HR Wallingford
Working with water

HRPP 413

Development of Guidance for the Management of the Toe of Coastal Defence Structures

M. Wallis, R. Whitehouse & N. Lyness

Reproduced from a paper presented at:
EA/Defra Flood and Coastal Management Conference
Telford, UK
30 June - 2 July 2009

DEVELOPMENT OF GUIDANCE FOR THE MANAGEMENT OF THE TOE OF COASTAL DEFENCE STRUCTURES

Michael Wallis[1] BSc, MSc, AIEMA., Richard Whitehouse[1] BSc, PhD, CGeog FRGS, Nick Lyness[2] BSc, CEng, MICE, MCIWEM

[1] *HR Wallingford Ltd, Wallingford, UK*
[2]*Environment Agency, Blandford Forum, UK*

Key Words
Asset management, toe scour, trigger levels

Abstract
The sustainable management of coastal defence assets requires information regarding the ground levels at the toe of the structure as this has a direct effect on the structural performance. The failure of structures due to toe scour is a recognised problem and research has been completed in recent years to increase understanding of the process and its prediction. This work is being translated to guidance which will inform asset management and design of new or remedial works.

Introduction
Beach lowering and the effects of scour in front of coastal defences and erosion protection structures are recognised as the principle causes of their failure including collapse/breaching and washing out of fill materials. Both localised scour and more widespread beach lowering can lead to undermining of the toe (see Figure 1). This can promote structural instability and result in partial or total collapse with subsequent reduction in, or loss of performance for flood defence or erosion protection.

Lowering of the ‘ground levels’ in front of seawalls, revetments or other coastal structures is a common phenomenon not only in the U.K. but also around the world. Toe scour is a serious and costly problem – moreover, it is one which is not limited to any particular coastal environment or to any particular type of defence structure. Porous sloping structures as once suggested, are not necessarily less susceptible to scour. The prevention of, design for, and management of beach lowering and scour at the toe of coastal structures is therefore very important.

Understanding, designing for and managing toe scour at coastal structures therefore is a key issue for coastal managers, designers and engineers. To date there has been no guidance available tailored specifically to meet these needs. Recognising this, the Defra/ Environment Agency Flood and Coastal Erosion Risk Management programme commissioned the development of guidance on the management of the toe of coastal defence structures in 2008 (Toe Scour Guide).

This work draws together recent key research and development work on beach lowering and scour including ‘Understanding the Lowering of Beaches in Front of Coastal Defence Structures’ (Sutherland et al, 2006 and 2008). The guide is also integrating work on performance and reliability of coastal structures developed through the Performance-based Asset Management Project (PAMS) including performance analysis and asset inspection methods. This paper reflects on and highlights some of the developments made in the preparation of the guide.

Risk and Asset management

Society demands increased reliability and safety in regard to assets used to protect it from natural hazards. Increasingly, politicians, businesses and decision-makers require that risks associated with civil engineering structures, especially infrastructure, are quantified. Risk can be evaluated by involving multi-disciplinary competences including engineers, geoscientists and statisticians to carry out reliability analyses and provide risk estimates that can assist in decision-making. The derivation of risk requires the use of probabilistic approaches because these provide a rational framework for taking into account uncertainties.

Managing risk first involves the identification, analysis and assessment of those risks to enable informed decisions to be made on whether and how they should be controlled or mitigated. This approach to risk is necessary because some factors are uncertain and others cannot be controlled. Risk is evaluated by identifying the hazards or 'sources', evaluating the likelihood of a failure of controls or defences, evaluating the potential consequences of failure, and then assessing the results for acceptability. The treatment of risk is the process of selecting and implementing measures for managing identified risks. Risk treatment may involve simply monitoring low risks or developing mitigation plans for addressing higher risks. Risk mitigation is achieved by either reducing the likelihood of an occurrence, or its consequences, or both. Thus the management of defence or protection assets is a key component in the treatment and mitigation of flood and erosion risks.

Figure 2 illustrates a simplified conceptual cycle of asset management for the toe of coastal defence structures within which the management of risk is implicit. This paper is primarily concerned with the top and right hand elements of the cycle – the definition and understanding of the physical processes and the measurement, monitoring and assessment of the impacts of those processes. It also seeks to show how this information and various methods can be used together to assist coastal managers in their decision-making and planning regarding when they might need to consider remedial options or to intervene.

