Bottom Boundary Layer Wave Measurements for Particle Studies

Albert J. Williams 3rd
Woods Hole Oceanographic Institution
Woods Hole, MA 02543, USA
awilliams@whoi.edu

Abstract: **Suspended particles, which attenuate light and restrict visibility in moderate depths of the ocean, are commonly resuspended from the bottom by waves. This turbid layer initially consists of fine particles with settling rates of 0.01 mm/s that require weeks to settle out. However, the relaxation of the turbid conditions is often only a day or less implying particle settling rates of 1 mm/s, a rate requiring that the small particles aggregate into large particles that can settle more rapidly. Conditions that suspend and possibly disaggregate the fine sediment on the bottom and the aggregated particles in suspension are wave dominated in most continental shelf conditions. Thus formation of a turbid layer requires a shear stress exceeding a threshold. Relaxation of a turbid layer conversely requires a shear stress that remains always or nearly always below another threshold. This dependence of turbidity and the lifetime of turbid layers on shear stress focuses attention on what the shear stress is and what it depends upon.**

Shear stress at the bottom is a combination of Reynolds stresses from the mean current and the wave boundary layer. The thickness of the wave boundary layer is too small for direct Reynolds stress determinations in the boundary layer but the wave effects can be included into the model in other ways. Thus wave velocities in the wave boundary layer are very important in estimating the mean Reynolds stress. Even more important for the determination of the peak boundary layer stress felt by the bottom interface where the sediment may be eroded and the large particles disaggregated into smaller particles are the instantaneous velocities consisting of the sum of the mean current and the wave velocity.

Determination of wave velocity should not be difficult for a rapidly sampling current meter near the bottom. The information required is present in the time series recorded by such an instrument. Yet the waves responsible for this sediment interaction at shelf depths are generally not revealed in conventional directional wave measurement instruments and wave spectra processing programs. Wave measuring instruments that are physically located on the surface or that sense the sea surface elevation acoustically or by wires are even more restricted by the dominance of short period, high amplitude waves when wind is present. Surface wave measurements rarely detect the low amplitude, very long period waves that are the dominant influence on the bottom in depths exceeding 10 meters because these waves are swamped by short period waves in all conditions except glassy calm.

In order to adequately measure the waves that are significant for resuspension of benthic sediment, measurements of orbital wave velocity near the bottom in the depths of interest are preferred. While such near-bottom measurements present a problem for extrapolation back to the surface in generation of conventional directional wave spectra, the depth imposes a natural filter that attenuates the signal from short period surface waves yet permits the long period swell to be detected and measured. Direct velocity and pressure measurements from a fixed platform on the bottom are ideal for this purpose. Prefiltering of the data before extrapolating to the surface with a cutoff frequency to reject short period waves can permit conventional directional wave spectral software to reveal these long period waves. No changes need to be made to the directional wave spectrum program when short period waves are naturally attenuated. However, the cutoff must be set to a frequency that prevents the attenuated short period waves from being extrapolated back to the surface where they are dominant. Such a modification of a program will reveal the information needed for studies of turbidity and the relaxation of turbidity on the shelf from depths between 10 meters and 120 meters where long period waves penetrate to the bottom and short period waves are attenuated.

I. INTRODUCTION

Boundary layer shear stress, surface stress of the flow against the bottom boundary, is responsible for eroding and suspending or resuspending sediment. Small mineral or organic particles are bound to each other and to the substrate by weak van der Waals forces or by electrostatic forces that can be exceeded by the shear stress, Reynolds stress on the average, in the flow. When this happens, the particle or clump of particles leaves the bottom and becomes entrained in the fluid above. Shear associated with turbulence in the boundary layer flow tears apart clumps of particles and their disaggregation results in very fine particles, often less than 10 microns and even as small as 1 micron in diameter in many cases. The settling rate of such small particles is less than 0.01 mm/s yet after an episode of turbulent stress resulting in turbid water in the bottom boundary layer, the water often clears in a matter of hours or days, not the weeks expected from the settling rate of the individual particles.

The aggregation of particles into larger, faster settling particles is the process that leads to such clearing, the small particles bumping into one another and sticking to make marine snow [1] or other aggregates of particles with larger diameter. Even though these particles contain volume filled with sea water they have a higher mass to surface area than the individual particles that make up the aggregate and consequently settle faster. In the deep sea, below say 300 meters, bottom flow responsible for shear stress capable of resuspending sediment and of breaking apart clumps of particles, results from linear combinations of tidal, barotropic, and baroclinic flows. However, in depths less than 300 meters, and especially depths less than 100 meters, the peak bottom stresses are associated with surface waves of long period. Since the attenuation of wave velocities with depth and frequency ensures that only the longest period waves are responsible for significant wave velocities at these shallower depths (but still relatively deep), cutting off the directional wave spectrum to show only the long period portion is appropriate for estimating bottom velocities and stresses. In so far as turbidity results more from such long period waves, even of low amplitude, than from the shorter period sea, a way to accurately measure such long period waves is valuable. In shallow depths, less than 10 meters, long period waves lose the attenuation advantage they have over short period waves at greater depth and may be relatively less significant as a source of bottom stress. Between 10 meters and 100 meters, long period waves are probably the dominant source of bottom stress on the continental shelf exposed to oceanic wave climates.

