

The time evolution of scour around offshore structures

The Scour Time Evolution Predictor (STEP) model

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Abstract

This paper describes the development of an engineering model to predict the development of scour evolution through time around an offshore structure under current, wave and combined wave-current flows. The model has been tested against a range of data as well as being run for idealised tests. From the results of these tests issues with respect to scour prediction have been highlighted. In particular, the initial growth rate of scour appears to be too rapid based on the large-scale laboratory tests and tidal field data against which the model has been compared. Application of the model to a field scale study has been carried out and shows that in shallow water depths storm waves dominate the scour process if present. In deeper water depths, currents generally dominate even under storm conditions, although this will be dependent on the wave height and period and the actual water depth. The STEP model can be applied to scour assessment studies where there is a requirement to have an indication of the time-history of scour. Whilst the model clearly has a role in offshore wind turbine studies it is not limited to this sector and can be applied to bridge scour situations or other situations where scouring around monopile structures is an issue. Also if the scour at other types of structures or objects needs to be evaluated then providing the equilibrium scour depth and time-scale functions are available these could be implemented within the framework of the STEP model.

Notation

A	=	parameter
B	=	parameter
C_B	=	coefficient (scour depth multiplier)
C_D	=	drag coefficient
d_{50}	=	median grain diameter of seabed sediment (m)
d_{84}	=	84 th percentile of seabed sediment grading (m)
dt	=	time-step of input data (s)

D_*	= dimensionless grain size
D_p	= external diameter of pile (m)
f	= Coriolis parameter (1/s)
f_w	= wave friction factor
Fr	= Froude number
g	= gravitational acceleration (m/s^2)
h	= total water depth (m)
H_{rms}	= root-mean-square (rms) wave height (m)
H_s	= significant wave height (m)
K_1	= correction factor for pile nose shape
K_2	= correction factor for angle of attack of flow
K_3	= correction factor for bed condition
K_4	= correction factor for size of bed material
KC	= Keulegan-Carpenter number
n	= coefficient
s	= specific gravity of sediment
$S(t)$	= depth of scour with respect to time (m)
S_C	= depth of scour for the steady-current
S_e	= equilibrium scour depth (m)
S_W	= depth of scour for waves (m)
S_{WC}	= depth of scour for combined waves and currents (m)
t	= time (s)
T	= wave period (s)
T_*	= dimensionless time-scale of scour
T_p	= peak wave period (s)
T_s	= time-scale of the scour process (s)
u_c	= current speed at a height of $D_p/2$ above the bed (m/s)
u_{*cr}	= undisturbed (threshold) friction velocity (m/s)
u_{0m}	= near-bed wave orbital velocity (m/s)
U_a	= semi-major axis of tidal current ellipse (m/s)
U_b	= semi-minor axis of tidal current ellipse (m/s)
U_c	= depth-averaged current (m/s)

- U_{cr} = threshold depth-averaged current speed (m/s)
 U_{cw} = wave-current velocity ratio
 z_0 = bed roughness length (m)
 δ = boundary layer thickness (m)
 θ = Shields parameter
 θ_{cr} = critical Shields parameter
 ν = kinematic (molecular) viscosity of water (m²/s)
 ρ = density of water (kg/m³)
 ρ_s = density of sediment (kg/m³)
 σ = angular frequency of tidal motion (1/s)
 ϕ = angle of repose (deg.)
 τ_c = current-induced bed shear stress (N/m²)
 τ_{cr} = critical bed shear stress (N/m²)
 τ_w = wave-induced bed shear stress (N/m²)
 ϕ = angle of repose of sediment (deg.)

1. Introduction

Scour development under waves and time-varying currents is also a time-varying process. Whether a scour hole will continue to develop, remain at some equilibrium or fill in is a function of the hydrodynamic processes existing at any given time and the sediment characteristics at the given location of interest. Therefore, scour development is analogous to the growth and decay of seabed ripples. In the shallow waters around the world's coastlines the flows are tidal, whether semi-diurnal, mixed or diurnal in nature. Under tidal flows the current reverses direction with the given tidal state; consequently the scour development will take place in two directions. In addition, the current magnitude will vary over a given spring neap tidal cycle.

Relatively little work has been undertaken to investigate scour due to tidal flow in comparison to studies undertaken for unidirectional flow. The work of Ecarnameia and May¹ is one of very few studies that have investigated scouring under tidal conditions. However, recently Jensen² presented recommendations for the prediction of local scour for piles under tidal conditions. Previously, the local scour depth was estimated using the same equations as for unidirectional river flow, although it was considered that scour development is typically reduced due to sediment eroded during the first phase of the tide being deposited on the reversing part of the tidal cycle. Jensen and his co-workers recommended the use of Breusers *et al.*³ formula with a modified factor of 1.25 rather than the standard 1.5, with a standard deviation of 0.2 (it should be noted that the sample size was statistically small - 30 samples). They also stated that the equilibrium scour depth under strong tidal flow conditions was the same as that under steady flows. In addition to the astronomical variation of the tide, other factors that may affect local scour in tidal areas are meteorological effects such as storm surges, and their associated currents, and the relative magnitudes of the fluvial and tidal flows. Under steady flow conditions the scour process will take some time to develop a scour hole and the development of the depth of scour with time, $S(t)$, can be defined by the following formula (Whitehouse⁴):

$$S(t) = S_e \left[1 - \exp\left(-\frac{t}{T_s}\right)^n \right] \quad [1]$$

Where T_s is the time-scale of the scour process, S_e is the equilibrium scour depth and n is a power normally taken to be 1 (e.g. Sumer *et al.*⁵).

Whilst it is not always necessary to know the variation of scour through time, there can be occasions where knowledge of the likely variation in depth of scour is important, for example, predictions of scour development may be required to inform the evaluation of the duration of time after pile driving for a fully developed scour hole to form for installation of scour protection.

This paper describes the development of an engineering model to predict the time evolution of scour around a monopile structure in the marine environment. The model is capable of looking at cylindrical, square and rectangular structures.

2. Previous Studies

2.1. Time-scale of scour

The time-scale of the scour process can be defined in various ways. The scour depth develops to equilibrium conditions through a transitional period, which is generally asymptotic in form. In the case of live-bed scour the equilibrium scour depth is achieved more rapidly than for the clear-water case. A review of the time-scale of scour development is presented by Gosselin and Sheppard⁶.

Clear-water scour is defined as occurring when the seabed material upstream of the scouring process remains at rest, whilst live-bed scour conditions exist when there is general sediment transport taking place across the seabed.

One of the earliest studies carried out to investigate the temporal variation of scour was reported by Shen *et al.*⁷. They performed 21 experiments with a single diameter cylinder and a single sediment grain size, but with varying water depths and flow speeds covering both clear-water and live bed conditions. The tests were limited to the use of a single sediment size and cylinder diameter. To try and cover some of these deficiencies Shen *et al.*⁸ carried out additional experiments, 37 in total, for a range of sediment sizes (median grain diameter, $d_{50} = 0.24 \text{ mm} - 0.46 \text{ mm}$) with both whole and half cylinders under live bed conditions. They concluded that the time required to reach 75% of the equilibrium scour depth given similar conditions is greater for larger diameter sediment, whilst this time reduced for larger values of the square of the depth-averaged velocity. They found no dependence of time-scale on cylinder diameter, however, the range of cylinder diameters tested was limited.

Carstens⁹ looked at the rate at which scour occurs in laboratory flume tests. He made several assumptions in his study including that the velocity distribution in the vicinity of the obstruction is a function of the geometry of the obstruction and the scour hole. For a cylinder he assumed the scour hole took the form of an inverted truncated cone.

Hjorth¹⁰ developed a stochastic model to describe local scour based on the method originally proposed by Einstein¹¹. The model assumes that the shear stress at the base of the scour hole is a function of the instantaneous depth of the hole and is derived based on conservation of vorticity.

The method proposed by Johnson and McCuen¹² was undertaken to analyse the scour around bridge piers related to time-dependent hydrological flows. The scour depth time history equation requires the fitting of constants, which were determined based on laboratory data. However, the equations on which this method is based are very sensitive to time-step size and the form of the equation taken leads to a non-smooth transition to the equilibrium scour depth.

The method applied in the present study is that presented by Sumer *et al.*⁵, which attempted to describe the scour depth time history for both steady currents and periodic flows.

For steady currents the dimensionless time-scale is given by:

$$T_* = \frac{\delta \theta^{-2.2}}{2000 D_p} \quad [2]$$

Where δ is the boundary layer thickness (assumed to be the flow depth for tidal flow), θ is the Shields parameter and D_p is the pile diameter.

