

Toe scour at seawalls: monitoring, prediction and mitigation

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Abstract

This paper summarises the main results from the Defra/EA R&D project Understanding the Lowering of Beaches in front of Coastal Defence Structures, Stage 2 (FD1927). Evidence has been presented showing beach lowering and recovery happening over a range of timescales. In particular, beach levels have been shown to drop and recover close to their original levels within a tidal cycle. This behaviour cannot be detected from beach profiles alone. A large set of toe scour data from medium- to large-scale laboratory and field experiments has been analysed to produce a new equation for the maximum scour depth.

Beach profiles have been analysed to show that the annual rate of beach lowering in front of a coastal structure varies considerably from one decade to the next. The residual beach levels about the long-term trend were found to have a probability distribution close to Gaussian, providing there were no significant changes in beach management. A list of monitoring methods has been compiled and an indication of the suitable timescale for deployment has been given. The use of remote sensing is becoming more common and is likely to lead to the greatest changes to the type and quantity of data available for monitoring.

A review has also been carried out of the mitigation methods that have been, or could be used to delay or to reduce the severity of problems arising from the lowering of beach levels in front of a seawall or a similar coastal structure. These measures include ones that reduce the hazard without removing the lowering. Mitigation methods include filling in scour holes with rock, encouraging deposition of sediment using, for example, groynes, beach recharge and the underpinning of seawalls so that they remain structurally sound when beach levels drop.

Keywords

scour, seawalls, mitigation

1. Introduction

This paper summarises the results from the Defra/EA R&D project Understanding the Lowering of Beaches in Front of Coastal Defence Structures, Stage 2 (FD1927). The objective of the research was to improve the prediction of short term beach lowering in front of coastal defence structures. Stage 1 (FD1916) produced a scoping study (Sutherland et al., 2003) which identified shortcomings in knowledge about beach lowering and set the research agenda for Stage 2, from which the Stage 2 project map, shown as Figure 1, was derived.

Toe scour is of interest as it is blamed for the failure of many coastal structures (CIRIA, 1986) although toe scour holes are infrequently observed in the field (e.g. Griggs et al, 1994). Moreover, a better understanding of processes may lead to better design of coastal protection schemes and hence reduce costs.

Stage 2 has included detailed research on the short term and small scale phenomena of toe scour, which involves mainly the redistribution of sediment close to the structure toe, rather than long term loss of sediment and more widely distributed lowering of beaches and / or foreshores. Short term is here defined as during a tide or storm, which may last for a few consecutive tides. This work has been placed within a broader context of general beach lowering, which involves medium and long term processes. Medium term is treated as weeks through to seasons, while long term is taken as years through to decades. Predictions at different timescales have been reviewed and in particular a link has been made to the data available from beach monitoring.

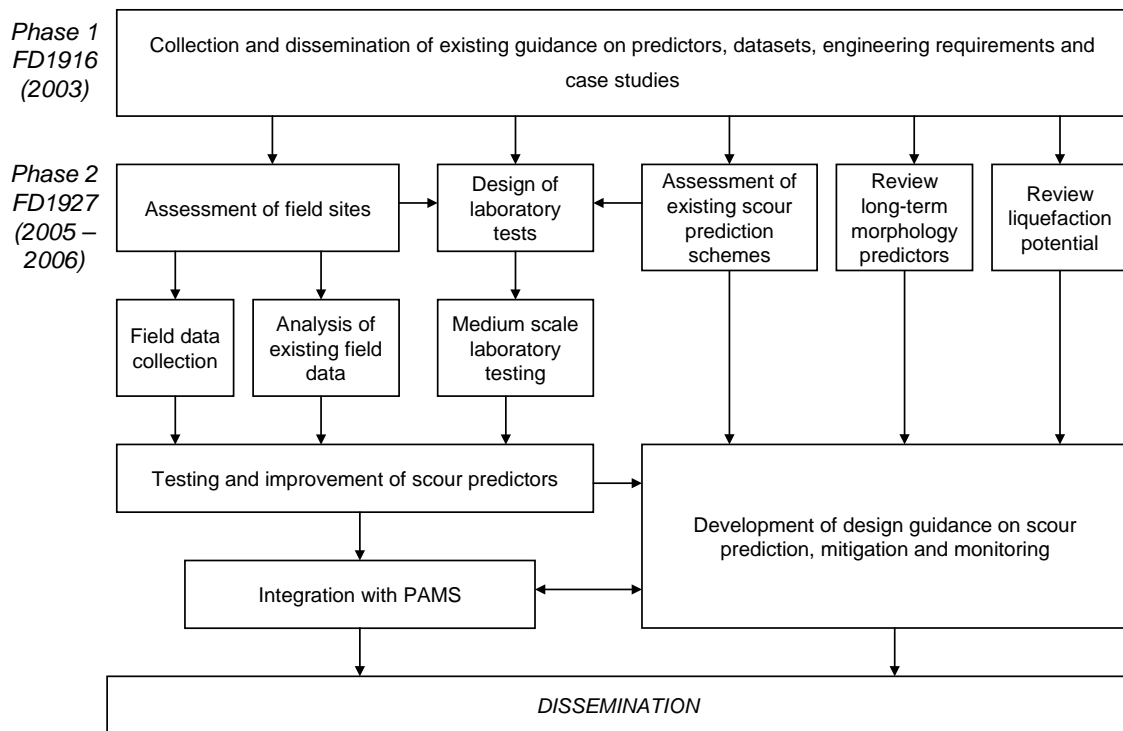


Figure 1: Project map of FD1927

This paper includes:

