |

16. *Tables 7.3.4* and *Table 7.3.5* provide the predictions of equilibrium scour depth on a granular sea bed, due to the effects of extreme waves and currents combined, for return periods of 1 and 50 years for minimum and maximum GBS dimensions, respectively. Larger scour depths occur for the maximum structural footprint, but owing to the relatively long periods of the waves, the strongest driver of scour is the water depth.

**Table7.3.4. Granular material sea bed scour for the conical gravity base structures: *minimum* anticipated structural diameter at the intersection of cone with the base plate**

| Location ID | Return period (years) | Hs (m) | Tp (s) | Uc (m/s) | Depth (m) | Structure base diameter (m) | Predicted equilibrium scour depth (m) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 5.1 | 10.2 | 1.4 | 37.4 | 25.0 | 1.94 |
| 2 | 1 | 4.9 | 10.0 | 1.5 | 34.3 | 20.0 | 1.92 |
| 3 | 1 | 6.0 | 11.1 | 1.3 | 30.8 | 20.0 | 2.94 |
| 4 | 1 | 5.7 | 10.8 | 1.4 | 39.6 | 25.0 | 2.24 |
| 5 | 1 | 5.2 | 10.3 | 1.5 | 23.2 | 20.0 | 3.15 |
| 6 | 1 | 5.6 | 10.7 | 1.4 | 32.7 | 20.0 | 2.50 |
| 7 | 1 | 6.7 | 11.7 | 1.2 | 26.7 | 20.0 | 4.00 |
| 1 | 50 | 6.2 | 11.3 | 1.6 | 37.4 | 25.0 | 2.98 |
| 2 | 50 | 6.0 | 11.1 | 1.7 | 34.3 | 20.0 | 2.94 |
| 3 | 50 | 7.3 | 12.3 | 1.4 | 30.8 | 20.0 | 4.25 |
| 4 | 50 | 7.1 | 12.1 | 1.5 | 39.6 | 25.0 | 3.48 |
| 5 | 50 | 6.2 | 11.3 | 1.6 | 23.2 | 20.0 | 4.32 |
| 6 | 50 | 6.9 | 11.9 | 1.6 | 32.7 | 20.0 | 3.79 |
| 7 | 50 | 8.3 | 13.3 | 1.4 | 26.7 | 20.0 | 6.09 |

**Table7.3.5. Granular material sea bed scour for the conical gravity base structures: *maximum* anticipated structural diameter at the intersection of cone with the base plate**

| Location ID | Return period (years) | Hs (m) | Tp (s) | Uc (m/s) | Depth (m) | Structure base diameter (m) | Predicted equilibrium scour depth (m) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 5.1 | 10.2 | 1.4 | 37.4 | 55.00 | 2.49 |
| 2 | 1 | 4.9 | 10.0 | 1.5 | 34.3 | 50.00 | 2.57 |
| 3 | 1 | 6.0 | 11.1 | 1.3 | 30.8 | 50.00 | 3.94 |
| 4 | 1 | 5.7 | 10.8 | 1.4 | 39.6 | 55.00 | 2.89 |
| 5 | 1 | 5.2 | 10.3 | 1.5 | 23.2 | 50.00 | 4.23 |
| 6 | 1 | 5.6 | 10.7 | 1.4 | 32.7 | 50.00 | 3.36 |
| 7 | 1 | 6.7 | 11.7 | 1.2 | 26.7 | 50.00 | 5.36 |
| 1 | 50 | 6.2 | 11.3 | 1.6 | 37.4 | 55.00 | 3.84 |
| 2 | 50 | 6.0 | 11.1 | 1.7 | 34.3 | 50.00 | 3.94 |
| 3 | 50 | 7.3 | 12.3 | 1.4 | 30.8 | 50.00 | 5.70 |
| 4 | 50 | 7.1 | 12.1 | 1.5 | 39.6 | 55.00 | 4.48 |
| 5 | 50 | 6.2 | 11.3 | 1.6 | 23.2 | 50.00 | 5.79 |
| 6 | 50 | 6.9 | 11.9 | 1.6 | 32.7 | 50.00 | 5.08 |
| 7 | 50 | 8.3 | 13.3 | 1.4 | 26.7 | 50.00 | 8.16 |

### 7.3.3.2 Monopiles under Granular Sea Bed Conditions

17. For the monopiles, scour depth predictions were made using the methods of Sumer and Fredsɸe (2002) and Harris et al. (2010). The worst case for scour of these structures is that due to current loading alone. This is because under the combined action of non-breaking waves and currents, the wave disrupts the horse-shoe vortex that otherwise develops around a slender pile due to currents, leading to a corresponding reduction in the scour depth. Sumer and Fredsɸe (2002) and later, Harris et al. (2010) and many other investigators, have referred to this phenomenon.

However, for completeness, this study also gives the predicted scour depths under the action of currents and waves combined, in addition to that due to currents acting alone.

18. Scour predictions have been calculated using the methods described by Harris et al. (2010) and then checked against the earlier wholly empirical approach developed by Raaijmakers and Rudolph (2008). In the present context, the slenderness of the pile is relative to the water depth and the associated hydraulics and is not taken to mean an absolute property; an 8m diameter pile is a large diameter structure, but, relative to the operating water depth and the associated hydraulics, it can be classed as slender. [Note: Since completion of the scour assessments, the upper size range of the monopole foundations being considered within the project description for use with 12MW turbines has been increased to 12m in diameter (for water depths greater than 35m), but the principle made regarding the 'slenderness' of monopole structures remains valid].

19. The physics of scour for a monopile may be considered as very different from that applying to a large diameter caisson. In the latter case, wave reflections off the structure play an increasingly significant role as the relative scale of the structure to the water depth and the associated hydraulics increases.

20. *Table 7.3.6* summarises the expected minimum and maximum diameters for monopiles. These dimensions were applied to the prediction of the scour depths for the granular sea bed assumption. [Note: Since completion of the scour assessments, the upper size range of the monopole foundations being considered within the project description for use with 12MW turbines has been increased to 12m in diameter (for water depths greater than 35m). However, the upper size range of monopiles that would be considered in water depths below 35m remains unchanged and therefore the direct comparison between foundations types being considered at Point 3 (in 30.8m LAT water depth) remains valid]. It is acknowledged that 12m diameter monopiles in water depths greater than 35m may generate scour volumes (in the absence of scour protection material) of approximately a similar (or perhaps slightly greater) magnitude to the worst case considered for gravity base structures and therefore if 12m diameter monopiles are to be used widely across the site without scour protection material then the previous scour assessments may need to be re-evaluated in this context. However, whilst the magnitude of sediment released due to scour around 12m diameter monopiles (in the absence of scour protection material) may be greater than that previously assessed, it will be of a similar order of magnitude and therefore the conclusions relating to the assessment of effects would

be expected to be similar.  Through consultation with Natural England under Section 42 of the Planning Act (*Appendix 7.1* section 7.1.4), it was agreed that no further examination of this issue was required and it should be noted that the scour generated from monopiles would be far less than that of gravity base foundations which are considered as the worst case scenario within the assessment (Chapter 7 section 7.6.2.4).