II. OBSERVATIONS

A. Governing Equations

In deep water, high wave number (short period) waves are attenuated more rapidly with depth than low wave number (long period) waves. The pressure variations, horizontal velocity, and vertical velocity under the waves are all attenuated with depth. Measurements of these quantities at depth are represented by the following equations:

$$\Delta p(x,z,t) = \pm\frac{\rho a\omega^2}{k}\frac{\cosh(kz)}{\sinh(kh)}\sin(kx\pm\omega t) \tag{1}$$

$$\Delta v_x(x,z,t) = -a\omega\frac{\cosh(kz)}{\sinh(kh)}\sin(kx\pm\omega t) \tag{2}$$

$$\Delta v_z(x,z,t) = a\omega\frac{\sinh(kz)}{\sinh(kh)}\cos(kx\pm\omega t) \tag{3}$$

where p is pressure, x is horizontal downstream position, z is observational distance above bottom, t is time, ρ is density of water, a is amplitude of the wave, ω is angular frequency of the wave, k is radian wave number of the wave, h is depth of the water, v_x is the horizontal downstream velocity, and v_z is the vertical velocity [2]. In deep water:

$$k = \omega^2 h/g \tag{4}$$

while in general, k is related to ω by:

$$k\tanh(k) = \omega^2 h/g \tag{5}$$

The relation between depth of water, period of the wave (period, T, is given by $T=2\pi/\omega$), and measurement height above bottom gives a magnitude curve for the observation of pressure variation, horizontal velocity, and vertical velocity as shown in Figs. 1, 2, and 3. In these figures, the red curve is from (1), the blue curve is from (2), and the green curve is from (3). Assume for example that the wave amplitude, a, is 1 m, from which the pressure variation just beneath the surface is 1 decibar or dbar (a non-SI unit equal to 10000 Pa). Then a magnitude of 10^{-2} is a pressure signal measured 1 m above bottom of 0.01 dbar or 1 cm of hydrostatic head in pressure. For velocity, if the wave amplitude is 1 m and wave angular frequency is ω, the velocity just below the surface is ω m/s. A magnitude of 10^{-2} in velocity in this case is an observed velocity of ω cm/s. It can be seen from the curves of Figs. 1 through 3 that there is a sharp cutoff at a period about 14 s for the 100 meter depth, a period about 7 s for the 20 meter depth, and a period about 4.5 s for the 10 meter depth. These changes of slope mark the transition for those depths where the wave ceases to be deep water and becomes shallow water; where the radian wavelength is half the water depth.

From Fig. 1, swell on the continental shelf at a depth of 100 m and a period of 18 s will have a horizontal velocity of 20 cm/s and a vertical velocity of 0.25 cm/s for a wave height (amplitude) of 1 m. This vertical velocity is small for the UVW (three velocity vector) method of determining the directional wave spectra of surface waves. However, the pressure signal is 0.4 dbar or 40 cm head, which allows a directional wave spectrum to be computed from UVP (two velocity vectors and pressure) instead of UVW.

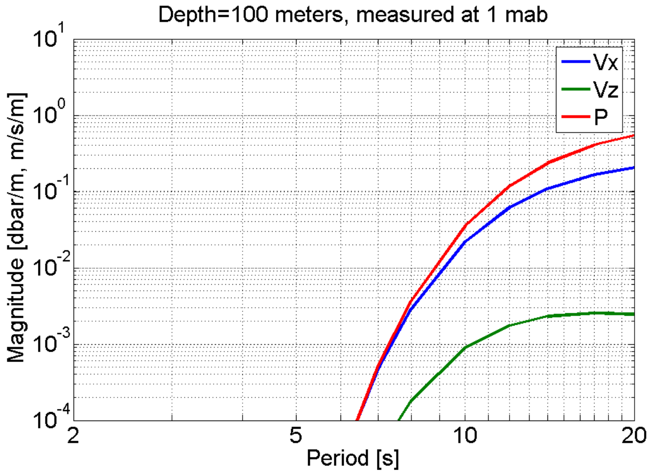

Fig. 1. Magnitude curves for surface gravity waves in water of 100 meters depth measured 1 meter above bottom as a function of period.