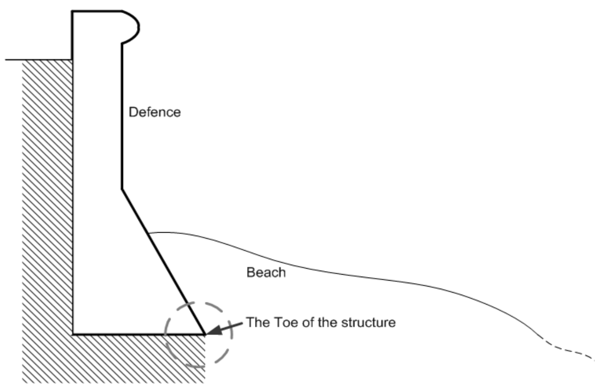

Figure 1 Definition of the toe of the defence structure and the level of the beach (a variable quantity)

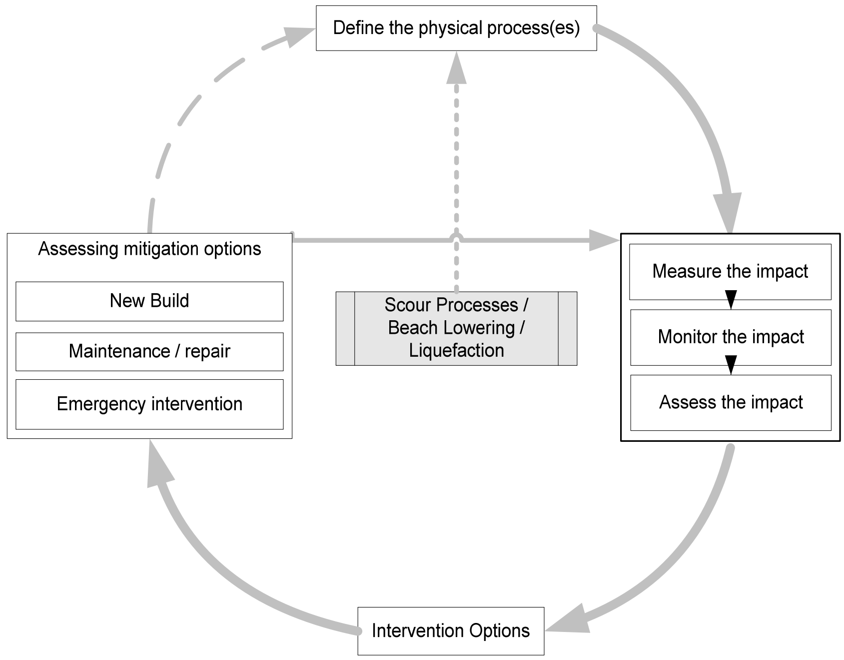

Figure 2 Conceptual cycle of asset management for the toe of coastal defence structures

Risks associated with the failure of the Toe of defence structures

Both localised scour and the more widespread beach lowering can lead to problems with coastal structures. An example of this is shown in Figure 3 where there was failure of the toe piling and structure over a 50 m length of frontage. The failure occurred due to a general lowering of the beach as well as scour in two storms, a prolonged north-easterly storm in November 1999 and a shorter storm in April 2000. Remedial works were subsequently implemented (Patterson et al, 2004).

The ongoing occurrence of scour related problems supports the findings of a comprehensive survey published over twenty years ago by CIRIA (1986). That survey concluded scour at the toe of coastal defence/protection structures represented the most serious form of damage to seawalls in the UK. It directly accounted for 12% of the seawall failure case histories studied and was linked indirectly to a further 5% of cases. Similar conclusions were drawn in the USA for rubble-mound structures (Markle, 1986). The causes of failure include:

- The loss of supporting beach material from in front of a coastal defence structure;
- A gradual dislocation of the rubble mound or blockwork foundation;
- The washing out or winnowing of granular 'fill' from behind the face of the structure; and,
- A modification of the wave and flow conditions in front of the structure, which may, for example, increase the rate of overtopping, which can lead to erosion.

Toe structures are a key component in coastal defence design as they are built, and often 'retrospectively' installed, to stabilise existing structures and prevent or mitigate the risk of failure of the original defence structure. Toe structures are however subject to the same physical processes as the original or 'parent' structure - i.e. removal of foundation elements and passive resistance through beach lowering and scour, and the impact forces of waves. The

Toe highlighted in Figure 1 is the physical Toe of the structure but the intersection of the beach level and the structure form a 'visible' toe, i.e. what an inspector would see. The physical toe of the structure may remain buried beneath beach sediment year on year. The level of the beach will vary and hence the depth of burial of the foundation at any time is variable. As the beach level lowers the position of the interface of high variability may move closer to the physical toe of the structure. To evaluate the risk an understanding of the physical factors and processes is required. The impact of the change in beach levels on the structure can be encapsulated in the concept of a "trigger" level set as discussed below.

Trigger Levels

An important concept in beach management is the criticality of beach levels at the toe of coastal structures. Over time the levels increase and decrease – they are variable. Effective management aims to understand and act upon this variation should it extend and persist beyond certain limits in the future – either too much sediment, if this is a problem – or, more typically, too little sediment. The examination of statistics on mean beach levels in relation to the toe of a structure together with prediction methods and structure geometry information (level of the structure toe and structural stability modes) can be combined to provide information that the asset manager can use to determine the physical limits and timescale within which intervention options should be considered (i.e. beach renourishment, remedial defence works, decommissioning etc). This concept is illustrated in Figure 4.

