Prediction and observation of scour around the temporary river works for the Thames Tideway Tunnel

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ABSTRACT

Estimations of scour potential at the Thames Tideway Tunnel temporary works cofferdams were made during the design phase using the Erodibility Index approach of Annandale (1995, 2006), modified by Harris et al. (2010). Intense quarterly monitoring ongoing since 2014 designed to allow an adaptive approach to scour risk management also provides a case study, allowing the approach taken for the pre-construction scour predictions to be verified. The results show excellent agreement between predictions and observations, supporting the use of a method that can take into account soil profile variability when predicting scour on the inter- and sub- tidal foreshore.

INTRODUCTION

London's sewerage system dates back more than 150 years and is based on a combined sewer system approach. In this system the wastewater from homes and businesses uses the same sewer network as the rain runoff from streets to be carried to treatment works. During high rainfall events, to avoid sewage backing up, the system is allowed to overflow. In London the Combined Sewer Overflows (CSOs) are located along the bank of the tidal River Thames.

A combination of drivers has brought the need to upgrade and improve the sewage system in London; population growth (the system was designed for 4 million people, the present population is 9 million and increasing), increased water use per person and more impermeable areas within the city leading to higher and more rapid rainfall flows into the system. These factors have increased the number of overflow events from once or twice per year when the system was designed, to 50-60 events a year presently leading to the discharge of approximately 39 million m^3 of combined sewage discharged into the tidal Thames in a typical year.

As part of addressing these issues and helping to achieve compliance with the Water Framework Directive (WFD) Thames Water developed the Thames Tideway Tunnel (TTT) project (https://www.tideway.london/), a £4.2 billion project to redirect the largest and most regularly discharging CSOs into bespoke individual drop shafts and from thence into the new tunnel. The 25 km long tunnel with a total volume of 1.6 million m^3 allows the discharges to be conveyed and treated at an expanded treatment works built in East London.

The numerous constraints on the works required to intercept the CSOs have meant that at some locations these engineering activities will take place on the river embankment and the adjacent inter- and sub-tidal foreshore. The five CSO interception sites along the Central Section of the Tideway 'super-sewer' project (**Figure 1**) utilised temporary river works that included cofferdams, piled structures and jack-up barges (**Figure 2**). All of these construction elements have an inherent scour risk, which must be considered at the design stage and beyond. Given the limited lifespan of the temporary works, monitoring and mitigation of scour risk, rather than the use of pre-emptive scour protection, was the preferred strategy for the project construction phase.

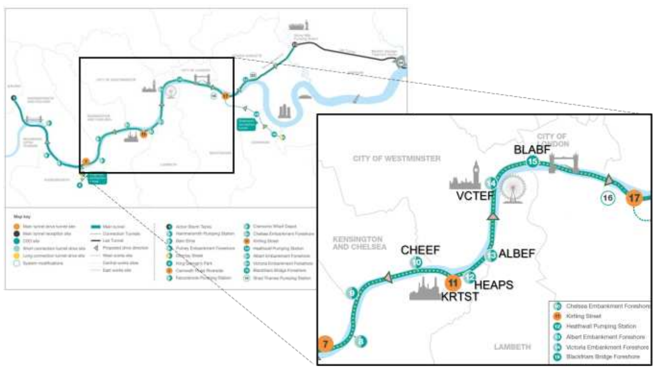


Figure 1. Thames Tideway Tunnel site map, with the Central Area highlighted.

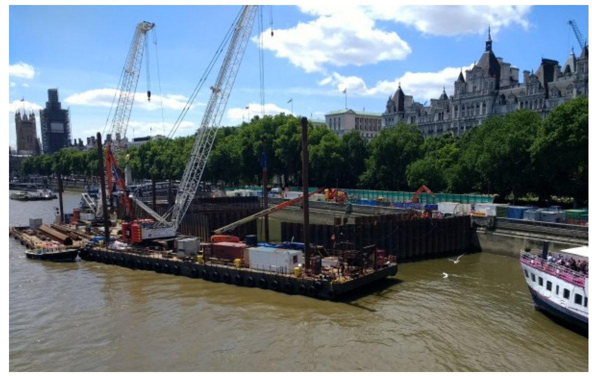


Figure 2. The temporary works under construction at VCTEF.

This paper presents comparisons of scour predictions, made using the Erosion Index method of Annandale (1995; 2006) modified by Harris *et al.* (2010) for the different temporary works scenarios at the TTT Central section interception sites, with observations obtained across eight years of quarterly monitoring campaigns. The methods derived and employed for processing and flagging the monitoring data are described. For each site, a timeline of observations is presented, and some examples of adaptive mitigation are described. The validity of the Erosion Index approach for scour estimation on a tidal foreshore is then discussed based on comparison with the monitoring data and the laboratory tests of Whitehouse et al. (2021).

THE TIDAL THAMES THROUGH CENTRAL LONDON

The Thames Estuary is macrotidal with a mean spring tide range of 5.3 m at the mouth of the estuary increasing upstream to around 6.4 m in the TTT Central area (PLA, 2023). The estuary displayed evidence of a morphological response to anthropomorphic modification in the early 20th century, with tidal range historically increasing by 6.8 mm/yr (Bowen, 1972) across the years following embankment construction and dredging. The river bed is composed of worked sands and gravels, with finer deposits on the foreshores, all of which overlie the notoriously high strength London Clay stratum at varying depths below the river bed. The Thames Barrier, completed in 1984 with the aim of protecting Central London from flooding during surges and/or high river discharges, restricts the limits of the extreme conditions that may affect the TTT sites during construction.

Detailed numerical modelling of the tidal Thames flow field was undertaken using the Thames Base model, a 2D numerical flow model set up by HR Wallingford in partnership with the Environment Agency (EA) and the Port of London Authority (PLA) to assist them with their regulatory responsibilities (HR Wallingford, 2009). The model used is TELEMAC-2D, which solves the depth averaged equations of flow on an unstructured triangular model mesh. The model mesh was focussed on each site in turn to resolve the marine elements of the proposed temporary works, including cofferdams and piles. Three scenarios were modelled for each site to provide the input flow fields for scour prediction: a typical spring tide plus mean daily river flow (denoted 'MN') and 100 year return period river flow (denoted 'HI'); and a spring tide enhanced by passage of surge plus mean daily river flow (denoted 'FLD').

Typical spring tide main channel flow speeds can reach > 2 m/s at BLABF, with slower peak speeds on the foreshore in the range 0.7 to 1.4 m/s across the five interception sites. The upper limit of this range occurs for 100 year river flows. Considering the observation period of the monitoring, ongoing since 2014, **Figure 3** shows a plot of maximum annual river discharge to 2021 (NRFA, 2023). The peak occurring pre-construction in 2014 was close to a 20 year return period event (HR Wallingford, 2006), whilst the peaks of 2020 and 2021 during construction approached 10 year return period discharge rates.