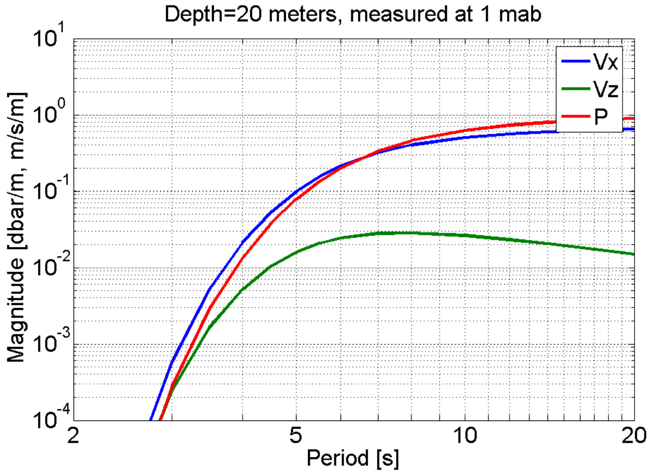

Fig. 2. Magnitude of surface gravity waves in 20 meters depth measured 1 meter above bottom as a function of period.

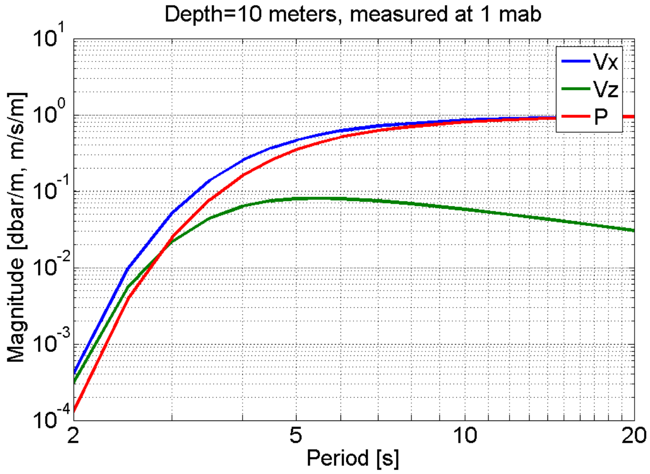

Fig. 3. Magnitude of surface gravity waves in 10 meters depth measured 1 meter above bottom as a function of period.

Sensors of pressure and velocity are capable of resolving signals of 10^{-2} dbar (1 cm head) and 10^{-2} m/s (1 cm/s) without excessive noise. Based upon such sensitivities, thresholds can be determined for detecting surface waves at depth. These thresholds are related to the noise level of the sensors. For example, if the threshold is selected as 10^{-3} as illustrated in Fig. 4, a wave of 10 m amplitude would be detected with the sensitivity described above or a 1 m amplitude wave could be detected with sensitivity of 1 mm head in pressure and 1 mm/s in velocity if such sensitivities were available. Other thresholds are plotted in Figs. 5 and 6. Each plot shows the threshold for pressure, horizontal, and vertical velocity for a 1 m wave.

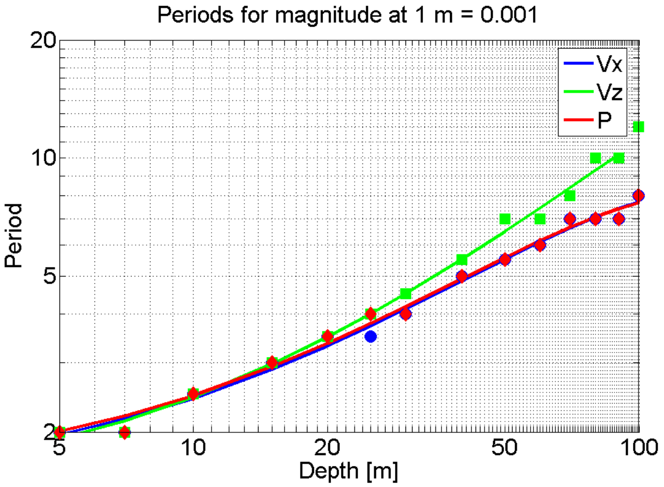

Fig. 4. Periods of surface gravity waves as a function of depth at which the attenuation at a measurement height of 1 mab (meters above bottom) is 10^{-3}. At 100 m depth, the pressure signal exceeds the threshold (1 mm head for a 1 m wave or 1 cm head for a 10 m wave) at periods greater than 8 s. The horizontal velocity exceeds the threshold (1 mm/s for a 1 m wave or 1 cm/s for a 10 m wave) at periods greater than 8 s. Vertical velocity exceeds the threshold (1 mm/s for a 1 m wave or 1 cm/s for a 10 m wave) at periods greater than 12 s.

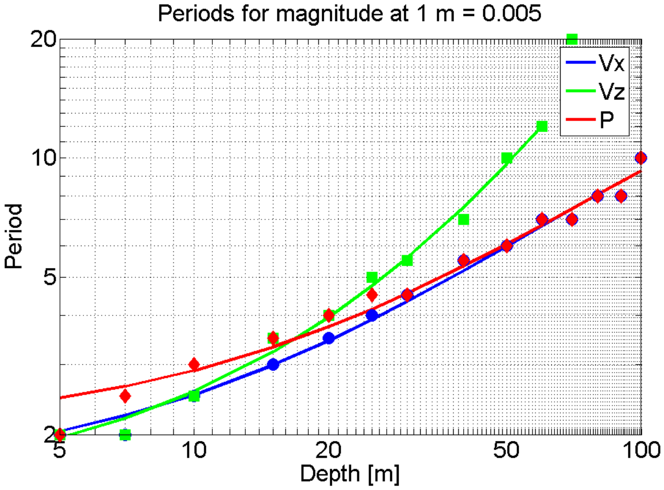

Fig. 5. Periods of surface gravity waves as a function of depth at which the attenuation at a measurement height of 1 mab is $5\cdot10^{-3}$. Pressure exceeds the magnitude threshold for 10 s waves and longer at 100 m depth. At 20 m depth, pressure and velocity exceed the threshold for 4.0 s waves.

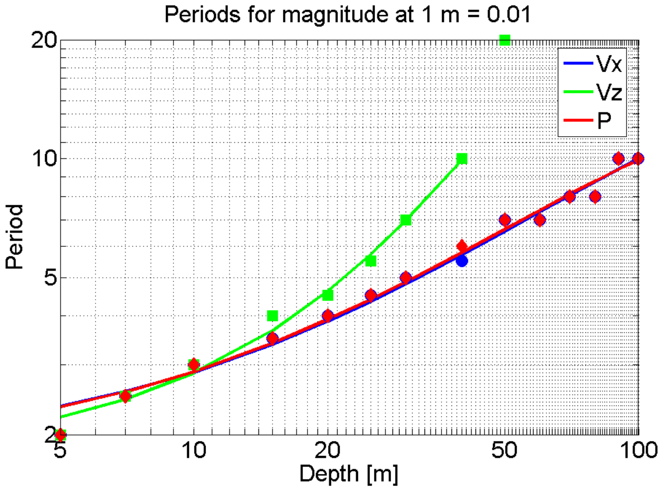

Fig. 6. Periods of surface gravity waves as a function of depth at which the attenuation at a measurement height of 1 mab (meters above bottom) is 10^{-2}. At 10 m depth, pressure and velocity exceed the threshold for 1 m wave amplitude at periods longer than 3 seconds.

Long period waves can be measured in deep water from a sensor near the bottom. However, a near-bottom wave measuring sensor is limited in the ability to sense short period waves in deep water. Figs. 4, 5, and 6 illustrate the period cutoff for a near-bottom sensor as a function of depth for threshold values of 0.001, 0.005, and 0.01 respectively. In order for a sensor capable of measuring 1 cm head of water pressure or 1 cm/s velocity to estimate accurately the amplitude of waves at the surface, the amplitude of the wave on the surface must exceed 1 m or its signal at depth will not be resolved above the noise. As can be seen in Fig. 4, this requires a wave period of 8 s for 100 meters depth and 10 m wave amplitude. At 20 meters depth, a 10 m wave of 3.5 s period would be resolved but this is an extreme wave. Fig. 5 suggests that at 20 m depth a 4 s wave of amplitude 2 meters could be resolved. Fig. 6 shows that at 20 m depth, a 4.5 s wave could be resolved with amplitude of 1 meter. Longer period waves are more easily resolved but Figs. 4, 5, and 6 illustrate why it is necessary to generate directional wave spectra for surface elevations from the bottom.

B. Bottom Observations of Surface Waves

Rigidly mounted current meters, with pressure sensors in some cases, are able to measure velocity components caused by waves and with three axes of velocity measured (UVW technique) or with two horizontal components of velocity and pressure measured (UVP technique), the directional wave spectrum can be computed for wave amplitude at the surface. Fig. 7 shows such a wave measuring instrument. The tripod was designed originally for determination of directional surface wave spectra from the bottom but current and waves are measured on this tripod close to the bottom where the stress of the instantaneous velocity affects the sediment. Thus this instrument provides a valuable observational capability for particle studies beyond its original purpose.

Since short period waves are attenuated more than long period waves, the spectrum of bottom measured velocities must be amplified more in the blue (short period) than in the red (long period) as is indicated schematically in Fig. 8. This presents a challenge for measurements and for the noise of the velocity sensor since noise at short periods is amplified along with the short period signal. To obviate this problem, some current meters used for directional wave spectra measurements use a surface following strategy that actually obtains the instantaneous water height above the sensor directly by an acoustic surface range measurement [3]. Even a slightly rough surface provides a return that can be tracked, however, in glassy conditions the acoustic beam may be reflected specularly rather than scattered and not return to the source. While this is a good way to resolve high frequency surface waves and by extension, surface wave velocities as well as low frequency waves and their velocities at the surface, the long period waves of very low amplitude can be easily buried in the short period waves of higher amplitude.

In a conventional directional wave spectrum, the highest energy surface waves are selected and their period, amplitude, and direction are reported as significant wave height [4]. Waves with lesser energy are also detected and presented in the directional wave spectrum but weak waves of long period are lost in the significant wave height report. Even ubiquitous ocean swell is generally missed unless conditions become calm and the sea goes down, leaving only the long period swell, now exposed and distinguishable as shown in Fig. 9. For example, on day 2 when there is very low wave height the wave period is 9 s. Conversely on day 11 with high wave height, the period is 5 s. Presumably this swell with period greater than 8 s was present most of the time but only reported as the period of the most significant wave ($H_{1/3}$) when the sea was less than 0.3 m.

On the bottom however, in depths greater than 10 m, the swell is often the only thing that is detectable and even when shorter period waves are felt, the long period waves are often the dominant source of bottom fluid velocity and fluid stress. Fig. 10 illustrates the attenuation of the 4 s sea that was often present at the deployment presented in Fig. 9. For example, the maximum wave height of 1.2 m seen on day 11 corresponded to a period of 5 s which from Fig. 10 gives a velocity at 1 mab of 0.3 m/s/m · 1.2 m = 0.4 m/s. Meanwhile the 8 s swell with amplitude of only 0.2 m has a velocity at 1 mab of 0.8 m/s/m · 0.2 m = 0.16 m/s, a third of the velocity due to the local sea.

Fig. 7. Bottom tripod for wave and current measurements. The velocity measurement volume is 0.75 m above the bottom. The tripod is shown with a MAVS (Nobska Development, Inc.) current meter, mounted sensor down. Pressure is measured at a height of 0.85 m.

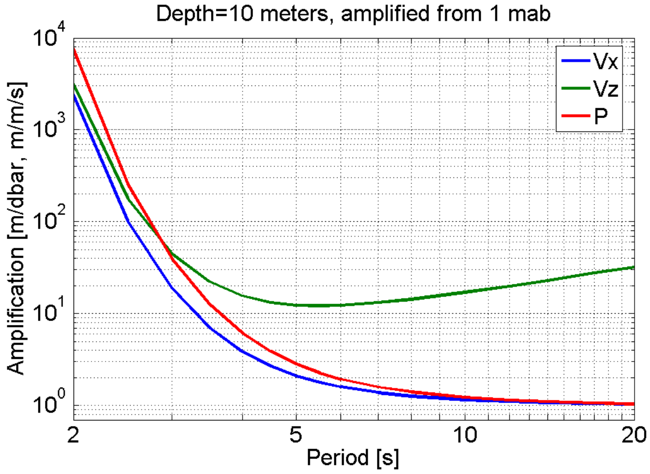

Fig. 8. Amplification is required to project measurements near bottom to surface elevations and this figure gives the amplification required as a function of wave period for a measurement 1 mab in 10 m depth.

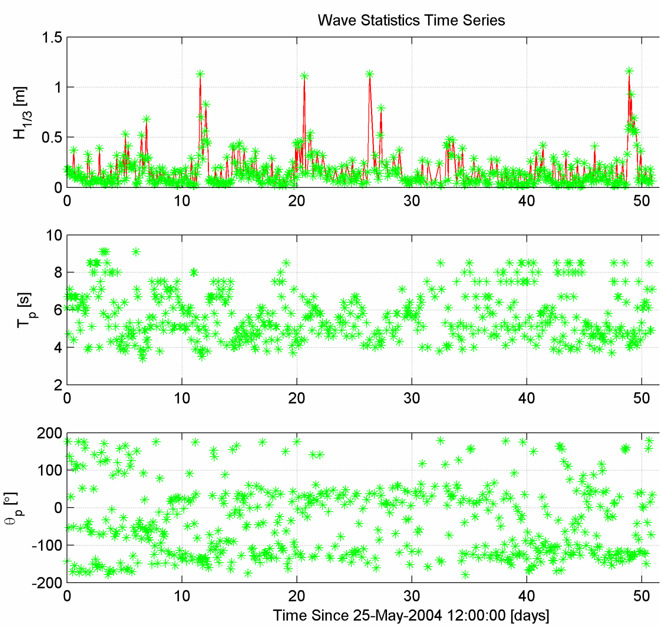

Fig. 9. This plot shows waves with a period of 9 s at times when the wave heights are at a minimum. Such episodes are when the swell is not hidden by the local wind-generated sea. These data are derived using MWAVES from 11 meters depth measured by MAVS on the tripod of Fig. 7.

The effect of water depth on wave attenuation for short period waves is noticeable but not a dominant feature at 11 m depth. At greater depths it becomes a larger effect, particularly on the shelf where the wave climate often includes long period swell of distant origin. Observations of bottom visibility at the Martha's Vineyard Coastal Observatory by divers confirm that local sea conditions are important for operations as they affect transfer of divers from the boat but the swell is of far greater concern for visibility on the sand bottom at depths of 12 m and 15 m. Diver observations of their movement on the bottom from such swell confirms the current meter records that 7 s or longer period swell is the dominant motion at those depths in sea conditions that permit diving.

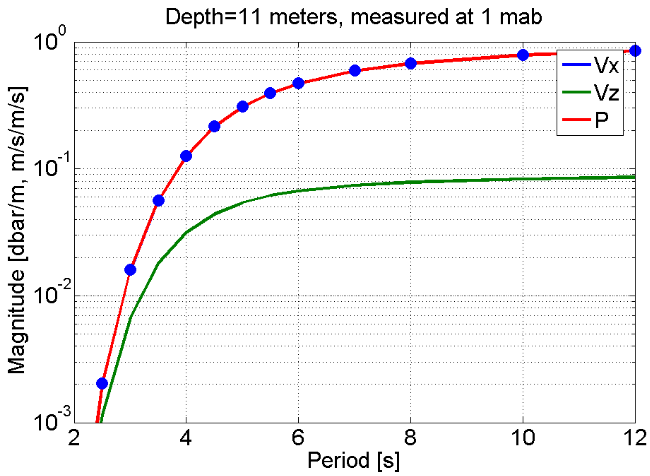

Fig. 10. Attenuation of swell at the 11 m depth of the tripod deployment of Fig. 8. 9 s waves have magnitude of 0.8 for pressure and horizontal velocity but only 0.06 for vertical velocity.

C. Directional Wave Spectra

Three components of flow or two components of flow and pressure permit a directional wave spectrum to be calculated. If these are obtained from a rigid platform near the surface, the surface wave spectrum can be computed with little difficulty. Such an installation is shown in Fig. 7. If, however, the flow measurements are made well beneath the surface, the attenuation of wave velocity with depth reduces the signal and makes detection more difficult. The vertical component of wave velocity decreases faster than the horizontal velocities (e.g. Fig. 10) and if the measurement is made very near the bottom, it may be necessary to use two horizontal components of velocity and pressure to obtain the signals needed for the computation. At this point the actual velocities and pressure signals can be combined to obtain the in situ wave velocity directional wave spectrum. In fact, this is the information that is relevant to determining bottom stress. However, the determination is only valid at the depth of the measurement. At this point, the normal procedure is to project the in situ wave spectrum back to the surface to make it a wave height spectrum as shown in Fig. 11, and a directional wave spectrum an example of which is shown in Fig. 12. Equivalently, a measurement of velocity and pressure above the bottom could be projected to the bottom to make it a bottom wave velocity spectrum but this is not routinely done. For purposes of this paper, the bottom velocity spectrum is the more valuable.

D. Deep Shelf Observations

At 90 m on the California shelf the velocity measured at 2 Hz by BASS is displayed in Fig. 13. Bursts of such measurements were made every 21 hours for 8.4 minutes and burst 4 of the display shows the highest velocity for the period January 12 to March 9, 1991 [5]. Velocity vectors were obtained with a noise level of 0.3 mm/s from six heights above bottom. Three are shown from the bottom, middle, and top.

Analysis of this burst yields the spectrum shown in Fig. 14. This shows a peak at 18 s to 19 s with a lower peak at 15 s and a lower yet peak at 12 s. When projected back to the surface with the amplification curve of Fig. 15, these three peaks become 200, 1.8, and 1 respectively.

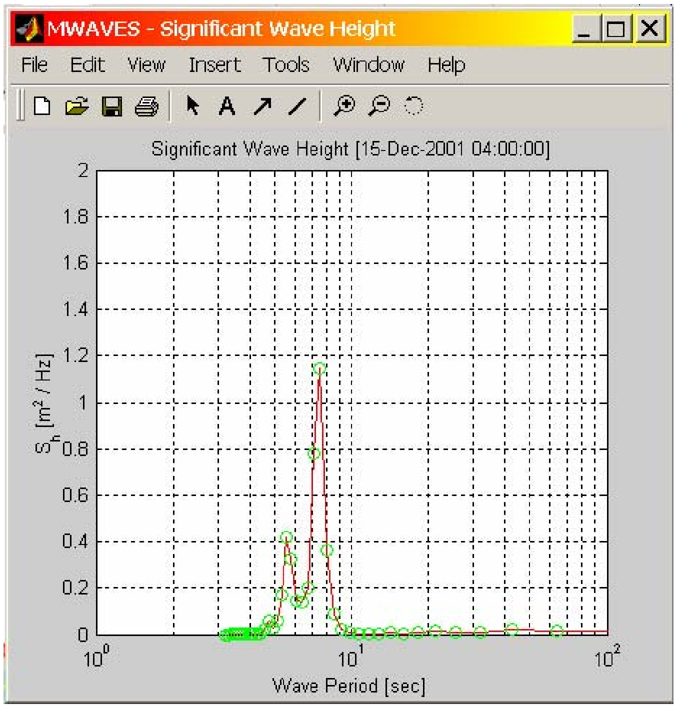

Fig. 11. Wave height spectrum from measurements in Lake Ontario illustrates the MWAVES analysis capability on one of the display screens (from [4]).

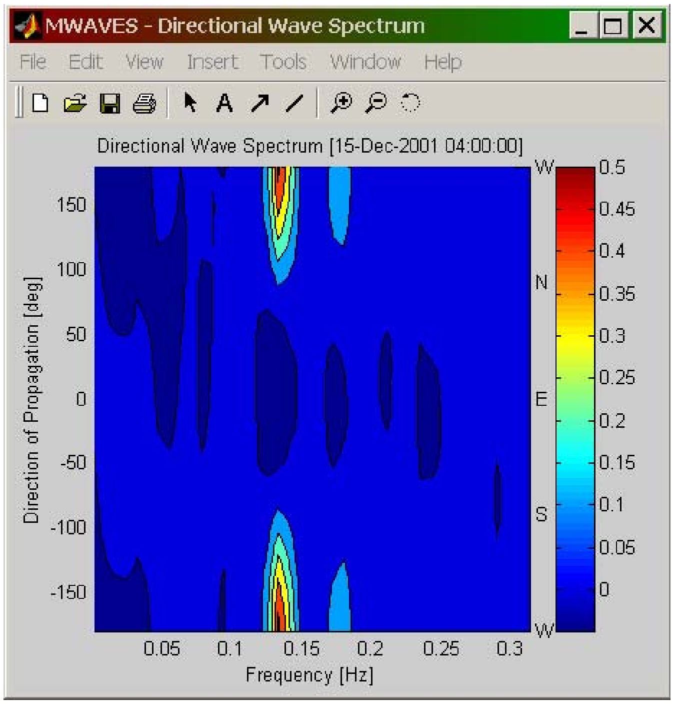

Fig. 12. Directional wave spectrum from measurements in Lake Ontario illustrate the MWAVES analysis capability on one of the display screens (from [4]).

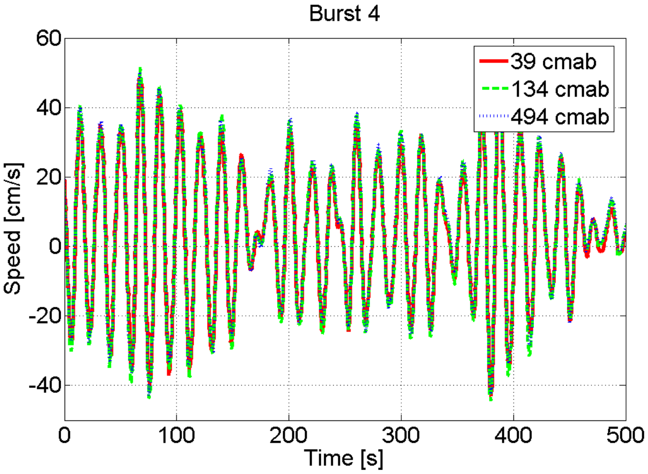

Fig. 13. Burst of horizontal velocity measurements in 90 m depth observed in the STRESS deployment off northern California in 1991. Measurements at 2 Hz from three heights off bottom are shown. Currents are less than 6 cm/s but wave velocities are as much as 50 cm/s within 39 cm of the bottom. The wave period that is obvious is 18 s.

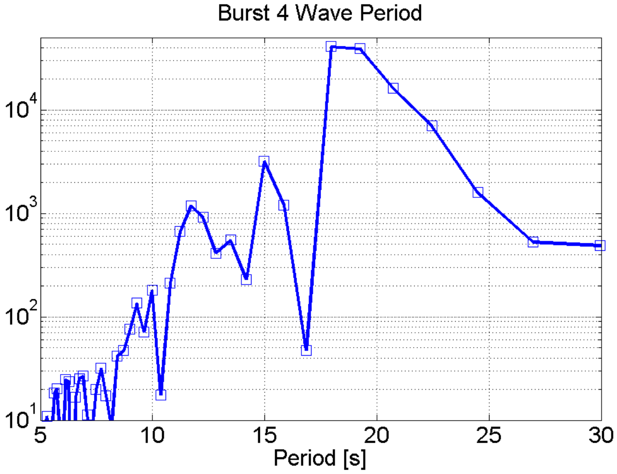

Fig. 14. Period spectrum for the burst of velocities in Fig. 13. The dominant peak is at 18 s and 19 s but there is a small peak at 15 s and at 12 s.

III. CONCLUSIONS

The unattenuated long-period wave-induced current is often the source of the turbidity observed optically. If it is the source of the turbidity, it may also be the agent that changes the size distribution of the marine particles that obstruct the transmission of light and lead to high turbidity [6]. Initially, the enhanced stress due to the wave may resuspend and break up the particles and clumps of particles, later the stress of the bottom turbulence associated with the wave may cause the small particles to bump into one another and aggregate forming larger, faster sinking particles. Certainly a moderate background level of turbulence accelerates clearing. Direct measurements of bottom current from in situ sensors gives the velocities associated with waves that are the agent of such turbulence and bottom stress. Significant wave heights and period at the surface do not tell the story on the seafloor that is important for particle dynamics that affect visibility there.

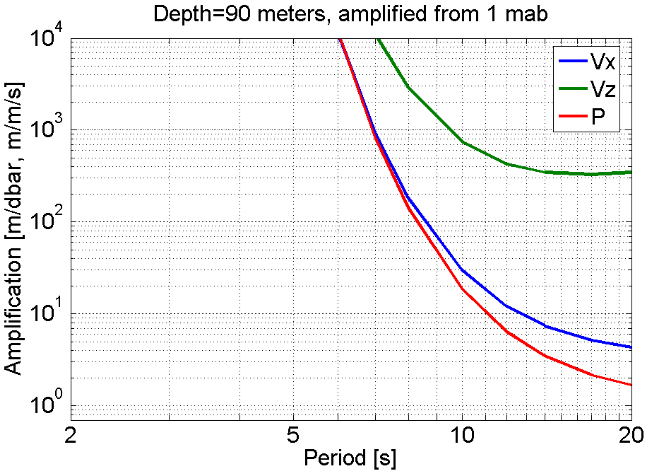

Fig. 15. Amplification for 90 m depth to project measurements of waves 1 mab to surface elevations.

AKNOWLEDGEMENTS

Woods Hole Oceanographic Institution provided support for attendance at this conference. ONR supported the STRESS program responsible for the data from the shelf. Nobska Development, Inc. supported the development of MWAVES.

REFERENCES

[1] Dickey, T.D., G.C. Chang, Y.C. Agrawal, A.J. Williams 3rd, and P.S. Hill, 1998. Sediment Resuspension in the Wakes of Hurricanes Edouard and Hortense, *Geophys. Res. Let., 25(8)*, pp. 3533-3536.

[2] Kinsman, B., *Wind Waves*, Englewood Cliffs, NJ, Prentice-Hall, 1965, pp. 133-144.

[3] Pedersen, T. and A. Lohrmann, (2004). "Possibilities and limitations of acoustic surface tracking", *Proceedings OCEANS '04. MTS/IEEE TECHNO-OCEAN '04,* Volume: 3, 9-12 Nov. 2004 pp 1428- 1434 Vol.3 Digital Object Identifier 10.1109/OCEANS.2004.1406331

[4] Morrison, A.T. III, (2003). "MWAVES – Software for Calculating the Directional Spectra and Statistical Properties of the Wave Field from MAVS-3 Triplet Measurements", *Proceedings of the IEEE Seventh Working Conference on Current Measurement*, IEEE/OES, March 2003, pp. 128-134

[5] Morrison, A.T. III, NetCDF and Matlab Archive of STRESS II BASS Data, Woods Hole Oceanographic Institution, CD available from author, unpublished archive, 1996.

[6] Gardner, W.D., J.C. Blakey, I.D. Walsh, M.J. Richardson, S. Pegau, J.R.V. Zaneveld, C. Roesler, M.C. Gregg, J.A. MacKinnon, H.M. Sosik, and A.J. Williams 3rd, 2001. Optics, Particles, Stratification, and Storms on the New England Continental Shelf, J. Geophys. Res. 106(C5), 9473-9498