As well as the general trend and statistics of beach level indicated in Figure 4 the potential local scour needs to be taken into account as the local bed level at the wall may drop below the critical level during a storm before the average beach level does.

Physical Processes

As discussed above beach levels in front of coastal defence structures are continually changing. Beach lowering is caused by a number of processes that take place at a range of different spatial scales and timescales and which combine cross-shore and longshore sediment transport. These timescales cannot be treated in isolation.

Figure 3 Structure collapse at Corton (April 2000) (photograph courtesy of Waveney District Council)

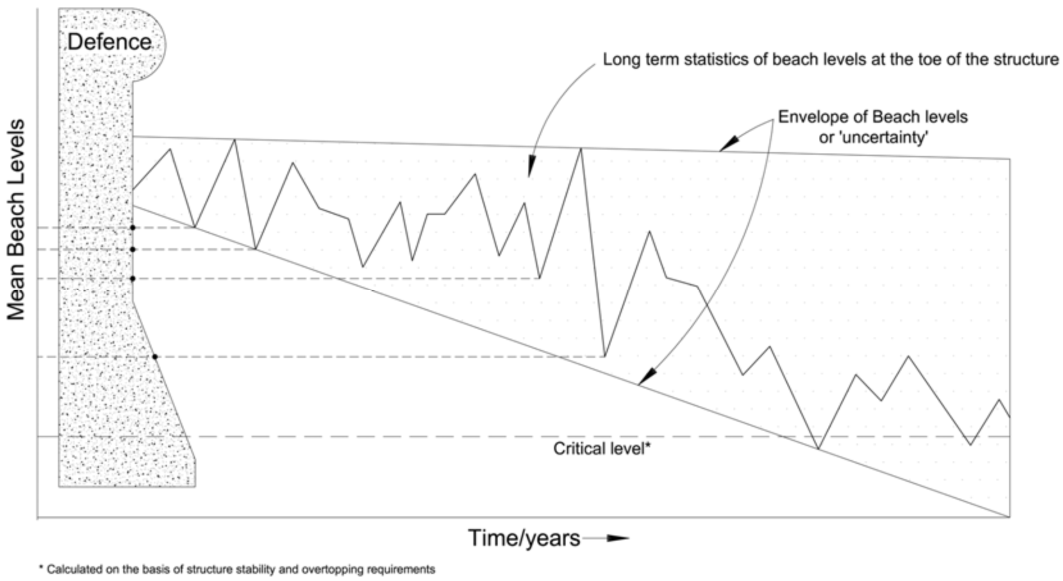

Figure 4 Schematic diagram showing the development of beach levels in time and the concept of a critical level for foundation performance based on asset management requirements

Seawall toe scour occurs when the face of the wall can be acted upon by waves, either directly, when the sea level is higher than the bottom of the wall, or through wave run-up. The presence of a structure in relatively shallow water, for example, abruptly breaks the wave and the energy is dissipated within a much smaller zone than on a natural, unimpeded beach profile. This sudden release in energy is converted into turbulence and wave reflection. The extra kinetic energy released around the toe of the seawall induces lowering of the beach at the bottom of the wall by:

- Increasing local shear stress on the bed to levels exceeding the threshold for sediment motion;
- Generating shock waves through the impact of waves breaking on the seawall. The pressure waves set up in the water column are transmitted to the bed, and away from the wall, these high pressure gradients disturb the sediment and make it more vulnerable to erosion. Wave-induced liquefaction of bed sediments may become a contributing process at this time.
- Increasing removal of the suspended sediment by longshore currents as the extra turbulence sustains sediment motion and allows it to be transported by currents; and,
- Reducing sedimentation as the greater water velocity close to the seawall reduces the rate of settlement of sediment brought into the area by longshore drift.

The process of toe scour can be self-perpetuating. For example, consider the situation where the beach level at the base of the seawall is above the mean high water spring tide level and therefore not vulnerable to scour under normal conditions. Once a sufficiently large storm, i.e. surge water level plus storm waves, produces initial scour, a greater range of wave/water level conditions can reach the seawall and the beach level in front of the seawall may then lower progressively.

As the beach lowers further the water table is closer to the surface, pore pressures increase and the sand can be fluidised, increasing the degree of sediment removal through backwash (Powell and Lowe, 1994). Periodically, conditions may allow a recovery of the beach level if there is sufficient sediment supply, but for narrow beaches with a sediment deficit it may never accrete to the pre-scour level. Further discussion about the processes of scour can be found in Kraus and McDougal (1996), van Rijn (1998, 2003), Whitehouse (1998) and Sumer and Fredsøe (2002) amongst others.

There are particularly complex physical relationships involved in attempting to model the physical processes and to ascertain the level of risk of failure of Toe structures. This makes predicting any future changes in performance of such structures particularly difficult, but changes in the environmental or loading conditions, or the state of the structure, will determine the ability of the defence to maintain its effectiveness with risk reduced to an intended and acceptable level. There are various predictive analyses that can be carried out to inform risk based assessment and the decision-making process which will now be described.