As stated above, it is assumed for present purposes that the tidal boundary layer thickness occupies the majority of the water column and hence the boundary layer thickness is equivalent to the water depth, which is a reasonable assumption for many sites around the coastline of the British Isles. This is based on work undertaken by Soulsby (summarised in Soulsby¹³) who demonstrated that, for large areas of the shelf seas around the British Isles, the boundary layer thickness, δ , exceeds the water depth. The boundary layer thickness can be evaluated using Eqn. [3]:

$$\delta = 0.0038 \left(\frac{U_a \sigma - U_b f}{\sigma^2 - f^2} \right) \quad [3]$$

Where σ is the angular frequency of the tidal motion, f is the Coriolis parameter and U_a and U_b are the semi-major and semi-minor axes of tidal ellipse, respectively. For a rectilinear flow, near to the coastline, U_b becomes zero.

For the following parameters:

- $\sigma \approx 1.40 \times 10^{-4}$ 1/s
- $f \approx 1.10 \times 10^{-4}$ 1/s

and a range of values of U_a typical of tidal velocities (m/s) around the British Isles (0.5, 0.75, 1.00) the boundary layer thickness (m) equates to (35, 53, 71) exceeding the water depth for all coastal sites.

Therefore, the assumption that the boundary layer thickness is equivalent to the water depth is reasonable in this instance.

When the model is applied to other locations it is necessary to assess whether the water depth can be taken to represent the boundary layer thickness as given in Eqn. [2] as in situations where the boundary layer is thinner than the water depth, the use of the water depth would lead to an over-prediction of the scour depth for a given value of θ .

For waves:

$$T_* = 10^{-6} \left(\frac{KC}{\theta} \right)^3 \quad [4]$$

Where KC is the Keulegan-Carpenter number.

We have adopted Equations [2] and [4] which were originally intended to be valid for non-cohesive sediments and live bed scour conditions. The live bed scour condition covered Shields parameters typically in the range from threshold of sediment motion up to 0.3, and KC numbers in the range 7 to 34 (Sumer *et al.*⁵). In the present model no upper or lower limit is set on the Shields parameter or KC number in the model application and hence the equations have been applied in the clear water scour regime and for cases with Shields parameters greater than 0.3.

To put these normalized expressions for time-scale back into a real time frame Sumer and Fredsøe use the following expression:

$$T_* = \frac{(g(s-1)d_{50}^3)^{1/2}}{D_p^2} T_s \quad [5]$$

Where g is the gravitational acceleration, s is the specific gravity and d_{50} is the median diameter of the bed sediment. This approach is used in DNV¹⁴.

2.2. Time-scale scour models

Fredsøe *et al.*¹⁵ presented a non-dimensional formula for the time-scale development of scour below a marine pipeline. The model was validated against experimental data collected at laboratory scale for both currents and waves. Within the paper Fredsøe *et al.* demonstrate the effect of a change in the wave climate on the scour depth, however, the studies are limited in that the conditions tested represent static cases rather than dynamic wave climates or time-varying currents.

Whitehouse⁴ presented a methodology for predicting the scour development in non-steady flows based on the assumption that a quasi-steady flow exists if the time-step is small enough relative to the period of the non-steady fluctuation. There is also a requirement to know how much scour has already occurred. The method requires careful application since if the equilibrium scour depth value goes to zero, division by zero would occur.

Harris *et al.*¹⁶ looked at scour depths at the met. mast deployed on Scarweather Sands as part of the proposed offshore windfarm (United Utilities Green Energy Ltd) and also made a time-series prediction of scour through several tidal cycles. They applied a variety of empirical scour prediction methods including the slender pile formulation for currents of Sumer *et al.*¹⁷. The time-series prediction was verified against data collected from a multi-beam survey. The met. mast foundation consisted of a 2.2 m pile located on the 6 m contour (CD Port Talbot). The met. mast was installed at Scarweather in May 2003.

A multi-beam sonar survey was completed shortly after installation and covered an area 300 m by 300 m, approximately, centred on the mast. The survey was undertaken on the flood tide from around low water up to high water, two days after lowest neap tide. The tidal range on the day of survey (25/6/2003) was about 4.8 m at Port Talbot.

The following observations were made:

- Scour effects were limited to the immediate area around the mast
- The seabed responded to changes in flow over a half-cycle of tide

At low water the scour hole was elongated in a north-westerly direction, with the steepest scour hole slope about 29° and the shallower “downstream” slope about 14°. At high water the bed all around was rougher

(bedforms) and scour was more symmetrical. From the survey data plotted it was shown that there were no bedforms in the immediate vicinity of the met. mast in the scour hole.

However, whilst the model appeared to give a reasonable prediction of the scour depth at around the time of the field measurements, the model failed to take account of the development of the scour hole relative to scour depth at that point in time. In addition, the proposed model neglected the effects of waves.

Whitehouse¹⁸ highlighted the need to develop time-series methods for scour development and, in particular, investigating the probability of exceedence of scour to occur at a structure. Such approaches require a range of field measurements against which such models can be validated and calibrated.

More recently Nielsen and Hansen¹⁹ presented an engineering model for time-varying wave and current-induced scour around offshore wind turbines. In addition, to predicting the variation of scour depth through time they presented a model for the variation in scour hole width based on the angle of friction for the sediment and assumed angles for the sides of the scour hole as well as the downstream slope.

It is not certain as to whether Nielsen and Hansen in their model formulation take account of the relative scour depth at a particular time relative to the predicted equilibrium scour depth for that same moment and adjust the time-scale accordingly. In addition, the example that they show for a combined wave-current case at Horns Rev, Denmark applies an assumed current profile. The approach adopted in their paper appears similar in formulation to the methods applied in previous studies and in the extended model presented in this paper.

3. The STEP Model

The formulation of the **Scour Time Evolution Predictor (STEP)** model is based on research carried out by HR Wallingford (Whitehouse^{4,18}), used as the basis of approach for scour prediction within the OPTI-PILE tool by HR Wallingford (for published information see den Boon *et al.*²⁰), and on Eqn. [1].

Previous unpublished studies at HR Wallingford have suggested that the power, n , in Eqn. [1] may take the value of 0.5. However, some analysis undertaken in the present study suggests that a value of 1 provides a better fit to data at prototype scale. It is noted, though, that the growth rate of the scour holes from both prototype scale experiments and laboratory scale experiments is much slower than that obtained by applying Eqn. [1] with $n = 1$. This may well be a response to the method used for the determination of the value of the time-scale, T_s – and any associated errors – compared with the actual time required to achieve the equilibrium scour depth.

3.1. Equilibrium Scour Depth

The time-stepping approach requires the determination of the equilibrium scour depth, which for a steady current without waves present would remain constant, whilst under a time-varying current the equilibrium scour depth would also vary in time. The STEP model was originally coded with three approaches for calculating the equilibrium scour depth, Breusers *et al.*³, Escameia and May¹ and Richardson and Davis²¹. However, the present version only uses the approach of Breusers *et al.* Table 1 and Figure 1 show a comparison of these empirical equations against laboratory measurements.

There is some variability in the results from the various empirical equilibrium scour predictor expressions compared to the values measured in the laboratory. However, overall the various models have a reasonable agreement with the measurements and some of the scatter will be as much a function of experimental

inaccuracies as it is to the nature of the formulae. Therefore, it can be concluded that these empirical relationships are a reasonable starting point for developing a time-varying model for scour depth for both tidal, wave and combined tidal and wave conditions.

It is interesting to note the differences in the present formulation of the STEP model compared to the OPTI-PILE tool for a factor of 1.75 in the Breusers *et al.*³ formulation. This difference is due to the way the combined wave-current flows have been implemented in the two applications. Further work is required in respect to this aspect of the model as both approaches give favourable results for certain hydrodynamic conditions, but neither method works well for all cases.

Breusers *et al.*³ developed an empirical relationship for scour based on various observations including measurements of scouring under tidal flow and which can be expressed as:

$$S_C = 1.5K_1K_2K_3K_4D_p \tanh\left(\frac{h}{D_p}\right) \quad [6]$$

in which:

- D_p = the pile diameter or pier width (m)
- h = total water depth (m)
- K_1 = correction factor for pile nose shape
- K_2 = correction factor for angle of attack of flow
- K_3 = correction factor for bed condition

$$K_3 = 0 \quad \text{If } \frac{U_c}{U_{cr}} < 0.5$$

Where:

$$K_3 = 2\left(\frac{U_c}{U_{cr}}\right) - 1 \quad \text{If } 0.5 \leq \frac{U_c}{U_{cr}} < 1$$

$$K_3 = 1 \quad \text{If } \frac{U_c}{U_{cr}} \geq 1$$

U_c is the depth-averaged current speed and U_{cr} is the threshold depth-averaged current speed. Therefore, K_3 allows for both clear water and live bed scour to be taken into account.