- Evidence for beach lowering during a tide and over seasons / years collected in the project.
- A summary of the available methods for obtaining beach level data.
- A review of prediction methods for beach levels that concentrates on short-term and medium-term methods and places the work on short-term beach level fluctuations in a broader context. This work also included the derivation of an improved scour predictor, based on pre-existing analysed laboratory and field data, new field data collected at Southbourne (Bournemouth), added-value analysis of old field data from Blackpool and a new set of mid-scale physical model tests performed in a wave flume at HR Wallingford;
- Information on mitigation measures based on a review of existing schemes, guidance and laboratory tests.

In addition the project has looked at the following topics, which will be included in the final report, but not here.

- Description of a method to assess the likelihood of liquefaction of the seabed in front of seawalls;
- Integration with Defra/EA R&D project Establishing a Performance-based Asset Management System (PAMS). The overall aim of PAMS is to manage flood risk as efficiently and effectively as possible by inspecting, maintaining, repairing and if necessary replacing flood defences in order to achieve the required performance and to reduce risk. Central to PAMS are two concepts that will be helped by receiving improved information from FD1927, namely fragility and condition indexing. Fragility has been defined as the probability of failure of a particular defence or system given a load condition. The improved toe scour prediction formula derived in FD1927 will be included in a new fragility curve for the failure of seawalls due to scour. Condition indexing uses visual indicators that relate directly to Performance Features that may be specific to one function of a defence element (or one failure mode). FD1927 is investigating whether the Flood Defence Visual Condition Indexing Methodology can be extended to provide additional information about beach lowering or scour.

The main output from the project (in August 2006) will be a best practice guide on scour prediction and scour mitigation schemes and an improvement to the fragility curves for seawalls.

2. Evidence for beach lowering

2.1. Beach lowering and recovery during a storm

HR Wallingford deployed two of their Tell-Tail scour monitors at Fisherman's Walk at Southbourne (Bournemouth) between 9 May and 7 June 2005 (HR Wallingford, 2005a). The monitors were installed along Channel Coastal Observatory (CCO) profile line 5f00409, which has been surveyed three times per year since July 2002. Water levels were obtained from the Bournemouth Pier tide gauge, provided by the National Tidal and Sea Level Facility <<http://www.pol.ac.uk/nts1f/>>. Wave data was obtained from the Directional WaveRider buoy in 10.4mCD depth in Boscombe Bay, via the CCO website at <<http://www.channelcoast.org/>>.

The Tell-Tail scour monitor system consists of 8 omni-directional motion sensors, mounted on flexible "tails" and connected to a solid state data recorder. Under normal conditions, the sensors remain buried and do not move. When a scour hole begins to develop, the sensors are progressively exposed and each begins to oscillate in the flow. Each oscillation is logged. Use of an eight level array of sensors provides a more accurate measurement of the depth of scour and also indicates when the scour hole fills in again.

Figure 2 shows that as the wave height and water level rose during the morning of the 24th, the beach level dropped by at least 0.60m. The bottom monitor became exposed, so nobody knows exactly how far the beach level dropped below this level. However, as water levels fell during the afternoon, the beach recovered to its previous low-tide level. The beach level fell again as water levels rose during the afternoon of the 24th, even though wave heights were lower. The bottom scour monitor again became exposed and again the beach recovered fully by low tide. There was only a small change in bed level during the next high tide as water levels were lower and wave heights were smaller.