Predictive Analyses

There are three key predictive measures that the management of toe structures should consider. These are:

- Predicting the lowering of beach levels;
- Predicting sediment scour at the toe (Localised sediment scour at the toe of a structure is a different physical process to beach lowering, although partly dependent upon that of broader scale beach lowering); and
- Predicting deterioration of the structure and failure (not included in the present discussion).

Predicting beach lowering

The performance of a beach largely depends on the volume of material present and the limits to its plan and profile changes – influenced particularly by sediment control structures within it (e.g. groynes). Where there is a continuing net loss of sediment, then beach recovery is an issue. In general, failure is a result of depletion in the volume of the beach through increased longshore and / or cross shore transport of beach sediment, or, a reduction in supply of sediment onto the frontage. Beach levels are constantly changing although trends of depletion or accretion are generally gradual (long term), however significant erosion and lowering can occur during ‘one-off’ storm events.

The variations in beach levels near coastal structures at a range of time scales from one tide to the order of a year are the accumulation of residual changes in level that occur during each tide. However, it is common to find beach levels lower in winter than in summer, due to the increased occurrence and severity of storms during winter. It also follows that beach levels may show a greater variation about their seasonal mean during winter (Sutherland *et al,* 2008).

A range of advanced linear and nonlinear data analysis methods can be used to analyse the long-term prediction of beaches (Larson et al., 2003, HR Wallingford 2008c). Data based analysis will become more powerful as the amount of regularly-sampled and accurate data collected, stored and managed by organised regional coastal observatories and others increases. The evaluation of profile data may be supplemented by the results from process-based numerical models of cross-shore beach evolution (e.g. van Rijn et al., 2003).

One dilemma the analyst faces is what prediction ‘horizon’ can be expected when extrapolating beach level time series data. Analysis of beach monitoring data from Lincolnshire (HR Wallingford, 2008a, Sutherland *et al,* 2008) illustrates that the predictive ability of a straight line fit from more than 10 years of data is limited to a few years beyond the end of the dataset, but this should be sufficient for the purposes of supporting annual inspection combined with predictive modelling (that is the assumption made here). An indicative per annum allowance for beach lowering based on data provides a guide to potential beach lowering rates and informs the design and maintenance of coastal defences. The indicative allowances for beach lowering can be applied in the same way as, say, indicative allowances for sea level rise.

Predicting sediment scour at the toe

The development of toe scour is a dynamic process, highly dependent on the water level at the wall and the incident wave conditions. In areas of varying tidal range and wave climate, the development of a scour hole will be an episodic process with periods of erosion followed by infilling, and perhaps even general accretion of the bed (Powell and Lowe, 1994). The scour hole itself may therefore be a short-lived feature with no obvious evidence of its extent, or perhaps even its existence after a storm has declined and infilling has taken place as the tide recedes. This means that the profile seen before and after the storm may be quite similar in consecutive beach profiles taken at low water. Hence, there is a need to be able to predict the maximum depth of the scour hole during storms, as well as the more widespread and longer-term processes that cause the lowering of beach/shore-platforms. This is important both in the design stage of a coastal structure, and in its subsequent monitoring if the risk to the future integrity of the wall is to be fully understood and timely remedial action undertaken.

As storm event scour is frequently short-lived, the typical twice-yearly beach profile monitoring carried out around the English coast is unlikely to capture a major scour event but can indicate the way in which the beach is evolving and record seasonal variations (summer and winter) at the seawall. Indeed, the evidence supplied by data from bespoke scour monitors (Sutherland *et al*, 2006) suggests that a significant amount of a scour hole can fill in within a few hours of the peak of a storm. Therefore even regular beach profiling with a spacing of a few weeks, supported by profiles collected within a day or two of each large storm may not be enough to capture the transient phenomenon of toe scour in the field. So a combined evaluation of beach level trends and scour prediction is an appropriate way forward.

Prediction of toe scour depths at vertical seawalls with sand beaches

A rule of thumb for vertical seawalls is that the scour depth is equivalent to the deep water (unbroken) significant wave height H_s (Whitehouse, 1998). As an improvement on this (Sutherland *et. al,* 2008 and HR Wallingford, 2008b) recommended the use of a conservative predictor of scour depths which may be used in the absence of site-specific information on beach slope. It is reproduced as Equation (1) with H_s as the commonly used scaling parameter for predicting scour depth:

$$\frac{S_{t\max}}{H_s} = 4.5e^{-8\pi(h_t/L_m+0.01)}\left(1-e^{-6\pi(h_t/L_m+0.01)}\right)$$

$$[-0.013 \le h_t/L_m \le 0.18] \qquad (1)$$

where:
S_{tmax} is the maximum toe scour depth (m);
h_t is the water depth above the sediment level at the toe of the seawall (m); and
$L_m = g\,T_m^2/2\pi$ is the linear theory wavelength based on acceleration due to gravity g (assumed to be 9.81 m/s^2) and mean wave period T_m (s).