- K_4 = correction factor for size of bed material
- S_C = equilibrium scour depth under steady flow

The OPTI-PILE tool allows for the determination of the equilibrium scour depth for currents alone, waves alone and combined wave current flows (den Boon *et al.*²⁰). The core of the time-stepping model is essentially compatible with the existing methodology applied in the OPTI-PILE spreadsheet tool for scour assessment with the exception of the wave and combined wave and current routines. Details of the model formulation are presented next.

3.2. Formulation

The STEP model inputs, variables and associated equations are listed here:

3.2.1. Input Constants:

- D_p = External diameter of pile (m)
- d_{50} = Median grain diameter of seabed sediment grading (m)
- d_{84} = 84th percentile of seabed sediment grading (m)
- ρ = Density of water (kg/m^3)
- ρ_s = Density of sediment (kg/m^3)
- g = Gravitational acceleration (m/s^2)
- ν = Kinematic (molecular) viscosity of water (m^2/s)
- dt = Time-step of input data (s)

3.2.2. Input Variables:

- U_c = Depth-averaged current (m/s)
- h = Total water depth (m)
- H_s = Significant wave height (m)
- T_p = Peak wave period (s)

3.2.3. Model Derived Constants:

The threshold of motion for the given sediment grain size can be given in terms of the bed shear stress. D_* is a dimensionless grain size given by the equation:

$$D_* = \left[\frac{(s-1)g}{\nu^2} \right]^{1/3} d_{50} \quad [7]$$

The critical Shields parameter for sediment motion is determined by the expression:

$$\theta_{cr} = \frac{0.3}{(1+1.2D_*)} + 0.055[1 - \exp(-0.02D_*)] \quad [8]$$

The above expressions are based on a comparison with measured data (see Soulsby¹³). The critical bed shear stress, τ_{cr} is defined in terms of the Shields parameter:

$$\tau_{cr} = \theta_{cr}(s-1)\rho g d_{50} \quad [9]$$

3.2.4. Model Derived Current Variables

The Froude number, F_r is used as a determination of the nature of the flow, that is, whether it is critical, super-critical or sub-critical and is defined as:

$$F_r = \frac{U_c}{\sqrt{gh}} \quad [10]$$

The Breusers *et al.*³ empirical current scour model, which is used in the present formulation, does not utilise the Froude number in its expression but the Froude number is used by Richardson and Davis²¹.

The threshold depth-averaged current speed, U_{cr} is taken from Soulsby¹³ and is valid for any non-cohesive sediment and water conditions for which $D_* > 0.1$ and is the velocity at which general sediment movement begins to take place.

$$U_{cr} = 7 \left(\frac{h}{d_{50}} \right)^{\frac{1}{7}} [g(s-1)d_{50}fn(D_*)]^{0.5} \quad [11]$$

and

$$fn(D_*) = \frac{0.30}{1 + 1.2D_*} + 0.055[1 - \exp(-0.02D_*)] \quad [12]$$

The undisturbed u_{*cr} friction (bed shear stress) velocity is given by the expression:

$$u_{*cr} = \frac{0.4U_c}{[\ln(h/z_0) - 1]} \quad [13]$$

Where z_0 is the bed roughness length.

The current-induced bed shear stress, τ_c , is given by the expression:

$$\tau_c = \rho C_D U_c^2 \quad [14]$$

where C_D , the drag coefficient is expressed as (Soulsby¹³):

$$C_D = A \left(\frac{d_{50}}{h} \right)^m \quad [15]$$

$$A = 0.020408$$

$$m = 0.285714$$

In the STEP model a form of the Breusers *et al.*³ equation is applied with a multiplying coefficient, C_B , (Eqn. [16]) that can be varied (typical range between 1.25 – 1.75). However, a value of 1.3 has generally been applied in field applications in line with DNV guidance¹⁴:

$$S_C = C_B K_1 K_2 K_3 K_4 D_p \tanh \left(\frac{h}{D_p} \right) \quad [16]$$

3.2.5. Model Derived Wave Variables

An early version of the model used linear wave theory to determine the wavelength for a given wave height and wave period and thus, the near-bed wave orbital velocity, u_{0m} . However, to give the code wider range of applicability the following expression is used (also reported separately by Soulsby²⁴):

$$u_{0m} = 0.25H_{rms} \left(\frac{g}{h} \right)^{0.5} [1 + \cos(8.055x)] \quad [17]$$

where

$$x = \left(\frac{h}{gT^2} \right)^{0.5} \quad [18]$$

For the purpose of undertaking scour calculations, the near-bed wave orbital velocity is calculated using H_{rms} , which is assumed to be equivalent to $H_{rms} = H_s / \sqrt{2}$. The period, T , is taken as the peak period T_p . H_{rms} is selected on the basis of work undertaken by Soulsby¹³ and Sumer and Fredsøe²².

The amplitude of the fluid motion relative to the pile diameter is expressed as the Keulegan-Carpenter number, KC , where:

$$KC = \frac{u_{0m}T}{D_p} \quad [19]$$

The wave friction factor, f_w , is given by the empirical expression of Soulsby¹³:

$$f_w = B \left(\frac{d_{50}}{u_{0m}T} \right)^n \quad [20]$$

$$B = 0.993$$

$$n = 0.52$$

The wave-induced bed shear stress, τ_w , is given by:

$$\tau_w = \frac{1}{2} \rho f_w u_{0m}^2 \quad [21]$$

It is expected that the mechanism of scour will also be governed by the Keulegan-Carpenter number (Sumer and Fredsøe²⁵). Based on their experimental results, Sumer *et al.*¹⁷ provide the following expression for depth of scour under waves alone S_w :

$$S_w = S_c [1 - \exp\{-0.03(KC - 6)\}] \quad \text{for } KC \geq 6 \quad [22]$$

where S_c is the depth of scour for the steady-current only.

3.2.6. The Combined Wave- Current Case

Early studies on the scour depth due to combined waves and current have been undertaken by Wang and Herbich²⁶, Herbich *et al.*²⁷ and Eadie and Herbich²⁸. More recently, Sumer and Fredsøe²² undertook a detailed investigation of the influence of a superimposed current on the scour depth in combination with waves. Based on Sumer and Fredsøe's data, Sumer and Fredsøe²⁵ derived an empirical expression for the depth of scour, S_{WC} , for the combined wave and current case in live-bed conditions with data for KC in the range 4 to 26:

$$S_{WC} = S_C [1 - \exp\{-A(KC - B)\}] \quad \text{for } KC \geq B \quad [23]$$

where S_C is the depth of scour for the steady-current only case and the parameters A and B are given by the equations:

$$A = 0.03 + \frac{3}{4} U_{cw}^{2.6} \quad [24]$$

$$B = 6 \exp(-4.7 U_{cw}) \quad [25]$$

and U_{cw} is the velocity ratio given by the equation:

$$U_{cw} = \frac{u_c}{u_c + u_{0m}} \quad [26]$$

where u_c is the current speed at a height of $D_p/2$ above the seabed. This formulation is valid for the live-bed scour regime.

The fact that the above expression for the combined wave-current scour is only valid for live-bed conditions is something that is inconsistent with the expression for current alone scour, Eqn. [16], which is valid for both clear-water and live-bed scour conditions. Within the OPTI-PILE tool a taper from the wave-alone case to the current alone case was applied based upon bed shear stress. However, based on the results from comparison tests between the various methods as shown in Table 1, and as it is clear that neither of these approaches are entirely satisfactory, this is an area that needs further consideration. Given this uncertainty the method of Sumer and Fredsøe^{22,25} has been adopted for the STEP model. This is also consistent with Høgedal and Hald²⁹ and their assessment of scour at Scroby Sands.

4. Results

4.1. Sheppard³⁰

Sheppard³⁰ reported on Phase I of a study with the key objectives to collect measurements for local scour under steady current conditions for larger values of D_p/d_{50} than were previously available and provide accurate scour depth data against time for a range of sediment, flow and structure parameters. Phase I of the study covered the clearwater scour range of velocities and it is these results for which a comparison is shown.

