Assessment of the Stability of Bed Material Adjacent to Marine Structures

The effects of breaking waves, turbulence, and vortex-shedding

R R Simons

Report TR 99
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Summary

Assessment of the Stability of Bed Material Adjacent to Marine Structures

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The prediction of seabed scour by waves and currents is a key aspect of marine engineering projects (vertical piles, seawalls and breakwaters). The processes governing scour at these structures are reasonably well understood and the depth and extent of scour can be predicted.

However, in practice there are a number of forcing processes for which the influence on seabed scour is not clearly documented or well understood. This report presents a summary of the current state-of-the-art relating to the influence of these factors, namely:

- breaking waves
- turbulence
- vortex shedding

on the stability of bed material adjacent to marine structures.

Some recommendations are made about (1) assessing the influence of these processes and (2) a simple method for determining the bottom shear stress in areas with enhanced turbulence.

Contents

1. INTRODUCTION

This report is intended to summarise current understanding of certain phenomena that influence scour around marine structures (vertical piles, seawalls and breakwaters), taking particular account of the effects of breaking waves, turbulence, and vortex shedding phenomena.

Detailed descriptions of the various methods for assessing the extent of scour have been presented elsewhere. In particular, Fowler (1993) has given an overview of scour prediction methods under the action of waves and currents for rubble-mound breakwaters, vertical piles, vertical seawalls, and seabed pipelines. Whitehouse (1998) has provided a more comprehensive review and includes a section on multiple piles. And Hoffmans and Verheij (1997) have presented a design manual which extends earlier work by Breusers (1966), and Breusers and Raudkivi (1991) covering wave and current effects on many different coastal structures. These and other authors have considered the effects of waves and currents but do not offer design methods to account for the changed hydrodynamic conditions resulting from enhanced turbulence and vortex shedding, breaking waves, or from a sloping seabed.

More recently, a "state-of-the-art" summary of scour with particular relevance to coastal processes has been published by Sumer and Fredsøe (1999). Much of the content is based on the results of their own recent and ongoing research.

Existing methods rely heavily on empirical solutions to predict the extent of scour and assume that the bed material is effectively uniform. However, focussing on the geotechnical aspects of scour, Annandale (1995) has developed a method that characterises the "erodibility" of a particular bed material to improve the quantitative aspects of scour protection design. There is scope for a similar measure to be presented as contours in areas that are particularly likely to suffer from scour. Erodibility could be redefined as the ratio of peak shear stress (including the effects of potential flow enhancement, and RMS contributions from turbulence, breaking waves and vortices) to a Shields criterion (modified to account for the effects of coherent turbulence structure effects). To develop this approach further, the ideas contained in the papers by Annandale (1995) and Anglin et al.(1996) need to be extended.

2. APPLICABILITY

It is important to take special note of the presence of breaking waves, turbulence and coherent vortex phenomena when designing cylindrical structures (piles, pipelines and outfalls) in marine environments. In such cases, the standard design methods would not necessarily include them and their relevance has to be determined as a preliminary stage in the assessment of scour. The relative importance of these phenomena is discussed below.

In contrast, the assessment of scour around breakwater toes and seawalls implicitly includes the potential contribution from breaking waves. Other mechanisms, such as propeller wash, that can generate turbulence of greater intensity than that intrinsically related to the roughness of the structure, are beyond the scope of the present study. It does not, therefore, seem appropriate to make special reference to such structures in this document.

The division of the processes suggested below is in effect an attempt to separate those actions that are random in time and space (turbulence) from those that are fixed spatially – either relative to the structure (coherent vorticity) or to the hydrodynamic conditions (breaking waves). This characterisation can also be viewed in terms of horizontal vorticity, which provides a significant mechanism for mobilising and suspending bed material, and vertical vorticity, which may induce shear stresses and bed load but does not directly enhance the transport of suspended material.

3. BREAKING WAVES

The influence of breaking waves on the scouring process has not yet been clearly defined. Indeed, the prediction and modelling of fluid velocities under breaking waves remains a research topic in its own right. However, it can be concluded (Barnes et al. 1996, Pedersen et al. 1998) that the influence of spilling breakers and broken waves is constrained to a thin layer near the water surface and can therefore be neglected in the present study.