The equation is plotted with data on Figure 5. The range of validity of Equation (1) is given in the [ ] brackets in terms of h_t and L_m. When this equation was tested by validating laboratory tests with field data from two UK sites, Blackpool and Southbourne, it was found that the field data generally had lower scour depths than the laboratory data. This is believed to have been caused by the fact that wave height, wave period and scour depth were only measured at a single tidal state in the laboratory. The field data was collected in situations with constantly varying water levels and wave heights. However, the upper limits of the field observations confirm the laboratory data and envelope curve of equation 1

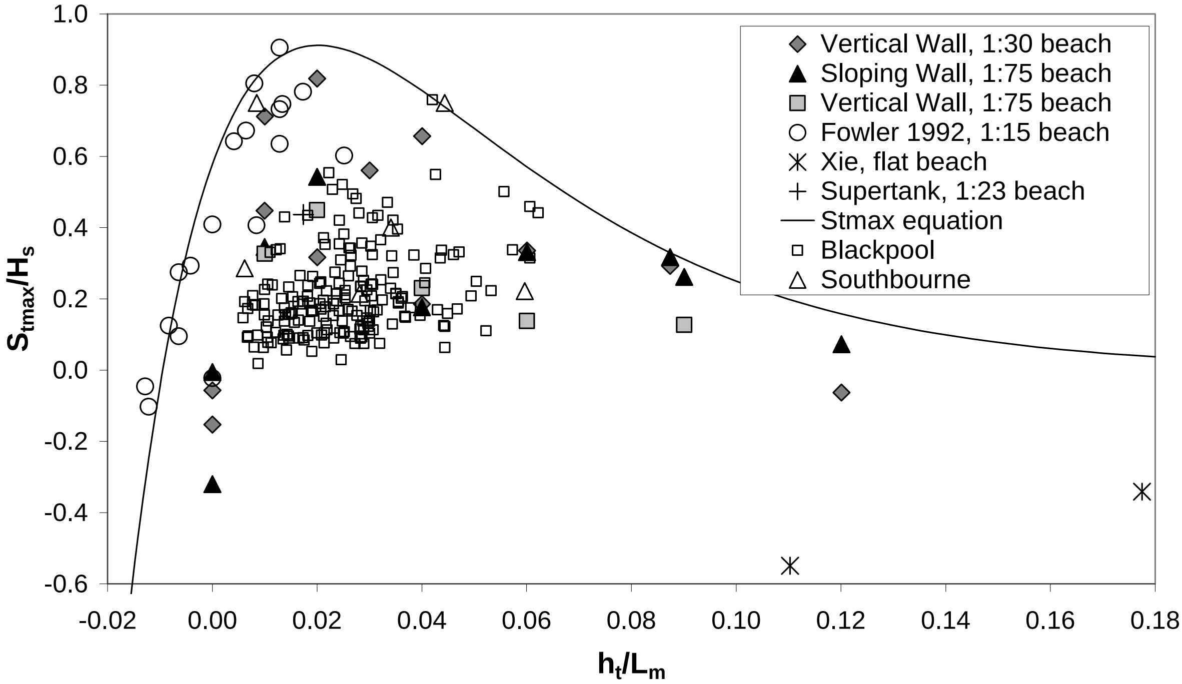

Figure 5 Envelope toe scour predictor – Equation (1) – with laboratory data and field data from Blackpool and Southbourne; after Defra (2008)

It can be seen from Figure 5 that the scour depth is everywhere less than H_s, and that the peak scour depth occurs for relative water depths (h_t/L_m) of around 0.01 to 0.02 and that the scour depth reduces for shallower and deeper water.

In situations where the beach slope is known then an alternative empirical equation for the depth of scour at the toe of a vertical seawall developed using the laboratory data in Figure 5 can be used (HR Wallingford 2008b, Sutherland *et. al* 2008). HR Wallingford (2008b) showed that the relative toe scour depth can be given with a beach slope dependency by:

$$\frac{S_t}{H_s} = 6.8(0.207\ln(\alpha)+1.51)e^{-5.85k_m h_t}\left(1-e^{-3k_m h_t}\right)-0.137$$

$$[-0.04 \le h_t/L_m \le 0.12] \qquad (2)$$

where:
S_t is the scour depth at the toe of the structure (m);
H_s is the deep water (unbroken) significant wave height (m);
α is the beach slope (radians);
k_m is the linear theory wavenumber $k_m = 2\pi/T_m$ (1/s) with T_m the mean wave period (s);
h_t is the water depth above the sediment level at the toe of the seawall (m);

The range of validity of Equation (2) is given in the [ ] brackets. An extended version of this predictor including wave set up on the beach was also developed (Sutherland *et.al*, 2008). Equation (2) was derived from tests with normally-incident irregular waves and beach slopes of 1:15, 1:30 and 1:75. The equation predicts the maximum scour depth reduces with decreasing beach slope as seen in the laboratory data.