**Table 7.3.6. Minimum and maximum monopile diameters**

| Water depth (m) | Minimum diameter | Maximum diameter |
|---|---|---|
| Up to 35 | 5.0m | 7.5m |
| 35 to 45 | 6.0m | 8.5m |

Note: After undertaking the assessments presented here, the maximum monopole diameter for 35 to 45m water depth increased to 12m, but the 7.5m diameter remains the worst case for water depth up to 35m.

21. *Tables 7.3.7* and *Table 7.3.8* provide the predictions of equilibrium scour depth on a granular sea bed, due to the effects of currents alone and extreme waves and currents combined, for return periods of 1 and 50 years for minimum and maximum monopile dimensions, respectively.

22. It is noted that both of the above scour models for waves combined with currents predicts that in the presence of waves, the equilibrium scour depth is reduced by a considerable margin.  The influence of the waves was obtained using the predictive method for the sea bed water particle velocity as recommended by Harris et al (2010), which was the parametric solution due to Soulsby (2006).  This solution is general for all finite amplitude waves and provides a rapid result.  Nevertheless, research undertaken in the present study also suggests that for extreme waves, it can result in an over-estimate of the maximum sea bed water particle velocity, compared to that derived from stream function wave theory.  For this reason, it is possible that the scour depths in waves and currents combined, as given in *Tables 7.3.7* and *Table 7.3.8*, may represent an under-estimate.  However, it is the scour in currents alone that dominates the response of a monopile, and the results from the two independent methods suggest that these estimates are entirely appropriate, under purely granular sea bed conditions.

**Table 7.3.7. Granular material sea bed scour for monopiles: *minimum* anticipated structural diameter**

| Location ID | Return period (years) | Hs (m) | Tp (s) | Depth (m) | Uc (m/s) | Monopile diameter (m) | Predicted equilibrium scour depth (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Harris et al (2010) | | Raaijmakers and Rudolph (2008) | |
| | | | | | | | Currents alone | Currents and waves combined | Currents alone | Currents and waves combined |
| 1 | 1 | 5.1 | 10.2 | 37.4 | 1.4 | 6.0 | 7.80 | 1.91 | 9.00 | 1.70 |
| 2 | 1 | 4.9 | 10.0 | 34.3 | 1.5 | 5.0 | 6.50 | 2.03 | 7.50 | 1.98 |
| **3** | **1** | **6.0** | **11.1** | **30.8** | **1.3** | **5.0** | **6.50** | **1.92** | **7.50** | **1.98** |
| 4 | 1 | 5.7 | 10.8 | 39.6 | 1.4 | 6.0 | 7.80 | 2.04 | 9.00 | 1.91 |
| 5 | 1 | 5.2 | 10.3 | 23.2 | 1.5 | 5.0 | 6.50 | 2.07 | 7.50 | 2.20 |
| 6 | 1 | 5.6 | 10.7 | 32.7 | 1.4 | 5.0 | 6.50 | 2.03 | 7.50 | 2.10 |
| 7 | 1 | 6.7 | 11.7 | 26.7 | 1.2 | 5.0 | 6.50 | 1.79 | 7.50 | 1.80 |
| 1 | 50 | 6.2 | 11.3 | 37.4 | 1.6 | 6.0 | 7.80 | 2.46 | 9.00 | 2.51 |
| 2 | 50 | 6.0 | 11.1 | 34.3 | 1.7 | 5.0 | 6.50 | 2.54 | 7.50 | 2.86 |
| **3** | **50** | **7.3** | **12.3** | **30.8** | **1.4** | **5.0** | **6.50** | **2.24** | **7.50** | **2.46** |
| 4 | 50 | 7.1 | 12.1 | 39.6 | 1.5 | 6.0 | 7.80 | 2.45 | 9.00 | 2.56 |
| 5 | 50 | 6.2 | 11.3 | 23.2 | 1.6 | 5.0 | 6.50 | 2.38 | 7.50 | 2.68 |
| 6 | 50 | 6.9 | 11.9 | 32.7 | 1.6 | 5.0 | 6.50 | 2.53 | 7.50 | 2.91 |
| 7 | 50 | 8.3 | 13.3 | 26.7 | 1.4 | 5.0 | 6.50 | 2.57 | 7.50 | 2.54 |

**Table 7.3.8. Granular material sea bed scour for monopiles: *maximum* anticipated structural diameter**

| Location ID | Return period (years) | Hs (m) | Tp (s) | Depth (m) | Uc (m/s) | Monopile diameter (m) | Predicted equilibrium scour depth (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Harris et al (2010) | | Raaijmakers and Rudolph (2008) | |
| | | | | | | | Currents alone | Currents and waves combined | Currents alone | Currents and waves combined |
| 1 | 1 | 5.1 | 10.2 | 37.4 | 1.4 | 8.5 | 11.05 | 1.77 | 12.75 | 1.40 |
| 2 | 1 | 4.9 | 10.0 | 34.3 | 1.5 | 7.5 | 9.75 | 1.95 | 11.25 | 1.61 |
| **3** | **1** | **6.0** | **11.1** | **30.8** | **1.3** | **7.5** | **9.74** | **1.79** | **11.24** | **1.63** |
| 4 | 1 | 5.7 | 10.8 | 39.6 | 1.4 | 8.5 | 11.05 | 1.91 | 12.75 | 1.58 |
| 5 | 1 | 5.2 | 10.3 | 23.2 | 1.5 | 7.5 | 9.71 | 1.97 | 11.20 | 1.81 |
| 6 | 1 | 5.6 | 10.7 | 32.7 | 1.4 | 7.5 | 9.75 | 1.93 | 11.25 | 1.72 |
| 7 | 1 | 6.7 | 11.7 | 26.7 | 1.2 | 7.5 | 9.73 | 1.64 | 11.23 | 1.50 |
| 1 | 50 | 6.2 | 11.3 | 37.4 | 1.6 | 8.5 | 11.05 | 2.38 | 12.75 | 2.12 |
| 2 | 50 | 6.0 | 11.1 | 34.3 | 1.7 | 7.5 | 9.75 | 2.55 | 11.25 | 2.40 |
| **3** | **50** | **7.3** | **12.3** | **30.8** | **1.4** | **7.5** | **9.74** | **2.17** | **11.24** | **2.08** |
| 4 | 50 | 7.1 | 12.1 | 39.6 | 1.5 | 8.5 | 11.05 | 2.35 | 12.75 | 2.17 |
| 5 | 50 | 6.2 | 11.3 | 23.2 | 1.6 | 7.5 | 9.71 | 2.32 | 11.20 | 2.26 |
| 6 | 50 | 6.9 | 11.9 | 32.7 | 1.6 | 7.5 | 9.75 | 2.52 | 11.25 | 2.48 |
| 7 | 50 | 8.3 | 13.3 | 26.7 | 1.4 | 7.5 | 9.73 | 2.32 | 11.23 | 2.19 |

### 7.3.3.3 Suction Caisson Designs under Granular Sea Bed Conditions

23. *Table 7.3.9* provides a summary of the applications of suction caissons in the development. There is potential for a worst case 30m diameter caisson to directly support a wind turbine tower, or for three or four smaller (5m diameter) caissons to support a tripod or jacket superstructure.

**Table 7.3.9. Summary of the dimensions of suction caisson solutions for the East Anglia THREE site**

| Structural solution | Caisson dia. | Tower/pile diameter | Number of units per structure |
|---|---|---|---|
| Monopile on caisson | 30m | 9m main tower | 1 |
| Jacket | 5m | 2.5m pin piles | 4 |
| Tripod | 5m | 2.5m pin piles | 3 |

In all cases, it is assumed that the suction caisson main cylinder projects 0.5m above the seabed. The transition piece is assumed to be entirely above the seabed level.