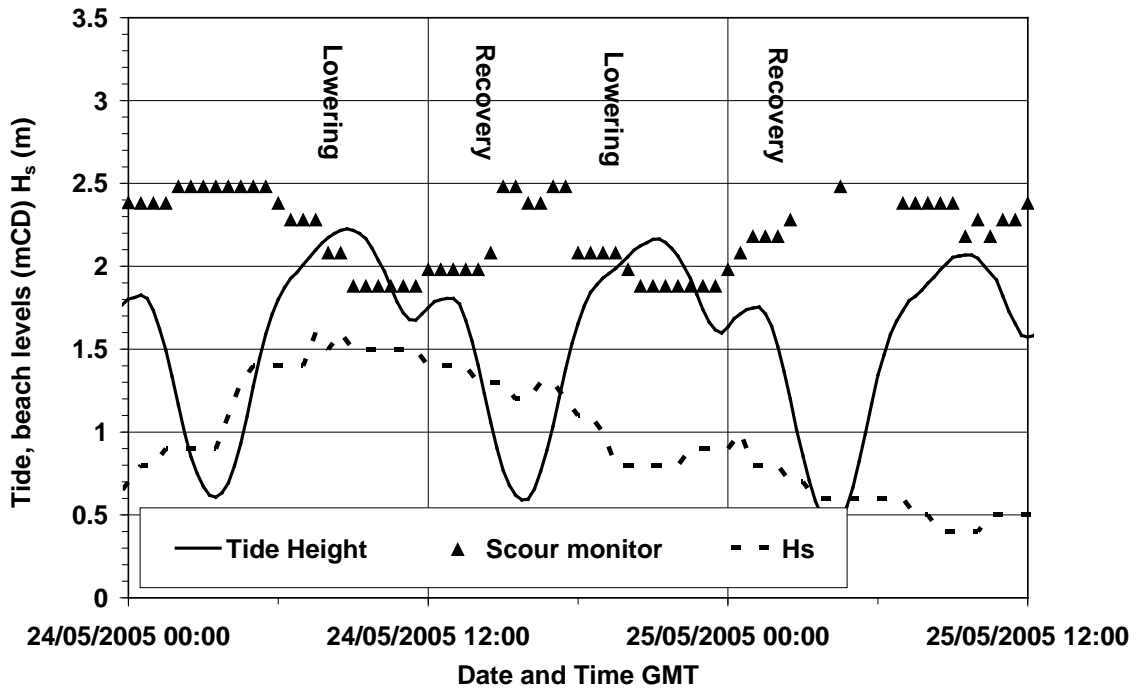


Figure 2: Beach lowering and recovery during a tide measured at Southbourne

The results from Southbourne and extensive analysis of scour monitor data collected at Blackpool between 1995 and 1998 (HR Wallingford, 2005b) has shown that beach levels frequently drop and recover to, or close to, their original level within a single tide, providing the water levels and wave heights are high enough. This beach lowering and recovery *could not have been detected* from beach profiles conducted at low tide, even if the profiles had been collected at successive low tides before and after the tide in question, as the beach levels recovered partially or completely during the falling tide.

2.1.1. Beach levels in front of a seawall on a monthly to decadal scale

Cross-shore beach profiles were collected approximately monthly at 18 locations in Lincolnshire from Mablethorpe to Skegness between 1959 and 1991 (HR Wallingford, 1991). Typically about 310 profiles were measured at each location during this period and most of the profiles started from a seawall. Each beach profile has been interpolated using HR Wallingford's Beach Data Analysis System (BDAS) to produce the beach level at the same chainage in front of the seawall. The time series of levels at 10m chainage at Mablethorpe Convalescent Home (NRA profile 12 at 551278mE, 384400mN) is shown in Figure 3. The straight line is the best-fit straight line through the points and is used to define the mean beach level in any year and the trend in beach level. The profile was falling at an average rate of 23mm per year during this period.

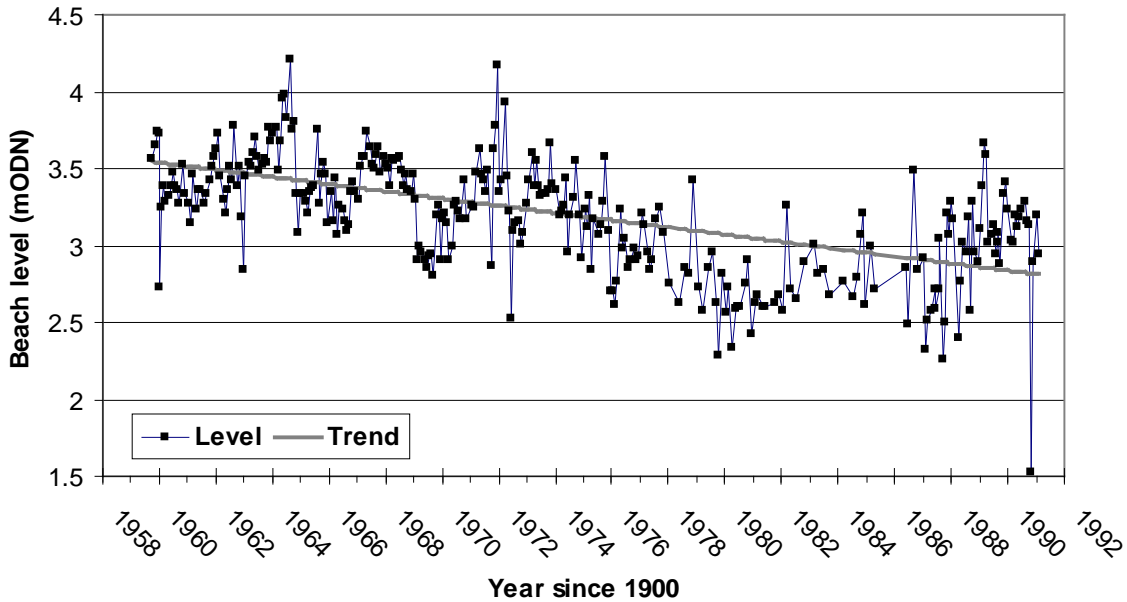


Figure 3: Time series of beach levels in front of a seawall at Mablethorpe in Lincolnshire

Figure 3 shows that there is a significant amount of variability about the best fit straight line, which is, nevertheless, a reasonable representation of the trend in beach levels over a scale of several years. The variation about the best-fit straight line was investigated for certain profiles by first subtracting the best fit line to give a residual level. Figure 4 shows that the residual beach levels have a distribution that is close to a Gaussian distribution with the same standard deviation as the residual levels.