The experiments were carried out at the USGS-BRD Conte Anadromous Fish Research Center, in Turner Falls, Massachusetts. The channel was 6.1 m wide, 6.4 m high and 38.6 m long. The flow in the flume was generated by about a 6.4 m head difference between a reservoir and the floor of the flume. The reservoir was adjacent to the laboratory and was part of a hydroelectric power plant. The flow from the flume is discharged into the Connecticut River. The flow through the main intake pipe was controlled by two sluice gates. To reduce the requirement for sediment a 1.6 m layer of gravel was placed everywhere except within the test section. The sediment was placed to a depth of 1.8 m in the test section and 0.328 m over the gravel.

A platform was placed across the flume to allow placement of the instrumentation, give access to the test structures and provide additional support for the test cylinders. A weir at the downstream end of the flume was used to control the water depths and discharge.

Figure 2 shows a comparison between the model and test 12 (multiplier used was $1.25D_p$). The model provides a good agreement with the equilibrium scour depth, but the model's rate of growth for the scour hole is faster than that measured.

4.2. Sensitivity tests

A series of sensitivity tests were carried out to look at the behaviour of the STEP model under different hydrodynamic conditions. Figure 3 shows the output from one of these tests showing the scour development resulting from an increasing and decreasing current. The current is applied in a step-wise manner which is shown in the figure. The plot also shows both the predicted equilibrium scour depth and time-varying scour depth. It is clear from the figure that the rate of growth of the scour depth is faster than the infill. However, for the scour hole to infill the target equilibrium scour depth at any given time must be less than that currently existing or aiming to be achieved. Therefore, the rate of infill must be less than the rate of scouring to achieve the hole. Whether this is correct in reality is not possible to determine at this time due to a lack of measurements recording this information both at laboratory and prototype scale. No scour occurs when the velocity is below the critical threshold for sediment movement. During this period the scour hole if present remains unchanged.

The back-filling process is currently assumed to take place using the same approach as scouring. However, knowledge of the backfill process is currently limited and further research is required to investigate it.

4.3. Validation Testing

4.3.1. Sheppard and Albada³¹

Having undertaken initial testing against steady current laboratory data and some sensitivity testing, the model's predictive capability can be tested against field data. The time-varying measurements of scour in the marine environment are few and far between, except for the Scarweather data reported earlier. However, as a test case the Scarweather data is lacking good local metocean parameters. Instead a well documented test from the USA (Sheppard and Albada³¹) has been utilised for current only tidal conditions.

Sheppard and Albada³¹ reported on local scour measurements undertaken at a bridge pile in a tidal inlet on the Gulf of Mexico, in northwest Florida. The existing scour hole was filled with sand from the surrounding area and then the scour process was monitored continuously for around 10 days.

The chosen structure was a 0.61 m wide square pile located on the south side of the East Pass Bridge, near Destin, Florida. The water at this location is generally clear and the sediment is cohesionless and relatively uniform in size with a median grain size, d_{50} , of 0.280 mm. The pier is skewed to the flow running from corner to corner as shown in Figure 4. The water depth has been assumed to be constant, at 3.8 m, as the actual tidal variation is not known (but the tidal range is only around 1m – based on NOAA tidal data local to study area). The measured velocity is shown in Figure 5. Also shown in Figure 5 are the measured scour depth and the modelled scour depth. The model was run with a correction factor, K_1 , of 1.2 to adjust for the non-circular pier shape. Although the model over predicts the scour depth through time, the general time variation in scour depth is well reproduced. It should be noted that the measured velocity and scour depth were digitized from paper and are, therefore, subject to a certain level of error. However, the digitized record was a close match to the original and it is not considered that these errors can account for the general over prediction in the model.

Figure 5 also shows the results of a sensitivity test in which the time-scale for equilibrium scour to occur was increased arbitrarily by 300%. The fit against the measured data is surprisingly good and would suggest that the calculation of the time-scale parameter is important in providing good predictions from the model. Given the limited number of measurements of scour development through time at prototype scale it is not possible at this stage to determine whether this magnitude of correction in the time-scale is site specific or can be applied in general. If rates of scour development at a particular site are known then the time-scale parameter could be adjusted to improve the STEP model prediction. However, if the model is being used in a purely predictive mode with no prior knowledge of the scour development history then clearly the time-scale is important in the predicted variation in scour depth with time. Given that the time-scale of scour development is, generally, significantly longer under tidal flows than wave dominated flows, errors in this parameter will be most important in tidally dominated situations.

It is true that we do not know how to predict the modification to the time-scale. The comparison of time-scale for scour to form at a field scale and laboratory scale is partly dependent on the scale of the laboratory physical experiments. In general, the determination of the time-scale is somewhat subjective in physical models and based on an assumed form of response (e.g. Eqn. [1]) and scaling to prototype scale is based on the geometric scale of the laboratory model and the application of sediment transport theory. The issues raised in the paper to do with the shape of the time response curve and the scaling between model and prototype require further investigation in additional research.

4.4. Application

The STEP model has been used to predict the time-evolution of scour at prototype scale using pile diameters typical of that used in offshore windfarm construction, i.e. between 4 m and 6 m. Three different water depths were used representative of a very shallow water depth (≈ 4 m mean sea level, msl), a moderate water depth (≈ 8 m msl) and a deeper location (≈ 20 m msl). The hydrodynamics also varied at each of the three locations and were generated from actual field measurements collected off the UK coast (Table 2). It is assumed that the boundary layer can be represented by the flow depth at the three sites and this can be demonstrated by using relevant input parameters for the location of the Application and Eqn. [3] (Soulsby¹³):

- $\sigma \approx 1.40 \times 10^{-4}$ 1/s
- $f \approx 1.10 \times 10^{-4}$ 1/s
- $U_a \approx 1.3$ m/s
- $U_b \approx -0.2$ m/s

The boundary layer thickness is calculated to be 103 m, approximately, which is greater than the water depths in Table 2. Therefore, it is reasonable to use to the water depth as the scaling parameter.

For comparison the STEP model was run with the combined wave and current hydrodynamics and with the wave hydrodynamics removed at each of these three locations (i.e. current only). Following DNV¹⁴ guidance the multiplier C_B in Eqn. [16] was set to 1.3; this is in line with analysis of monitoring data from built windfarms³². The results from the model simulations are shown in Figures 6 – 8. It was assumed the scour depth was zero at the start of each model run. The key results from the three locations are given below.

4.5. Shallow water depth (Figure 6)

1. The STEP model was run for tidal conditions with and without the wave conditions applied. The results from these two simulations suggest that at this site the scour depth is limited by the shallow water (i.e. much less than $1.3D_p \approx 6.1$ m) and the waves can have a significant influence on the scour evolution.
2. There is no significant difference between the initial rate of growth of scour with and without waves at this location.

4.6. Moderate water depth (Figure 7)

3. There is a clear difference between including the waves and not including them, although without waves there is more of a tidal effect evident in the scour depth evolution than was predicted at the deeper water depth (see below).
4. The peak scour depth achieved under both scenarios is less than the maximum equilibrium scour depth ($1.3D_p \approx 6.1$ m) and this indicates that at this location there is still a slight modification to the scour depth as a result of pile diameter to depth ratio.
5. There is significant difference between the initial rate of growth of scour with and without waves at this location with a much smaller initial rate of scour with waves present.
6. Deep water depth (Figure 8):

7. The influence of the waves leads to a reduction in the depth of scour hole whilst with no waves present there is little variation in the scour depth achieved, which is close to the maximum equilibrium scour depth ($1.3D_p \approx 7.4$ m).
8. The initial growth rate of the scour hole is similar under currents alone as under the combined wave-current case.
9. The variation in scour depth is low and it is likely that equilibrium or near equilibrium scour depths will exist for the majority of time at this location.

These predictions show the detailed nature of time variations in scour depth which might be expected to occur in the marine environment and can be used to determine the statistics of scour depth occurrence (i.e. probability of exceedence). Time-series measurements of scour and co-located metocean parameters are required to demonstrate the predictive capability of the model with wave and current forcing. The reason for the differences between the response of the scour curves in Figures 6, 7 and 8 are to do with the relative role of currents and waves in causing the growth and decay of scour. In deep water (Figure 8) the current dominates the scour process and, therefore, it is only when there is a more persistent period of high wave activity, e.g. in the period between 07/07/2004 and 16/08/2004, that there is a noticeable effect of waves in modifying the current generated scour. This competing wave effect is more noticeable in the moderate water depth (Figure 7). At the shallow water site (Figure 6) storms influence both the wave orbital velocities and the local current speeds, i.e. the current is not just of tidal origin. Therefore, there is a very complex interplay of current and wave generated scour at this location. As illustrated by these results further investigation of the relative role of current and wave scour at sites of different water depth are required. This can be achieved using laboratory scale tests but ultimately needs to be proven using field scale data (Whitehouse *et al.*³²).

