

Scour at Coastal Structures

Invited lecture at the Third International Conference on Scour and Erosion,
Amsterdam
November 1–3, 2006

R. J. S. Whitehouse

HR Wallingford Ltd, Howbery Park, Wallingford, OX10 8BA, UK. Tel: +44 1491 822434

I. INTRODUCTION

The subject of scour (and siltation) at coastal structures continues to receive much interest in the consulting and research fields. Coastal structures can be categorised as having four functions, either (1) to provide permanent protection against flooding (e.g. dykes and seawalls), (2) water level control during storm surges (e.g. barriers) or (3) benefits in coastal management such as preventing shoreline erosion (e.g. seawalls, breakwaters, groynes), or (4) for other industrial or economic functions such as harbour breakwaters and jetties, outfalls/intakes, and windfarms. Therefore the topic of scour at coastal structures can be said to cover structures built on the shoreline as well as structures built in tens of metres of water, and waves and currents operate in varying combinations and relative magnitudes.

In engineering projects scour needs to be considered for two phases, the installation/construction phase and the operational phase. The limiting case for design may require consideration of the erosion of seabed soils adjacent to the completed foundation. However, it is also important to evaluate what kind of scour might develop during installation as this may have a direct bearing on the stability of the structure that is being built, or on the construction methodology that is adopted. In most cases the main issue for design relates to the target scour development that can be expected under design conditions, i.e. location, depth and extent, but knowing the time development is also important in some cases. A general approach for assessing the mobility of the seabed soil at a structure was presented by Whitehouse (1998). An approach for determining the scour hazard is shown in Fig. 1.

This requires input data on waves, currents and water depth (chart depth plus water level variation). These inputs may be determined from modelling or analysis of field measurements made over a sufficiently long time, with analysis for relevant return period conditions. The input data are combined at point A to produce a set of robust inputs and once combined with information on the soil characteristics obtained from the site investigation they are analysed to provide information on the bed shear stress and the critical value of bed shear stress for erosion of the soil. This allows an assessment of the soil mobility status and the scouring status is determined by adding in at point C the information on how the structure changes the flow locally. The local flow acceleration and turbulence levels due to the structure cause the sediment

to become mobile at a lower level of forcing than on the open seabed.

Once the scouring status has been assessed, either a yes or no answer can be provided for a certain return period event or it is possible to say for how many hours per year the forcing is sufficient to cause scouring. The next step in a more detailed assessment is the requirement to determine the depth and extent of scour occurring and how fast it might take to develop. By combining results on likelihood of scour and the magnitude an assessment of scour hazard is arrived at.

The paper develops the discussion in a number of key areas, examines a number of projects and presents a summary of some of the key (in the author's view) requirements for Research and Development in the field of scour at coastal structures.

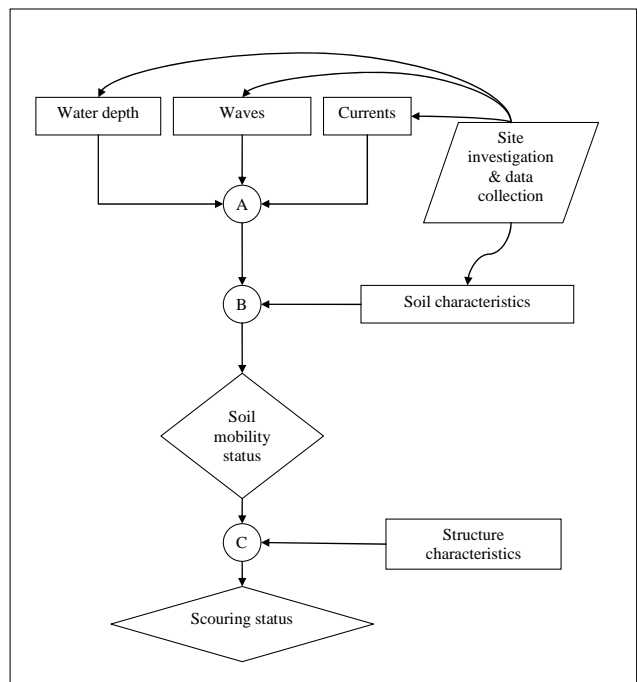


Figure 1. Scour hazard flow chart

II. KEY AREAS

There are a number of key areas in which information is required when assessing scouring and these will be discussed below.

Processes – cause and effect: To provide a clear basis for understanding it is necessary to examine cause and effect which relies on a firm grasp of the key parameters and processes that cause scour at a particular location. Without this understanding it is not possible to get a firm grip on the problem. Appropriate predictive methods combined with proactive monitoring can be used to good purpose in understanding and formulating a mitigation plan for problems caused by scouring. In making a prediction a range of empirical and analytical methods are available, and where necessary computational fluid dynamics methods and laboratory scale physical modelling with sediment beds in wave and current tanks can both be applied to investigate new situations.

This area is encapsulated in Fig. 1 as it encompasses knowing - what are the drivers for change, the structure characteristics and whether there are any cumulative or in-combination effects of other structures, and realizes the importance of time varying forcing.