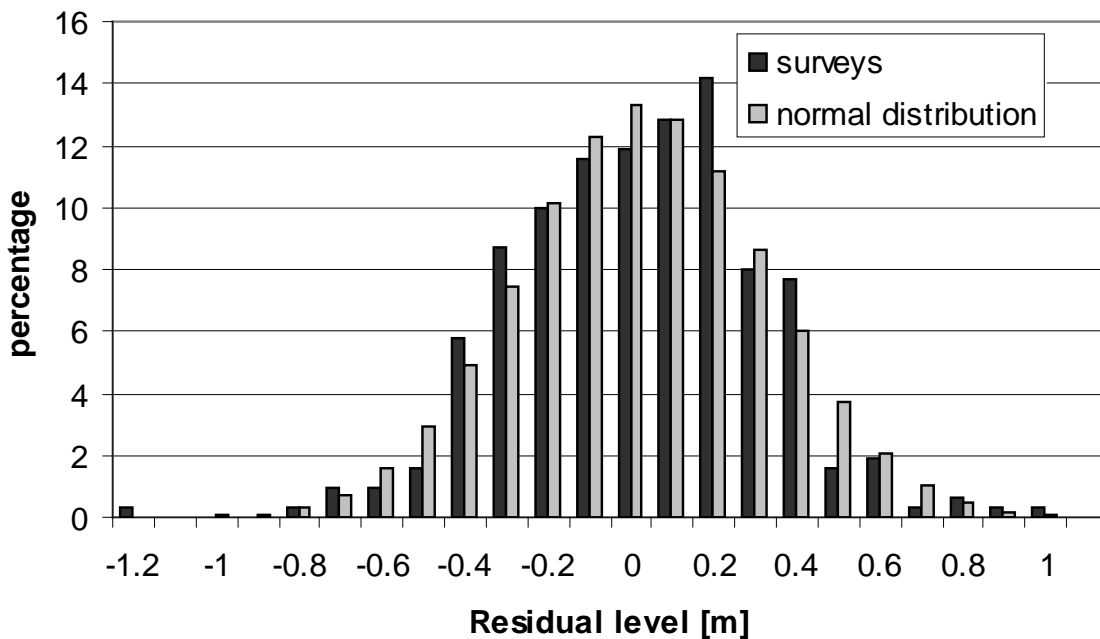


Figure 4: Distribution of residual beach levels in front of a seawall at Mablethorpe in Lincolnshire

Figure 5 shows the mean beach level and the root-mean-square (rms) residual, or standard error, for each month. The results are the average from ten stations, smoothed by a three-month running filter. There are slight, but by no means universal, seasonal trends. Figures 2 to 5 illustrate that there is a need to understand beach level changes at a number of timescales, from a single tide, through storms, seasons, years and decades.

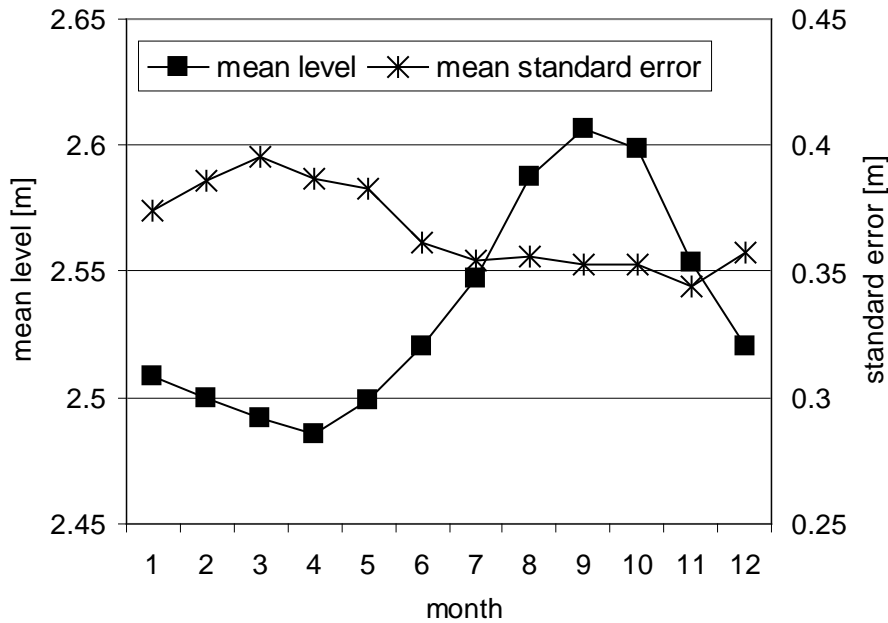


Figure 5: Three-month average mean beach levels and rms residual levels through a year

3. Monitoring

All beach management relies to a greater or lesser extent on data. There are an increasing number of beach monitoring methods available and regional coastal monitoring programmes, such as the Channel Coastal Observatory typically utilise a variety of them. Monitoring techniques are summarised in HR Wallingford (2006a) for a range of spatial scales and Table 1 shows a selection of the methods used in the UK to measure beach levels. The column ‘Used’ indicates (Yes / No) if the method has been used for measuring beach levels in front of a seawall. The column ‘Duration’ indicates the time scale that the techniques are typically used over: Short, Medium or Long. ‘Remote/Manual’ indicates whether measurements can be made remotely or need someone present (Manual).