In contrast, plunging breakers are the source of intense vorticity that can have a significant influence on turbulence levels near the seabed, and their importance for the scouring process can be included in the form of a modified distribution of turbulence in the vertical. But even under such conditions there is no consensus that the effect is to increase the erosive nature of the flow. Cox (1999) quotes Svendsen (1987) as suggesting that most turbulence from breakers is dissipated in the upper flow, and does not therefore play an important role in erosion at the bed. And Deigaard (1991) has reported that the oscillatory logarithmic boundary layer is disrupted by intermittent turbulence from the breakers, thus reducing the main components of bed shear stress.

Bijker (1986), and Bijker and de Bruyn (1988) have looked at scour around a pile in currents combined with breaking waves. Based on laboratory scale tests with cylinder diameters < 90mm, the conclusion is that breaking waves (and long waves) increased the scour depth from the value for current alone. They also note that short waves reduce scour, although this is probably related to Keulegan Carpenter numbers (KC) falling below 6, thus inhibiting vortex formation (Sumer and Fredsøe, 1999).

In a study of beach processes, Svendsen (1987) adopted an eddy viscosity distribution for the large-scale turbulence in the upper flow arising from plunging breakers, and contrasted it to the small-scale turbulence in the thin bottom boundary layer.

Pedersen et al. (1995) commented on the wide range of possible forms of plunging breaker and different ways in which they can be modelled – ranging from deflection of the jet by the surface through to complete penetration. They adopted a 2-d simulation of the vorticity in their discrete vortex model, and followed Nadaoka (1989) in assuming “obliquely descending eddy structures”. Their predictions appeared to match measured sediment concentrations well.

Shiereck and Fonteijn (1996) have considered the scour around a pipeline in the surf zone. They adopted methods proposed by Battjes (1975, 1987) and Battjes and Janssen (1978) to quantify the turbulence in the surf zone and to identify the location of the breakers. Turbulence intensities are deduced by equating the turbulent energy to the dissipation of wave energy in the breaking process. This offers a simpler approach than a k-ε theory and avoids many of the assumptions implicit in such models.

Pedersen et al. (1998) have reported detailed experiments aimed at measuring the vertical scale of the turbulence created by breaking waves. Their results give some indication of the turbulent velocity distribution and length scales through the vertical, but do not offer a direct link to enhancement of shear stress or sediment transport rates.

The modelling of sediment transport under breaking waves involves making an assumption about the vertical distribution of turbulence and/or eddy viscosity. For instance, Duy et al. (1996) have used a time-varying eddy viscosity in their model, although they concluded that their results are not significantly improved in comparison to results using a constant value.

At the present stage, the methodology suggested by Sheireck and Fonteijn (1996) forms a sensible basis for scour assessment under breaking waves – although additional and alternative steps should be incorporated to customise it to current HR practice in identifying, for example, breaker type and breaker location relative to the structure.

4. TURBULENCE

On the assumption that the assessment of scour will at some stage be related to a Shields criterion for sediment mobility, it should not be necessary during the design process to take special account of the turbulence associated with the bottom boundary layer. This is because the original Shields curves, and versions modified by various authors (Grass 1971, Van Rijn 1991, Soulsby and Whitehouse 1998, Keshavarzy and Ball 1999) to account for the effects of waves, combined waves and currents, or coherent turbulent structures, have implicitly included the effects of the turbulence in the normalisation of their data. Hoffmans and Verheij (1997) show a graph of modified Shields curves, indicating qualitatively the probability of sediment mobility. And Van Rijn (1989, 1993) used a time-averaged shear stress when normalising data from tests on sediment motion under waves. A recent paper by Sechet and Le Guennec (1999) provides a further insight into the basic processes of sediment transport by coherent turbulent structures, but is not of immediate use in scour calculations.