24. The suction caisson connects to the pile or column that frames into it, through a substantial transition piece, which spreads the load uniformly from the pile into the circumferential ring of the main caisson and then into the seabed material. The transition piece can be formed by a set of cast fins, or it can be a bulbous shell.

25. The scour exhibited by a column framing into a caisson may be controlled by the caisson itself, the column, or by a combination of the two. The relative contribution to scour from the two components depends upon the diameter of the column compared to that of the caisson.

26. Yeow and Cheng (2003) investigated this issue and reported that when the diameter of the column was less than around 0.25 times that of the caisson, then the caisson mainly governed the scour process. Then, as the column progressively increased in diameter relative to the caisson, the combined scour tended towards the single pile result.

#### 7.3.3.3.1 30m Diameter Suction Caisson under Granular Sea Bed Conditions

27. The solutions presented by Khalfin (1983), modified by Bos et al (2002b) and informed by Yeow and Cheng (2003) have been adopted in the present study for application to the 30m suction caisson.

28. Since the column framing into the 30m diameter caisson is 9m in diameter, we can assume that under those circumstances, the scour is controlled by the caisson, according to Yeow and Cheng (2003). The transition piece was taken as being formed by a set of cast fins, or by a bulbous shell. The effective height of the transition piece was assumed to be represented by the expression:

$$h_t = 0.50 \cdot (D_c - D_p) + p_c$$

Where:
$D_c$ = caisson diameter (taken as 30m)
$D_p$ = diameter of the column framing into the transition piece (taken as 9m)

$p_c$ = projection of the top of the main caisson above the seabed (taken as 0.5m).

29. This equation has been inferred by inspection from several published designs and also from the photographic information shown by Margheritini (2012). The use of this equation in the scour prediction method reproduces the scale model test results published by Margheritini (2012).

30. In waters of intermediate depth, in which the wave activity generates significant but not necessarily dominant water particle velocities on the sea bed, and also the current speed happens to be large, it is possible for scour due to currents alone to be the dominant factor. This scenario was tested using the modified Khalfin solution (Khalfin 1983 and Bos et al. 2002a).

31. *Table 7.3.10* presents the results for the two situations, namely waves and currents combined and currents acting alone. The results indicate that the scour depths are larger when the currents alone are acting. In shallower water depths, the granular-material scour depths could be larger than in deeper water depths.

**Table 7.3.10 – Predicted equilibrium scour depths for the 30m diameter suction caisson on granular sea bed**

| Location ID | Return period (years) | Hs (m) | Tp (s) | Uc (m/s) | Depth (m) | Predicted equilibrium scour depth (m) due to waves & currents combined | Predicted equilibrium scour depth (m) due to currents acting alone |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 5.1 | 10.2 | 1.4 | 37.4 | 0.47 | 2.92 |
| 2 | 1 | 4.9 | 10.0 | 1.5 | 34.3 | 0.56 | 3.33 |
| **3** | **1** | **6.0** | **11.1** | **1.3** | **30.8** | **1.34** | **3.00** |
| 4 | 1 | 5.7 | 10.8 | 1.4 | 39.6 | 0.51 | 2.82 |
| 5 | 1 | 5.2 | 10.3 | 1.5 | 23.2 | 2.35 | 4.20 |
| 6 | 1 | 5.6 | 10.7 | 1.4 | 32.7 | 0.94 | 3.16 |
| 7 | 1 | 6.7 | 11.7 | 1.2 | 26.7 | 2.32 | 2.97 |
| 1 | 50 | 6.2 | 11.3 | 1.6 | 37.4 | 0.74 | 3.42 |
| 2 | 50 | 6.0 | 11.1 | 1.7 | 34.3 | 0.88 | 3.86 |
| **3** | **50** | **7.3** | **12.3** | **1.4** | **30.8** | **1.80** | **3.27** |
| 4 | 50 | 7.1 | 12.1 | 1.5 | 39.6 | 0.84 | 3.06 |
| 5 | 50 | 6.2 | 11.3 | 1.6 | 23.2 | 2.96 | 4.53 |
| 6 | 50 | 6.9 | 11.9 | 1.6 | 32.7 | 1.35 | 3.70 |
| 7 | 50 | 8.3 | 13.3 | 1.4 | 26.7 | 3.02 | 3.56 |

32. The predicted scour depth around the suction caisson is influenced by the assumed height of the caisson. The true structural height of the caisson above the seabed is equal to the elevation of the top of the main 30m diameter cylinder, plus an allowance for the transition piece connecting the main cylinder to the surface-piercing vertical column framing into it. Inspection will reveal that the height of the transition piece is likely to be quite considerable and this will affect the intrusion of the structure into the water column, and hence the amount of scour that it can develop. The effective height of the caisson that has been adopted in this study has been inferred from photographs and drawings of model and prototype suction caisson designs and physical model test pieces.

33. When the dimensional characteristics of the suction caisson design become better established, it may be necessary to revise the predictions of the depth and volume of the scour hole accordingly.

#### 7.3.3.3.2 5m Diameter Suction Caissons for Jackets or Tripods under Granular Sea Bed Conditions

34. If the column diameter is large compared to that of the caisson, then the scour should be checked by idealising the column as a monopile and ignoring the caisson. This situation applies to the jacket and the tripod solutions where 5m diameter suction caissons are possible foundations for each leg.

35. In practice, however, it is likely that the top of the caisson will partially suppress the downward-descending vortex that develops around a monopile, but the extent to which that will occur with a 2.5m diameter column framing into a 5m caisson is uncertain. Yeow and Cheng (2003), for example, found that when the ratio of column diameter to that of the caisson was increased to more than around 0.25, then the scour tended in the limit towards that exhibited by the column acting alone as a monopile, with little influence from the suction caisson.

36. Consequently, the scour case for the 2.5m diameter column framing into a 5m diameter suction caisson has been idealised as a process of scour around a 2.5m diameter monopile alone, due to waves and currents combined and currents acting alone.

37. This assessment is described further in sections 7.3.3.4 and 7.3.3.5 for tripods and jackets respectively, with results summarised below.

38. Under the action of currents alone, the predicted scour depth around each leg of a 2.5m maximum diameter tripod or jacket obtained using the methods presented by

Harris et al (2010) is 3.25m and by the earlier solution offered by Raaijmakers and Rudolph (2008), the corresponding figure is 3.75m.

39. Under the action of waves and currents combined at the 1-year return period, the corresponding scour depths around each leg are 1.77m (Harris et al. 2010) and 2.36m (Raaijmakers and Rudolph 2008). At a return period of 50-years, the respective values are 1.98m and 2.70m.

#### 7.3.3.4 Tripod Design under Granular Sea Bed Conditions

40. The tripod design features a set of three raking piles, each of between 1.0 to 2.5m diameter, piled into the sea bed. The upper ends of the raking piles all frame into a main central column with a diameter of up to 9m.

41. As far as the scour around the columns is concerned, the results are likely to be similar to those applying to a jacket foundation (see section 7.3.3.5), with the caveat that there could be more interaction between the individual scour holes, depending upon the distance between the piles.