Both equations (1) and (2) predict the scour after 3,000 waves (i.e. 6.7 hours for an 8 second wave) and a correction must be used to predict scour for time intervals other than 3,000 waves.

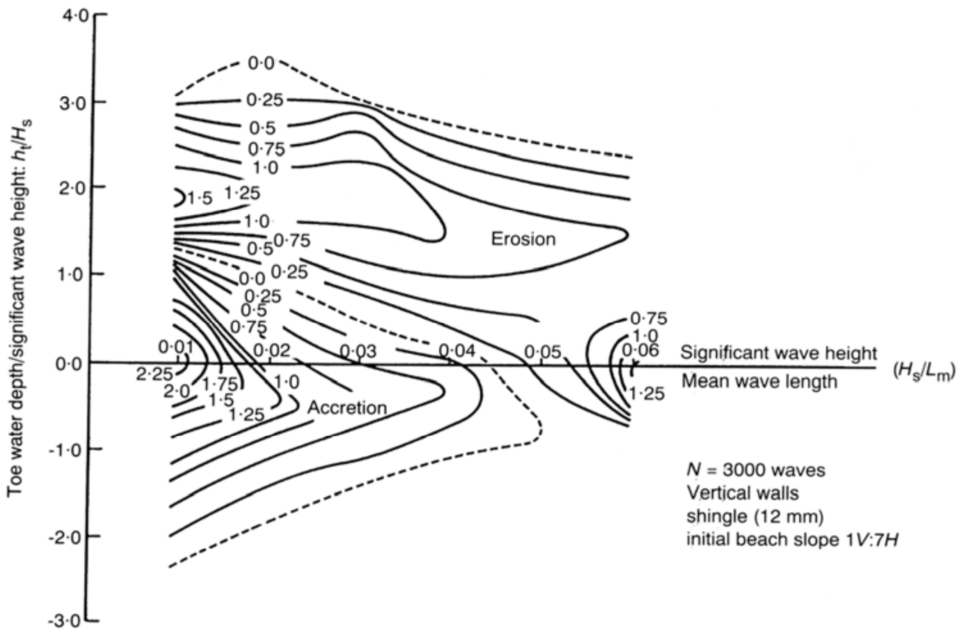

Figure 6 Prediction diagram for scour (erosion) and accretion at vertical seawalls with shingle beaches (Powell and Lowe, 1994) – contours of dimensionless scour depth S_{3000}/H_s

Prediction of toe scour at vertical seawalls with shingle beaches

Scour depths in shingle beaches can be predicted using the parametric plot of Powell and Lowe (1994) reproduced as Figure 6 (also used by Whitehouse, 1998). This was based on an extensive set of laboratory tests conducted with normally-incident irregular waves that broke on a 1:7 slope shingle beach, with a vertical impermeable seawall. The maximum scour predicted was $1.5H_s$. The method is valid for beach sediment in the range $5mm<d_{50}<30mm$ (modelled at 1:17 scale).

Figure 6 shows contours of S_{3000}/H_s plotted on a graph with axes of relative depth, h_t/H_s and relative wave steepness, H_s/L_m, where:

h_t/H_s is the relative water depth;
h_t is the water depth above the sediment level at the toe of the seawall (m);
H_s is the deep water (unbroken) wave height (m);
H_s/L_m is the wave steepness;
L_m is the mean wavelength (as Equation (1)) (m); and,
S_{3000} is the scour depth after 3,000 waves.

The scour depth associated with a given water depth and wave condition is obtained by calculating the wave steepness H_s/L_m and the dimensionless toe water depth h_t/H_s and reading off the value of dimensionless scour depth S_{3000}/H_s. A correction for time intervals other than 3,000 waves is required (Powell and Lowe, 1994).

Monitoring

Beach level and scour hole monitoring at the toe

Methods for measuring beach levels (and changes) were reviewed by Sutherland et al (2006), including measurements during the tide using scour monitors (e.g. Figure 7). If a long-term record of beach levels in front of a structure is available, such as the Environment Agency's twice yearly beach surveys carried out in Anglian Region for the last 10 years, then long-term trends in mean beach level in front of the structure and in intertidal beach volume can be calculated. If these values show a statistically significant decrease in mean beach level with time then existing trends can be projected forwards to identify when the structure may become vulnerable to the additional effect of local toe scour, should those trends continue.

The deployment of scour monitoring systems that remain on-site just in front of a structure (for weeks or longer) are one practical way of assessing the temporal variability of a beach surface including lowering and scour.

An array of scour monitors could be installed that looks for the bed lowering to the point at which short-term fluctuation from the time-dependent mean level could de-stabilise the asset (‘trigger’ level). The data can be recorded and analysed after recovery of the monitor or the data can be fed onshore through a cable to a data logger displaying the bed level. Analysis of the data for storm events can be used to confirm the predictions from the equations presented in this paper and real time data can be used to evaluate if the bed drops near to or below the trigger level. The monitoring could then take place a few times per year (at least twice) and a more detailed study or remedial action undertaken before the beach level drops below pre-determined values (or the ‘trigger’ level).