Equilibrium predictors: These are required to predict the size and extent of scour holes formed at a structure in response to design condition forcing; for example at a seawall the design water level and wave data are prescribed and the scour is assessed for those conditions. Generally the equilibrium predictors have been determined from process studies in the laboratory for sandy sediments at small to medium scale with, in some cases, verification by field measurements. Section V summarises useful references to equilibrium predictors for a range of different coastal structures. It is then recommended that the predictions of these formulae are verified using large scale laboratory data or field data wherever possible. The difficulty with using field data is that often a number of factors come into play and it is not always clear whether the observed scour development is in equilibrium with the prevailing conditions. Another key factor is 3-dimensional effects, for example at a breakwater the scour at the trunk is determined by the combined effect of the incident and reflected waves whilst the scour at the head is controlled by flow around the head. This has been studied by Sumer and Fredsøe (2002) and predictive equations are presented for both the trunk and the head of the breakwater. In practical applications predictions of the scour at both locations are required and an understanding of how to apply the two 2-dimensional predictors to a 3-dimensional problem is required.

Real soils: The challenge of real soils brings together the disciplines of hydraulic and geotechnical engineering, as site investigation data is predominantly aimed at determining the strength of the soil for engineering design and construction. The site investigation data is a valuable input in assessing the susceptibility of a soil to erosion but some further testing or analysis of the relationship between hydraulic and geotechnical properties is required to be able to make statements about when and how that particular soil will erode.

Transience: At a coastal site the tidal and meteorological variation in water level causes the water depth to vary and at the coast the water sweeps back and forth across the intertidal foreshore. The occurrence of scour at a seawall (or other structures) is controlled by the beach level combined with the water level when the wave conditions are sufficient to cause erosion. In many cases the scour that occurs at structures may be transient in that the deepest scour will occur during a period of higher

energy forcing, whether that is due to currents or due to waves. The scour that occurs during a storm (i.e. at the event scale) may not be apparent from an examination of the bed level after the storm has subsided. Although not the topic of this paper, liquefaction of the seabed due to waves is a form of transient event which can lead to the settlement or deformation of a structure or sinking of scour protection material into the bed. This topic is dealt with in a Special Issue of the Journal of Waterway, Port, Coastal and Ocean Engineering (Sumer, 2006) highlighting results from the recently completed EC project LIMAS – Liquefaction at Marine Structures.

Another form of transience is the scour that develops during the construction process, for example due to the installation of a coffer dam, building of a construction dock (Section III C) or presence of construction vessels (flow blockage, vessel generated waves and propeller/thruster velocities).

Long-term changes: There will be long term signals of change which will prevail independently of the local scour at the structure. The long term changes are often manifest by variations in the plan location of key features such as the shoreline, sandbanks or channels. The changes can be determined from the analysis of historical data, the expert analysis of geomorphological features, or the application of a predictive method to extend the range of historical data. The longer term changes are not always that easy to assess and may be monotonic, such as occurs with a progressively eroding seabed, or cyclic such as is associated with the movement of bedforms. The predictive methods can be applied in a deterministic, probabilistic or stochastic fashion. An understanding of the sediment transport pathways and the sediment budget will help to assess changes that have and might occur, for example the beach at a coastal site may become lowered because of an interruption to the sediment supply further up the transport path.

Mitigation measures: The mitigation of scour is normally possible if scour has been anticipated to occur so that protective measures can be taken immediately following construction or a monitoring and scour mitigation programme can be put in place. The scour hazard assessment can be used to inform such a decision.

The paper presents a number of cases where scour prediction and monitoring have been used to aid understanding during the design or construction process, or to provide improved knowledge.

III. PROJECT EXAMPLES

A subset of coastal structures are now referred to, namely seawalls, breakwaters and offshore windfarm foundations.

A. Seawalls

There are still situations where scour contributes to the undermining of seawall toes (Fig. 2). Seawalls are subject to a continuing evolution of the fronting beach level and as the water level and wave conditions change this can produce additional local scour at the toe. To better understand how the beach level responds to storms it is possible to monitor the levels in situ, for example using HR Wallingford's "Tell-Tail" scour monitors. This has been carried out at a number of locations, for example at Teignmouth on the south coast of England monitoring of

scour was carried out at two locations on the same beach, one on the high part of the beach adjacent to the straight section of seawall and the other on a low part adjacent to a recurved section of the wall. The high part of the beach had sufficient sediment that it did not suffer scour due to storm events that occurred (Fig. 3 – lower right panel). At the other location a few hundred metres along the beach the bed level was lower (Fig. 3 – upper right panel) and the measurements showed that transient scour took place during the tide; i.e. the beach dropped during the tidal immersion period and recovered prior to the beach drying out. The beach levels at this location were controlled to a large extent by sediment supply from the adjacent, and higher, part of the beach due to longshore transport.



Figure 2. Seawall damage on the east coast of England (photograph courtesy of Waveney District Council)



Figure 3. Monitoring scour on the beach with HR Wallingford “Tell-Tail” monitors

Understanding of the 2-dimensional case on sandy coasts has been extended by HR Wallingford in a Defra (UK Government) funded research project. In this project a combination of medium scale laboratory tests including suspended load sediment transport, re-analysis of existing field data and collection of new field data has been used to test and improve existing scour predictors. The project captured in measurements the occurrence of beach lowering during storms and Fig. 4 shows an example of the response that was observed. During the rising tide with wave action the beach lowers locally to the toe of the seawall and during the falling tide the beach level recovers its former level. The two periods of tidal inundation with waves lead to a beach lowering of at least 0.5m, with the scour response much reduced when the waves are lower.