42. Stahlmann and Schlurmann (2010) show that scour hole interaction can occur between the three pin piles of a tripod structure, and also that a substantial amount of activity occurs beneath the central column. The example presented by these authors is for a large scale (1/12) physical model test on granular material, however, it does demonstrate the principle that strong scour hole interaction could occur around a tripod, depending upon the metocean and seabed conditions.

43. At present, the elevation of the base of the central column above the sea bed is unknown, as is the diameter of the bottom of the column, which could taper near its lower extremity. These design details are yet to be resolved and therefore the potential depth of the scour hole under the base of the central column has been predicted using the methods which were proposed by Sumer and Fredsφe (2002).

44. This solution applies to scour under a horizontal circular cylinder and therefore its use in the present situation is an adaptation. Sumer and Fredsφe (2002) reported that the presence of waves exerted a reducing effect upon the scour depth that could develop under a raised horizontal cylinder in a granular material due to currents alone. Diagram 7.3.2 shows the predicted scour depths that could develop according to their solution. On that basis, the equilibrium scour depth under the central column could be of the order of 3m to 5m in a granular sea bed, depending upon height of the base of the central column above the sea bed.

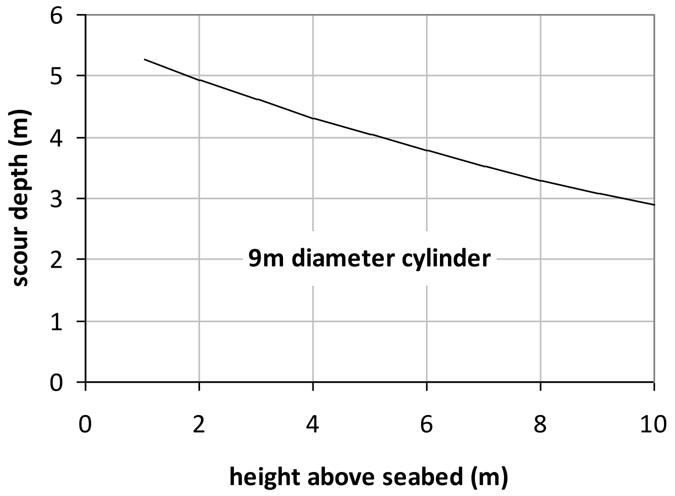

**Diagram 7.3.2. Predicted depth of the equilibrium scour developing under a horizontal cylinder raised a given height above the sea bed (based upon Sumer and Fredsφe, 2002)**

45. According to Sumer and Fredsφe (2002), the width of the scour hole caused by currents alone could be of the order of 6 cylinder diameters. If again that result is adapted to the present situation and a scour pit width of 6 times the basal diameter of the vertical column is implemented, it is easy to see why the interaction between the scour holes appears to be so strong.

### 7.3.3.5 Jacket Design under Granular Sea Bed Conditions

46. Under the action of currents alone, the predicted scour depth around each leg of a 2.5m maximum diameter jacket obtained using the methods presented by Harris et al (2010) is 3.25m and by the earlier solution offered by Raaijmakers and Rudolph (2008), the corresponding value is 3.75m.

47. Under the action of waves and currents combined at the 1-year return period, the corresponding scour depths around each leg are 1.77m (Harris et al, 2010) and 2.36m (Raaijmakers and Rudolph, 2008). At a return period of 50-years, the respective values are 1.98m and 2.70m.

### 7.3.4 Scour Predictions Accounting for the Strength of the Sea Bed Material

48. The influence of the strength of the sea bed material in limiting scour depth when predicting scour was considered using the methods developed by Annandale (1995, 2001 and 2006).

49. The soil conditions were defined as reported by the site investigations specifically undertaken for the East Anglia Zone and the East Anglia THREE site in particular.

50. The Noble Denton (2011) metocean modelling Point 3 is located within the East Anglia THREE site. The investigations made so far into scour on a granular sea bed suggest that it is broadly typical of the ‘average’ metocean conditions at the seven modelled points across the East Anglia Zone by Nobel Denton (2011) and is, therefore, likely to inform a representative prediction of the scour hole development suitable for purposes of Environmental Impact Assessment.

51. To obtain more detail of variation in scour across the East Anglia THREE site would require numerical modelling to a finer resolution than is available at present and also more comprehensive borehole data. It is therefore considered reasonable for the modelled metocean data from Point 3 to be used in the more detailed assessment of scour, taking account of sea bed soil strength.

52. Scour depth predictions taking soil strength into account have primarily been informed using strength data from the boreholes that are located within or near to, the East Anglia THREE site. These are boreholes G001, G002, G004, G006, G026 and G030; the remainder of the boreholes are located at least 20 km west of these boreholes. Nevertheless, all 30 of the borehole datasets were used for predicting the scour depths and the values obtained across the ensemble were compared against those applying to the most relevant boreholes.

53. This process was undertaken with a view to establishing that a conservative but realistic estimate of scour depth. In fact, borehole G002 frequently provided a maximum or near-maximum scour depth across the entire ensemble of 30 locations; boreholes G004 and G006 also made strong contributions.

54. Annandale (1995, 2001 and 2006) gives an example of the full process of deriving a scour depth that accounts for the strength of the soil.

**Table 7.3.11 – Predicted equilibrium scour depths under the specified return periods, taking account of the strength of the soil in the calculations**

| Return period (years) | Foundation Type | Assessment Method | Main diameter (m) | $S_e$ (m) | $S_{e,s}$ (m) |
|---|---|---|---|---|---|
| 1 | Monopile | Harris et al (2010) | 5.0 | 6.50 | 4.00 |
| | | | 7.5 | 9.74 | 5.20 |
| 50 | | | 5.0 | 6.50 | 5.00 |
| | | | 7.5 | 9.74 | 7.00 |
| 1 | Conical GBS | Khalfin (2007) & Soulsby & Clarke (2005) | 20.0 | 2.94 | 2.06 |
| 1 | | | 50.0 | 3.94 | 2.24 |
| 50 | | | 20.0 | 4.25 | 3.30 |
| 50 | | | 50.0 | 5.70 | 4.62 |
| 1 | Suction Bucket | Khalfin (1983) modified Bos et al (2002a) | 30.0 | 3.00 | 2.20 |
| 50 | | | 30.0 | 3.27 | 2.48 |
| 1 | | Raaijmakers & Rudolph (2008) | 5.0 | 3.75 | 2.06 |
| 50 | | | 5.0 | 3.75 | 2.84 |
| 1 | Jacket (pin piles) | Raaijmakers & Rudolph (2008) | 2.5 | 3.75 | 2.06 |
| 50 | | | 2.5 | 3.75 | 2.84 |
| 1 | Tripod (pin piles) | Raaijmakers & Rudolph (2008) | 2.5 | 3.75 | 2.06 |
| 50 | | | 2.5 | 3.75 | 2.84 |
| 1 | Tripod (main column) | Sumer and Fredsфe (2002) | 9.0 | 4.0 (avg) | 2.22 |
| 50 | | | 9.0 | 4.0 (avg) | 2.90 |

Where:
*Method* = the method that was used to calculate the granular scour depth
$S_e$ = the predicted equilibrium scour depth for a granular sea bed
$S_{e,s}$= the equilibrium scour depth taking the material strength of the sea bed into account

55. Note that for the small diameter piles, or under the tripod main column, the predicted equilibrium scour depth for the granular assumption is the same for both return periods because, for such a configuration, if the sea bed exhibits live scour then the scour depth around the pile (or under the tripod column) is the same in both cases. However, when accounting for the strength of the sea bed material, the erosive power is characterised by the sea bed shear stress and the applied water particle velocity. The sea bed shear stress was adjusted according to the method developed by Soulsby and Clarke (2005), to include a wave contribution, and the shear stress is larger at the higher return period. Hence in the results for the small piles or the tripod main column, the granular scour depth is the same for both return periods, but when the sea bed material strength is taken into account, the 50-year return period result is larger than that for the 1-year.