Boundary layer turbulence can be enhanced by breaking waves (see above), complex and adjacent structures, the passage of ships, and propeller turbulence. The maximum shear stress is then liable to be significantly higher than predicted using the mean (or oscillatory) flow velocity – although the mean flow field available to transport any sediment mobilised is not changed greatly except in narrow channels – and there is more likelihood of live-bed scour than clear water scour. Sumer and Fredsøe (1999) note that the local scour around a pile is increased if that pile forms part of a larger complex structure which is generating an enhanced turbulence in the flow field. In general, the effects of enhanced turbulence in the vicinity of the structure may be as important as those of increases in the average bed shear stress. They go on to say that basic research is urgently needed to improve the understanding of how turbulence increases local sediment transport, and hence scour.

Apart from the observations above, the direct effects of turbulence on scour do not appear to have been quantified. Looking only at hydrodynamic phenomena, Sarpkaya (p.65) noted that one effect of turbulence is to trip the boundary layer at a lower critical Reynolds number, thus modifying the width of the downstream wake. And Makita and Sassa (1987) used flow visualisation to record a widening of the wake downstream of a pile, with occasional intensification and weakening of the wake vortices. The importance of these changes on the scour pattern awaits a proper quantification of both the streamwise and lateral scales of the wake – and of the velocities therein. It may then be possible to use the statistical methods adopted by Keshavarzy and Ball (1999) to relate these velocities to a probable scour pattern.

The methods used in Escarameia (1998) to account for turbulence appear to be empirical formulae related to specific fluvial conditions. They are not considered relevant in this study.

5. COHERENT VORTICITY

Coherent vortices are shed from cylindrical structures under both unidirectional and oscillatory flow conditions. The characteristics of the shedding process and the near-bed velocities induced depend on Reynolds number and on KC number (relative orbital excursion in oscillatory flow). There will also be an interaction with externally generated turbulence from adjacent structures and breaking waves.

The scour around vertical piles has been studied in depth by many authors, and for most wave-current flow conditions the process is well understood. Sumer et al. (1992) performed an extensive range of laboratory-scale experiments under live-bed scour conditions and quantified the scour around a vertical pile for various wave conditions. No scour was observed for $KC<6$, which is the regime where no vortices are shed from the structure and hence there is no mechanism for transporting any eroded material.

Many of the tests were carried out at relatively low Reynolds number, although comparative tests were also performed to evaluate any Reynolds number effects. No equivalent study of clear water scour has yet been undertaken.

Grass et al. (1987) recommended that, under regular wave loading, velocities within 2D from the centre of the cylindrical pile should be calculated from Potential Flow theory, but with an additional 0.5Um added to account for the velocity enhancement as vortex pairs swing back past the structure. This implies a velocity close to the wall of the structure 2.5 times greater than the free-stream value. However, these conclusions were based on measurements outside the bottom boundary layer. Basing their findings on similar reasoning but using measurements from within the boundary layer, Sumer et al. (1992) predicted a factor of 2 on the shear stresses.

Ali and Karim (1999) have carried out a study of scour around bridge piers in a unidirectional flow, using the FLUENT software package. This can predict the three-dimensional flow field around structures, but cannot simulate the “bursting” phenomenon often associated with sediment entrainment. They develop a simple formula for prediction of the maximum scour depth caused by a current. However, they conclude that the scour observed in their laboratory experiments cannot be explained by bed shear stresses alone, and that turbulence contributes significantly. Graf and Yulistiyanto (1998) have also made measurements of velocity and vorticity fields around a cylinder in a unidirectional flow. They have published many velocity profiles, giving a good perception of the detailed flow structure for a particular flow rate, although the conclusion that a horseshoe vortex forms near the bed is far from an original finding.

Scour within pile groups (or downstream of them) has been considered by a number of authors. The effects of changing the spacing between piles can be characterised within three regimes: (a) widely spaced piles where there is no interaction and any wake effects have been lost before the flow impinges on the adjoining units; (b) a spacing which gives a critical density below which scour requires careful consideration – because turbulent scales within the wake can interact with the scouring process; and (c) closely spaced piles with a high density, where the system behaves as a single large pile. Sumer and Fredsøe (1998) have carried out extensive tests in the laboratory propagating waves into lines and square arrays of piles at different spacing and orientation. The relative spacing was scaled using the KC number (calculated using the pile diameter rather than the group size), but the net downstream effect on the turbulence was not quantified. They found that the direction of wave incidence was an important parameter – so design considerations have to identify the worst case. This work has been extended for steady current conditions by Sumer et al. (2000-in press) who report measurements of global and local scour and of velocities within a large group of piles. Their experiments considered the range of pile diameter to spacing between 0.3 and 4.