5. Scour hole extents

An initial development of a subroutine to model the planshape of the scour hole through time has been undertaken. This initial development has applied a simplified approach, which can be used as a starting point for applying a greater level of sophistication at a later stage. The principal assumption of the approach is that the slope of any scour hole is based on the angle of repose, also termed angle of friction, of the sediment. The upstream slope of the hole is the angle of repose, whilst the downstream slope is about half this angle $\pm 2^\circ$, approximately. The factor of two difference in slope is in line with the observations at Scarweather (Harris *et al.*¹⁶) The side slopes of the scour hole are about 5/6 of the angle of repose. This is similar to the method adopted by Nielsen and Hansen¹⁹. Table 3 gives typical values for the angle of repose based on those provided in Hoffmans and Verheij³³ and a value of 32° has been assumed in the present application.

The general shape of the hole has been assumed to take the form of an asymmetric ellipse as shown in Figure 9. For tidal flows this is a reasonable assumption. The orientation of the scour hole is assumed to be that of the dominant scour process taking place at that point in time. Therefore, there is a requirement to modify the STEP model code to read in the direction of the mean depth-averaged current and the wave angle, if waves are present this will influence the asymmetry of the scour hole. It should be noted that the angle of the current is taken as going to, whilst the wave angle is assumed to be coming from.

There are three different cases to consider, wave dominated scour, current dominated scour and no scour taking place. If only waves exist or only currents exist then the orientation the scour hole takes will be that of the particular hydrodynamic process present. However, for combined wave-current flows this is more complex and for the present version of the model it is assumed that if the combined velocity ratio U_{cw} , Eqn.

[26], is greater than 0.7 then currents dominate the scour process. This is consistent with the time-scale process adopted in the STEP model for combined wave-current flows.

It is likely that the form of the scour hole will change depending on the shape of the particular structure. At this stage of development no differentiation of structure shape has been implemented. It is also uncertain what the response of an existing scour hole would be to changing flow directions. For example, whether there would be a lag in the response to changing flow direction and what the inside form of the scour hole might be given that the flows are reversing under tides; if waves are present then the planshape may be more complex.

Figure 10 shows an example of the STEP model run with the scour hole shape subroutine for the shallow water simulation shown in Figure 6. The results shown in the figure were generated at the 1 hour time-step and plotted at 12 hour intervals to allow the different shapes to be seen more clearly. It is generally considered that the depth of the scour hole scales with the characteristic length scale of the structure (i.e. pile diameter) in both the physical model and prototype (Whitehouse⁴). We have assumed that the scour hole planshape is linked to the scour depth change. The relationship between plan extent and depth of scour in a time-varying (tidal) current and wave field requires further investigation in the laboratory, and ultimately in the field. The depth of scour time-series can be measured using one or more single beam sonar devices attached to the foundation (e.g. similar to Sheppard and Albada³¹), but the scour profile and planshape will need to be measured using more advanced scanning sonar devices.

6. Selection of time-step

We have explored the sensitivity to time-step for the model predictions. The time-step Δt used for the predictions in Figure 5 was 6000 s which was considered appropriate to capture the time-varying nature of the tidal signal. The time-series results in Figures 6, 7 and 8 were generated using the time-step of the input data, namely 1 hour (3600 s). The results are sensitive to the use of time-steps longer than 1 hour. For the moderate water depth site the scour at the end of the simulation will be increased by about 40% if a time-step of 2 hours is used instead of 1 hour. This is because the structure of the combined wave current influence is smoothed out. The sensitivity is less for the deeper water site because the scour is current dominated.

Based on the results from the various simulations carried out and on the dominant hydrodynamic processes operating at a given site the selection of time-step may be important in resolving the time-varying scour process. For example, waves generally operate on time-scales of seconds, therefore, averaging out waves over longer periods of time (600 – 1200 s) may ‘smooth’ the predicted variation in scour depth. Equally, tides operate over time-scales of hours, therefore, the use of longer time-scales (1200 – 3600 s) should be possible without any significant reduction in the ability of the STEP model to accurately predict the time-history of the scour hole depth. Therefore, the optimal time-step for use in the STEP model is likely to be between 60 – 600 s for wave dominated scour, and between 600 – 3600 s for current dominated flows. For combined wave and current flows the optimum time-step is probably around 600 s. However, ultimately the limiting factor may lie with data against which the model is being compared, assuming data is available.

7. Conclusions

The formulation of the **Scour Time Evolution Predictor** (STEP) model has been developed based on research carried out by HR Wallingford (Whitehouse^{4,18}), which was carried through as the basis of an

approach for scour used within the OPTI-PILE tool by HR Wallingford (for published information see den Boon *et al.*²⁰), and on the following equation:

$$S(t) = S_e \left[1 - \exp\left(-\frac{t}{T_s}\right)^n \right]$$

The model has been tested against a range of data as well as being run for idealised tests. The model has highlighted issues with respect to scour prediction:

- The initial growth rate of scour appears to be too rapid based on the large-scale laboratory tests and tidal field data against which the model has been compared.
- The implementation of waves and combined wave-current flows is based on the method given in Sumer and Fredsøe²⁵ which applies to live bed scour conditions. However, we have also taken into account some of the approach used in OPTI-PILE (den Boon *et al.*²⁰) which took account of clear water and live bed scour conditions. Because of the need to make predictions under all combinations of currents and waves the time-scale equations as given in Sumer and Fredsøe²⁵ have been applied outside their intended range. Whilst the results obtained look plausible further investigation is required in the laboratory to extend the range of the existing equations.

As general outcomes from the model development the general comments have been made:

- From the model results waves suppress the scour development, consistent with the equations used within the model. To test these assumptions the model should be tested against field data. Based on limited information it appears the 1.75Dp factor applied in OPTI-PILE may over-estimate the scour depth in the STEP model formulation, although it may represent the uncertainty in the maximum achievable equilibrium scour, and that 1.25Dp is more appropriate in the present application. This is close to the value of 1.3Dp recommended by DNV14 and seen in monitoring data at built foundations (Whitehouse *et al.*³²).
- Application of the model to a field scale study with the DNV factor of 1.3Dp has been carried out and shows that in shallow water depths storm waves dominate the scour process if present. In deeper water depths, currents generally dominate even under storm conditions, although this will be dependent on the wave height and period and the actual water depth.
- The model can be used with hindcast or forecast metocean conditions for piled foundations providing information is available on the foundation diameter, water depth, significant wave height and peak or mean wave period, depth averaged current speed and direction, and sediment grading at the seabed. Alternatively the model can be driven with measured values of these parameters as has been done for the application case in this paper. The modelling completed for the application case indicated that the tidal currents were important but also that non-tidal currents, apparent during storm wave periods, were also important in driving scour development in shallow water.

The STEP model can be applied to scour assessment studies where there is a requirement to have an indication of the time-history of scour. Whilst the model clearly has a role in offshore wind turbine studies it is not limited to this sector and can be applied to bridge scour situations or other situations where scouring around monopile structures is an issue. Also if the scour at other types of structure or objects needs to be evaluated then providing the equilibrium scour depth and time-scale functions are available these could be implemented within the framework of the STEP model.