### 7.3.5 Scour Hole Plan Areas and Volumes

56. The plan areas and volumes of the scour holes generated by the various structures were predicted based upon an elliptical scour hole, after Harris et al (2010) and as observed in a large number of published experiments by others.

57. *Table 7.3.12* provides the results of the calculations. It is noted that in the case of the jacket and tripod structures, the individual scour holes produced by each structural element could interact, possibly leading to a larger total scour volume than that attributed to the sum of the contributions from the individual holes. Stahlmann and Schlurmann (2010) show a potentially typical example, on a granular sea bed.

58. In this table, the results are based upon a friction angle of 30° obtained from inspection of the borehole data. Length, width and plan areas apply to one structural element, in cases when there is more than one element in a structure.

**Table 7.3.12. Schedule of scour hole volumes and plan areas**

| Type of structure | RP (years) | $S_{e,s}$ (m) | D (m) | Length incl. structure (m) | Width incl. structure (m) | Plan area incl. structure ($m^2$) | N | $V_e$ total excl. structure ($m^3$) | $A_e$ total incl. structure ($m^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Monopile | 1 | 4.00 | 5.0 | 27 | 22 | 484 | 1 | 694 | 484 |
| Monopile | 1 | 5.20 | 7.5 | 36 | 30 | 879 | 1 | 1625 | 879 |
| Monopile | 50 | 5.00 | 5.0 | 32 | 26 | 689 | 1 | 1239 | 689 |
| Monopile | 50 | 7.00 | 7.5 | 46 | 38 | 1387 | 1 | 3490 | 1387 |
| Conical GBS | 1 | 2.06 | 20.0 | 31 | 29 | 699 | 1 | 370 | 699 |
| Conical GBS | 1 | 2.24 | 50.0 | 62 | 60 | 2890 | 1 | 1003 | 2890 |
| Conical GBS | 50 | 3.30 | 20.0 | 38 | 34 | 1007 | 1 | 1033 | 1007 |
| Conical GBS | 50 | 4.62 | 50.0 | 75 | 70 | 4078 | 1 | 4580 | 4078 |
| Suction Bucket | 1 | 2.20 | 30.0 | 42 | 39 | 1288 | 1 | 606 | 1288 |
| Suction Bucket | 50 | 2.48 | 30.0 | 44 | 41 | 1375 | 1 | 781 | 1375 |
| Jacket (suction bucket) | 1 | 2.06 | 5.0 | 16 | 14 | 194 | 4 | 532 | 776 |
|  | 50 | 2.84 | 5.0 | 21 | 17 | 294 | 4 | 1167 | 1176 |
| Jacket (pin piles) | 1 | 2.06 | 2.5 | 14 | 11 | 127 | 4 | 374 | 508 |
|  | 50 | 2.84 | 2.5 | 18 | 15 | 213 | 4 | 867 | 852 |
| Tripod (pin piles) | 1 | 2.06 | 2.5 | 14 | 11 | 127 | 3 | 281 | 381 |
|  | 50 | 2.84 | 2.5 | 18 | 15 | 213 | 3 | 650 | 639 |
| Tripod (main column) | 1 | 2.22 | 9.0 | 21 | 19 | 365 | 1 | 233 | 365 |
|  | 50 | 2.90 | 9.0 | 25 | 21 | 475 | 1 | 433 | 475 |

Where:

| | |
|---|---|
| RP | Return Period |
| $S_{e,s}$ | Predicted equilibrium scour depth including a contribution from the strength of the sea bed material |
| D | Principal diameter of structure |
| N | Number of units in the whole structure |
| $V_e$ | Total volume of scour hole(s) (excluding the structure itself) |
| $A_e$ | Plan area of the scour hole(s) around the structure (including the structure itself). |

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# ANNEX A: SUPPLEMENTARY ASSESSMENT - JACKETS WITH SUCTION CAISSONS

## A.1 Background

59. Subsequent to the scour assessments presented in *Appendix 7.3*, the project description was altered to include a worst case of a jacket with up to 10m diameter suction caissons at the foot of each leg (the previous assessments were performed using suction caissons up to 5m in diameter).

60. With all other parameters (e.g. jacket leg diameters, wave and current conditions) remaining constant, the scour assessment was repeated at Noble Denton (2011) modelling point 3 (in 30.8m water depth), with the updated worst case dimensions for the suction caissons at the foot of each leg.

61. The purpose of this supplementary assessment was to confirm the worst case foundation type (of the size ranges applicable to a water depth of 30.8m) in terms of scour hole development. The results showed that the gravity base structures remain a worse case than the jackets with increased diameter suction buckets.

62. NB: The other change in the project description related to an increase in the maximum upper size of a monopole foundation in water depths of 35 to 45m, but the size range of monopoles valid for a water depth of 30.8m was unaltered.

## A.2 Consideration of Scour Around Pin Piles of the Jacket Structure when using 10m Diameter Suction Caissons

63. The diameter of the jacket piles is 2.5m and the original design configuration framed these in to 5m diameter suction caissons, which protruded 0.5m above the surface of the sea bed.

64. Yeow and Cheng (2003) reported the results of a series of physical model tests on the scour due to wave action around slender piles framing in to larger diameter supporting caissons. They found that if the caisson was of a sufficient diameter relative to that of the pile, then it would suppress the development of the downward vortex that the pile would normally generate, leading to a reduction in the equilibrium scour depth compared to that developed by the pile acting alone.

65. However, they found that when the diameter of the pile was as large as 0.5 times that of the supporting caisson, as it is in the original design considered here, then the caisson cannot entirely disrupt the behaviour of the horseshoe vortex originating from the pile, and scour proceeds around the edge of the caisson. This is particularly

true if the caisson is of a shallow height, as Diagram A.1 suggests. However, the scouring was not quite to the same extent as would apply if the caisson were absent. When the diameter of the pile was 0.8 times that of the supporting caisson and the caisson height was shallow, then Yeow and Cheng found that the scour depth was almost the same as that which would apply in the absence of the caisson.

66. For these reasons, taking into consideration the behaviour shown in Diagram A.1 below and the paucity of further available data on this subject, East Anglia THREE Limited (EATL) took a conservative view when predicting the scour around the 5m diameter caissons attached to the 2.5m diameter pin piles. EATL predicted the equilibrium scour depth for the 2.5m diameter pin piles, in the absence of the caisson and then calculated the scour plan area and volume using that depth, but with the caisson diameter in place.

67. Consideration is now being given to the scour that can develop if the 5m diameter caisson is replaced by one with a diameter of 10m, making the ratio of the pile to the caisson diameter equal to 0.25. Assuming that the height of the top of the caisson above the seabed remains at 0.5m, then Figure 2, also taken from Yeow and Cheng (2003), suggests that the equilibrium scour depth will be relatively small and less than that applying to a pile acting alone.

68. Furthermore, de Sonneville et al (2010) reported on the use of circular collars fitted at seabed level, to control scour around vertical piles in currents and in combined wave and current activity. The collars were up to three times the pile diameter in size. They found that the collars were effective at preventing scour in currents alone. Under the action of combined waves and currents, the collar delayed the onset of scour and tended to reduce the equilibrium scour depth. Taking this result into consideration with the data published by Yeow and Cheng (2003), it seems likely that the adoption of a 10m diameter suction caisson is unlikely to lead to a substantial increase in scour volumes, compared to that which would apply with the 5m diameter caisson.

## A.3 Scour Predictions

69. The method developed by Bos et al. (2002) for deriving the scour around submerged gravity structures, indicates that the predicted 50-year equilibrium depth due to the 10m diameter caisson itself would be of the order of 0.2 metres at Noble Denton modelling point 3. This is based upon the assumption that the caisson projects 0.5m above the seabed. The corresponding maximum predicted scour depth occurs at

Noble Denton modelling point 7 and is 0.4 metres. Therefore, it is the presence of the pin pile that will invoke the principle contribution to scour volume.

70. If the conservative approach previously adopted is retained, then the predicted equilibrium scour depths will remain the same as before, (since they were derived from the pin pile diameter) which are 2.84m at 50 year return and 2.06m at a return period of 1 year. The corresponding equilibrium scour volumes will then be 1,767m$^3$ and 848m$^3$ respectively, for a total of four pin piles framing into 10m diameter caissons. For the 5m diameter caisson, the corresponding scour volumes at 50 year and 1 year return were 1,167m$^3$ and 532m$^3$ respectively.

71. Referring to Diagram A.2 and ignoring the single data point at the origin, it appears highly likely that the true equilibrium scour depth for the 2.5m diameter pile framing into a 10m diameter caisson will be considerably less than that applying to a free-standing 2.5m diameter pile. The equilibrium scour depth for a full height 10m cylinder is of the order of 13m to 15m. Applying a correction to that value, to account for the true height of the caisson, which is 0.5m and based upon Diagram A.2, the equilibrium scour depth at 50 years is unlikely to be much more than around 1.0 to 1.25m. This is considerably less than the 2.84m that was derived based upon scour around the 2.5m diameter pin pile alone.

72. Consequently, EATL believe that the adoption of a 10m diameter suction caisson will not be detrimental to the results of the environmental assessment, compared to the results that would obtain for a 5m caisson.

## A.4 References

Bos, K.J., Veheij, H.J., Kant, G. and Kruisbrink, A.C.H. (Bos et al 2002): *Scour Protection around Gravity Based Structures Using Small Size Rock*. Proceedings. ICSF-1: First International Conference on Scour of Foundations, Texas, Nov 17-20, 2002

de Sonneville, B., Rudolph, D. and Raaijmakers, T. (2010): *Scour reduction by collars around offshore monopiles.* ASCE Scour and Erosion: pp 460-470. doi: 10.1061/41147(392)44

DHI/Snamprogetti (1992): *SISS Project: Sea bottom instability around small structures*. Erodible Bed Laboratory Tests Phase 1. Final Report. Contract INGE91/03060, June 1992.

Yeow, K. and Cheng, L. (2003): *Local scour around a vertical pile with a caisson foundation*. Proc Cong Asian and Pacific Coasts 2003.

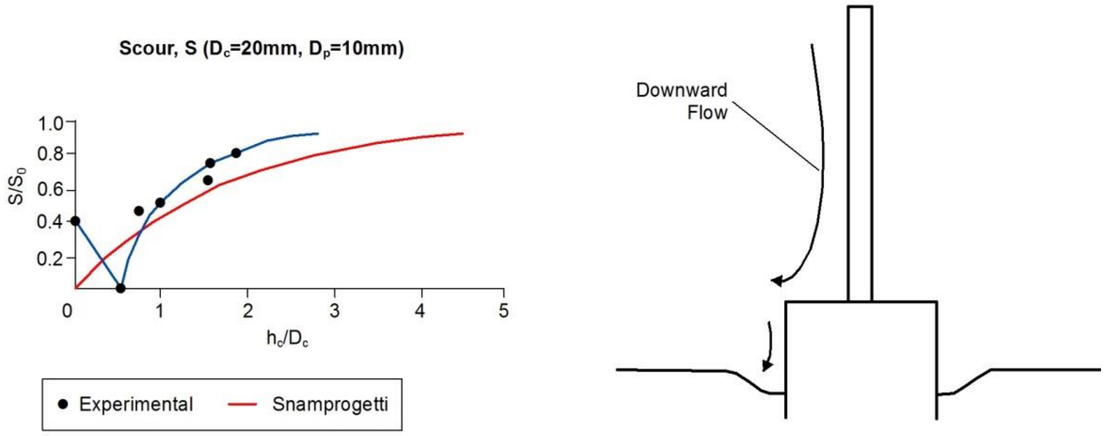


**Diagram A.1 – Physical modelling results and approximate flow visualisations presented by Yeow and Cheng (2003) for scour around a model pile framing in to a caisson which has a diameter twice that of the pile. (The curve labelled 'Snamprogetti' refers to the output from a study reported by DHI and Snamprogetti in 1992).**

Key to plot: $h_c$ – height of the top of the caisson above the seabed level; $D_c$ – diameter of the caisson; S – equilibrium scour depth at the ratio of $h_c/D_c$ under consideration; $S_0$ – limiting equilibrium scour depth

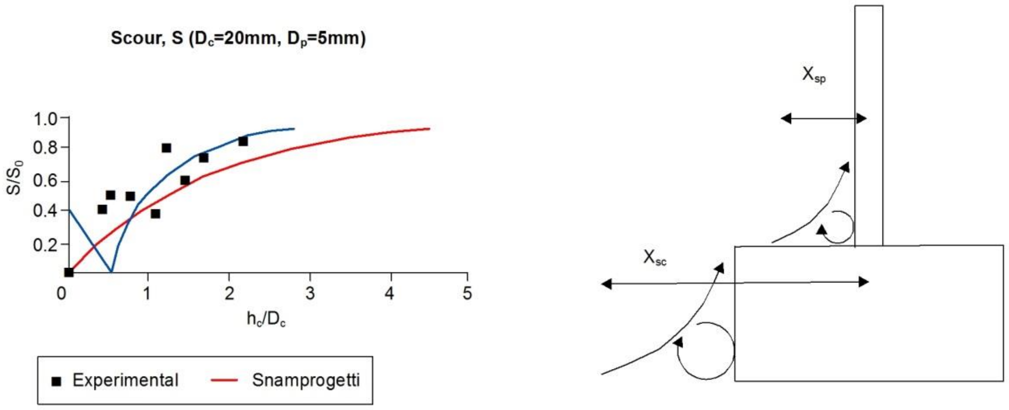


**Diagram A.2 – Physical modelling results and approximate flow visualisations presented by Yeow and Cheng (2003) for scour around a model pile framing in to a caisson which has a diameter four times greater than that of the pile. (The curve labelled 'Snamprogetti' refers to the output from a study reported by DHI and Snamprogetti in 1992).**

Key to plot: $h_c$ – height of the top of the caisson above the seabed level; $D_c$ – diameter of the caisson; S – equilibrium scour depth at the ratio of $h_c/D_c$ under consideration; $S_0$ – limiting equilibrium scour depth

# ANNEX B:
# SUPPLEMENTARY ASSESSMENT – UPDATED METOCEAN DATA

## B.1 Background

73. Subsequent to the scour assessments presented in *Appendix 7.3*, updated data became available to the project in the form of a metocean study by Deltares (Deltares 2012). This considered 'normal' and 'extreme' metocean parameters at a series of twenty model output points across the East Anglia Zone, two of which were directly within the East Anglia THREE site and one of which was directly on the boundary of East Anglia THREE site (see *Figure 7.3.2*). Note: a further two model output points were directly north of the East Anglia THREE site and have been included in the supplementary assessment to provide a broader spatial context.

74. The scour assessments presented in *Appendix 7.3* were based on an earlier metocean study by Noble Denton (Noble Denton 2011) which considered 'normal' and 'extreme' metocean parameters at a series of six model output points across the East Anglia Zone, one of which was directly within the East Anglia THREE site (at a water depth of 30.8m). In the scour assessments, a 'deeper water' sensitivity test was also performed.

75. The purpose of this supplementary assessment was to examine the sensitivity of the previous scour assessments to the updated metocean data that become available subsequently, recognising that the scour assessments were intended to provide a first order estimate of scour volumes to inform the environmental assessments.

## B.2 Effects of Updated Metocean Data

76. *Figure 7.3.2* shows the locations of the metocean modelling points considered by Noble Denton (2011) and Deltares (2012). *Table 1* lists the critical 1 year and 50 year conditions; the values in parentheses after each point-number are the water depths at mean sea level (these values are taken from *Table 2.2* of the Deltares report). Noble Denton's model output point 3 and Deltares' model output point A9 are approximately coincidentally located.

77. This supplementary assessment presents scour predictions using the extreme current speeds taken from the Noble Denton report for their model output point 3. The values provided are the averaged current speeds over the top 20m of the water column – which is the closest definition to the full depth-averaged current speed that is available to this study. The Deltares report does not provide estimates of extreme return period depth-averaged current speeds.

**Table B.1 – Critical metocean cases from the Deltares report for return periods of 1 and 50 years.**
Note: Deltares Point A9 is approximately coincident with Noble Denton Point 3

| Point | RP | Worst direction | $H_s$ (m) | $T_p$ (s) | Point | RP | Worst direction | $H_s$ (m) | $T_p$ (s) |
|---|---|---|---|---|---|---|---|---|---|
| A6 (38.4m) | 1 | N | 4.6 | 10.5 | A11 (36.5m) | 1 | N | 4.8 | 10.5 |
| A6 | 1 | NW | 4.9 | 9.8 | A11 | 1 | NW | 4.9 | 10.0 |
| A6 | 50 | N | 8.0 | 14.7 | A11 | 50 | N | 8.2 | 14.8 |
| | | | | | | | | | |
| *A9 (30.8m)* | *1* | *N* | *4.6* | *10.5* | A12 (40.4) | 1 | N | 4.7 | 10.5 |
| *A9* | *1* | *NW* | *4.7* | *9.6* | A12 | 1 | NW | 5.0 | 10.0 |
| *A9* | *50* | *N* | *8.0* | *14.6* | A12 | 50 | N | 8.2 | 14.7 |
| | | | | | Noble Denton Modelling Point 3<br>1-year conditions: $H_s$ – 6m, $T_p$ – 11.1s<br>50-year conditions: $H_s$ – 7.3m, $T_p$ – 12.3s<br>This point is approximately coincident with Deltares Modelling Point A9 | | | | |
| A10 (43.7m) | 1 | N | 4.8 | 10.5 | | | | | |
| A10 | 1 | NW | 4.9 | 9.5 | | | | | |
| A10 | 50 | N | 8.6 | 14.6 | | | | | |

### B.2.1 *Granular scour case*

78. *Table B.2* and *Table* B.3 show the predicted scour depths for the granular scour case, applying to the minimum and maximum diameters of the gravity base structures that would be used in the appropriate water depth for the given model output point. In each table, the scour depth in parenthesis and labelled with an asterix is the worst case value obtained at Noble Denton model output point 3 from the previous scour assessments (presented in *Appendix 7.3*).

**Table B.2 - Granular material sea bed scour for the conical gravity base structures: *minimum* anticipated structural diameter at the intersection of cone with the base plate**

| Point | Return period (years) | $H_s$ (m) | $T_p$ (s) | $U_c$ (m/s) | Depth (m) | Structure base diameter (m) | Predicted equilibrium scour depth (m) |
|---|---|---|---|---|---|---|---|
| A6 | 1 | 4.6 | 10.5 | 1.3 | 38.4 | 25.0 | 1.75 |
| *A9* | *1* | *4.6* | *10.5* | *1.3* | *30.8* | *20.0* | *2.08 (2.94)** |
| A10 | 1 | 4.8 | 10.5 | 1.3 | 43.7 | 25.0 | 1.55 |
| A11 | 1 | 4.8 | 10.5 | 1.3 | 36.5 | 25.0 | 1.93 |
| A12 | 1 | 4.7 | 10.5 | 1.3 | 40.4 | 25.0 | 1.68 |
| | | | | | | | |
| A6 | 50 | 8.0 | 14.7 | 1.4 | 38.4 | 25.0 | 5.16 |
| *A9* | *50* | *8.0* | *14.6* | *1.4* | *30.8* | *20.0* | *5.76 (4.25)** |
| A10 | 50 | 8.6 | 14.6 | 1.4 | 43.7 | 25.0 | 4.92 |
| A11 | 50 | 8.2 | 14.8 | 1.4 | 36.5 | 25.0 | 5.58 |
| A12 | 50 | 8.2 | 14.7 | 1.4 | 40.4 | 25.0 | 5.07 |

**Table B.3 - Granular material sea bed scour for the conical gravity base structures: *maximum* anticipated structural diameter at the intersection of cone with the base plate**

| Point | Return period (years) | $H_s$ (m) | $T_p$ (s) | $U_c$ (m/s) | Depth (m) | Structure base diameter (m) | Predicted equilibrium scour depth (m) |
|---|---|---|---|---|---|---|---|
| A6 | 1 | 4.6 | 10.5 | 1.3 | 38.4 | 55.00 | 2.25 |
| *A9* | *1* | *4.6* | *10.5* | *1.3* | *30.8* | *50.00* | *2.79 (3.95)** |
| A10 | 1 | 4.8 | 10.5 | 1.3 | 43.7 | 55.00 | 1.99 |
| A11 | 1 | 4.8 | 10.5 | 1.3 | 36.5 | 55.00 | 2.48 |
| A12 | 1 | 4.7 | 10.5 | 1.3 | 40.4 | 55.00 | 2.16 |
| | | | | | | | |
| A6 | 50 | 8.0 | 14.7 | 1.4 | 38.4 | 55.00 | 6.64 |
| *A9* | *50* | *8.0* | *14.6* | *1.4* | *30.8* | *50.00* | *7.72 (5.70)** |
| A10 | 50 | 8.6 | 14.6 | 1.4 | 43.7 | 55.00 | 6.33 |
| A11 | 50 | 8.2 | 14.8 | 1.4 | 36.5 | 55.00 | 7.18 |
| A12 | 50 | 8.2 | 14.7 | 1.4 | 40.4 | 55.00 | 6.52 |

79. It is notable from *Tables B.2* and *B.3* that the greatest scour depths are predicted to occur at Deltares model output point A9 (which is approximately coincident with Noble Denton model output point 3), where the water depth is 30.8m LAT, and that scour depths reduce in areas of deeper water. This is in keeping with the findings of the scour assessments presented in *Appendix 7.3* which incorporated assessments directly at Noble Denton model output point 3 (in water depth of 30.8m LAT) and a 'deeper water' sensitivity test.

80. The Noble Denton 1-year return period conditions at their model output point 3 are more severe than those obtained by Deltares at the same return period, for their model output point A9. The two modelling points are however, approximately coincident. This indicates that at the 1-year return period, the previous scour assessments at Noble Denton model output point 3 represent a worse case than would be obtained using the metocean data from Detares model output point A9.

81. At the 50-year return period, the results at Deltares model output point A9 are more severe than those applying to the Noble Denton model output point 3. This explains why the granular scour depths calculated at the 1-year return period, obtained using the Deltares data, are less severe than those obtained using the Noble Denton metocean predictions, but the situation is reversed under the 50-year scenario.

### B.2.2 *Soil strength scour case*

82. To investigate the effects of the more severe metocean conditions under 50-year conditions on predictions of scour volumes, predictions have been made here of the equilibrium scour depth, taking account of sea bed soil strength, using the Deltares metocean predictions at their model output point A9.

83. The resulting scour depth, by applying the Annandale soil strength method described in *Appendix 7.3*, is of the order of 4.9 to 5.0m. This is slightly greater than the 4.62m obtained using the Noble Denton metocean data at model output point 3, but the difference is deemed insufficient to warrant a full re-appraisal of scour assessments, especially as Deltares model output point A9 represents a worst case in terms of scour depths compared with the other model output points.

84. The predicted scour volume at this location is 5,194m$^3$ (based upon a scour hole depth of 4.9m and using the 50 year metocean data from Deltares model output point A9), compared to the 4,580m$^3$ that was reported previously and which was based upon the metocean data from Noble Denton model output point 3.

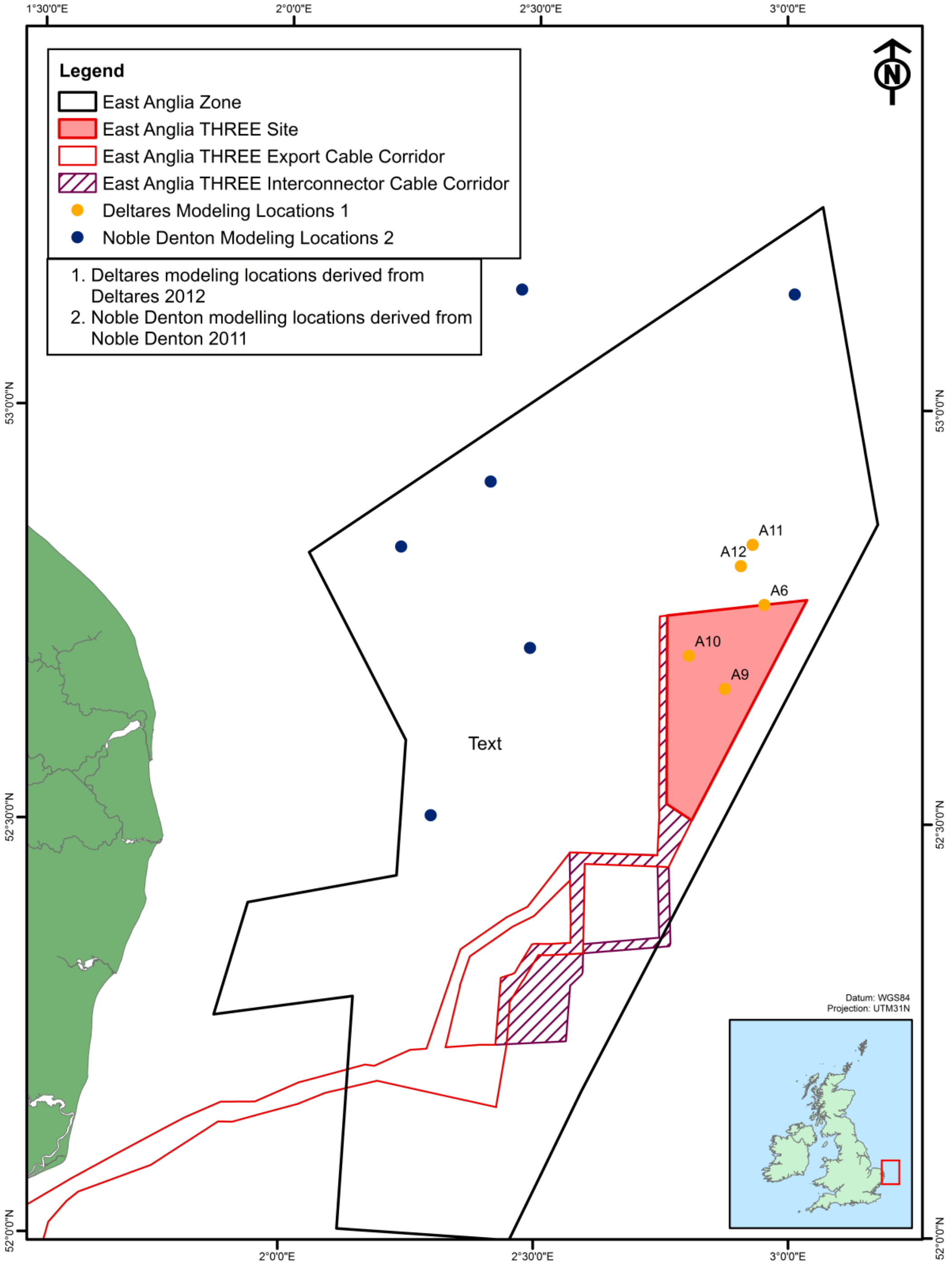
85. Given that both of these volumes remain lower than the volumes of sediment that would be released into the water column from the worst case scenario for sea bed preparation activates, the results of the previous scour assessments remain valid for use in the ES.

## B.3 References

Deltares (2012). *East Anglia Offshore Wind Farm: Metocean Study*. Report to East Anglia Offshore Wind Ltd., October 2012.

GL Noble Denton (2011). *Metocean Conditions Study*. Report No. L24718.

*Figure 7.3.2* presented below illustrates the Layout of East Anglia THREE within the context of the Zone boundary, and shows the most relevant Deltares modelling points along with those originally adopted by Noble Denton.



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## East Anglia THREE Limited

Location of Relevant Deltares and Noble Denton Modelling Points

| Rev | Date | By | Comment |
|---|---|---|---|
| 1 | 22/10/15 | DT | Second Issue. |
| 1 | 29/09/15 | DT | First Issue. |

Original A4 Plot Scale 1:700,000

0 5 10 km
0 2 4 6 nm

Volume 3
Figure 7.3.2

| Layout | Date | Rev | Dwg No. |
|---|---|---|---|
| N/A | 22/10/2015 | 2 | EA3-L-139 |

Ref:

**Appendix 7.3 Ends Here**