Ball et al. (1996) have tested unidirectional flows past square arrays of piles with 3 different spacings. Using both physical and numerical modelling, they identified the spacing at which the large-scale downstream wake becomes intermittent – suggesting a critical value of spacing for that particular flow rate. Zhao and Sheppard (1998) have studied scour around circular and square pile groups in a unidirectional flow. They identified the relative importance of the horseshoe vortex and wake vortices for different angles of attack. Mory et al. (1999) have reported measurements of both global and local scour around two rows of closely spaced piles under the action of normal and obliquely incident waves on a gently sloping beach. Tests were performed at two values of KC corresponding to the strongest modes of vortex shedding (Mode 1 for KC $\approx$ 10, Mode 2 for KC $\approx$ 20: see Sarpkaya and Isaacson, 1985). As might be expected, these conditions were found to produce the greatest volume of exposed pile (the criterion chosen to indicate the effective seriousness of the scour). However, the effect of pile spacing was not explored. And Bayram and Larson (1999) have reported the results of similar scour experiments around a group of piles on a beach.

6. CONCLUSIONS

At the start of this review, the questions to be addressed were:

- Can the MAXIMUM predicted stress move the material?

- By how much do breaking waves enhance the capability to erode the bed?
- Will vortices shed from the structure or from adjoining ones enhance scour?
- Are there external sources of turbulence that influence the scouring process?
- Over what plan area will scour take place?
- To what depth will scour take place?
- How rapidly will material be removed?
- How high should protection go up a sloping structure?

The above review has focussed on the understanding of three important factors, namely, breaking waves, turbulence, and vortex shedding, and has provided a valuable first step in developing a practical methodology for scour assessment. Some of the objectives originally identified have subsequently been deemed beyond the scope of the present study. However, the work has led to the provision of a **simple** method for calculating scour under breaking waves and regions of enhanced turbulent activity. The calculation outlined in **Appendix A** gives such a simplistic procedure for determining the bottom shear stress in areas of enhanced turbulence, although it does not offer any method for determining the spatial extent of increased scour, or the potential scour depth possible under those conditions.

The main comments arising from the review are:

- There is a need to develop the concept of "erodibility" to map areas of seabed that are most liable to scour. This will relate the maximum bed shear stress induced by the mean flow, enhanced turbulence, coherent vorticity, and breaking waves to the critical stress for sediment motion, and incorporate a velocity component to account for the associated transport.
- The vertical distribution of turbulence under plunging breakers can be described in terms of an eddy viscosity or a time-varying eddy viscosity. Ongoing research has been targeted at identifying the scale of the breaker-induced turbulence near the bed.
- Turbulence intensity can also be related to the wave energy lost during breaking.
- There is evidence that spilling breakers do not enhance near-bed turbulence.
- Local scour is enhanced by the turbulence induced by neighbouring structures.
- It is not clear how rapidly the wake expands and weakens downstream of a vertical pile.
- Scour within a pile group is dependent on angle of incidence and pile spacing. The effect of pile spacing implies three regimes, resulting in either global or local scour dominating the process.

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Appendices

Appendix A

Simple approach for calculating the shear stresses downstream of a vertical pile

Appendix A Simple approach for calculating the shear stresses downstream of a vertical pile

Below is a simple approach to calculate shear stresses downstream of a vertical pile.

First, note that the mean bed shear stress induced by a turbulent boundary layer is:

$$\bar{\tau} = \tfrac{1}{2}\,\rho\,\overline{u'w'} = \rho\, u_*^{\,2}$$

assuming fully-developed turbulent conditions. In such a case, the maximum shear stress can be characterised by:

$$\tau_{max} = \tfrac{1}{2}\,\rho\; u'w'$$

although it is not obvious what values to attach to u′ and w′ for a realistic estimate of transport rates. For this calculation, let us assume that they are the basic RMS values for the respective velocity components, and also let us take an unsubstantiated step regarding the correlation between u′ and w′ when calculating the maximum shear stress. Then, for our typical boundary layer, taking:

$$u' = 0.3\,\bar{u}\,; \qquad u' = 2.5\,u_*; \qquad v' = 1.0\,u_*: \qquad w' = 1.0\,u_*$$

where $u_* = \sqrt{\dfrac{\bar{\tau}}{\rho}}$, we can deduce that the maximum shear stress is given by:

$$\tau = \tfrac{1}{2}\,\rho\,(2.5\,u_*)\,(1.0\,u_*) \;=\; 1.25\,\rho\,u_*^{\;2} \;=\; 1.25\,\bar{\tau}$$