8. Acknowledgements

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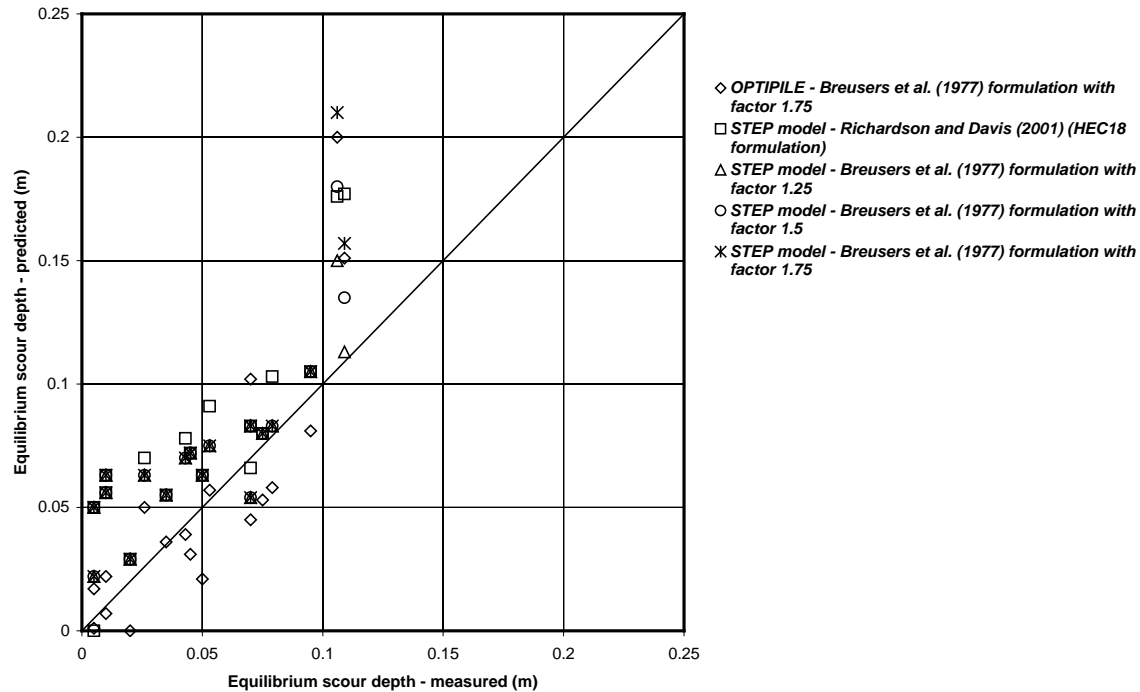


Figure 1: Comparison of empirical equilibrium scour expressions against laboratory data

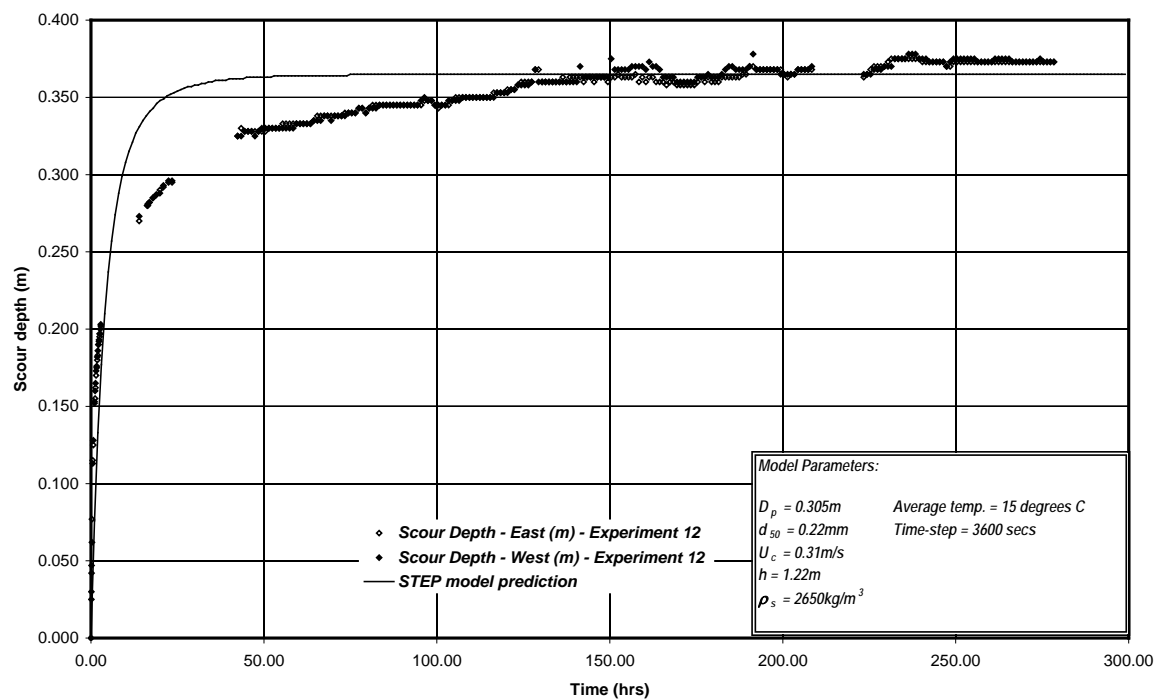


Figure 2: Comparison of scour evolution model against Sheppard³⁰ test 12

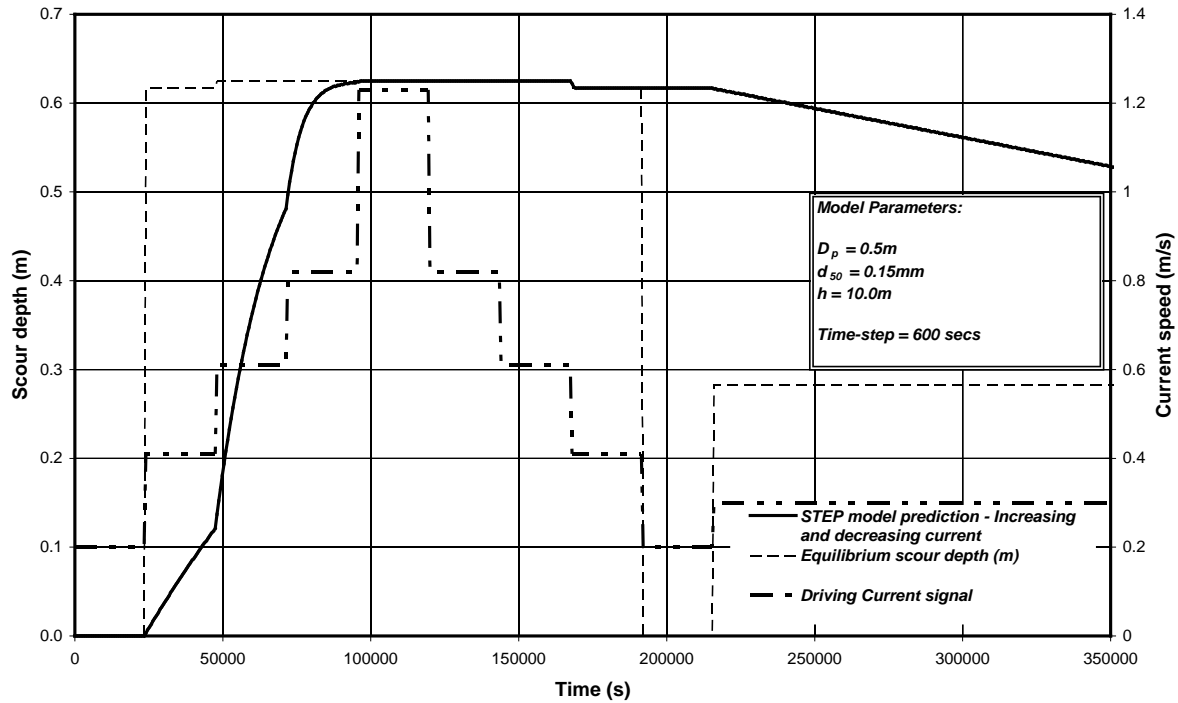


Figure 3: Comparison of scour evolution with a constant water depth and a time varying current (S/D_p multiplier: 1.25)

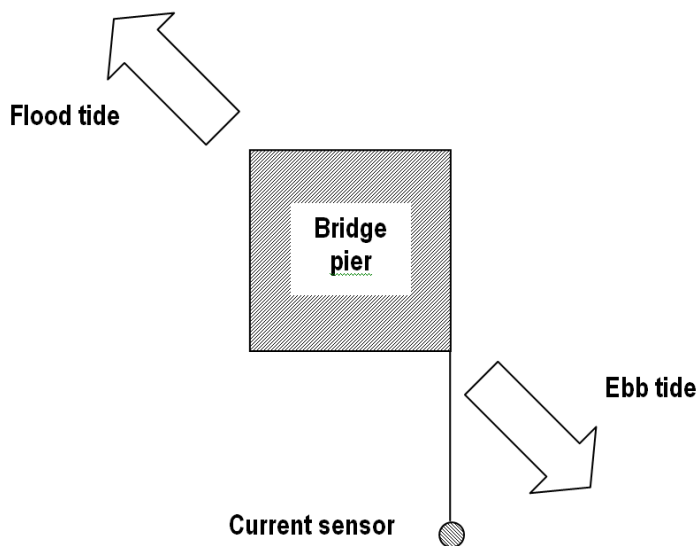


Figure 4: Schematic of bridge pier showing flow orientation. (After Sheppard and Albada³¹)