A few of the available monitoring techniques listed in Table 1, denoted by ‘Used’ = ‘No’, have not yet been used for monitoring beach levels at the toe of coastal structures, as far as the authors are aware. The innovative use of remote sensing by, for example, using a sonar altimeter to monitor bed levels each tide for a prolonged period of time, could be used to build up a picture of beach level distributions at relatively low ongoing labour cost.

Table 1: Methods of measuring beach levels. Used = Y if method used at toe of seawall

Type	Method	Used	Duration	Remote/Manual
Point Measurements during a tide	Tell-tail scour monitor	Y	S/M	Remote
	Photo-electric erosion pin	N	S	Remote
	Sedimeter	N	S	Remote
	Electrical conductivity meter	N	S	Remote
	Sonar altimeter	N	S	Remote
	Autonomous Sand Ripple Profiler	N	S	Remote
Point measurements between tides	Sonar altimeter	N	S/M	Remote
	Photography of datum	N	M/L	Remote
	Measurement of datum marks	N	S/M/L	Manual
	Plug holes with e.g. stacked disks	Y	S	Manual
	graduated rods	N	S	Manual
	Sand tracers	N	S	Manual
Beach profiles between tides	Total station	Y	S/M/L	Manual
	DGPS	Y	S/M/L	Manual
Beach area between tides	DGPS & quad bike	Y	S/M/L	Manual
	Laser scanner	Y	S/M/L	Manual
	ARGUS	Y	S/M/L	Remote
	X-band radar	N	S/M/L	Remote
	Orthorectified Aerial photos	Y	M/L	Remote
	LIDAR (high/low, fast/slow)	Y	M/L	Remote
	Hydrographic LIDAR	Y	M/L	Remote

3.1. Prediction of beach lowering

Different tools are needed to predict the response of the coastline at different scales (HR Wallingford, 2006a). These tools come with different levels of reliability, accuracy, skill and required expertise. These tools may be allocated to one of four basic types:

1. Statistical models;
2. Process-based numerical modelling;
3. Geomorphological analysis; and
4. Parametric equilibrium models.

3.2. Long-term prediction

Defra's revised Shoreline Management Plan (SMP) Procedural Guidance (Defra 2003, Appendix D) describes and analyses the advantages and disadvantages of tools intended to apply to relatively long timescales (10 to 100 years). Burgess (2006) introduces the results for Defra/EA R&D project FD2324 "Risk assessment of coastal erosion" which has developed generic methodologies that can be applied at 'High', 'Intermediate' and 'Detailed' levels. This project has concentrated on the techniques that can be used for medium- and short-term determination of beach levels in front of seawalls.

3.3. Medium-term prediction by extrapolation of monitoring

The most commonly available form of monitoring data is beach profiles. These are typically recorded two to four times a year and in many places, such as the EA Anglian Region and the Channel Coast, there are now regional data collection programmes for such data. Beach profiles can be used for different purposes and these affect when and how often the profiles should be measured. If the aim is to establish a long-term trend then the profiles should be measured at a time of year when the rms residual level is at its lowest, to give the best signal-to-noise ratio. If, on the other hand, the aim is to establish the highest and lowest levels that the beach can attain the measurements should be made when the rms residual level is at its highest, and average levels are at their lowest.

Figure 5 indicates that the lowest average rms residual levels occurred from September to November while the largest values occur from February to April. Conversely, the highest average beach levels occurred from August to October, while the lowest occurred from February to May. These conclusions are not true at all profiles, but broadly support the idea of profiling in autumn for long-term trends and spring to detect the lowest levels.

Figure 5 also shows that the average beach levels throughout the year exhibit a slight seasonal trend, which was not reproduced at all locations. The addition of a seasonal trend to the annual trend would reduce the rms residual level about the combined trend, but this may need to be established for each location.

The Lincolnshire dataset is rare in having more than 30 years of data. It is still more common to have consistent datasets that are less than or about half this duration. In order to look at the effect of the length of sampling period, the best-fit linear trend was calculated for three different 10-year periods using the data from Mablethorpe convalescent home (Figure 3) and the gradient of that line gave the rate of beach lowering. The rate for 1960-1970 was 15mm/year, for 1970-1980 it was 63mm/year and for 1980-1990 it was -47mm/year (i.e. beach levels increasing). The rates of beach lowering varied considerably between decades and none were particularly close to the average of 23mm/year from 1959-1991. These results suggest that historical rates of lowering should only be extrapolated a limited distance into the future, with the duration of the extrapolation into the future being possibly nearer half the length of the historical record, rather than twice its length.

3.4. Short- to medium-term prediction by modelling

Process-based coastal profile models have often been used to model the response of beaches to storms. Their use over seasonal timeframes requires additional calibration (based on bathymetric data) which may be site-specific (van Rijn et al., 2003). Profile models can be extended to include the influence of waves reflected from seawall (HR Wallingford, 2006a) and thereby to predict scour. These models can be

calibrated and / or verified using the results of laboratory experiments or field measurements and could be coupled to wave forecasting systems to provide some advanced notice of potential scour hazards.