If, now, an externally generated vortex is superimposed onto the flow, with a velocity at the perimeter of its core of ū, the “maximum” shear stress is now:

$$\tau_{max} = \tfrac{1}{2}\rho(u'+\bar{u})w' = \tfrac{1}{2}\rho(2.5u_* + \frac{2.5}{0.3}u_*)\,(1.0u_*) = \frac{3.25}{0.6}\rho\, u_*^{\,2} \;=\; 5.4\,\bar{\tau}$$

This implies that the maximum stress has increased by more than a factor of 4 over the undisturbed turbulent value, which exactly matches the stability criterion of Izbash and Khaldre (1970) and Shields (1936) based on the potential flow prediction for amplification.

Having established some credibility for the scale of predicted shear stress using this simple method, it is then possible to extend it to include other sources of coherent or random velocity fluctuation – the latter being added quadratically to the RMS.

Against this approach, a number of obvious limitations exist:

- At the bed, the vortex may not be driven by the outer flow velocity because of the velocity gradient down the pile; however, as vorticity cannot end in a fluid, it is likely that the velocity scale at the bed will be similar to that above;
- The shear stress described by Reynolds stresses are fluid stresses, and may not reflect the stress on the bed material;
- Velocities within the vortex will be decreased as the vortex expands in the diverging wake, so the shear calculated would apply only very close to the pile;

- The estimates used for the relationships between u_* and u', w' and $\bar{u}$ are taken from classical studies of equilibrium turbulent boundary layers. They are approximate only, and are not strictly applicable once the boundary layer has been disrupted by the upstream structure. On the other hand, Hoffmans and Verheij (1997, p.23) use an **average** relative turbulence intensity (averaged over the flow depth) - this does NOT seem appropriate.

An alternative view is to consider the passage of the vortices as an additional random turbulent component (a sinusoidal fluctuation) imposed onto the basic turbulence. On this basis, the extra RMS would be $0.707\,\bar{u}$, and adding the turbulent components in the conventional way the equations would become:

$$\tau = \tfrac{1}{2}\,\rho\,(2.5u_*\sqrt{1+0.707^2/0.3^2}\,)\,(1.0\,u_*) \quad = \quad 3.20\,\rho\,u_*^{\,2} \quad = \quad 3.20\,\bar{\tau}$$

This suggests only a factor of 2.6 enhancement of shear stress over the upstream value.

Symbols

$\bar{\tau}$	bed shear stress, overbar denotes mean value
ρ	fluid density
u', w'	horizontal and vertical instantaneous fluid velocities
$\bar{u}$	mean fluid velocity
u_*	shear velocity
τ_{max}	maximum bed shear stress

Appendix B

Shear stress calculations by University of Liverpool (Dr C P Rose)

Appendix B Shear stress calculations by University of Liverpool (Dr C P Rose)

A message from Richard Whitehouse:

"Richard and Jesper,

here is a further clarification from Chris Rose re. the turbulence approach they are taking in SCARCOST *at Liverpool.*

11/10/99
For the instantaneous shear stress generation I simply use:

*Tau=Taumean +Taurms*Gaussian distributed random number (with limits +1 to -1).*
No weighting or lag effects are included at present, though this work is being looked at in SASME.*

The approach with velocity fluctuations is to use:
*Tau=rho*Cd*(Umean+U')^2. at some reference height.*

* Kozakiewicz, A, Sumer, B M, Fredsøe, J, Deigaard, R and Cheng, N-S. 1998. Effect of externally generated turbulence on wave boundary layer", Progress Report, Tech. Univ. Denmark, Institute of Hydrodynamics and Water Resources (ISVA), No. 77, pp. 1-12.