Structure condition monitoring

Toe structure condition monitoring as part of a ‘normal’ condition inspection regime can be hampered by the fact that toe structures are often unobserved because they are either submerged or below beach level at the time of the scheduled inspection. If the structure is thought not to be covered by sediment then an inspection can be scheduled for a time and date when the tide is low enough for its inspection. Otherwise, if it is permanently covered by sediment, then there is rarely a requirement to inspect it anyway as sediment provides a protective covering. Inspection pits or trenches may be used if knowledge is required about the toe structure or its configuration, especially for unknown foundations. One of the most frequent problems is the lack knowledge about the presence and depth of toe structures, especially for older structures where engineering drawings have been lost or do not exist.

Consideration should be given to the inspection of ground beneath revetted or stepped toe revetments to assess any washout of fill material. Installation of inspection access hatches, taking core samples, or installing holes for small camera probes could be prescribed for monitoring purposes.

Figure 7 Scour monitor for recording changes in beach levels – beach at low level

A simple way by which an inspector could form a judgement about beach levels is to use a 'Plimsoll' type line painted or fitted to a seawall, or by 'dipping' - measuring the beach level from the structure crest. A fixed line can visually indicate beach height at the wall in relation to the toe of the structure if it was measured in during construction or retrofitted. This can provide the asset manager with a datum to record information on beach level variability over time in an inexpensive and straight forward way. A pre-determined trigger level for beach height could be measured in such that when it was revealed and observed it would flag up the need for intervention. Monitoring localised responses in this way allows beach managers to be proactive in their maintenance programme and reduces the potential for damage. It also provides useful design information for future schemes.

Suggested predictive approach

For each location being considered the engineer needs to determine a trigger level for intervention (i.e. the critical level on Figure 1). This will be based on key parameters related to structural performance, beach safety etc. Once this level has been set a simple assessment for any section of a structure can be determined (initially) on a seasonal, e.g. summer and winter 6-monthly basis, using the following eight steps for sand or shingle foreshores:

1. Prescribe trigger level for beach level at the toe of the structure (see Figure 1 for definition – actual line prescribed on a case by case basis);
2. Determine whether the beach in front of the structure is sand or shingle;
3. Is the beach slope known?
4. Estimate the lowest beach level at the structure for the next two seasons based on a linear trend and the variance of historic bed levels (unless a more sophisticated approach is warranted);
5. Determine the maximum water depth at the structure for the next two seasons based on predicted tide levels with allowance for surge;
6 Estimate the extreme wave conditions (H_s and T_m) for the next two seasons.
7. Predict the combined beach level and scour level; and,
8. Carry out condition grade assessment and monitoring as necessary to confirm the expected position of the beach level.

With the above information the following decision process is implemented:

A. If the beach is sand and the answer to 3. is "no" use Equation (1) to predict scour depth and if "yes" use Equation (2) to predict scour depth;
B. If the beach is shingle use a look up table based on Figure 6 to predict scour depth;
C. Determine the combined beach level and scour depth for the next two seasons; and,
D. Evaluate whether this causes the beach level to drop below the critical level:
i. If it does not then reformulate the prediction for the next two seasons, updating the input parameters as appropriate based on site observations; or,
ii. If it does then plan appropriate monitoring of structure condition and beach levels at more frequent intervals and implement mitigation / intervention plans.

If a more detailed assessment is required for a particular asset the predictions can be made more frequently, given the relevant input data. Case examples illustrating the approach are included in the Toe Structures Guide. These cover a contrasting range of geographical locations, structure detail, foreshore sediment characteristics, and management approaches. With some further definition this approach can be implemented in a probabilistic assessment (HR Wallingford, 2006c). In addition an approach for soft rock soils is required. Some existing management guidance is given in Defra (2007) and this will be summarised within the framework of the Toe Scour Guide.

Conclusions

The following findings and recommendations form the conclusions of the paper:

1. For risk-based asset management of Coastal Defences and Toe Structures we need to combine condition grade assessments with monitoring and predictive approaches for beach levels and toe scour.
2. The monitoring and analysis of beach levels and assessment of structure condition provide essential information for predictive performance analysis.
3. A range of tools and methods are available to demonstrate applicability of the approach.
4. Some simple steps could help significantly with visual assessment (e.g. beach level height gage or 'Plimsoll' line placed on a seawall) facilitating early warning of beach levels.
5. Methods are available to assess beach lowering and predict scour hole depth. A method for combining these two estimates of future bed level has been proposed.
6. Monitoring of short time scale (within tide) variability of scour holes or beach levels at the toe is possible to check the predictions at a particular site.

Acknowledgements

The funding for the work described in this paper was provided by the Environment Agency R&D programme. Dr James Sutherland of HR Wallingford and Dr Noel Beech (Independent) provided useful comments on a draft of this paper.