3.5. Short term monitoring

The remote sensing of bed levels at each low tide could be used to build up beach level distributions. If the locations of such measurements were linked to wave buoy and / or water level measurements made by regional data collection programmes (as with CCO in FD1927) the link between beach levels and hydrodynamics could be investigated to improve short to medium term statistical predictors of beach levels, or be used for numerical model validation.

Short-term monitoring during a tide can only be used at present to inform the development of a scour predictor. If a critical level for erosion can be identified a scour detector could in theory be installed at, or just above, that level and connected to a warning system. However, by the time the warning was activated it would be too late to do anything other than evacuate or close that segment of seawall (if it was not already too late for that) so it would be better to develop a predictive warning system.

3.6. Short term scour predictor

During Phase 1 of the research (Sutherland et al., 2003) some shortcomings were identified in the presently available scour predictors for seawalls. A relatively large database of scour events was compiled to help assess existing scour predictors and to develop an improved predictor. This database was developed by:

1. Collating a large database of laboratory data on toe scour, selecting only datasets at medium to large scale which generated suspended sediment transport & which used irregular waves;
2. Measuring toe scour at Southbourne;
3. Analysing existing measurements of toe scour at Blackpool;
4. Performing medium-scale laboratory tests of toe scour in a wave flume at HR Wallingford.

The wave flume test programme (HR Wallingford, 2006b) showed that the depth of scour depends on the type of wave breaking at the seawall. Sea states where waves plunge directly onto the wall generate jets of water that may penetrate to the seabed and cause a local scour hole immediately adjacent to the seawall. This is illustrated in Figure 6 that shows beach profiles after 3,000 waves from 4 tests with the same wave height, $H_s = 0.2\text{m}$, period, $T_p = 3.24\text{s}$ and initial beach slope, 1:30, but different water depth at the toe. The test with 0m toe depth produced accretion, the test with 0.1m toe depth was in the inner surf zone and produced some scour, the test with 0.2m toe depth had waves plunging directly onto the wall causing the maximum scour at the wall and the test with 0.4m toe depth produced little breaking except for clapotis, which resulted in little turbulence reaching the wall and a lower scour depth. Note that the 0.4m toe depth profile also had its greatest scour depth away from the wall, in a pattern dominated by sediment transport in convection cells, rather than breaking.

Figure 7 shows all the laboratory and field test data for toe scour depth, S_t , from the database, where H_s is the incident significant wave height, h_t is the water depth at the structure toe and L_m is the linear theory deep water wavelength calculated for the mean wave period.

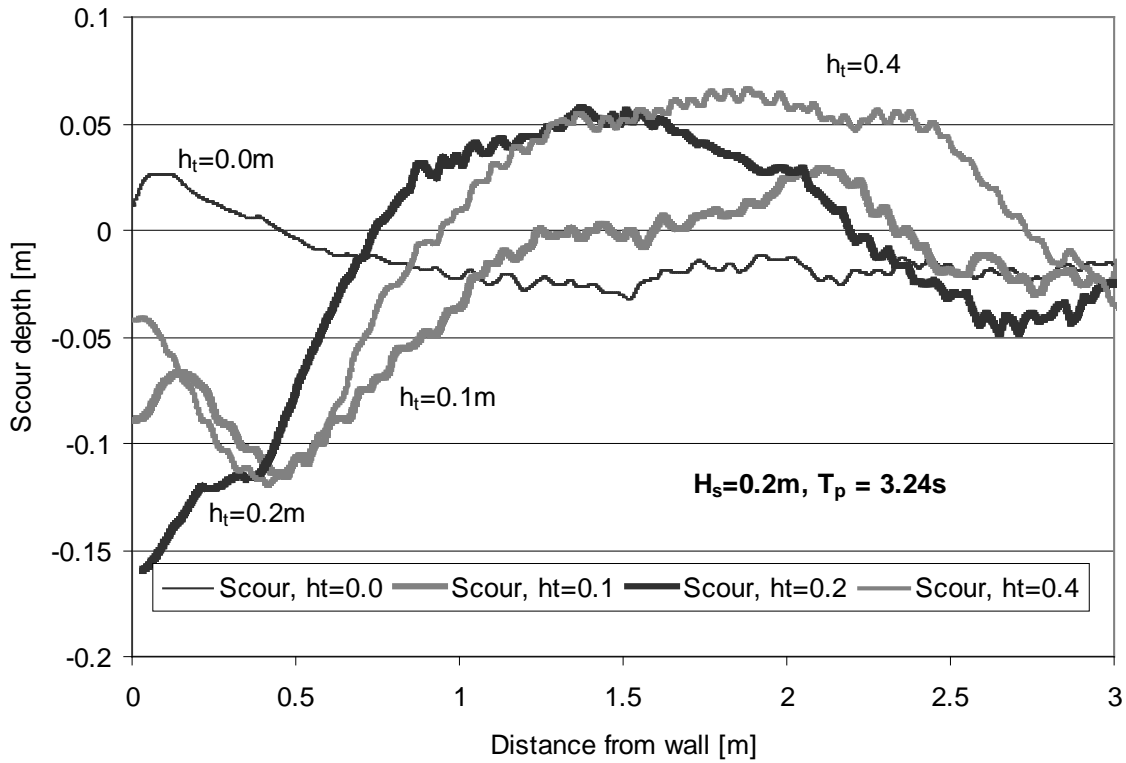


Figure 6: Beach profiles after 3,000 waves for different toe depths but same offshore waves and beach