The project has provided a new scour predictor for sand beaches using a more extensive database of laboratory and

field observations of scour than has been brought together before (Sutherland et al, 2006a). The laboratory tests and the resulting predictor have been summarised in Sutherland et al (2006b). This extends the predictive capability for sand beach scour as it also contains data for varying beach slopes (1V:15H to 1V:75H) and vertical and sloping walls. The work has been placed in the context of longer term and seasonal trends.

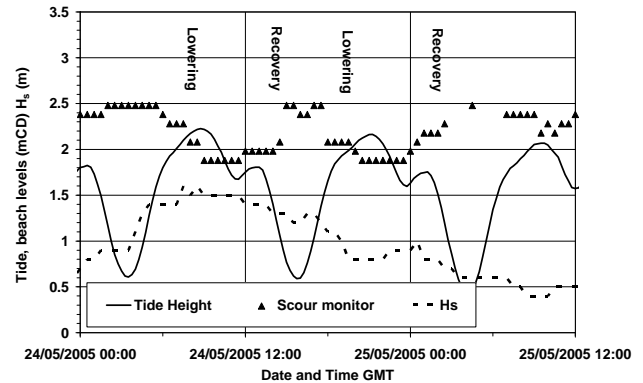


Figure 4. Beach lowering and recovery during a tide measured at Southbourne (from Sutherland et al, 2006a)

A complimentary approach for shingle beaches was already presented by Powell and Lowe (1994) and used in Simm et al (1996), Hoffmans and Verheij (1997) and Whitehouse (1998).

B. Breakwaters

In the EC funded project SCARCOST (Sumer et al, 2001) testing for scour development in the laboratory covered vertical and sloping breakwaters, detached breakwaters, as well as berm and submerged breakwaters. Laboratory tests carried out with waves and currents in a large tank allowed the scour depth and extent to be determined for a detached rubble mound breakwater (front slope 1V:2H) with waves head on and at an angle (Fig. 5), and a current parallel to the breakwater to simulate a coastal current (Sutherland et al, 2001).

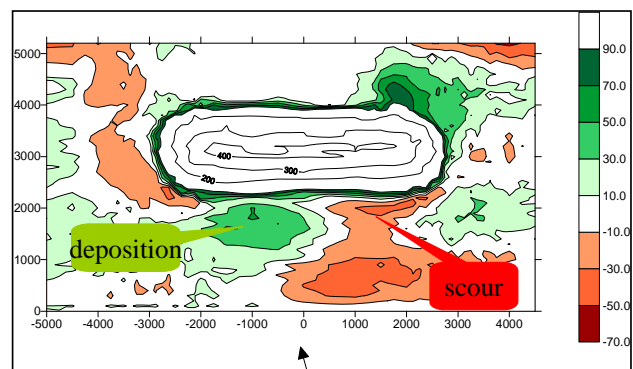


Figure 5. Scour development at breakwater in oblique waves after 30,000 waves (arrow shows wave direction) (Sutherland et al, 2001)

The programme of tests was used to show the way in which the processes combine to produce 3-dimensional patterns of scour and deposition. The time development is also an important parameter and information on this was also obtained showing how the pattern and magnitude of scour and deposition changed in time. Once the scour

development was understood tests were made to optimise the layout and stability of a rock apron placed as a scour protection measure.

The comparison of the results with the 2-dimensional case is shown in Fig. 6 (from Sumer et al, 2001; front slope of breakwater 1V:1.5H); the data for the 2-dimensional case taken from earlier tests are numbered 1 to 5. They also plotted a data point from the field, the square marked LH (Lillycrop and Hughes, 1993). The wave forcing is characterized by the Keulegan-Carpenter Number (KC).

A comparable set of results for the scour at the head was obtained in the 3-dimensional tests, as evidenced by the data point with the cross in the circle falling on the solid line following the trend of the earlier tests.

For the oblique wave case (squares with diagonal crosses) the scour depth at the head was considerably reduced (i) and only marginally increased with the current running (point (i) with the diamond and cross). However it was noticeable that the scour depth at the junction between the head and the trunk sections was seen to be greater than that at the head, but was similar for the oblique wave with and without current (symbols marked (ii)). The scour depth at the trunk was reduced in the oblique wave case (symbol marked iii) due to deposition of eroded sediment. The role of the current became clear, increasing the scour depth at the trunk by forming a scour trough running from the head to the trunk section and moving the zone of deposition down current.

Scour protection tests (circles marked D and E) showed effective reduction in the scour depth at the head but some scour was evident adjacent to the protected bed.