References

CIRIA. (1986). Seawalls: survey of performance and design practice. Tech Note 125, ISBN 086017 266X, ISSN 0305 – 1718.

Defra (2007). Understanding and predicting beach morphological change associated with the erosion of cohesive shore platforms. R&D Technical Report FD1926/TR prepared by Royal Haskoning, British Geological Survey, University of Sussex and Newcastle University, November 2007.

HR Wallingford (2008a). Understanding the lowering of beaches in front of coastal defence structures, Stage 2 Technical Note 3. Defra/EA R&D Project Record FD1927/PR3. Internet:http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD1927_7463_PR.pdf (page accessed 27/02/2009).

HR Wallingford (2008b). Understanding the lowering of beaches in front of coastal defence structures, Stage 2 Technical Note 9. Defra/EA R&D Project Record FD1927/PR9. Internet:http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD1927_7469_PR.pdf (page accessed 27/02/2009).

HR Wallingford (2008c). Understanding the lowering of beaches in front of coastal defence structures, Stage 2 Technical Note 5. Defra/EA R&D Project Record FD1927/PR5. Internet:http://sciencesearch.defra.gov.uk/Document.aspx?Document=FD1927_7465_PR.pdf (page accessed 27/02/2009).

Kraus, N.C. and McDougal, W.G. (1996). The effects of seawalls on the beach: Part 1 - An updated literature review. *Journal of Coastal Research*, vol 12, no. 3 – pp 691-701.

Larson, M., Capobianco, M., Jansen, H., Różyński, G., Southgate, H.N., Stive, M., Wijnberg, K.M. and Hulscher, S. (2003). Analysis and modelling of field data on coastal morphological evolution over yearly and decadal time scales. Part 1: Background and linear techniques. *Journal of Coastal Research*, 19(4) 760 – 775.

Markle, D.G. (1986). *Stability of Toe Berm Armor Stone and Toe Buttressing Stone on Rubble-mound breakwaters and jetties; physical model invesiation*, Technical Report REMR-CO-12, U,S, Army Engineer Waterways Experiment station, Vicksburgh, MS.

McDougal, W.G., Kraus N.C. and Ajiwibowo, H. (1996). The effects of seawalls on the beach: Part II, numerical modelling of SUPERTANK seawall tests. *Journal of Coastal Research,* vol 12, no. 3, pp 702-713.

Patterson, P., Glennerster, M. and Millar, G. (2004). Corton Coast Protection. In: *Proceedings of the 39th Defra Flood and Coastal Management Conference*, July 2004. Paper 06b-2.

Powell, K.A. and Lowe, J. P. (1994). The scouring of sediments at the toe of seawalls. In: *Proceedings of the Hornafjordur International Coastal Symposium*, Iceland - June 20-24. Edited by Gisli Viggosson - pp 749 to 755.
Sumer, B.M. and Fredsøe, J. (2002). *The Mechanics of Scour in the Marine Environment*. World Scientific Publishing. ISBN 981-02-4930-6. Advanced Series on Ocean Engineering, Volume 17.

Sutherland, J., Brampton, A. and Whitehouse, R. 2006. Toe scour at seawalls: monitoring, prediction and mitigation. Paper 3b in *Proceedings 41st Defra Flood & Coastal Management Conference,* The University of York., July 2006.

Sutherland, J., Brampton, A.H., Obrai, C., Dunn, S., and Whitehouse, R.J.W. (2008). Understanding the Lowering of Beaches in front of Coastal Defence Structures, Stage 2. R&D Technical report FD1927/TR, Defra, London. Internet http://sciencesearch.defra.gov.uk/fjp (page accessed: 27/02/2009)

Van Rijn, L.C. (1998). *Principles of coastal morphology*. Aqua Publications. ISBN 90-800356-3-7.

Van Rijn, L.C., Walstra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S. and Sierra, J.P. (2003). The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based Profile models. *Coastal Engineering* 47: 295 – 327.

Whitehouse, R.J.S. (1998). *Scour at marine structures. A manual for practical applications*. Thomas Telford. ISBN 0 7277 2655 2.

Fluid thinking...smart solutions

HR Wallingford provides world-leading analysis, advice and support in engineering and environmental hydraulics, and in the management of water and the water environment. Created as the Hydraulics Research Station of the UK Government in 1947, the Company became a private entity in 1982, and has since operated as a independent, non profit distributing firm committed to building knowledge and solving problems, expertly and appropriately.

Today, HR Wallingford has a 50 year track record of achievement in applied research and consultancy, and a unique mix of know-how, assets and facilities, including state of the art physical modelling laboratories, a full range of computational modelling tools, and above all, expert staff with world-renowned skills and experience.

The Company has a pedigree of excellence and a tradition of innovation, which it sustains by re-investing profits from operations into programmes of strategic research and development designed to keep it – and its clients and partners – at the leading edge.

Headquartered in the UK, HR Wallingford reaches clients and partners globally through a network of offices, agents and alliances around the world.

HR Wallingford
Working with water

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk