Application of Sediment Transport Technologies to Offshore Energy Installations

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Abstract

Development and implementation of technologies to harness offshore energy will require large installations and inner cable arrays that are often located significant distances offshore. Deployed technologies typically require systems to be anchored through sediments and into the ocean floor with cables laid beneath the sediments. Critical to the successful deployment of offshore energy generating technologies is an assessment of the impacts from sediment transport on both individual devices and device arrays. Sandia National Laboratories (SNL) has unique expertise specifically relevant to cable installations in the seabed. Because areas with adequate wind or wave resources typically correspond to regions of significant wave, current, and sediment activity, the effects of post-installation sediment erosion and transport processes must be considered. In many cases, combined wave- and current-driven sediment transport will be important.

SNL's efforts in this arena have born recent innovations in measurement and modeling techniques and have significant implications for sediment transport prediction in combined wave/current environments that could be applied to wind- or wave-farm applications and their associated cable arrays. The purpose of this research is to develop and provide a predictive tool, applicable to installations (including buried cable arrays) where a variety of structural, hydrodynamic, and sediment conditions can be assessed.

Keywords: Offshore Energy, sediment transport

1. Introduction

Sediment transport in offshore, wave-dominated environments has been of great interest in relation to dredged materials disposal and contaminated sediments. There are significant prior efforts to understand these processes, many of which are applicable to issues of sediment scour related to offshore wave and wind farms. Because the shear stress at the sediment-water interface during wave events is the primary driver for erosion and transport, it is of great importance to accurately assess stresses in both experimental systems and model simulations. In addition to the shear stress, the erosion potential of sediments as a function of shear must also be determined. There is currently no developed and deployable capability to either predict the shear stress time history or effective shear stress of a combined wave-current flow near the sediment-water interface, much less a formulation to predict subsequent erosion. To address this shortcoming, SNL has recently developed and patented a laboratory and field device called the Sediment Erosion Actuated by Wave Oscillations and Linear Flow (SEAWOLF) Flume in which Particle-Image Velocimetry (PIV) measures turbulent shear stresses for a broad array of flow conditions. Erosion rates are also recorded directly. PIV data for a full wave cycle show a transition from fully developed turbulent flow, to relaminarization, and an abrupt transition back to turbulence. SEAWOLF testing with PIV provides shear-stress time histories and commensurate effects on erosion, both of which are integral for estimating sediment transport in wave-dominated environments.

2. Flow Characterization and Modeling

Flow around foundations of wind power devices, arrays of devices, and their inner-array cable installations is the primary driver in structural stability prediction, specification of hydrodynamic loads, and prediction of local sediment response. Foundation arrangements vary from shallow water installations, where a single large anchor point is used, to transitional and deep water installations, where more complex, multiple anchor points are employed. Hydrodynamic flow characterization is the first step toward understanding the stresses to which these foundations and cables are exposed. Flows are also required to develop accompanying sediment transport models applicable to various wave- and wind-farm installations and issues associated with jet-plow-buried cable arrays. Data needed include flow measurements near the sediment bed and representative erosion rate data as a function of shear stress to estimate scour.

Prior methods of predicting erosion in wave-dominated environments have employed field or laboratory data from linear flow systems where relationships were developed for erosion as a function of shear stress. Specifically, model analyses used equations such as those developed by Cristoffersen and Jonsson [1] and Grant and Madsen [2] where the shear stress is proportional to the velocity squared. However, there are no data demonstrating that the oscillatory shear stresses generated by waves are proportional to the square of the velocity throughout the wave cycle. Moreover, it is not clear that oscillatory-flow-induced erosion is similar to linear-flow erosion. While other researchers have collected field data at wind farm installations or employ scaled models with data collected under expected hydrodynamic conditions [3], these may be cost prohibitive, site specific, and fail to provide a predictive tool for infrequent hydrodynamic conditions (i.e., storms) or for varied structure designs.

In wave-dominated environments, the near-bed velocity and shear stress are transient and modeling these discretely and accurately is impractical. Because erosion and scour rates of sediments are usually a function of shear stress to a power greater than 2, the average shear stress for the wave cycle may not be an appropriate metric for "effective" shear stress. Effective shear stress, a critical input for accurate models, can only be collected by direct measurement of the shear stress at the sediment-water interface. These data must be collected using appropriate and relevant sediments and for a variety of wave types. The unique capabilities of the SEAWOLF flume with its PIV measurements provide the only available tool to simulate this in a controlled laboratory environment for reconstructed or ex-situ core samples.

3. Field and Laboratory Sediment Transport Characterization

Quantifying the erosion and transport of sediments is critical for modeling and predicting sediment fate for assessing scour potential. The erosion characteristics of cohesive, sandy, or mixed sediments vary both with depth below the sediment/water interface and applied shear stresses; no "universal" empiricism is available, nor is likely to be developed in the near future. Typically, erosion is site specific and should be measured locally. To adequately characterize the behavior of sediments, the current state of the art relies on in-situ, ex-situ, and laboratory measurements. Until the mid 1990s, contemporary erosion measurement devices were limited to surficial measurements (~ top 1 cm) under low-flow conditions (not exceeding 1 Pa). It is important to note that these devices do not directly measure erosion rate. Rather, they measure sediment suspension potential, which is problematic for model development because of the tendency for these data to generate non-unique solutions (i.e., there are infinite combinations of erosion and deposition rates that yield identical suspended sediment concentrations). In addition, suspension potential may not be applicable to scour in sandy regions where most of the transport occurs as bedload.

SNL's SEDflume (SED - Sediment Erosion at Depth) directly measures erosion rate: (a) with depth below the sediment/water interface (to account for consolidated and stratified sediments); (b) at high shear stresses (for storm or flood simulations); and, (c) in the laboratory or field (because the device is mobile). Although the SEDflume was a major technical advance for erosion measurement devices, in the early 2000s SNL patented the SEAWOLF Flume for performing ex-situ and laboratory analyses of sediment erosion and transport properties in current and combined current-wave environments. The SEAWOLF Flume maintains all of the capabilities of the SEDflume while measuring the erosion rate with an oscillatory or combined unidirectional-oscillatory flow to simulate wave-dominated hydrodynamics at the ocean floor. It is important to note that while the SEAWOLF Flume can accurately reproduce the velocity time history for any waveform, the flow is inside an enclosed channel which in some cases may produce shear stress time history profiles somewhat different from those found in nature.

3.1 Hydrodynamics

An obvious choice to investigate wind farm inner-cable-array applications is the SEAWOLF Flume (Fig. 1). The primary reason this flume was invented was because previous erosion work for unidirectional flow [4,5] consistently demonstrated that erosion rate is a strong, non-linear function of shear stress ($E \sim \tau^{>2}$). This means that an accurate and realistic assessment of shear loading at the sediment-water interface is extremely important for erosion estimates. The utility of this flume along with its detailed design, flow modeling examples, and preliminary applications are discussed by Jepsen et al. [6]

In previous work with the SEAWOLF, flow rate and erosion measurements were collected by the operator, but shear stresses were estimated through CFD modeling for each flow case, $\tau = \mu dU/dy$. CFD model and experimental results appeared to suggest that during the transient flows of wave oscillations, the conditions inside the test channel were rarely fully developed. Moreover, maximum shear stresses calculated for wave peaks were generally higher than those determined for similar velocities under steady linear flow. Calculations also demonstrated that wave period was important with smaller periods having higher maximum shear stresses for similar wave amplitudes. This suggested that shear stresses calculated for fully developed linear conditions are not applicable to the oscillatory flows associated with wave environments. However, without direct measurement of the boundary layer, simulation was the only tool available to estimate the transient shear stresses for each experiment.

In recent work [7], PIV directly measured the boundary layer, and thus shear stress, for many flow regimes similar to those previously reported by Jepsen et al. [6] using CFD calculations. Results show that for lower wave amplitudes, maximum shear stresses were higher for larger wave periods. However, as wave amplitudes increase, this effect reverses and shorter wave periods have a higher maximum shear stress than longer wave periods. Finally, when linear and oscillatory flows are combined, the maximum shear stresses are less than wave-only cases with the same peak velocities. The trends of shear stress with wave period from PIV are mostly consistent with prior CFD calculations except for low-amplitude wave; previously reported CFD results suggested that shorter wave periods always had higher maximum shear stresses regardless of peak flow. More recent work demonstrates that elevated shear stresses are not necessarily an indicator of developing hydrodynamic conditions. Oscillating flows where dU/dx = 0 may be fully developed, but can display higher or lower shear stresses than their steady flow counterparts because the near-wall velocity profile is altered by different turbulence conditions and/or velocity profiles that "overshoot" near the wall. This is a result of a phase-lead of the "near-wall" flow relative to the flow in the center of the channel or in a free stream. These new insights observed during SEAWOLF studies can be applied to analyze real wave conditions applicable to offshore wave and wind farms in relatively shallow environments.

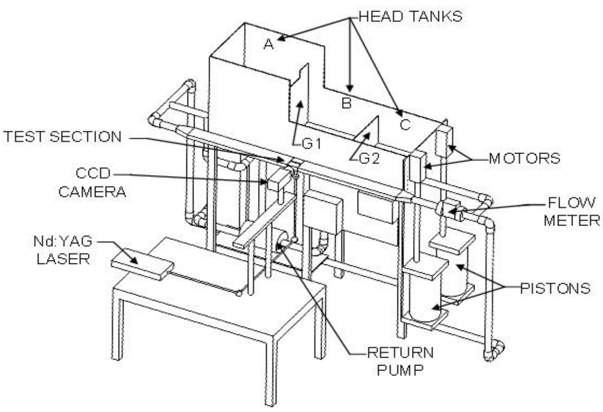

Figure 1. Schematic of the SEAWOLF test facility and PIV instrumentation.

An example of PIV results for a smooth-wall surface is shown in Table 1 with Fig. 2 illustrating the results. These flow parameters were selected based on realistic wave/current conditions from a near shore or shallow area. Clearly, there is a marked difference between the measured shear stress and that predicted analytically with the Blasius equation assuming turbulent flow [8],

$$\frac{2\tau}{\rho U^2} = 0.0791 Re_d^{-1/4}, \qquad (1)$$

where ρ is the fluid density, U is the velocity averaged across the channel height, and Red = $\rho Ud/\mu$ is the Reynolds number based on the flume channel hydraulic diameter, d, subject to viscosity, μ.

Case #	Max. flow (GPM)	Min. flow (GPM)	Mean flow (GPM)	Period (seconds)
1	30	-7	11.5	10
2	30	-30	0	10
3	50	-31	10	10
4	50	-50	0	10
5	30	-10	10	5
6	30	-30	0	5
7	47	-33	7	5
8	50	-50	0	5

Table 1: Summary of experiments.

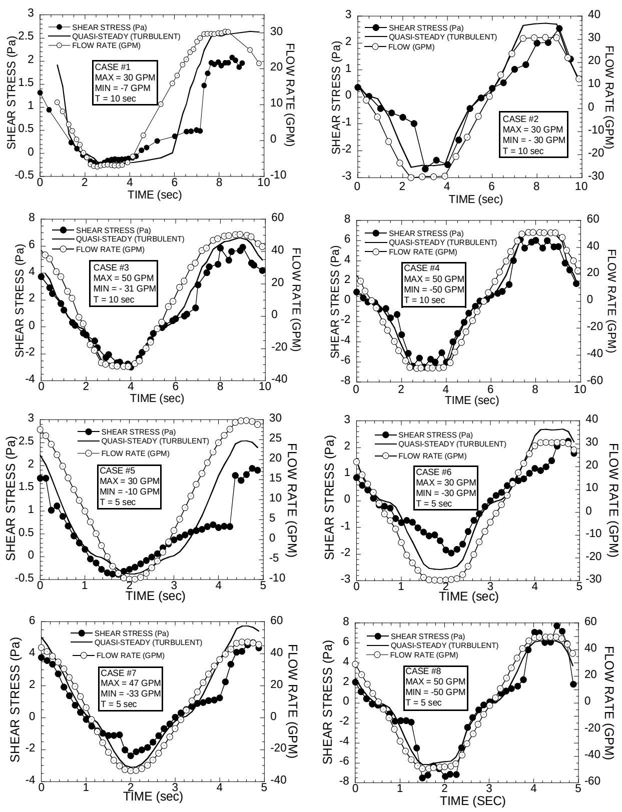

Figure 2: Phase-resolved, PIV-measured shear-stress data for 10- and 5-second wave periods. The "Quasi-Steady" (turbulent) values were calculated using the Blasius formula (Eq. 1) [10].

The work of Katz and others [9] using field PIV studies suggests that deep ocean wave environments do not undergo laminar to turbulent transitions, because length scales in the deep ocean are large, and boundary layers are thick and well developed throughout the wave cycle. Although this is an effect not identically simulated by the SEAWOLF Flume, it may not be of particular interest to erosion issues because deep ocean waves are quite different from wind generated waves that are far more likely to be associated with offshore energy installations. Also, the bottom shear stress developed by each of these wave types is different because wind driven waves are surface waves and subject to viscous dissipation down the water column. There are no known data for shear stress time histories at the sediment-water interface for shallow surface waves. Moreover, the lesser studied and perhaps more important question is whether or not relaminarization observed in the SEAWOLF tests also occurs in shallow waterways where the wave activity is prevalent and capable of inducing sediment erosion and transport. These issues for shallow-water, high-wave-energy environments are of growing importance regarding the progressive loss of coastline and erosion of near shore dredge deposits and would be directly applicable to regions where offshore energy installation are exposed to such conditions.

3.2 Erosion Implications

Because sediment erosion is strongly dependent upon shear stress (E ~ τ>2), it is important to accurately assess this parameter in wave environments. In addition, the critical shear stress for erosion is important to identify. Therefore, accurately predicting the shear stress in a wave environment is critical in determining whether erosion occurs and for how much of the wave cycle it is occurring. For example, if a sediment had a critical shear stress of 2 Pa, and was subjected to a wave environment such as Case 1 or 5 (Fig. 2 and Table 1), the Blasius (or similar) equation predicts erosion while the PIV data show no erosion.

To further investigate the importance of assessing the shear stress time history, the erosion rate was determined for a well-defined, fine-grained sediment, CDS-2, from a previous study [11]. This sediment was used extensively in prior studies to determine erosion rate as a function of shear stress [6]. Here we apply the experimentally determined relationship for erosion rate, E (cm/s), as a function of shear stress, τ (Pa):

$$E = 1.23 \times 10^{-4} \tau^{2.71}, \qquad (2)$$

It is also important to consider the critical shear stress for the CDS-2 sediment of 1 Pa because there are time intervals in the wave cycle that the shear stress is less than 1 Pa and the CDS-2 will not erode. For wave Cases 1, 5, 7, and 8 (Fig. 1), the erosion-rate time histories of this sediment are plotted in Fig. 3 for both the PIV-measured and the Blasius-predicted shear stresses. In addition, Table 2 shows the total amount of sediment predicted to erode per cycle for the cases in Fig. 3.

Notice that the over-prediction of shear stress by Blasius (compared to PIV) for Cases 1, 5, and 7 is now manifest in a grossly over-predicted erosion rate because of the relationship between erosion and shear stress in (2). The total erosion for these wave cycles is estimated a factor of 2 to 3 higher using the Blasius equation over the PIV measurements (Table 2). Even in Case 8 where the Blasius equation and PIV shear stress measurements have closest agreement, there are large differences in the peak amplitudes. In this case, the Blasius equation now under-predicts the shear stress measured by PIV although the total erosion for the cycles as predicted by Blasius and PIV are reasonably close. Overall, this analysis, including the erosion rate as a function of shear stress, demonstrates the nonlinearity of erosion in wave environments and highlights the necessity of obtaining accurate measurements or predictions of shear stress.

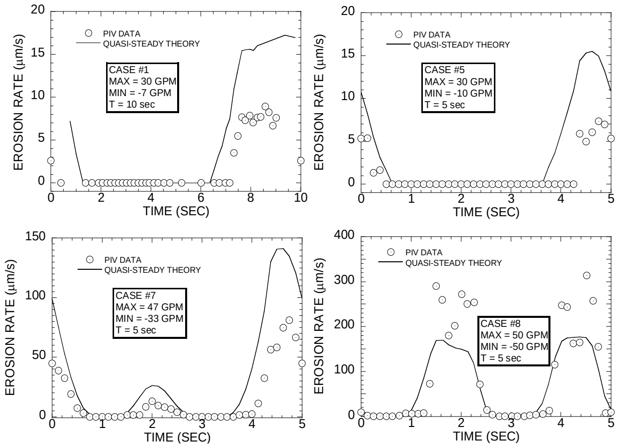

Figure 3. Erosion rate for CDS-2 sediment [11].

Case #	PIV	Blasius
1	0.0018	0.0057
5	0.0006	0.0017
7	0.007	0.017
8	0.045	0.036

Table 1: Total erosion (cm) per wave cycle in Fig. 2.

Using data like those shown for the CDS-2 sediment in conjunction with an erosion-shear stress relationship in the form of (2), one can estimate the effective shear stress applied by a wave or wave-current cycle. For example, the actual erosion rate for Case 1 is 0.0018 cm/s (wave cycle of 10 seconds) yielding an effective shear stress of 1.15 Pa. This could be calculated for any sediment and wave type and is more reliable if the majority of sediments are sandy in nature and do not display cohesive properties.

4. Application to Offshore Energy Installations

A thorough study and model implementation of scour potential at a proposed offshore site could be accomplished in stand-alone phases. The first effort would begin with data collection through literature review on spatial and temporal conditions for both hydrometeorological and sediment parameters for several existing and proposed offshore wind farm sites. If no data are available for surface wave shear stress time histories, then an assumption could be made that simulations by SEAWOLF are reasonable surrogates. The SEAWOLF flume could be used to model the range of expected temporal wave-current environments from nominal to storm conditions. One could experimentally determine the effective shear stress in these wave-current dominated environments using well-defined reconstructed laboratory core samples that represent the range of sediment properties found in the field. The next step would incorporate these data into an algorithm describing a wide range of sediment and hydrological conditions. Preliminary numerical simulations could then be used to evaluate the combined impact of hydrodynamics and sediment transport on offshore energy devices and inner cable arrays. For example, erosion and transport data can be input to the SNL-licensed SNL-EFDC code, an upgraded version of the EPA-sponsored EFDC (Environmental Fluid Dynamics Code), which is a fully three-dimensional combined hydrodynamic, sediment-transport, and water-quality code for simulating rivers, lakes, estuaries, and coastal systems. While SNL-EFDC is a suitable platform for this class of models, other ocean circulation or river hydrodynamics simulation codes could also be modified to accept SNL flume data.

Subsequent work could yield a more comprehensive model for simulations applicable over a broad range of offshore energy installations along with a framework and methodology to quantify uncertainties and sensitivities into a risk assessment. One component of the approach is to quantify the spatial variability in sediment properties. This could be addressed through representative sampling/collection of sediment cores for erosion and transport testing with the SEAWOLF Flume in conjunction with geostatistical interpolation algorithms. Another component would be incorporating temporal variability of hydrometeorological forcing functions on time-scales relevant to the analysis (e.g., construction, operation, decommissioning). In most cases, these data can be obtained from existing sources, although some site-specific measurements may be needed. Evaluating the combined impact of the spatial and temporal variability can be achieved through a Monte Carlo simulation approach.

5. Conclusion

Many of the areas currently proposed for future offshore wind farms are located in areas of high sediment transport rates and sand waves. If this is the case, then sediment characterization and determination of effective shear stress will only be a function of particle size, and algorithm development will be straightforward. If sediments are found to be silty or mixtures of silt and sand, then cohesive properties may dominate and will significantly complicate characterization, and direct SEAWOLF measurements from ex-situ core samples become increasingly necessary. Another area of focus will be determining the accuracy of the SEAWOLF simulations to the real wave environment for surface waves. It is not clear whether the phenomena associated with the turbulent to laminar transitions observed in the SEAWOLF also occur in the field for shallow surface waves or what effect they have on the overall measurements. If such phenomena are found in the field, then the SEAWOLF application becomes even more important.

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References

[1] Cristoffersen, J., and Jonsson, I. (1985). "Bed friction and dissipation in a combined current and wave motion." Ocean Engineering, 17(4), 479-494.

[2] Grant, W. D., and Madsen, O. S. (1979). "Combined wave and current interaction with a rough bottom." Journal of Geophysical Research, 84(C4), 1797-1808.

[3] den Boon, J. H., Sutherland, J., Whitehouse, R., Soulsby, R., Stam, C. J. M., Verhoeven, K., Høgedal, M., and Hald, T. (2004). "Scour behaviour and scour protection for monopile foundations of offshore wind turbines." In: 2004 European Wind Energy Conference & Exhibition, London, UK, 14.

[4] Jepsen, R., Roberts, J., and Lick, W. (1997). "Effects of bulk density on sediment erosion rates." Water, Air and Soil Pollution, 99, 21-31.

[5] Roberts, J. D., Jepsen, R. A., and Lick, W. (1998). "Effects of particle size and bulk density on erosion of quartz particles." Journal of Hydraulic Engineering-ASCE, 124(12), 1261-1267.

[6] Jepsen, R. A., Roberts, J. D., and Gailani, J. (2004). "Erosion measurements in linear, oscillatory, and combined oscillatory and linear flow regimes." J. Coast. Res., 20(4), 1096-1101.

[7] Kearney, S.P., T.J. O'Hern, T.G. Dimiduk, T.W. Grasser, J. Barney, and J.D. Roberts, (2008) "Particle-Image Velocimetry Investigation of an Oscillating Turbulent Channel Flow," AIAA 2008-693, Aerospace Sciences Meeting, Reno, NV.

[8] White, F. M. (1991). Viscous Fluid Flow, 2nd Ed., McGraw-Hill, New York, NY.

[9] Nimmo-Smith, W.A.M., J. Katz and T.R. Osborn, 2005. “On the Structure of Turbulence in the Bottom Boundary Layer of the Coastal Ocean,” Journal of Physical Oceanography, Vol. 35, 72-93.

[10] Jepsen, R. A., Roberts, J. D., Kearney, S. P., Dimiduk, T. G., O'Hearn, T. J., and Gailani, J. G. (2010). "Shear stress measurements and erosion implications for wave and combined wave-current generated flows." submitted to Journal of Waterway, Port, Coastal, and Ocean Engineering.

[11] Jepsen, R. A., Roberts, J. D., Lucero, A., and Chapin, M. (2001). "Canaveral ODMDS dredged material erosion rate analysis." Sandia National Laboratories, Albuquerque, NM.