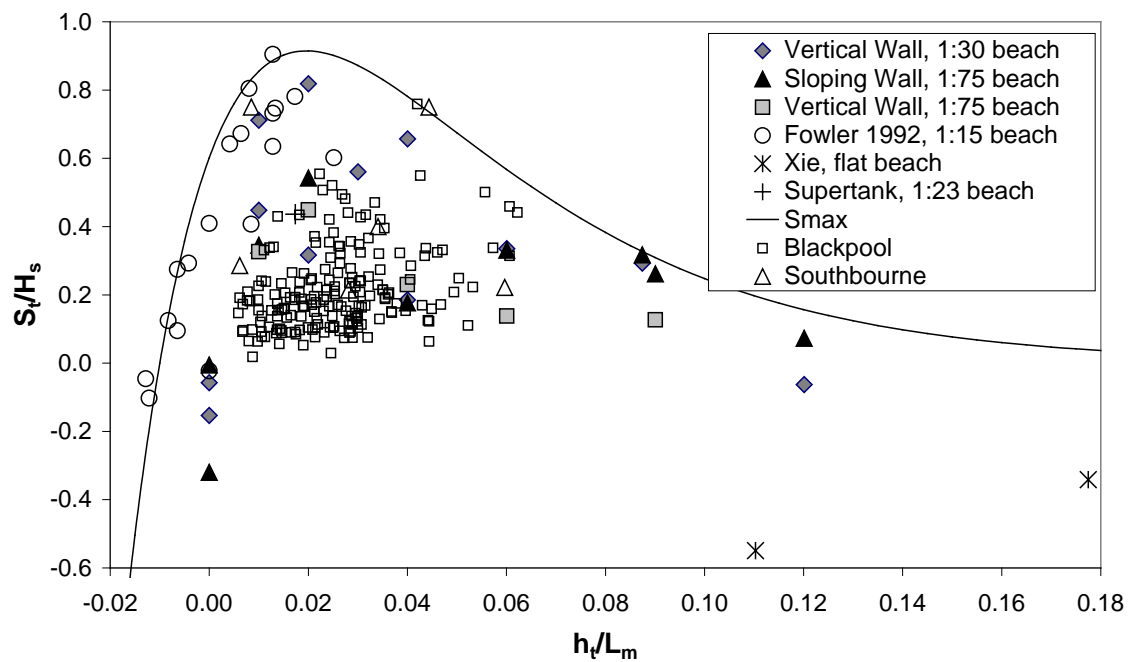


Figure 7: Summary of laboratory and field data on scour at toe of seawalls

Work on the development of an improved scour predictor had not been completed at the time of writing (the project does not finish until 14 August 2006) but Equation 1 is considered a reasonable predictor of the maximum scour depth likely to be encountered for a given water depth at the structure toe, h_t , and offshore linear theory mean wavelength, $L_m = gT_m^2/(2\pi)$, with T_m the mean wave period, so $k_m = 2\pi/L_m$ is the mean period wavenumber.

$$\frac{S_{\max}}{H_s} = 4.5e^{-5(k_m h_t + 0.125)} \left(1 - e^{-3(k_m h_t + 0.125)}\right) \quad (1)$$

The tests were within the following ranges: $-0.013 \leq H_t/L_m \leq 0.018$ and $0 \leq \text{Iribarren number} \leq 0.43$. Equation 1 should only be applied within those ranges and users should note that some parts of those ranges were covered more thoroughly than others. The maximum scour depth appears to decrease as beach slope decreases for the same offshore wave conditions. Moreover, the maximum scour depth seems to occur at larger relative depths for lower beach slopes. However, neither phenomenon has been well validated.

3.7. Combining timescales

The variations in beach levels in front of a seawall have been described for different time scales in the preceding sections. Techniques that can be used include (but are not limited to):

1. Long-term mean beach level from linear best fit to beach profiles;
2. Medium-term distribution of residual beach levels about the mean from beach profiles, using the assumption of a Gaussian distribution of residual levels;
3. Short-term maximum variation in level from Equation 1 or measurements.

Techniques 1 and 3 give a deterministic prediction of beach level while technique 2 gives a probability distribution, not linked to physical processes, so techniques 1, 2 and 3 cannot be combined to give a deterministic prediction of beach level.

In order to combine the probability distributions from different timescales, it is necessary to make assumptions about the joint probability of events at different timescales. Here it is assumed that toe scour events within a tide occur as a result of local processes driven by wave height and period, water level, beach level at toe and beach slope. Wave properties vary with season and so may beach levels and (presumably) beach slopes. Therefore the distribution of toe scour depths is also expected to vary with season.