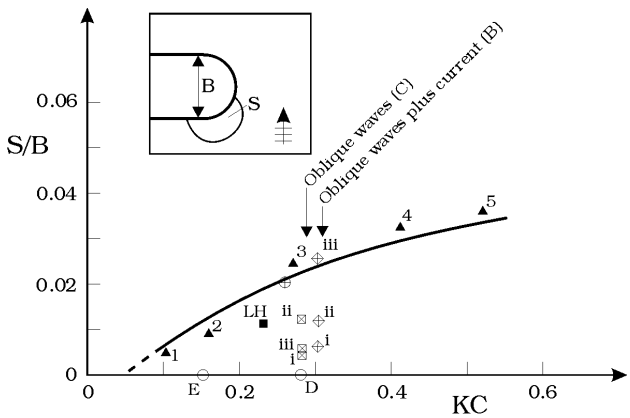


Figure 6. The influence of 3-dimensional wave and current field and scour protection in altering the 2-dimensional prediction of scour depth S at the head of a rubble mound breakwater with base width B (Sumer et al, 2001)

C. Construction works

The influence of scour during construction activities needs to be considered as it can adversely affect the schedule or require changes to the design. The scour that is manifest around temporary docks and causeways needs to be analysed as well as the scour at the primary structure. The application of scour protection during construction of a rubble mound breakwater or jetty can be used to good effect, as was studied for example by Hales and Houston (1983). The scour protection material is run out ahead of the structure as the bedding layer with

sufficient resistance to prevent scour under the storm conditions that can be expected during construction. In areas with strong currents a similar approach may be required to prevent the formation of a significant scour hole during construction; experience has shown that scour can also take place in cemented sands during the construction of a breakwater.

In many marine projects temporary facilities are required to be built close to the project site during the construction phase. One recent project required the building of a coastal harbour as a temporary dock to facilitate the main construction activities. The site was wave dominated and scour developed at one of the corners of the structure (Fig. 7) which influenced the design of an adjacent structure that was being built. The scour was monitored and the information obtained was used to modify the construction methodology for the adjacent structure.

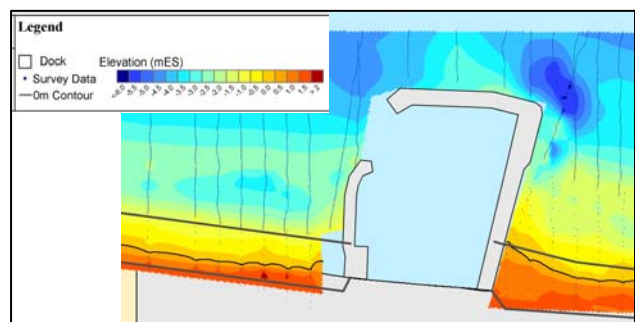


Figure 7. Monitoring data for scour hole at a construction dock

D. Windfarm foundations

The options for the foundations of offshore windfarms include monopiles, multi-leg structures, gravity bases and suction caissons. Guidance for offshore windfarms is to be found in the publication by DNV (2004).

The EC-industry project OPTI-PILE investigated the scour development in waves and currents that could be expected to occur around the foundations of the Q7 windfarm (Dutch Sector, Southern North Sea). A wide range of laboratory tests were used to validate a predictive approach for scour in waves and currents, the performance of static and dynamic scour protection measures, and the extents and volumes of scour protection rock required (Fig. 8). The results were applied within the OPTI-PILE design spreadsheet for scour and scour protection (Den Boon et al, 2004) which predicts:

- Scour hole depth and width;
- Size of static and dynamic rock armour; and,
- Extent and volume of rock armour.

And has an allowance for general bed movement. The spreadsheet can be used to show how the size of scour protection varies with a climate of waves and currents.

The spreadsheet tool is applicable to other windfarm locations and has been checked against the static and dynamic scour protection at Horns Rev and Scroby Sands (Den Boon et al, 2004). Høgedal and Hald (2005) concluded that the OPTI-PILE tool for assessing scour risk and scour protection stability predicts the scour depth very well.

Since then it has been assessed further using data for scour in strong currents and waves (Whitehouse et al,

2006). This work has indicated that it would be a valuable exercise to collect together additional field and laboratory data to validate the OPTI-PILE tool over a wider range of conditions.



Figure 8. Overhead photograph of end result of one of the physical model tests with a static protection design

Work on scour at suction caisson foundations – monopile and tripod solutions – has been completed by Whitehouse (2004) and Whitehouse et al (2004). The skirted foundations tested in this work had a diameter of 19m and a skirt tip depth of 9.5m. Tests were performed to determine the scour development in currents and waves and the results showed that in a vigorous scour environment, with adequate depth of soil, scour development could take place to a significant depth compared with the skirt tip depth. It was also shown that scour could be mitigated using an engineered rock dump placed around the foundation.

IV. LONG-TERM CHANGES

The challenge presented in understanding beach lowering and local scour for coastal structures is akin to the problem offshore, where allowance for scour at structures is required for both general scour and local scour.

The forced response with a structure in place can be determined using the time-stepping method presented in Whitehouse (1998). This can be applied with a time-series of inputs and target functions for the equilibrium scour depth and the timescale function. HR Wallingford has applied this approach to the prediction of scour at offshore windfarm foundations using the DNV guidance (DNV, 2004) to provide the target functions. This allows the variation in time to be assessed and more importantly the exceedance of particular scour depths to be analysed for the lifetime of the structure. Høgedal and Hald (2005) have examined the interaction of scour and fatigue loads on a monopile foundation.