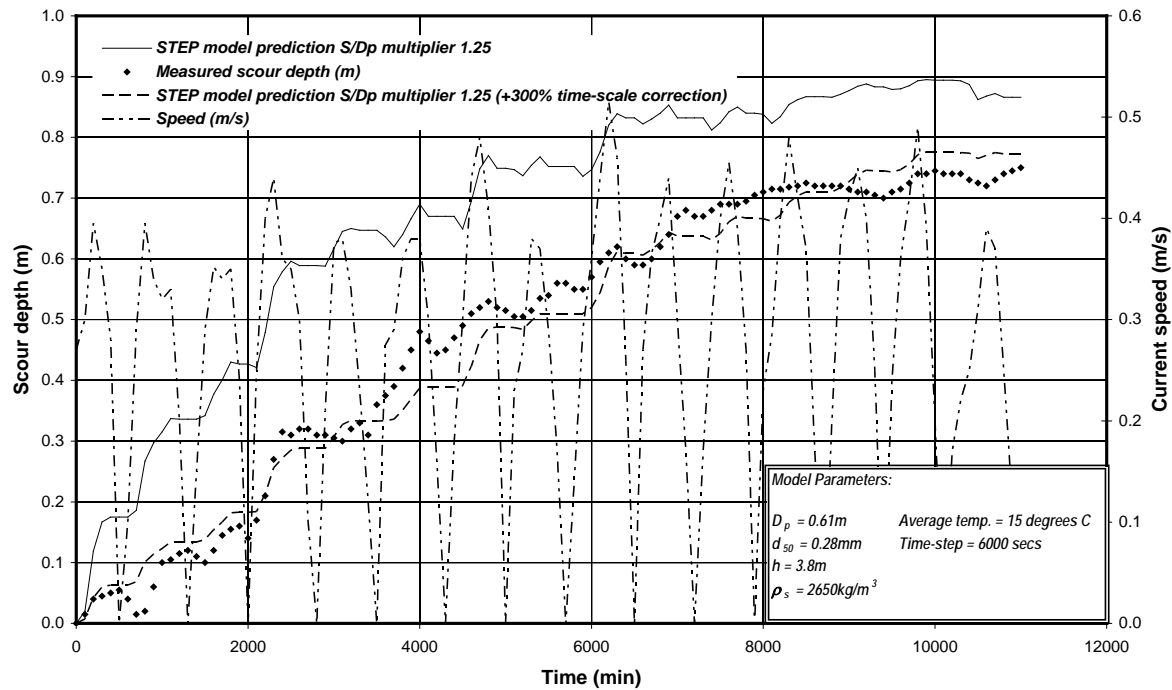


Figure 5: Comparison of scour evolution model with no time-scale correction and +300% correction applied against Sheppard and Albada³¹ field measurements