4. Mitigation

As a part of this study, a review has been carried out of the mitigation methods that have been, or could be used to delay or to reduce the severity of problems arising from the lowering of beach levels in front of a seawall or a similar coastal structure. There are numerous techniques that have been used to tackle the problems caused by beach lowering. They have been considered in the study under the following headings:

- Monitoring and acceptance of a certain degree of scour;
- Ancillary works to minimise/control scour;
- Adjustments to the structure itself; or
- Major beach improvement methods.

When considering such measures, whether they are used individually or in combinations, it is first worth identifying the problems that are being faced. In overview, the difficulties that arise from beach lowering can be divided into two classes, namely increased risks of:

- Structural damage and/ or wave overtopping, leading to flooding, resulting from increased water depths over a substantial area in front of a structure, i.e., alongshore and offshore;
- Undermining, the creation of voids and the collapse of a structure due to lowered beach levels just in front it.

There is no guarantee that the first category of problems will occur first, and increase over time, thus providing a warning about the possibility of the structure being undermined and hence being at risk of collapse. There have been many occasions where the “functional” performance of, for example, a coastal defence structure continued to be adequate until its sudden structural failure.

If continued beach lowering is likely to lead to undermining or damage to the structure before overtopping rates become unacceptable, then any intervention may need to involve the construction of ancillary works, or modification to the structure itself, as discussed later. However, if the result of future beach lowering will first be to decrease the performance of the structure, for example causing an increase in the frequency and rates of wave overtopping, then it may be possible to “accommodate” these effects without altering the structure. Possible options include storm warning systems to anticipate overtopping events and evacuate areas at risk, improving the drainage or storage of overtopped water, strengthening of surfaces behind the structure to withstand greater flows and/ or installing secondary flood defences to limit the extent of flooding. These measures do not directly deal with beach lowering but reduce the hazards that such lowering causes and may delay more expensive works.

Where it is already necessary to improve, or at least maintain beach levels at the toe of a structure, then a variety of methods have been used that do not involve any modifications to the structure itself. These include the infilling of scoured areas with materials that are less readily removed than the natural beach sediments, for example rock (see Figure 8), or encouraging the re-deposition of sediments, for example by installing groynes, sills or even offshore breakwaters. Some of these methods also aim to reduce the risks of damage to, or overtopping of the original structure directly, e.g. by intercepting some of the incident wave energy, as well as by reducing the water depths against its face. Where problems are serious along a substantial frontage, then such methods may be combined with or even replaced by a beach recharge scheme.



Figure 8: Mitigating scour at a seawall toe in Jersey using rock

An alternative to improving beach levels, and one that is still often used, is to accept that the beach levels in front of the structure will continue to fall and to adapt the structure so that it can deal with the changed circumstances. This will often involve “underpinning” of the structure, (see Figure 9), either directly under its existing toe, or by adding an apron, to increase the depth of its foundations.



Figure 9: Underpinning a seawall affected by beach lowering at Lee-on-Solent

Such modifications to the structure can be difficult to undertake, especially where beaches have dropped below mid-tide level making excavation and pouring concrete awkward. In view of this, it is now increasingly common to place a rock “fillet” at the base of a structure, designed to both prevent further scour and dissipate some of the incoming wave energy. For either technique, care is needed to ensure that wave run-up and overtopping is not going to increase, and to anticipate further beach lowering at the toe of the new works. The research has, so far, found little in the way of good guidance on evaluating the latter problem that can be used in the design of the new “toe” of the structure and a selection of didactic case studies are being reviewed and compiled as part of the project to assist coastal managers faced with similar problems.

5. Summary

This paper summarises the main results from the Defra/EA R&D project Understanding the Lowering of Beaches in front of Coastal Defence Structures, Stage 2 (FD1927). Evidence has been presented showing beach lowering and recovery happening over a range of timescales. In particular, beach levels have been shown to drop and recover close to their original levels within a tidal cycle. This form of beach lowering and recovery, referred to as toe scour, could not have been detected from beach profiles, even if they had been measured at the low tides before and after the event. A large set of toe scour data from medium- to large-scale laboratory and field experiments has been analysed to produce a new equation for the maximum scour depth.

A list of monitoring methods has been compiled, some of which have not yet been used in front of seawalls, and an indication of the suitable timescale for deployment has been given. The use of remote sensing is becoming more common and is likely to lead to the greatest changes to the type and quantity of data available for monitoring.

The extensive beach profile dataset from Lincolnshire (1959 – 1991) has been utilised to show that the annual rate of beach lowering in front of a coastal structure varies considerably from one decade to the next, showing the importance of long-term consistent datasets. The residual beach levels about the long-term trend were found to have a probability distribution close to Gaussian, at least for cases where there were no significant changes in beach management practices.

A review has also been carried out of the mitigation methods that have been, or could be used to delay or to reduce the severity of problems arising from the lowering of beach levels in front of a seawall or a similar coastal structure. These measures include ones that reduce the hazard without removing the lowering. Mitigation methods include filling in scour holes with rock, encouraging deposition of sediment using, for example, groynes, beach recharge and the underpinning of seawalls so that they remain structurally sound when beach levels drop.

6. Acknowledgements

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