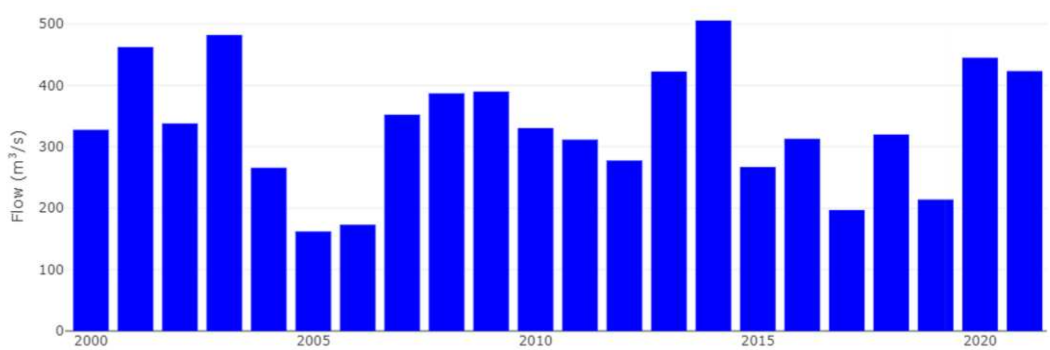


Figure 3. Maximum annual river discharge across 2000 to 2021 for the Thames at Kingston.

SCOUR PREDICTIONS

The soil profile of the riverbed in the tidal Thames can be characterised by a layer of widely graded interbedded sands and gravels overlying London Clay, the level of which below the riverbed varies between 0.3 and 4 m within the TTT Central area. Local scour depths, such as those observed around the numerous bridge piers, are limited by the geological control placed on the scouring process by the higher strength clay layer. Harris *et al*. (2010) present a method that allows for the *in-situ* physical properties of the soil to be considered in the assessment of scour potential. Following the Earth Materials approach of Annandale (1995; 2006), an Erodibility Index, *K*, can be defined taking information on the soil mass properties and structure:

$$\boldsymbol{K = M_s\, K_b\, K_d\, J_s} \qquad \textbf{(1)}$$

where M_S = the mass strength number; K_b = block size number K_d = discontinuity bond shear strength number; and J_S = relative ground structure number (see Annandale (2006) for more details). The Erodibility Index is compared with the stream power, *P*, supplied by the current and/or wave action. The scour potential is estimated via comparison of the required stream power to erode the bed sediment and that available from the force of the flow. In other words, if *P* exceeds the erosion threshold then scouring will occur.

Geotechnical data including boreholes and Cone Penetrometer Tests (CP T) were collected around the proposed temporary works. As part of the Harris *et al*. (2010) approach, the riverbed soil profile at each geotechnical location is discretised into $n = 1$ to N horizontal planes, based on the recorded soil characteristics at each plane level (derived normally from the borehole log). Each soil layer is assigned a required stream power for erosion, P_R, making use of the undrained shear strength derived from the CPT measurements in cohesive soils; and SPT blow count data and sediment grain size distribution in granular soils. Starting at the surface layer (n = 1) the stream power at the base of each plane, P_n, is calculated by applying a standard form of the reduction profile:

$$\boldsymbol{P_n = ae^{-b(S/S_{max})}P_a} \qquad \textbf{(2)}$$

where $a = 8.95$ for circular piles, or 8.42 for square piles, representing the increase in stream power caused by the presence of the seabed structure compared to the no-structure case; $b = 1.92$ for circular piles, or 1.88 for square piles, denoting the rate of reduction in stream power with depth as sediment layers are removed; S_{max} = the maximum scour depth independently determined; S = the depth of the base of each plane ($0 < S < S_{max}$); S/S_{max} = the relative scour depth and P_a is the stream power at the surface in the absence of a structure. Both a and b are fitted by Annandale (2006) to laboratory data, with the values given for *a* shown by Harris *et al.* (2010) to be of similar magnitude to the value estimated from potential flow theory.

Evaluation of Equation (2) requires the calculation of S_{max}, for which Harris *et al.* (2010) use the HEC18 methodology (Richardson and Davis, 2001). The HEC18 expression is based on an envelope curve produced from scour depth data collected around bridge piers, and is generally considered to be conservative:

$$\boldsymbol{S_{max} = 2.0\,K_1\,K_2\,K_3\,K_4\,h_0\,F_r^{0.43}\,(D_p/h_0)^{0.65}} \qquad \textbf{(3)}$$

where D_p = pile diameter (m); h_0 = the water depth (m); K_1 = correction factor for pile nose shape; K_2 = correction factor for angle of flow attack; K_3 = correction factor for bed condition; K_4 = correction factor for bed material size; and F_r = Froude number. While Equation (3) is derived from bridge pier data, application of the approach to a cofferdam is possible by treating the effective abutment exposed to the flow as being equivalent to a half-pier.

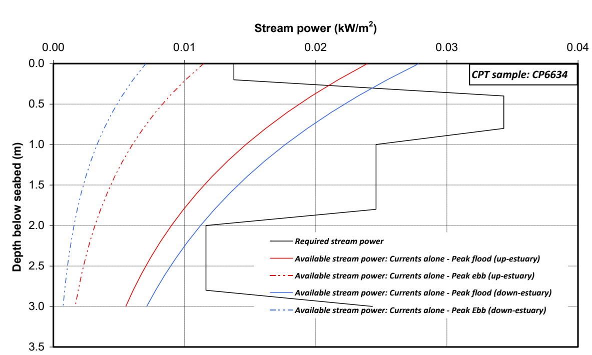


Figure 4. Example of stream power comparison predicting shallow scour.

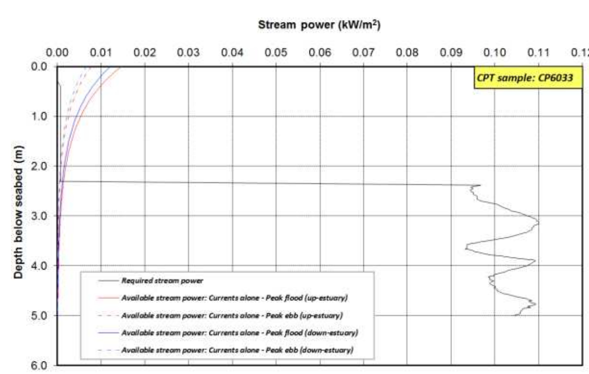


Figure 5. Example of stream power comparison predicting deeper scour.

The tidal hydrodynamic parameters used in the scour assessment, water depth and depth-average velocity, were obtained from the detailed numerical modelling of the site described above. The correction factors associated with the piles and cofferdams were derived from design drawings. **Table 1** summarises the type of temporary works (more details given in the dedicated site sub-sections below), the key inputs and the resulting scour potential estimates, for all five sites. Two examples of the graphical output of the approach for locations with high strength material occurring at different levels are given in **Figure 4** and **Figure 5**, from which the predicted scour potential is 0.3 m and 2.2 m, respectively. Scour extent was calculated for the predicted scour depth using the angle of repose information of Hoffmans and Verheij (1997) and assuming scour to be limited by the cohesive soil alone as a worst case scenario.

Table 1. Summarised inputs and outputs of the scour potential assessments at each of the five TTT Central sites. See main text for model scenario definition. The red and blue shading indicate peak speeds and associated water depths on the flood and ebb phase of the tide, respectively.

Structure		**Model scenario**	**Abutment / pile width**	**Abutment / pile length**	**Water depth**	**Depth-averaged current velocity**	**Predicted local scour**
Section		*MN/HI/ FLD*	*(m)*	*(m)*	*(m)*	*(m/s)*	*(m)*
BLABF							
Cofferdam	Up-estuary	HI	92.0	272.0	9.4	0.6	1.0
					5.0	1.4	
VCTEF							
Cofferdam	Up-estuary	MN	26.2	52.7	7.8	0.9	0.3
					7.5	0.6	
ALBEF							
Cofferdam	Down-estuary	MN/HI/ FLD	62.0	90.0	5.1	1.1	1.1
					5.0	1.0	
HEAPS							
Cofferdam	Up-estuary	MN/HI	38.0	25.0	0.8	0.8	0.3
					3.7	0.6	
KRTST							
Piled jetty	Riverward dolphins	MN/HI	1.2	1.2	9.1	1.0	2.3
					9.1	1.0	
CHEEF							
Cofferdam	Down-estuary	MN	39.0	140.0	5.1	1.2	2.1
					4.8	1.1	

The Harris *et al.* (2010) approach has not been widely used to date and there was a certain amount of uncertainty in its application to the TTT Central temporary works on the tidal Thames foreshore. The approach was originally developed for quarrying rock and then adapted to scouring in rock, but the methodology applies equally to less strong soils (Harris *et al*., 2010). Harris and Whitehouse (2015) used a wide range of field and laboratory data to confirm the validity of using undrained shear strength as a proxy for the erodibility of soil. While they showed that for the offshore field data considered the Erodibility Index method (e.g. Annandale,

2006) may sometimes not be conservative, they concluded that it is one of very few scour potential approaches that can account for changing soil layers and be applied using typical information obtained during geotechnical surveys. One of their key recommendations for application of the method was derivation of site-specific empirical constants *a* and *b* using erosion core tests of *in-situ* samples. Comparison of the detailed observations afforded by the monitoring program (described below) with the scour predictions provides a method for independent validation of applying the Erodibility Index approach to the tidal foreshore.

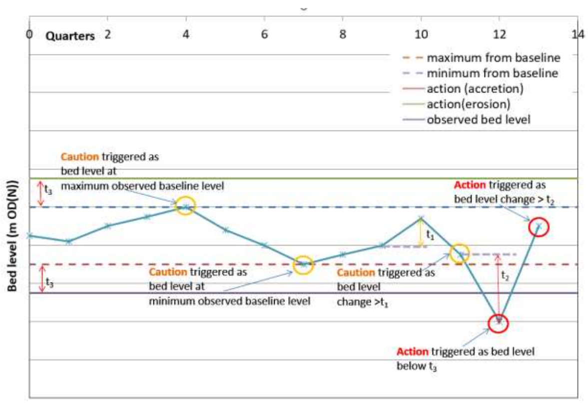
MONITORING AND OBSERVATIONS

The monitoring and mitigation approach was agreed under a condition of the Development Consent Order (DCO). Under protective provisions agreed with the statutory regulators (the Environment Agency (EA) and the Port of London Authority (PLA)), the 'Overall Strategy' was produced and implemented via individual site specific Scour and Accretion Monitoring and Mitigation Plans (SAMMPs). Each individual SAMMP took input from the geophysical and geotechnical data, and the site specific numerical flow modelling and scour assessments.

As the main method for monitoring, multi-beam echo sounder (MBES) surveys have been and continue to be collected quarterly since December 2013 in previously agreed areas around the TTT Central sites, with data gridded to 0.5 m by the contractor and depths relative to Ordnance Datum (Newlyn), equivalent to a mean sea level. To assess any spatial and temporal effect of the construction activities on patterns of scour and accretion, the 0.5 m gridded data were first filtered to a 5 m grid. For each site specific SAMMP, the 'caution' and 'action' threshold trigger levels were defined using the minimum, maximum and variability of bed levels across the baseline monitoring surveys collected between Dec 2013 and Dec 2015. The quarterly surveys collected during construction were processed soon after collection, comparing quarter-to-quarter bed level change, and rate of change, at each 5 m cell with the trigger thresholds (**Figure 6**) to produce maps identifying areas for caution or action due to scour/erosion (example in **Figure 7**). Each SAMMP included a tailored plan for the necessary responses to any triggers. In some cases survey frequency was increased to give coverage nominally every 6 weeks.

In addition to this spatial assessment, at each site a number of key points were defined considering where bed levels could be expected to change. Time-series of average, minimum and maximum bed levels were extracted at these points from the available surveys to evaluate whether any observed bed level changes were reaching an equilibrium. The extents of the area over which MBES data have been extracted are 1 m x 1 m at each point, so up to 9 data points of the 0.5 m gridded data will have been extracted and averaged to produce the time series plots. It should be noted that edge effects as a result of the averaging process have been observed for points close to the survey boundaries, which in some cases has created artefacts.

In the following sub-sections, the results of the MBES spatial and temporal assessments are presented site-by-site, drawing on the suite of available data to best present the story of each site. The vertical accuracy of the surveys (+/- 0.07 m) should be borne in mind when evaluating the figures presented.



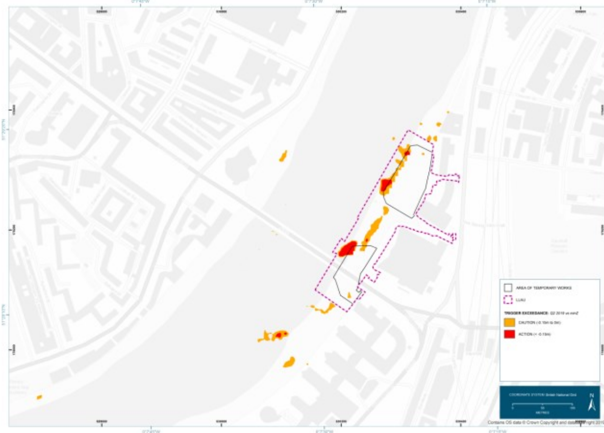


Figure 6. Example of bed level change threshold definition.

Figure 7. Areas of threshold exceedance for scour/erosion shown by Q2 2019 survey at ALBEF

Blackfriars Bridge Foreshore (BLABF)

The BLABF temporary works are located within Kings Reach of the River Thames on the north bank adjacent to Blackfriars Bridge in Central London (**Figure 9**). Two cofferdams, west and east, cover a total area of approximately 4,920 m^2, extending 43 m into the river beyond the existing river bank line (**Figure 8**). To the east of the cofferdams, a culvert has been placed in a dredged area to connect the existing CSO with the BLABF shaft. The temporary cofferdams have been constructed as vertical sheet piled and tubular piled, combi wall cofferdams.

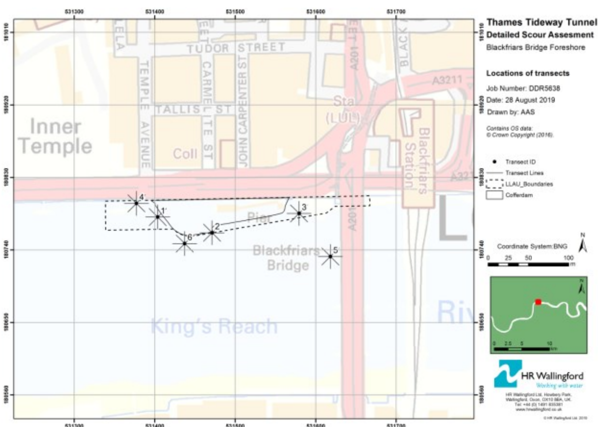


Figure 8. Outline of BLABF cofferdams, showing temporal data extraction points.

Figure 9. Google Earth image of BLABF temporary works, dated October 2020.

The estimate of local scour for the cofferdam at BLABF was limited to 0.5 m by the presence of a 0.3 m thick layer providing greater resistance to scouring at that elevation. However, calculations of available stream power suggested that granular material below could be exposed for higher return period conditions, or as a result of vessel disturbance, giving a total potential scour depth of 1.0 m. The associated scour extent was predicted to be 2 m using a steep slope angle to represent the cohesive nature of the clay layers.

For the west cofferdam, the first line of sheet pile was installed Nov 2017, the maximum cross-river extents of the upstream and downstream ends of the cofferdam were reached in

March 2018 and April 2018 respectively, with the cofferdam being completed and closed in July 2018. Scour around the edge of the cofferdam structure occurred as predicted, shown by the results of the temporal analysis in **Figure 10**. The development of the scour appears to have followed the leading edge of cofferdam cells during construction. The Q2 2018 survey in **Figure 11** shows the detail of the 0.5 to 1.0 m deep scour along the cofferdam corner. The general riverward extent of the scour was approximately 4 m but appears to have been locally increased to around 10 m by the presence of a spudcan depression from a visiting jack-up barge. An area of accretion immediately downstream of the scour along the line of the piling is likely associated with re-distribution of the eroded material.

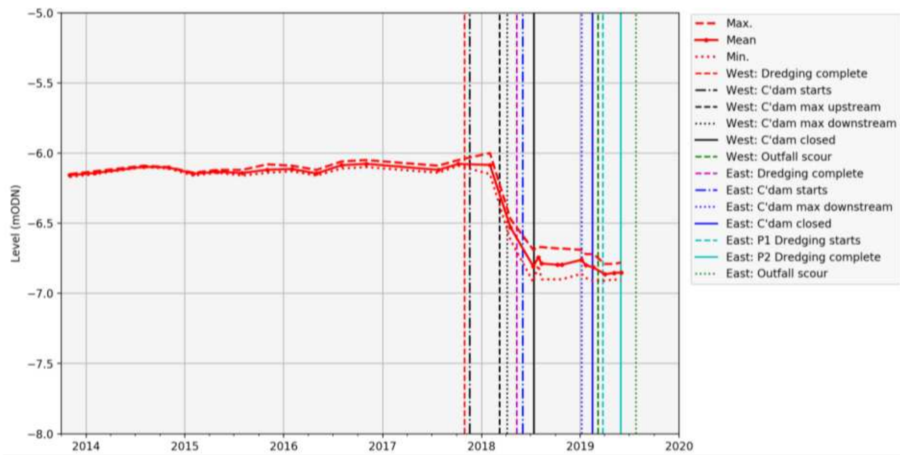


Figure 10. Time series of bed level evolution at BLABF Point 6, the downstream corner of the west cofferdam.

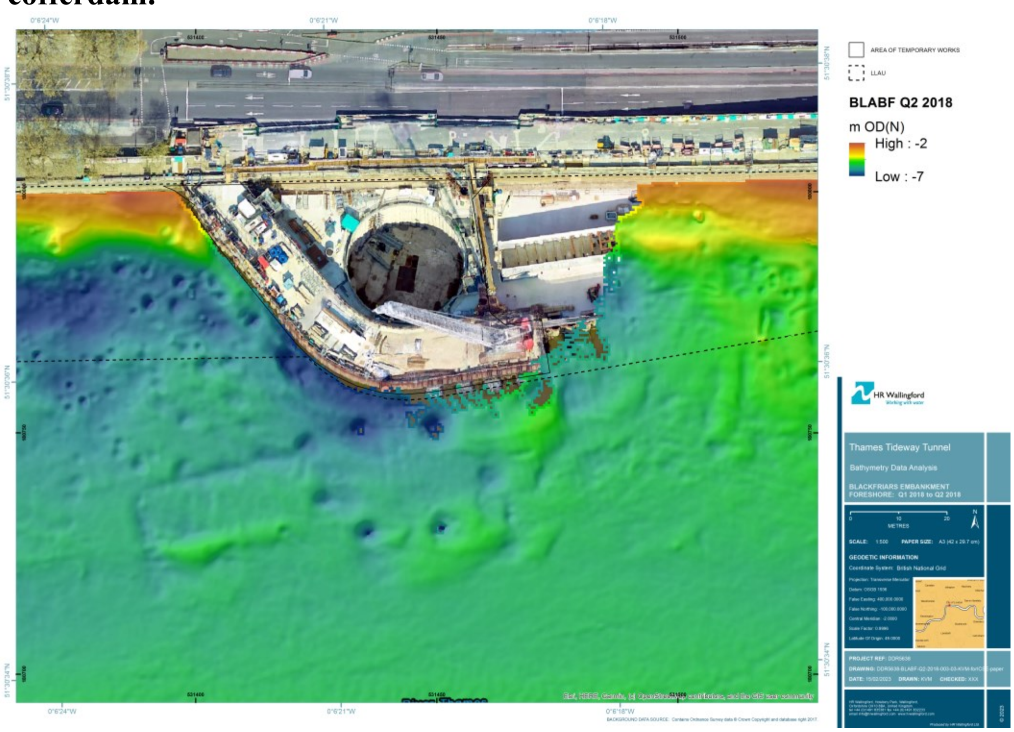


Figure 11. Bathymetry at BLABF in Q2 2018 during construction of the cofferdam. Scour is visible as the blue areas along the south west corner.

Additional construction elements were assessed for scour risk as the project progressed, including the cofferdam dewatering outfall on the western upstream side of the cofferdam. An arrangement of Kyowa rock filled bags was proposed to mitigate the risk of scour from the dewatering discharges, with rip-rap filling any spaces between the Kyowa bags and the cofferdam wall. During installation of this proactive scour protection in March 2019, some additional Kyowa bags were installed in the area shown to be scouring in **Figure 11**. The individual Kyowa bags have been visible in the subsequent monitoring surveys to date (0.5 m gridded). While levels against the cofferdam have stabilised, there is some evidence of edge scour along the riverward side of the single line of Kyowa bags.

Victoria Embankment Foreshore (VCTEF)

The VCTEF temporary works are located within Lambeth Reach of the River Thames on the north bank adjacent to Hungerford Bridge, opposite the London Eye (**Figure 12**). The vertical sheet piled cofferdam covers a total area of approximately 3,760 m^2, extending approximately 39 m into the river beyond the existing river bank line (**Figure 13**).

Despite predicted depth-averaged current increases of up to more than 0.4 m/s near the works, scour was predicted to be minimal around the outside of the temporary works, predicted to be in the order of 0.3 m. At VCTEF, rather than scour being limited by the presence of the clay layer, predicted scour depths were sensitive to the particle size distribution of the surficial granular material. The geotechnical data collected along the foreshore suggested that the upper granular soil layers become thicker with distance up-estuary, varying between 1.6 m towards Hungerford Bridge and 3.0 m at the upstream end of the site. Based on the information obtained from CPT measurements, boreholes and grab samples, when compared with the available stream power the upper granular soil layers were predicted to withstand significant scour development.

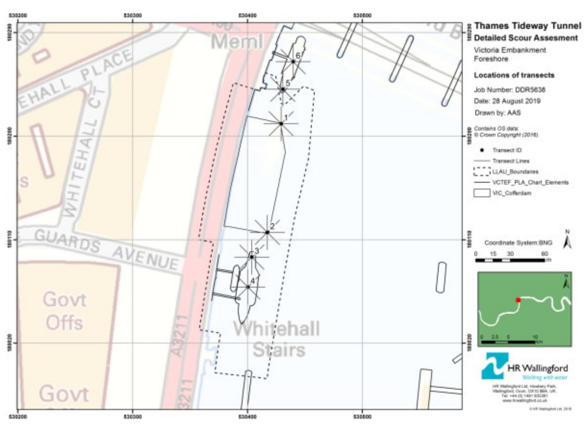


Figure 12. Outline of VCTEF cofferdam, showing temporal data extraction points.

Figure 13. Google Earth image of VCTEF temporary works, dated October 2020.

At VCTEF, dredging was undertaken prior to cofferdam piling in August 2017. The temporal monitoring results for a point at the upstream corner of the cofferdam in **Figure 14** show a decrease in bed levels after the dashed blue vertical line as a result of this dredging. The cofferdam reached its maximum cross-river extent at the upstream end in February 2018. Bed levels after this date showed a small decrease by around 0.2 m, with much wider variation in the range of observed levels relative to the mean than previously observed, indicating local scour of minimal depth and extent at the upstream end of the cofferdam.

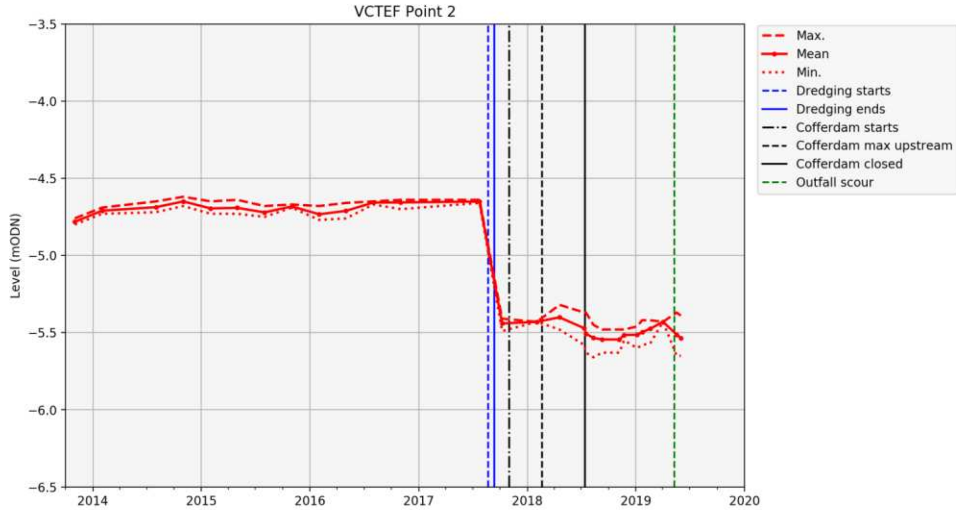


Figure 14. Time series of bed levels at VCTEF Point 2, the upstream corner of the cofferdam.

Albert Embankment Foreshore (ALBEF)

The ALBEF temporary works are located within Nine Elms Reach on the south bank of the River Thames, adjacent to Vauxhall Bridge and in front of the iconic SIS MI6 building (**Figure 16**). Three different scenarios for the layout of the three cofferdams are shown in **Figure 15**, with Cofferdams 2 and 3 being subject to design updates as the project progressed. The worst case Cofferdam 3 scenario was considered for the purposes of scour predictions. For this layout the vertical sheet piled cofferdams cover a total area of approximately 6,450 m^2, with the maximum extent into the river being approximately 50 m beyond the existing river bank line.

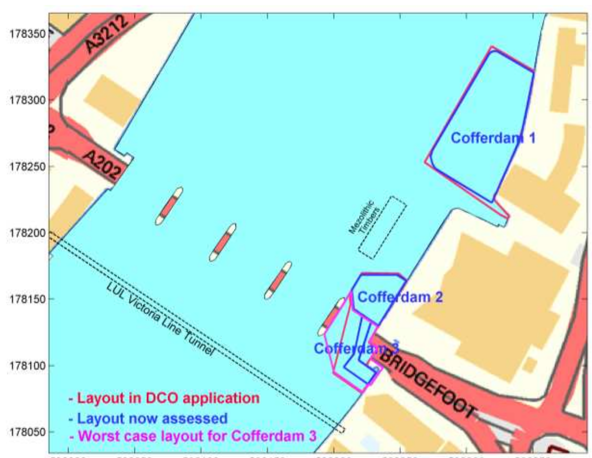


Figure 15. Cofferdam arrangement scenarios for ALBEF site.

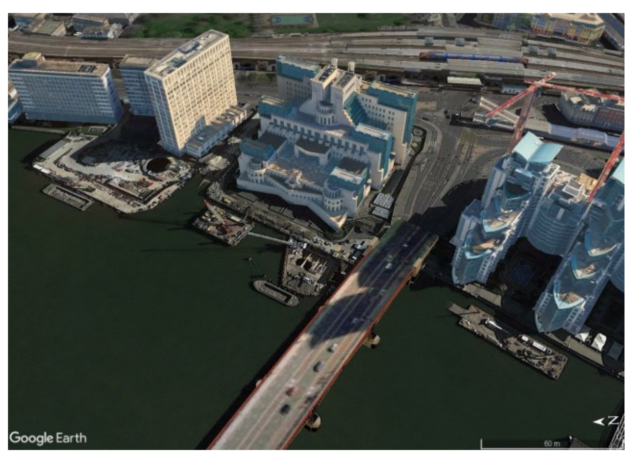


Figure 16. Google Earth image of ALBEF temporary works, dated April 2020.

The geotechnical data showed a surface granular layer thickness varying between 0.4 and 1.1 m towards Cofferdam 2 along the foreshore and into the main channel. The stronger clay layer beneath was shown to be resistant to stream powers generated by 100 year RP conditions, with the resulting precautionary estimate for scour at ALBEF limited to 1.1 m.

Figure 17. Bathymetric difference plot (0.5 x 0.5 m) at ALBEF for the period Q3 2018 to Q4 2018.

Given that the as-built design of Cofferdam 2 and 3 is reduced in area relative to the worst case assessed preconstruction, we here focus on Cofferdam 1 as a direct comparison with scour predictions. **Figure 17** shows bed level lowering of up to 0.4 m along the line of the sheet pile at the downstream end, and up to 0.6 m at the upstream end. The occurrence at the limit of survey coverage, adjacent to the sheet pile wall, suggests that this lowering is a result of scour.

Heathwall Pumping Station (HEAPS) & Kirtling Street (KRTST)

The HEAPS and KRTST works are located adjacent to each other within Nine Elms Reach of the River Thames, downstream of Battersea Power Station (**Figure 19**). Due to their proximity HEAPS was assessed and monitored at the same time as at KRTST. The tubular and vertical sheet pile cofferdam at HEAPS extends approximately 30 m into the river and a length of 33 m. A Muck Away barge campshed has been installed in front of the cofferdam, along with two mooring piles. The temporary works at KRTST include a piled access jetty and various other piled structures, plus moored access barges. **Figure 18** shows the arrangement of the two sites.

At HEAPS, a single CPT sample adjacent to the cofferdam showed a 1.3 m thick layer of dense to medium sand overlying the clay horizon. The required stream power calculated from the geotechnical information suggested that the upper granular soil layers are capable of withstanding significant scour development, but this is of course dependent on the sediment grading with depth into the riverbed which can vary over small spatial scales. Nevertheless, the available versus required stream power gave a scour potential estimate of 0.1 to 0.3 m at the HEAPS cofferdam. At KRTST, two CPT samples supplemented with borehole information showed medium to dense sand to a depth of 2.3 m overlying higher strength clay. The calculated required stream power to erode this layer was exceeded for typical spring tide conditions, meaning that scour estimates were limited by the maximum potential scour from a circular pile.

For the piles and dolphins ranging in diameter from 0.9 to 1.2 m, predicted local scour depths ranged from 1.9 m to 2.3 m.

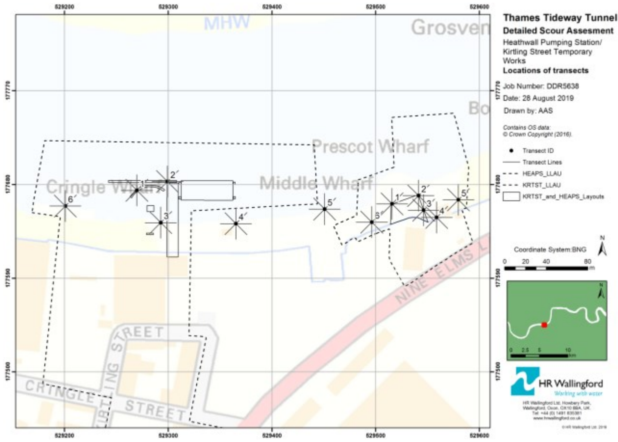


Figure 18. Outline of HEAPS cofferdam, and KRTST jetties and barges.

Figure 19. Google Earth image of HEAPS & KRTST temporary works, dated Nov 2020.

Quarter to quarter spatial assessment of the monitoring survey data at HEAPS demonstrated very little bed erosion and accretion during the temporary works construction. The time series of bed level change in **Figure 20** shows lowering immediately before the construction of the cofferdam, likely to be as a result of dredging along the line of piling. After a period of variability levels increased in Q2 2019 to almost pre-construction levels, with the increase thought to be associated with bed levelling activities alongside the cofferdam. The temporal data for KRTST in **Figure 21** show more classic bed lowering as would be expected for scour around a pile, with a decrease of approximately 0.4 m between the Q4 2017 and Q1 2018 surveys from previously stable levels.

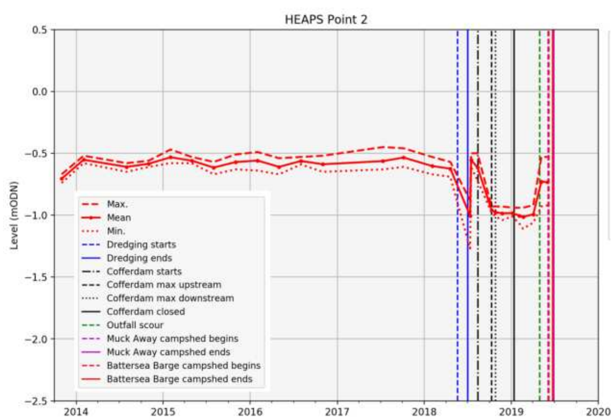


Figure 20. Time series of bed level evolution at HEAPS Point 2, downstream corner.

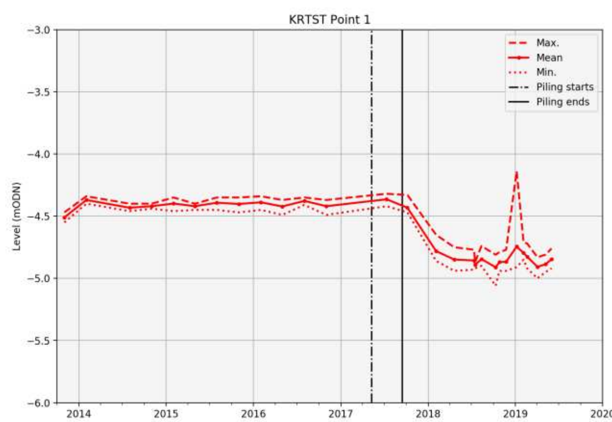


Figure 21. Time series of bed level evolution at KRTST Point 1, conveyer piles.

Chelsea Embankment Foreshore (CHEEF)

The CHEEF works are located within Chelsea Reach of the River Thames (**Figure 23**). The temporary works cofferdam covers a total area of approximately 4,400 m^2, extending 33 m into the river beyond the existing river bank line (**Figure 22**). The temporary works cofferdam has been constructed as a series of interconnected double skinned sheet pile cells. A barge campshed was installed in front of the cofferdam.

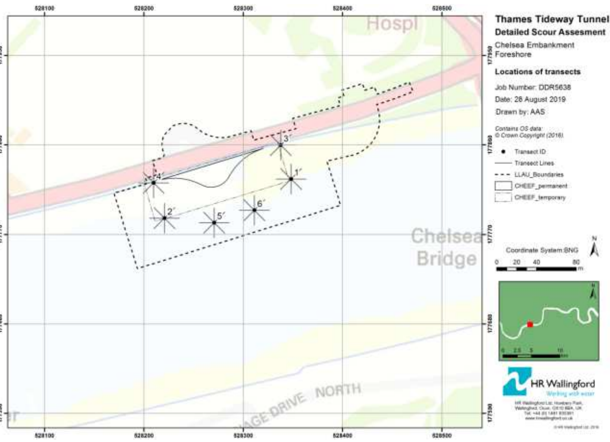


Figure 22. Outline of CHEEF cofferdam, showing temporal data extraction points.

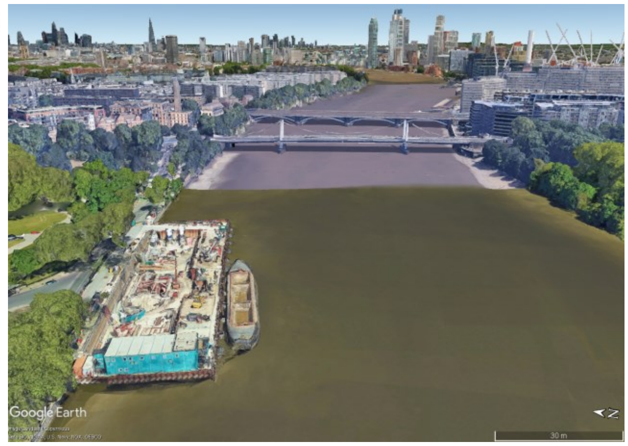


Figure 23. Google Earth image of CHEEF temporary works, dated November 2020.

CPT profiles were collected along the foreshore where the cofferdam was to be installed, which combined with grab samples and two boreholes, suggest a variation of the sediment characteristics along the foreshore. The scour predictions from the CPT sampling located close to the extent of the proposed temporary works gave a potential scour depth of between 0.3 and 2.1 m. Including CPT samples collected downriver, precautionary scour potential estimates of 2.8 m were suggested for design purposes. The associated maximum scour extent was predicted to be 7.8 m based on a slope angle equivalent to half the angle of repose (15°).

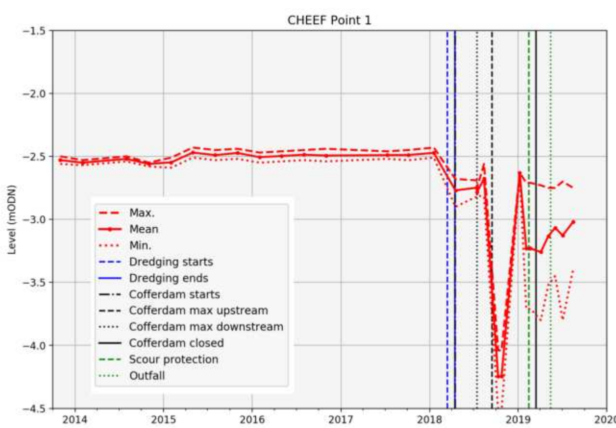


Figure 24. Time series of bed level evolution at CHEEF Point 1, downstream corner.

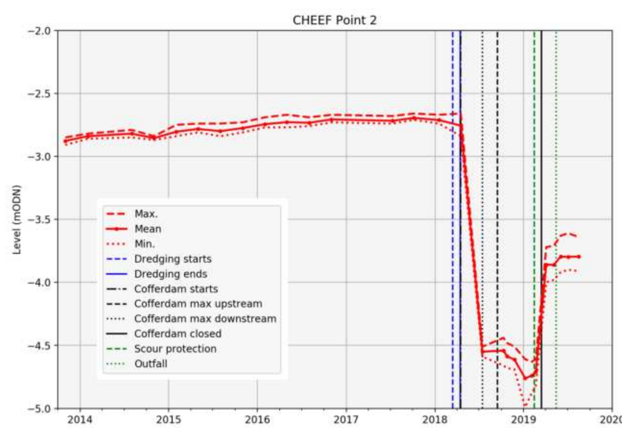


Figure 25. Time series of bed level evolution at CHEEF Point 2, upstream corner.

Cofferdam construction began with some initial dredging along the line of the cofferdam piling in April 2018, reaching the maximum cross-river extents of the upstream end in September 2018 and the downstream end in July 2018, with the cofferdam being closed in March 2019. Scour around the cofferdam structure occurred as predicted, illustrated by the results of the temporal analysis in **Figure 24** and **Figure 25**. The Q2 2019 survey in **Figure 26** shows the detail of the scour around the cofferdam corners. The scour depths shown are between 1.5 and

1.8 m. The riverward extent of the scour reached around 4.5 m before reactive scour protection of Kyowa rock bags was installed into the resulting scour pits, as indicated by the increase in bed levels at the green vertical line. After an initial period of lowering by < 1 m due to edge scour, average bed levels remained relatively stable. At both locations the wide range in the maximum and minimum bed is indicative of the variable height of the scour protection.

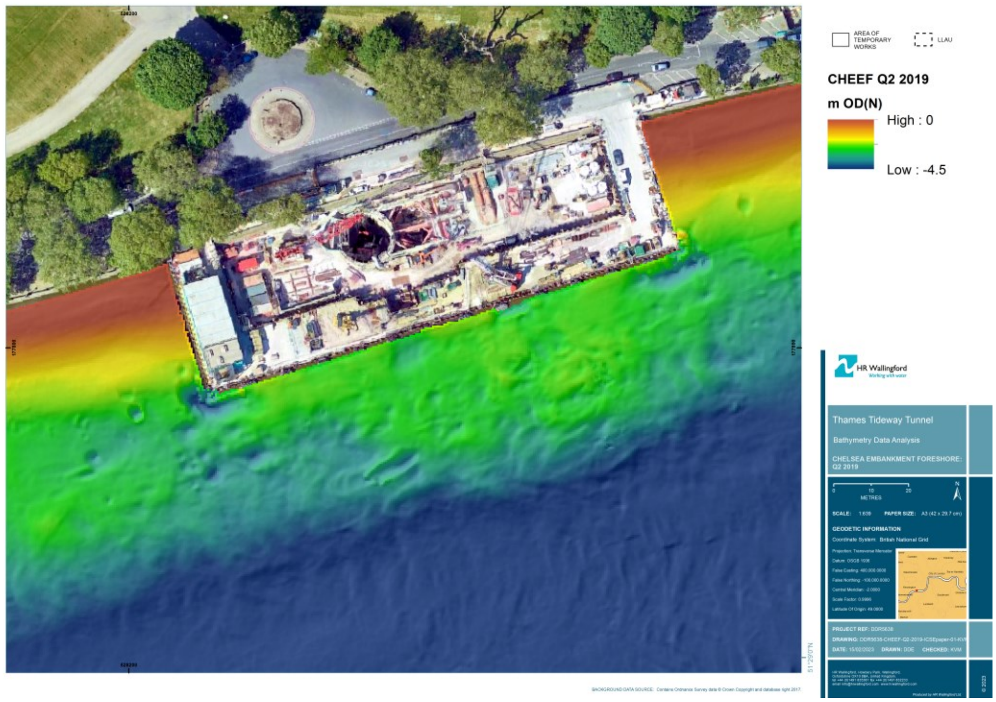


Figure 26. Bathymetry at CHEEF in Q2 2019 after closure of the cofferdam. Scour is visible as the blue areas at the corners of the cofferdam.

COMPARISON AND DISCUSSION

The pre-construction estimates of local scour for the TTT temporary works are compared with observations obtained from the monitoring campaign in **Table 2**. On the whole the comparison shows that the modified Erodibility Method of Harris et al (2010) has been successful at predicting the occurrence of scour for the temporary works structures on the tidal foreshore. The success of the method at predicting scour without the use of erosion tests as recommended by Harris and Whitehouse (2015) is most likely due to the current-dominated conditions in combination with the high strength of the underlying clay.

For the cofferdams where scour was observed, scour depths at BLABF were as predicted, while those observed at ALBEF and CHEEF were slightly over-predicted. These over-predictions are related to the precautionary nature of scour predictions for design purposes; and in turn local variability in the level of the higher strength clay layer. It should also be noted that river discharges during construction were limited to 10 year RP conditions, whilst the predictions used flow speeds associated with a 100 year RP river discharge to calculate the available stream power under extreme conditions. As per the recommendations for reactive scour protection in the SAMMPs, scour mitigation was deployed successfully to raise bed levels and limit any further scour at all three of the sites where scour was observed. The under-prediction of the scour around the jetty piles at KRTST is due to the lack of site specific data and the precautionary assumption of a loose granular layer. Scour extents were both over- and under-predicted, with these deviations most likely due to steeper side slopes in the cohesive soils present, and general increased river bed disturbance during construction, respectively. Estimates of scour extent are more susceptible to horizontal spatial variations in soil properties over relatively short distances that are not captured in the geotechnical surveys.

Table 2: Summary of predicted and observed local scour.

	Structure	Predicted local scour depth (m)	Observed local scour depth (m)	Predicted local scour extent (m)	Observed local scour extent (m)
BLABF	Cofferdam	1.0	**1.0**	2.0	**4.0 - 10.0**
VCTEF	Cofferdam	0.3	**0.2**	1.0	**0.5**
ALBEF	Cofferdam	1.1	**0.6**	4.1	**5.0 - 10.0**
HEAPS	Cofferdam	0.3	**-**	0.4	**-**
KRTST	Piled jetty	2.3	**0.4**	6.5	**1.0**
CHEEF	Cofferdam	2.1	**1.8**	7.8	**4.0 - 6.0**

At all sites, discerning scour in the classic definition as bed lowering adjacent to a structure was hampered by general bed destabilisation due to construction, but more so at VCTEF and HEAPS by the requirement of dredging prior to cofferdam construction. In these cases the artificially lowered bed level and additional available sediment may have masked any scouring processes occurring within the interval between surveys.

It is possible to compare the monitoring observations with laboratory tests undertaken by Whitehouse *et al.* (2021) measuring scour around different shaped cofferdams in a wide basin (precluding any flume edge effects). The results for the variety of shapes tested show favourable comparison with the patterns of scour observed at the BLABF and CHEEF cofferdams. Scour depths are harder to compare; normalising by riverward extension the laboratory scour depths are 5 times deeper than observed at CHEEF but are similar to those observed at BLABF. Whitehouse et al (2021) showed that the HEC-18 formulae used by Harris et al (2010) provided reasonable comparison with the results of the tests. Conclusions can be drawn from this case study as follows:

- The observations afforded by the intense monitoring of the TTT temporary works support the use of the modified Erodibility Index for scour prediction on the tidal foreshore.
- The comparison of the predictions with the observed scour shows the method to provide a reasonable basis for incorporating geotechnical site conditions as a limit to potentially costly overly conservative predictions.
- In the case of the TTT temporary works, the approach helped optimise the design and mitigation planning for the construction phase of the project.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding of the HR Wallingford strategic research program; and the Tideway delivery partner FLo for supporting the publication of this case study.

REFERENCES

Bowen, E.G. (1972). *Britain and the Western Seaways*, London: Thames and Hudson.

Harris, J.M, Whitehouse, R.J.S. and Sutherland, J. (2010). Scour Assessment in Complex Marine Soils – An Evaluation through Case Examples. *Proc. 5th Int. Conf. on Scour and Erosion*, Holiday Inn Golden Gateway, San Francisco, California, Nov. 7 -10.

Harris, J.M, Whitehouse, R.J.S. (2015). Scour prediction in non-uniform soils: undrained shear strength and erodibility. Published in the *Proc. 7th Int. Conf. on Scour and Erosion*, The University of Western Australia, 2-4 December 2014.

HR Wallingford (2006). *Thames Estuary 2100: Report EP3 Tidal/fluvial interaction on the tidal Thames*, HR Wallingford report EX5288 produced for Environment Agency.

HR Wallingford (2009). *Thames 2D Base Model. Model update and validation*. HR Wallingford report EX5994 produced for Environment Agency and Port of London Authority.

Hoffmans, G.J.C.M. and Verheij, H.J. (1997). Scour Manual. Netherlands: Balkema.

Littlewood, M.A., Malcolm, M. and Crossman, M. (2003). *Review and Update of the 'Tidal Thames Strategy Review*. Report to the Environment Agency, March 2003.

National River Flow Archive (NRFA), URL, Date Accessed National River Flow Archive, https://nrfa.ceh.ac.uk/data/station/peakflow/39001, 23rd Jan 2023.

Whitehouse, R.J.S, Chellew, E.S., Harris, J.M. and Couldrey, A.J. (2021). Scour at cofferdam structures on river walls. Published in the *Proc. 10th Int. Conf. on Scour and Erosion* [Virtual].