Recently it has also been possible to take a long term approach to the assessment of scour in a soft clay soil at a marine breakwater site. The wave forcing over a period of more than 10 years at 3 hour intervals in absence of the breakwater was determined using wave modelling. The corresponding field of wave kinematics for a distance of up to 100m in front of the structure was determined using the spectral method of O'Donoghue and Sutherland (1999). This provided statistics on the mean, minimum

and maximum envelope of bed velocities that could be expected.

In the absence of an equilibrium predictor for scour in clay it was assumed the equilibrium scour depth was determined by a predictor for sand but that the rate of scour was governed by the time development of scour obtained from the time series prediction (for example as is shown in Fig. 9 for one location in front of the breakwater). The results indicated how quickly the scour would develop in a year and multiple realisations of that year enabled an assessment of the variability in scour depth formation after one year. Because of the influence of the reflected wave field on the incoming waves the bed shear stresses were larger than the critical values for much of the time at the selected location. At other positions in front of the breakwater and at other sites with more resistant clay the scour development would be less fast.

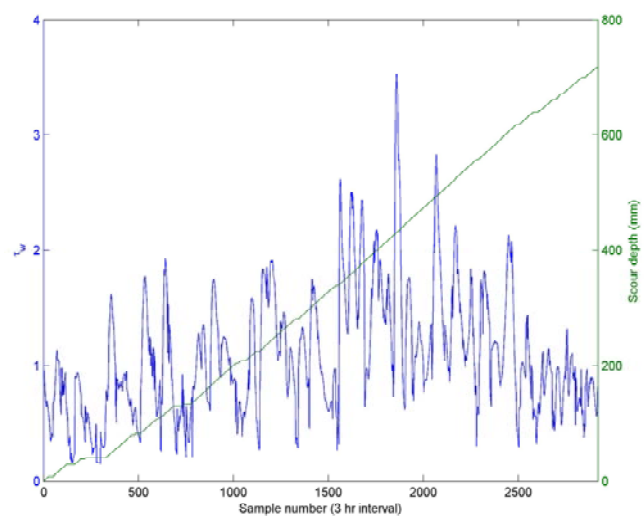


Figure 9. Example of the prediction of increase scour depth in clay in front of a breakwater over a period of one-year

Systematic changes related to the changes in the geomorphology have been made possible over periods of a year, for example the height, wavelength and migration of sandwaves can be predicted reasonably well (Whitehouse et al, 2004). Taking a single record of sandwaves it is possible to assess the exceedance of crests or troughs by fitting a Rayleigh distribution (e.g. O'Connor, 1992). At coastal sites the evaluation of toe scour needs to take place within a framework that recognizes the longer-term trends in beach levels (Sutherland et al, 2006a). Where a good dataset exists historical trend analysis can be used to assess how future changes might take place or prediction can be made using various more complex approaches.

Finally, there will be more random changes in bed level associated with the large-scale and long-term movements of sediments on the seabed. For example it might be important to determine whether the bed level at a particular location will drop below a certain level over a period of decades. On the basis of some historical data for bed level changes and with a representative time-series of hydrodynamic forcing it is possible to apply a prediction model; HR Wallingford has developed and applied a Stochastic Bed Level Model which allows predictions to

be made over periods of decades. Multiple (e.g. 30) realisations of the prediction allows the mean, minimum and maximum exceedance probability to be determined for a site. This has applications to projects where it is important to understand the depth to which the seabed may drop during the lifetime of a structure, such as a skirted foundation or a pipe trenched to some depth below the seabed.

V. SUMMARY OF REFERENCE MATERIALS

Since the early publications by Xie (1981) and Herbich et al (1984) amongst others, there has been a large increase in the information published in books and manuals that is available on the topic of scouring and scour protection in the marine environment. It is thought useful to list the available material (that the author is aware of) here – full references are given at the end of the paper. The author apologises in advance for any omissions and would be pleased to be informed of any new developments not listed.

- Herbich et al (1984)
- Breusers and Raudkivi (1991)
- Hoffmans and Verheij (1997)
- Van Rijn (1998)
- Whitehouse (1998)
- Melville and Coleman (2000)
- Schiereck (2001)
- HEC-RAS (2001)
- May et al (2002)
- Sumer and Fredsøe (2002)
- Annandale (2006)
- USACE (2006)
- CIRIA (2007)

The experience from river engineering such as is presented in Melville and Coleman (2000), HEC-RAS (2001) and May et al (2002) is also valuable for the marine context.

Therefore it can be concluded that the scour literature has matured in recent years with the large amount of effort that has gone into the preparation of these reference sources.

VI. RESEARCH AND DEVELOPMENT NEEDS

The information listed in Section V as well as the paper by Sumer et al (2001) provide the state-of-the-art information on scour at a large variety of coastal structures. However there are still a number of key areas requiring R&D to improve understanding and knowledge as well as predictive capability.

The predictors for toe scour at seawalls are based on small and medium-scale (e.g. 1:30 physical scale) laboratory tests with some field data for validation. There is very little data on scour from large scale laboratory tests to confirm the conclusions and scaling parameters. It would be very valuable to obtain data from a series of tests in a large scale laboratory flume (e.g. 1:5 physical scale or better) with varying beach slopes and sediments for vertical and sloping seawalls.