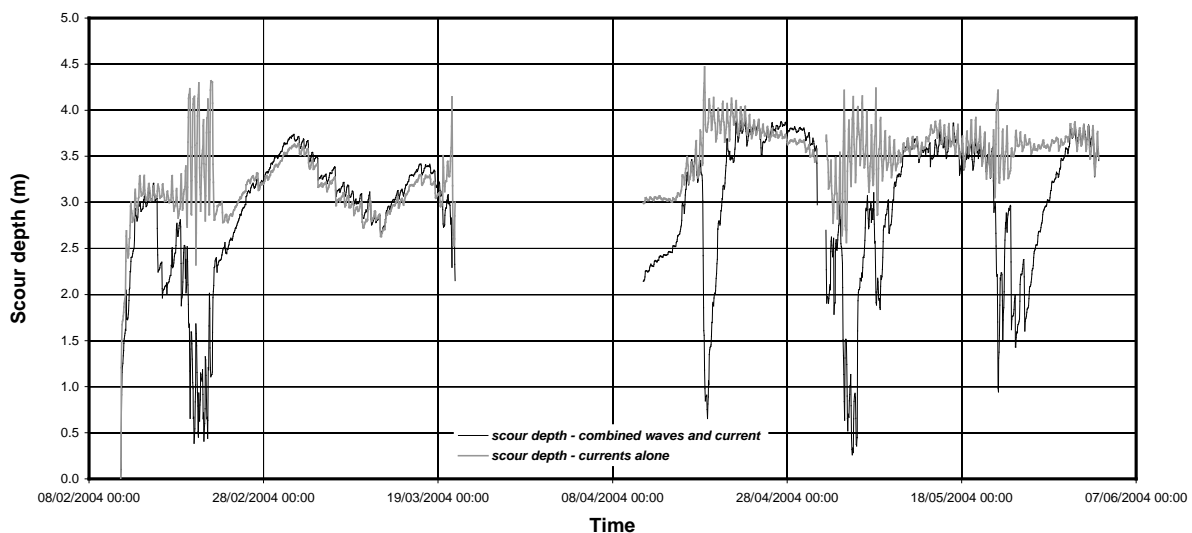


Figure 6: Scour prediction at shallow water site

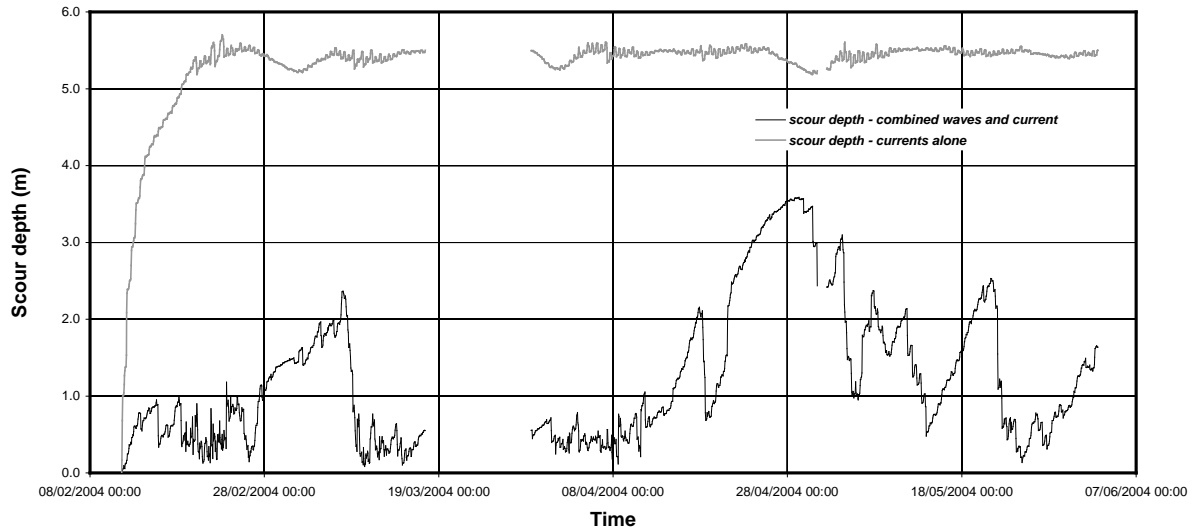


Figure 7: Scour prediction at moderate water depth site

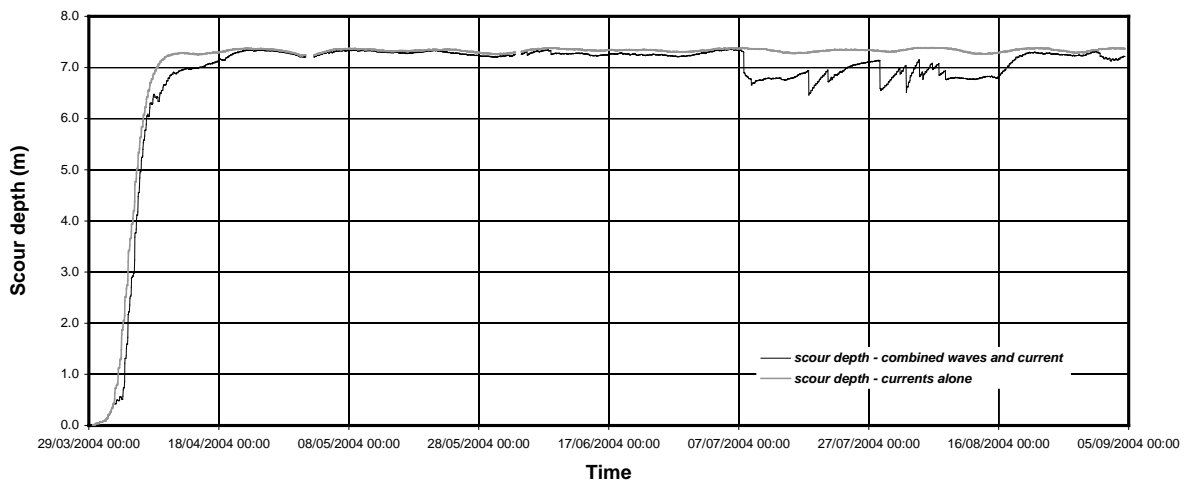


Figure 8: Scour prediction at deeper water site

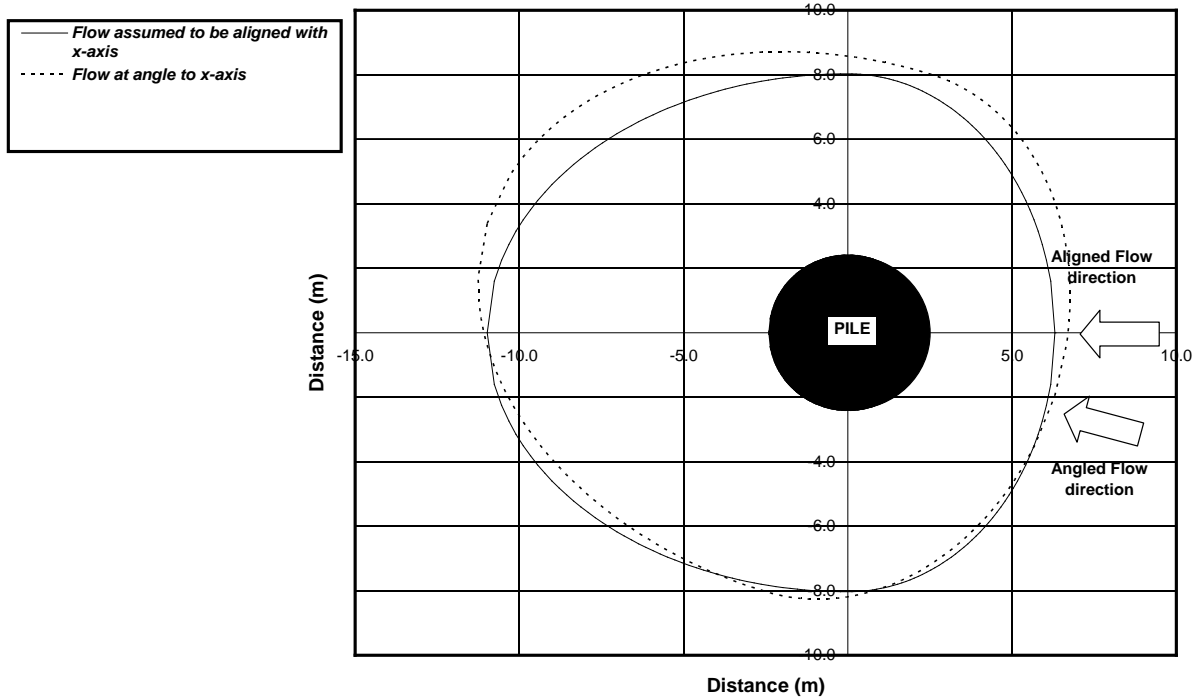


Figure 9: Example of assumed scour hole shape, shown for aligned axis flow and flow at an angle to the x-axis

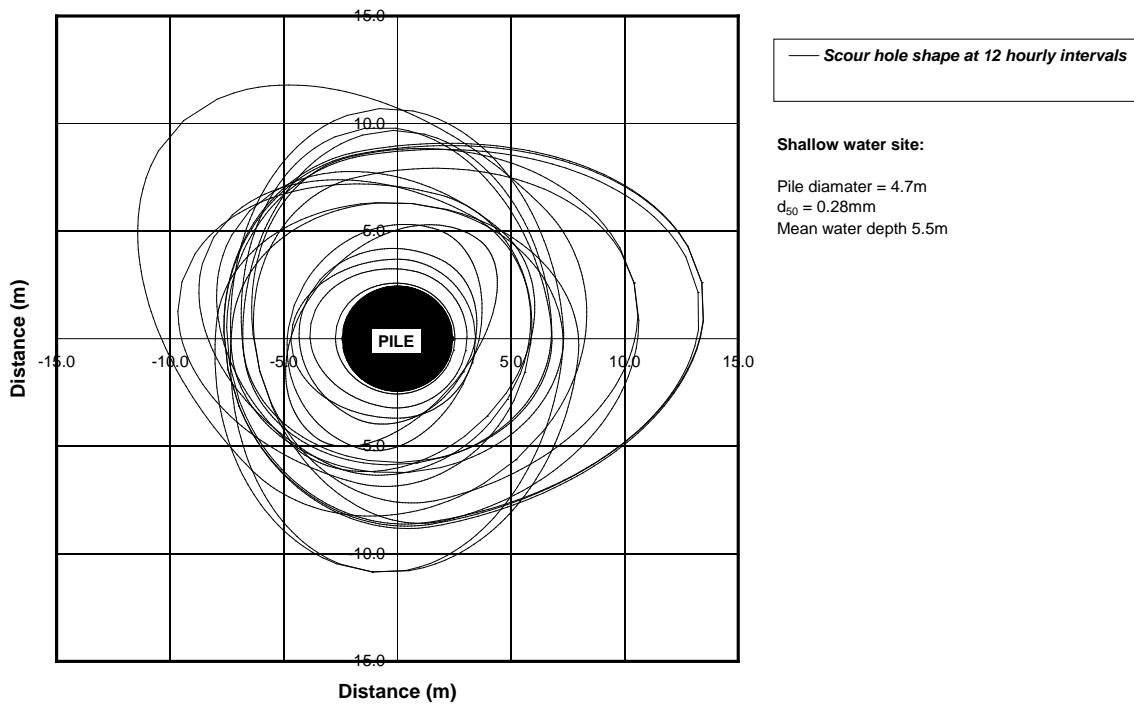


Figure 10: Variation in scour hole shape and size plotted at 12 hourly intervals, for metocean data

Table 1: Comparison of empirical equilibrium scour expressions against laboratory data

Data source	Run No.	Measured Equilibrium Scour Depth (m)	Predicted Equilibrium Scour Depth (m)				
			OPTI-PILE	STEP MODEL			
				1.75	HEC18	1.25	1.5
S & F	1	0.005	0.001	0.050	0.050	0.050	0.050
S & F	2	0.010	0.007	0.056	0.056	0.056	0.056
S & F	3	0.050	0.021	0.063	0.063	0.063	0.063
S & F	4	0.075	0.053	0.080	0.080	0.080	0.080
S & F	5	0.010	0.022	0.063	0.063	0.063	0.063
S & F	6	0.045	0.031	0.072	0.072	0.072	0.072
S & F	7	0.070	0.045	0.083	0.083	0.083	0.083
S & F	8	0.095	0.081	0.105	0.105	0.105	0.105
S & F	13	0.109	0.151	0.177	0.113	0.135	0.157
R & B	1-3	0.020	0.000	0.029	0.029	0.029	0.029
R & B	1-1	0.026	0.050	0.070	0.063	0.063	0.063
R & B	1-2	0.035	0.036	0.055	0.055	0.055	0.055
R & B	1-6	0.070	0.102	0.066	0.054	0.054	0.054
R & B	1-7	0.005	0.017	0.000	0.022	0.022	0.022
R & B	1-9	0.079	0.058	0.103	0.083	0.083	0.083
R & B	1-10	0.043	0.039	0.078	0.070	0.070	0.070
R & B	1-11	0.053	0.057	0.091	0.075	0.075	0.075
R & B	1-4	0.106	0.200	0.176	0.150	0.180	0.210

Where: S&F is Sumer and Fredsøe²², R&B is Rudolph and Bos²³, HEC18 refers to the method of Richardson and Davis²¹ and the various numbers (1.25, 1.5 and 1.75) are the applied multiplier in the Breusers et al.³ formulation (N.B. that 1.5 is the standard multiplier).

Table 2: Typical physical parameters at the various sites (based on metocean data)

	Shallow water site	Moderate depth site	Deep water site
H_s (m)	0.38 – 2.26	0.47 – 2.57	0.33 – 2.49
T_p (s)	2.03 – 9.85	2.98 – 10.67	1.63 – 11.64
h (m mwl)	1.29 – 6.86	5.62 – 10.62	17.91 – 22.75
U_c (m/s)	0.13 – 1.34	0.05 – 1.30	0.06 – 1.32

Table 3: Angle of repose for different soils (from Hoffmans and Verheij³³)

Sediment type	Soil type	Angle of repose ϕ (°)
Coarse sand	Compact	45
	Firm	38
	Loose	32
Medium sand	Compact	40
	Firm	34
	Loose	30
Fine sand	Compact	30-34
	Firm	28-30
	Loose	26-28