Information on bed processes, shear stress and scour development in waves at low Keulegan Carpenter

numbers (<1) is required for rubble mound breakwater and caisson roundheads. Some information on the effect of a current is available (Sumer and Fredsøe, 2002) but an improved understanding of the influence of a net current flowing past the end of the breakwater on processes and scour at the roundhead is still required.

Assessing scour in real soils continues to be a challenge yielded by the spatial, vertical and temporal variation in soil conditions. The scour hazard of a range of real soils needs to be further clarified as it has not been possible to date to find a unique relationship between geotechnical measures of soil properties and a hydraulic measure of resistance to erosion. So improvements are needed in the correlation between geotechnical measures and hydraulic estimates of erosion – the work of Annandale (1995, 2006) on the Erodibility Index provides a useful approach for converting geotechnical measures into erosion parameters and has been used in the UK to evaluate the erosion resistance of chalk based substrates.

A conceptual model for scour in a range of sediments is given in Fig. 10 but this requires quantification in general terms and in terms of scour at specific structures. If sand is taken as the benchmark case then in general terms the erodibility is expected to decrease for coarser and finer soils, although muds and clays may be quite variable in their response as is discussed below. Also in some sediments it is expected that the scour will increase with increased hydraulic forcing through storm waves whereas in other sediments it may actually lead to a decrease in the scour depth. The role of wave-induced liquefaction also needs to be considered (Sumer, 2006), and the soils subject to risk of liquefaction are indicated in Fig. 10.

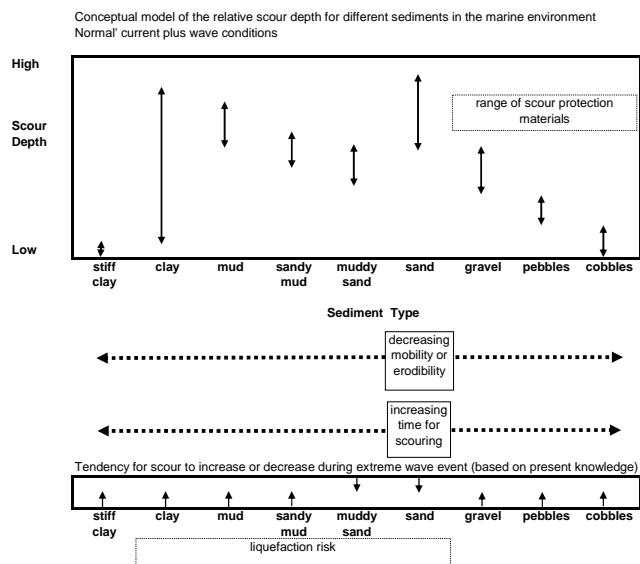


Figure 10. Conceptual model of the relative scour depth for different sediments

The resistance to erosion provided by clay still needs to be examined further; whilst firm clay with undrained shear strength of 100kPa is probably able to resist erosion in the open sea marine environment it can be eroded in tidal rivers. Jiang et al (2004) observed a scour depth of 5m adjacent to an oil-unloading terminal in firm clay. So it is clear that in some environments it is necessary to treat stiff clay as a scour hazard.

It may be necessary to develop in-situ methods to measure soil response to hydraulic forcing. The work of Briaud et al (1999) testing soil samples in the Erosion Function Apparatus (EFA) provides one way forward but there are other methods that can be used to estimate the erosion resistance including SedErode (Mitchener et al, 1996) and SERF (Jiang et al, 2004); a review of erosion devices was made by Black and Paterson (1997) and Annandale (2006). Information and approaches for predicting the erosion, transport and deposition of sands and muds have been published by (amongst others) Soulsby (1997) and Whitehouse et al (2000). For erosion of marine sediments comprising mixtures of mud and sand the work of Mitchener et al (1996) and Winterwerp and van Kesteren (2004) is useful. Using appropriate equipment it may be possible to develop a site specific relation between shear strength or other bulk sediment properties and the erosion shear stress and erosion rate *in situ* can be derived.

Time series methods offer attractive ways to investigate the exceedance probability for scour to occur at a structure but require suitable input data for the equilibrium scour depth, the timescale for scour and a sufficiently long-term series of inputs. This requires the combination of field measurements to determine the correlation between waves, tidal, oceanic and wind forced currents and numerical modelling to extend the time series over periods of years. To understand the local effects on the flow field it may be appropriate to apply numerical CFD (Computational Fluid Dynamics) panel models based on potential flow. In some applications it will be necessary to apply sophisticated models with turbulence closure as input data for scour assessments or analysis of the stability of scour protection. This type of CFD analysis has been used to good effect in analysing the scour development at a deep-water piled coastal jetty by representing the overall flow interaction between individual pile elements in a complex grouping in fast tidal flow.

The collation of (existing) data for the development of scour around large diameter piles in waves and currents is required to determine the response to alternating periods of strong wave and strong current forcing. HR Wallingford is currently leading a Department of Trade and Industry project bringing together data on scour observed through bathymetric monitoring obtained from a number of built offshore windfarm projects.

In the wider context there would be tangible benefits of collating field data on scour at structures from operating authorities, consultants and contractors at a European level and assessing the validity of predictive approaches. This could include seawalls, groynes, jetties, breakwaters, offshore windfarms and other structures, caissons and pipelines as validation datasets. This might also benefit from bringing in information from scour in deep water (50 to 100m) where oceanic currents can cause scour around subsea structures, which needs to be monitored and mitigated against. It could also include collation of scour protection and mitigation performance for rock solutions and mattresses in a range of coastal and subsea applications. However, an amount of that information is already presented in the forthcoming second edition of the rock manual (CIRIA, 2007).

Analysis of the significance of global climate change on scour development at structures; for example, sea level rise and the influence on tidal propagation and associated

water levels, increased storminess and storm persistence, or changes in prevailing wave direction. An application to coastal defence vulnerability was made by Sutherland and Gouldby (2003) including an assessment of climate change on overtopping of structures by waves and longshore transport of sediment. This approach could be extended to include an assessment of scour hazard and thereby work out the sensitivities to climate change.

VII. CONCLUSIONS

There is a large amount of information currently available on the development and prediction of scour at marine structures, and well established methods exist for the investigation of flow processes and scour using laboratory models or computational techniques. A number of interesting project examples have been presented in the paper.

In most cases it is possible to make a good estimate of scour based on the literature using the scour hazard approach in Fig. 1. There will still be cases where complex structures need to be investigated, or the information required is outside of the parameter range of existing experimental data. There will also be cases where liquefaction (Sumer, 2006) or shear failures and flow slides need to be assessed (Hoffmans and Verheij, 1997).

One area that continues to be of particular interest is in assessing the scour response and equilibrium scour depth for real mixtures of soil. Also some challenges remain where the impact of local scour needs to be considered in the framework of the longer-term natural changes that might have taken place without the structure in place.

Finally a number of recommendations for research and development have been made to take the state-of-knowledge further forwards.

VIII. ACKNOWLEDGEMENTS

The author acknowledges discussions with colleagues at HR Wallingford and elsewhere on the topics associated with this paper. The views expressed are those of the author.

IX. REFERENCES

- [1] Annandale, G.W. (1995). Erodibility. *Journal of Hydraulic Research*, 33 (4), 471-494.
- [2] Annandale, G.W. (2006). *Scour technology*. Mechanics and engineering practice. Mc Graw-Hill.
- [3] Black, K S and Paterson, D M. (1997). Measurement of the erosion potential of cohesive marine sediments: A review of current *in situ* technology. *J. Marine Env. Engg.*, 4, 43-83.
- [4] Briaud, J.-L., Ting, F.C.K., Chen, H.C., Cao, Y., Han, S.W. and Kwak, K.W. (2001). Erosion function apparatus for scour rate predictions. *Journal of Geotechnical and Geoenvironmental Engineering*, 127, 105-113.
- [5] Breusers, H.N.C. and Raudkivi, A.J. (1991). *Scouring*. IAHR-AIRH Hydraulic Structures Design Manual, 2, Balkema, Rotterdam.
- [6] CIRIA. (2007). *The rock manual*. The use of rock in hydraulic engineering (2nd Edition). Report C683 prepared by CIRIA, CUR and CETMEF.
- [7] Den Boon, J.H., Sutherland, J., Whitehouse, R., Soulsby, R., Stam, C.J.M., Verhoeven, K., Høgedal, M. and Hald, T. (2004). Scour behaviour and scour protection for monopile foundations of offshore wind turbines. In: *Proceedings 2004 European Wind Energy Conference*, London, UK. European Wind Energy Association [CD-ROM]. pp14.

- [8] DNV. (2004). Design of offshore wind turbine structures. Det Norske Veritas Offshore Standard DNV-OS-J101. (Draft)
- [9] Hales, L.Z. and Houston, J.R. (1983). Erosion control during construction; Report 4: stability of underlayer material placed in advance of construction to prevent scour; hydraulic model investigation. Hydraulics Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Technical Report (Series) HL-80-3.
- [10] Herbich, J.B., Schiller, R.E., Watanabe, R.K. and Dunlap, W.A. (1984). Seafloor scour: Design guidelines for ocean-founded structures. Marcel Dekker, New York and Basel.
- [11] HEC-RAS. (2001). Evaluating scour at bridges. Publication No. FHWA NHI 01-001. Federal Highway Administration. Hydraulic Engineering Circular No. 18. Fourth Edition.
- [12] Hoffmans, G.J.C.M. and Verheij, H.J. (1997). Scour Manual. Balkema.
- [13] Høgedal, M. and Hald, T. (2005). Scour assessment and design for scour for monopile foundations for offshore wind turbines. Proceedings of the Conference Copenhagen Offshore Wind.
- [14] Jiang, J., Ganju, N.K and Mehta, A.J. (2004). Estimation of contraction scour in riverbed using SERF. Journal of Waterway, Port, Coastal, and Ocean Engineering, 130, 215-218.
- [15] Lillycrop, W.J. and Hughes, S.A. (1993). Scour hole problems experienced by the Corps of Engineers; Data presentation and summary. Miscellaneous Papers. CERC-93-2, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MS.
- [16] May, R.W.P.M., Ackers, J.C. and Kirby, A.M. (2002). Manual on scour at bridges and other hydraulic structures. CIRIA Report C551.
- [17] Melville, B.W. and Coleman, S.E. (2000). Bridge scour. Water Resources Publications, LLC. 572pp.
- [18] Mitchener H.J., Torfs H. and Whitehouse R.J.S. (1996). Erosion of mud sand mixtures. Coastal Engineering, Vol. 29, pp1-25. [Erratum, Vol.30, (1997), 319].
- [19] O'Connor, B.A. (1992). Prediction of seabed sand waves. In: Computer Modelling of Seas and Coastal Regions, ed P.W. Partridge, pp.321-338, Elsevier, London.
- [20] O'Donoghue, T. and Sutherland, J. (1999). Random wave kinematics and coastal structures. Proc ICE Water and Maritime Energy. Vol 136 (Issue 2) pp 93 – 104.
- [21] Powell, K.A. and Lowe, J.P. (1994). The scouring of sediments at the toe of seawalls. In: Proceedings Hornafjörður International Coastal Symposium, Iceland, 20-24 June, ed. G. Viggosson.
- [22] Schiereck, G.J. (2001). Introduction to bed, bank and shore protection. DUP Blue Print. 408pp.
- [23] Simm, J.D., Brampton, A.H., Beech, N.W. and Brooke, J.S. (1996). Beach management manual. CIRIA Report 153.
- [24] Soulsby, R.L. (1998). Dynamics of marine sands. Thomas Telford, London.
- [25] Sumer, B.M. (special issue editor) (2006). Liquefaction around marine structures. Processes and benchmark cases. Special Issue of Journal of Waterway, Port, Coastal and Ocean Engineering, July/August 2006, 132, 4.
- [26] Sumer, B.M. and Fredsøe, J. (2002). The mechanics of scour in the marine environment. World Scientific, Singapore.
- [27] Sumer, B.M., Whitehouse, R.J.S. and Tørum, A. (2001). Scour around coastal structures: a summary of recent research. Coastal Engineering, 44, 153-190. [Erratum 2002 : 45, 69].
- [28] Sutherland, J. and Gouldby, B. (2003). Vulnerability of coastal defences to climate change. Water & Maritime Engineering, Proceedings of the Institution of Civil Engineers, 156, WM2, 137-145.
- [29] Sutherland, J., Brampton, A. and Whitehouse, R. (2006a). Toe scour at seawalls: monitoring, prediction and mitigation. Paper 3b in Proceedings 41st Defra Flood and Coastal Management Conference, York, July 2006. Published by Defra, London (www.defra.gov.uk).
- [30] Sutherland, J., Obhrai, C., Whitehouse, R.J.S. and Pearce, A.M.C. (2006b). Laboratory tests of scour at a seawall. Proceedings Third International Conference on Scour and Erosion, Amsterdam, 1-3 November 2006.
- [31] Sutherland J., Whitehouse R.J.S and Chapman B. (2000). Scour and deposition around a detached rubble mound breakwater. In: Coastal Structures '99, Santander, ed. I.J. Losada, 897-904, Balkema.
- [32] USACE (2006). Coastal Engineering Manual. Part VI Design of coastal project elements (chairman Steve. A. Hughes). Available for download from: <http://chl.ercd.usace.army.mil/>
- [33] Van Rijn, L.C. (1998). Principles of coastal morphology. Aqua Publications, Netherlands.
- [34] Whitehouse, R.J.S. (1998). Scour at Marine Structures. Thomas Telford. 216 pp.
- [35] Whitehouse R.J.S., Soulsby R.L., Roberts W., and Mitchener H.J. (2000). Dynamics of estuarine muds. Thomas Telford. 210 pp.
- [36] Whitehouse, R.J.S. (2004). Marine scour at large foundations. In: Proceedings of the Second International Conference on Scour and Erosion, Singapore, November 2004, eds. Chiew Y-M., Lim, S-Y. and Cheng, N-S. Pages 455-463.
- [37] Whitehouse, R., Damgaard, J. and Langhorne, N. (2004). Experiences from sandwave analysis and modelling from the Berau Bay (Indonesia) marine pipeline project. CD ROM Proceedings International Workshop Marine Sandwave and River Dune Dynamics II (MARID 2004), 1 & 2 April 2004, Enschede, NL.
- [38] Whitehouse, R.J.S., Dunn, S.L., Alderson, J.S. and Vun, P.L. (2005). Testing of the interaction of offshore windfarm foundations with the seabed: scour and liquefaction. In: Coastal Engineering 2004. Proceedings of the 29th International Conference, Lisbon, September 2004, ed. Smith, J.M. Pages 4215-4227.
- [39] Whitehouse, R.J.S., Sutherland, J. and O'Brien, D. (2006). Seabed scour assessment for offshore windfarm. Proceedings Third International Conference on Scour and Erosion, Amsterdam, 1-3 November 2006.
- [40] Winterwerp, J.C. and Van Kesteren, W.G.M. (2004). Introduction to the physics of cohesive sediment in the marine environment. Elsevier.
- [41] Xie, S-L. (1981) Scouring patterns in front of vertical breakwaters and their influence on the stability of the foundations of the breakwaters. Department of Civil Engineering, Delft University of Technology, Delft, The Netherlands, 61p.