University of New Hampshire

Submerged Oil Working Group
May 8, 2014
In conjunction with IOSC, Savannah, GA

Meeting Notes

Participants:

Nancy Kinner, CRRC/UNH
Chris Barker, NOAA
Sara Booth, USCG
Sarah Brace, Pacific States/BC Oil Spill Task Force
Steve Buschang, TX GLO
Ralph Dollhopf, USEPA
Jim Elliott, T&T Salvage
Rodrigo Fernades, IST, Portugal
Deb French McCay, RPS ASA
Kurt Hansen, USCG R&D
Steve Lehmann, NOAA ORR ERD
Michael Rancillio, ISCO
Benjamin Silliman, College of William & Mary
Glen Watabayashi, NOAA ORR ERD

Update Reports:

- Neutron Back scatter (Jim Elliott's paper)
  - See attached
- NOAA (Chris Barker)
  - Reported on the poster on waves (poster will be posted on IOSC proceedings website) (see attached)
- Pacific States/BC Oil Spill Task Force (Sarah Brace)
  - Submerged Oil UW report Here>>http://crrc.unh.edu/sites/crrc.unh.edu/files/media/noaa_oil_sands_report_09.2013.pdf
  - Vessel Traffic Risk Assessment of North Puget Sound Here>> http://www.seas.gwu.edu/~dorpjr/tab4/publications_VTRA_Update_Reports.html
  - Developing a crude transport map exploring where crude (including oil sands products) is moving within the western states. This map is being completed later this month and will be published in our upcoming 2014 Annual Report. It's still in progress.
  - Annual meeting on October 1, 2014 on crude by rail state of policy and what transported and what resources at risk and 2 part series on crude by rail
  - Clean Pacific in late May or June 2015 will have some focus on crude by rail
- USCG, RDC (Kurt Hansen)
  - PHMSA at ICCOPR – oil in water column (BSEE funded); OHMSETT dispersant test
  - NAS Report is out with new report; PHMSA ICCOPR March minutes
  - Athos I Spill (see Alex Balsley's IOSC paper) (BSEE funded project) Here>> http://ioscproceedings.org/
  - Rivers Project GL Restoration Initiative
    - Oil Sands Products (lakes, rivers); risk assessment of barge, truck, rail etc.; 6 month project begins in Sept 2014

- CRRC (Nancy Kinner)
  - Bruce Hollebone project (from 2007 RFP) is finishing. Different types of oils and which factors cause sinking.
  - UNH oil flume project: Poster at IOSC
  - CRRC funded Ali Khelifa, Environment Canada, to study sediment/oil interactions. Here>>http://crrc.unh.edu/center-funded-projects

- ISCO (International Spill control Organization) (Mike Rancilio)
  - Submerged oil is now becoming bigger issue
  - Wants connection between contractors and experts
  - Sept 2014 Forum conduct between federal agencies, scientists contractors, industry, and other spill response folks
  - Possible site for submerged oil working group meeting

- NOAA (Glen Watabayashi)
  - Amy MacFadyen more 3D currents into GOODS for GNOME.
    GOODS = http://gnome.orr.noaa.gov/goods. This is the GNOME Online Data Server where we go to download winds, currents, and maps for GNOME. It is open to the public for free.
  - Dilbit fate when sinks in freshwater or seawater
  - Need more on Synbit chemistry
  - KinderMorgan report & Witt O'Brien Report were noted (not yet public)

- USCG (Sara Booth)
  - Submerged Oil is a very hot topic

- TXGLO (Steve Buschang)
  - New TABS buoy will be deployed this summer; purchased wave glider
  - If anyone has potential projects, please contact him

- US EPA (Ralph Dollhopf)
  - Kalamazoo River – have pretty good 2D and 3D modeling with Faith Fitzpatrick , Ken Lee, Michel Boufadel, etc. modeling is now helping operators at sites
  - Great Lakes and rivers oil gets into legacy contaminated sediments; have new chemistry to help determine whether Kalamazoo spill or other legacy spill
  - Need residual volume of submerged oil work
  - All Kalamazoo science is supported by Enbridge funding, as it winds down so does the funding
  - Ralph is writing a report on Kalamazoo River spill; finished in ~6 months
  - Link to Kalamazoo site>> http://www.epa.gov/enbridgespill/

- RPI, ASA (Debbie French McCay)
  - Orimulsion toxicity work
  - This is difficult to model
  - Here>> http://www.asascience.com/about/publications/pdf/2003/French-McCay-IOSC2003.pdf

- Instituto Superior Técnico, Lisbon University, Portugal (Rodrigo Fernedes)
  - Working on 3D models, but submerged oil is new issue; difficult to know SPM in water

- T&T Marine Salvage (Jim Elliott)
  - Looking at neutron backscatter techniques for detection

Next Submerged Oil Working Group Meeting: to be held in conjunction with Clean Gulf, 2014

Subsurface Oil and Waves in The Coastal Zone

Christopher H. Barker

February 13, 2014

Abstract

Over the last decade, there have been more and more oil spill responses effected by subsurface waves in the coastal zone. These have ranged from oil leaking from sunken ships to heavy oils that have sunk to the bottom. A primary example is the DBL 152 incident on the Gulf of Mexico coast in November, 2006. The incident resulted in approximately 70,000 barrels of Slurry Oil (API 4) being released and sinking to the bottom. Waves played a significant role in the mobilization of the oil on the bottom, in addition to effecting sediment loading in the subsurface, often restricting visibility and making ROV operations difficult.

Waves can also play a major role disturbing sunken ships, and evidenced by the S.S. Jacob Luckenbach, sunken off San Francisco during WWII. The ship was a source of occasional incidents of oiled birds washing ashore after certain winter storms. The oil on the ship was removed as part of a major remediation effort in the summer of 2002.

The oil spill response community will be more effective, particularly with subsurface oils, with a better understanding of the role of waves on the mobilization of sediment and other deposited substances (such as subsurface oil). This paper provides an overview of wave mechanics and the implications for subsurface oil movement and spill response activities, using examples from the DBL 152 and S.S. Jacob Luckenbach incidents. Shortcomings of current understanding are highlighted, with suggestions for future research offered.

1 Introduction

Over the last few years, there have been more and more oil spill responses effected by subsurface waves in the coastal zone. These have ranged from oil leaking from sunken ships to heavy oils that have sunk to the bottom. A primary example is the T/B DBL 152 incident on the Gulf of Mexico coast in November, 2006. The incident resulted in approximately 70,000 barrels of Slurry Oil (API 4) being released and sinking to the bottom. Waves played a significant role in the mobilization of the oil on the bottom, in addition to effecting sediment loading in the subsurface, often restricting visibility and making ROV operations difficult.

Waves can also play a major role in disturbing sunken ships, and evidenced by the SS Jacob Luckenbach, sunken off San Francisco during WWII. The ship was a source of occasional incidents of oiled birds washing ashore after certain winter storms. The oil on the ship was removed as part of a major remediation effort in the summer of 2002.

This paper provides an overview of ocean wave mechanics and the implications for subsurface oil movement and spill response activities, using examples from the T/B DBL 152, and S.S. Jacob Luckenbach.

2 Steady Wave Theory

The basis of much of our understanding of wave mechanics is based on so called steady wave theory. Steady waves are a idealization of the waves in the ocean. A steady wave is a wave that has a single wavelength and period, and is unchanged in form as it travels. It is called "steady", because when observed in a reference frame that is moving with the crest of the wave, it is unchanging in form. Fig. 1 is a schematic that shows the nomenclature of steady waves.

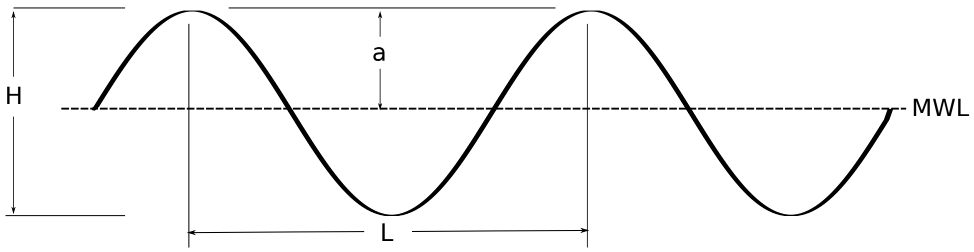


Figure 1: Schematic of a steady wave

In this figure, *a* is the wave amplitude, *H* is the wave height (twice the amplitude), *L* is the wave length: from crest to crest or trough to trough. If a water-level gage were to view this wave from a single point in space, the water surface would move up and down, tracing a similar path in time as this one in space. In this case, the time from crest to crest would be the wave period: T. Examining the behavior of this simplified version of waves, we can learn a lot about wave behavior and how they might influence oil in the environment.

2.1 Linear Wave Theory

Making the assumptions above for a wave train in water, with gravity as the primary restoring force driving the wave motion, leads to a simplified solution to the physics of the wave known as linear, or Airy, wave theory (Airy 1849),(Dean and Dalrymple 1991). Though encompassing many simplifications, this solution yields a great many insights into the behavior of waves in the ocean.

The form of the water surface from linear theory is a simple cosine function:

$$\eta(x,t) = a\cos(kx - \omega t) \tag{1}$$

where η is the water surface, x is the horizontal dimension, a is the wave amplitude, t is time, k is the wave number ($2\pi/L$), and ω is the wave frequency ($2\pi/T$).

This wave form satisfies the governing physics if and only if the wave frequency and wave number have the following relationship, know as the "dispersion relationship":

$$\omega^2 = gk\tanh(kh) \tag{2}$$

where g is the acceleration of gravity, and h is the water depth. This equation defines the relationship between the period of the wave and the wave length, and how that relationship is governed by the water depth.

2.2 Wave Speed

The wave speed (or celerity: C) is defined as:

$$C = \frac{\omega}{k} \tag{3}$$

and is influenced by the water depth. In deep water, when h and k are both large (wavelength is short: the depth is much larger than the wave length,

$\tanh(kh)$ is one, so $\omega^2 = gk$ and $C = \sqrt{g/k}$ or $C = g/\omega$: the wave speed increasing with increasing wave length and increasing wave period, but is not influenced by the water depth.

In shallow water, where $h \ll L$, $\tanh(kh) \approx kh$, so:

$$\omega^2 = gk^2 h \tag{4}$$

which leads to $C = \sqrt{gh}$: the wave speed decreases as the water gets shallower, and is dependent only on the water depth.

2.3 Wave Kinematics

Linear wave theory supplies an expression for the complete kinematics of the wave: how the water moves as the wave passes by:

$$u(x,z,t) = a\omega \frac{\cosh(k(h+z))}{\sinh(kh)} \cos(kx - \omega t) \tag{5}$$

where u is the horizontal component of the velocity, and z is the vertical coordinate (zero at the mean water level and positive-up).

$$v(x,z,t) = a\omega \frac{\sinh(k(h+z))}{\sinh(kh)} \sin(kx - \omega t) \tag{6}$$

where v is the vertical velocity. These expressions can tell us a great deal about how the water moves under waves, and how it may influence oil on or near the bottom. The time dependence is a cosine for the horizontal velocity, and a sine for the vertical, thus producing an ellipsoidal motion in the water as the wave passes over. The vertical velocities (v) dependence on z is the hyperbolic sin function, which goes to zero as z approaches h. i.e. there is no vertical motion at the bottom, which is the result of a defined boundary condition. The dependence on z for the horizontal motion is governed by hyperbolic cosine, which has a value of one when z approaches h: there is a horizontal motion at the bottom, governed by the $sinh(kh)$ term in the numerator – i.e. depending on the water depth.

2.3.1 The effects of depth

We can see from eqs. 5 and 6 that the velocity depends strongly on the $sinh(kh)$. kh can also be expressed as $2\pi h/T$, so is a measure of the water depth relative to the wave length. The hyperbolic sin function starts at zero, and increases exponentially with its argument, or, in this case with relative water depth. So in deep water, the water velocities decay rapidly with depth.

In shallow water, the vertical velocity decays rapidly as it approaches the bottom, but the horizontal velocity remains fairly constant.

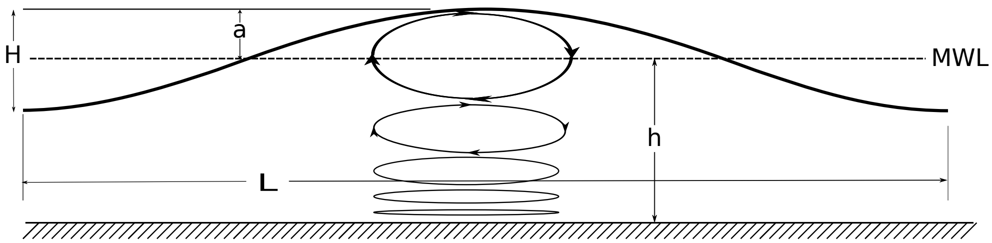


Figure 2: Schematic of the velocity under a shallow wave

Figure 2 is a schematic of the motion under a wave in shallow water. Note how the horizontal motion is fairly constant with depth, but the vertical motion is damped by the bottom, such that at the bottom the motion is purely horizontal. Note also that the range of the horizontal motion, and thus the maximum velocity is scaled by the wave height (the *a* in eq. 5.

In deep water, the waves do not "feel" the bottom, and the motions remain circular, but decay in amplitude with depth. Below about one half of a wavelength in depth, there is virtually no motion.

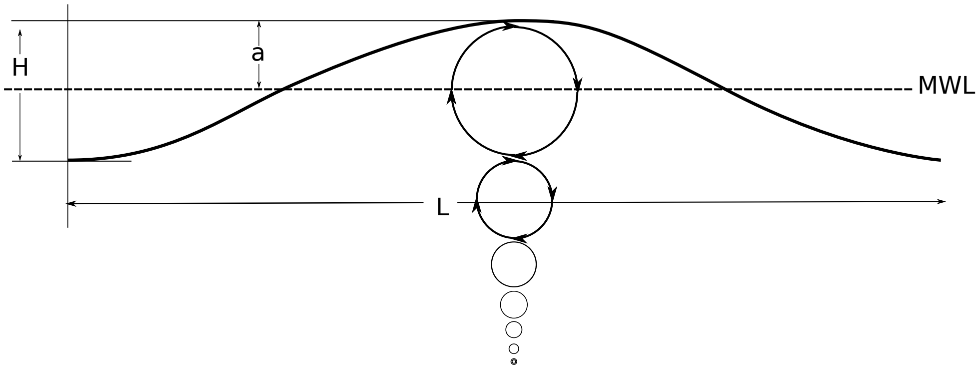


Figure 3: Schematic of the velocity under a deep wave

Most important is that "deep" and "shallow" are relative terms, scaled by the wavelength of the waves. So a "deep" wave will behave as a shallow wave as it approaches shallower water. The wave begins to “feel” the bottom when h/L is less than about 1/2. Deeper than this, the waves do not interact with the bottom, shallower than this, they do.

Similarly, at a single location in space, in a single depth of water, short wavelength (short period) waves do not interact with the bottom, but longer wavelength waves do. This is critical to understanding the intermittent effects that waves can have on oil or wrecked vessels on the sea floor.

2.4 Wave Energy

The total energy in the wave is a combination of both kinetic and potential energy, and sums up to:

$$\frac{1}{2}\rho g a^2 \qquad \text{or} \qquad \frac{1}{8}\rho g H^2 \tag{7}$$

where ρ is the density of the water. Note that the total energy in the wave scales with the square of the wave height – a wave with twice the height will contain four times as much energy.

Similarly to energy, the mean square velocity at the bottom is given as:

$$\overline{u_b^2} = \frac{gka^2}{\sinh(2kh)} \tag{8}$$

Also scaling with amplitude squared and the relative depth: kh.

3 Real Sea States

The previous analysis is all for a simple, single period steady wave. However, the ocean surface is never so simple. Rather it is a combination of many individual waves, all of different heights, periods and moving in different directions. This complex motion of the surface is known as the sea state. In real sea states the individual waves interact with and influence one another. However, the simplified mathematical description of a single linear steady wave given above allows a complex sea state to be described in terms linear superposition: that is, a number of individual waves overlapping, but not effecting one another.

3.1 The Spectral Description

Describing a complex sea state as the superposition of a number of individual waves leads directly to a spectral description of a real sea state. The

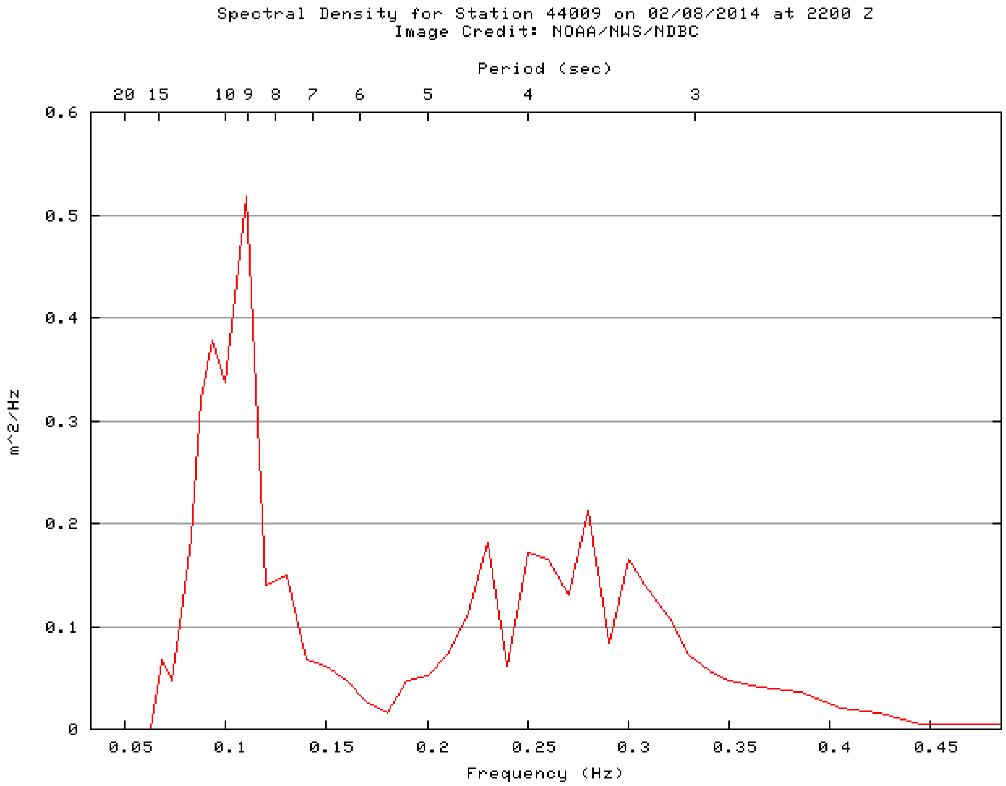


Figure 4: Spectral Density plot for a buoy off the coast of Delaware in Feb, 2013.

spectrum of the sea state is derived from measurements of the movement of the water surface (NDBC 2013), and is described in terms of “spectral density” – essentially the variance of the water surface location as a function of frequency. The spectral density is a measure of energy in the wave at each frequency. Some wave measurement devices can measure direction as well, in which case the spectral density is defined in terms of both frequency and direction. Figure 4 is a wave spectrum plot of the National Data Buoy Center for a buoy off the coast of Delaware for February 9, 2013. Note the peak of energy near the frequency of 0.1 Hz (10 sec. period). This means that there are relatively high waves with a period of about 10 seconds. There is also a wider peak surrounding the periods of around 4 seconds. The ten second waves are often describes as swell, and were probably generated by a weather event in the Atlantic removed from that location, whereas the waves with periods around 4 seconds would be describes as seas, and were likely generated by the local winds.

In the event of oil spills, wave spectra similar to this may be available in near-real time locally, and can provide the information to help determine how local waves may effect subsurface spills. The spectrum provides information as to how much energy is in each frequency of wave at the surface, and by assuming super-position of individual waves, the spectrum can be transformed to determine the energy near the bottom.

4 Mobilization of Oil

Most of the petroleum products, both crude oils and fuel oils, shipped are lighter than water, and thus float. Thus the oil spill response community has a great deal of experience with oil floating on the surface of the sea, and how it spreads, weathers, and is transported by winds, waves and currents. However there is a increase in the shipping of very heavy oils that may sink and end up at the bottom, as well as an increase in concern about the leaking of oil from wrecked ships that have been slowly decaying (Symons, Wagner, and Helton 2013).

At depth, ocean currents tend to be smaller near the bottom, as well as fairly steady. So if there is enough energy in the currents to mobilize the oil, the oil will tend to move with the currents. While difficult to track, the net motion is fairly well understood, if the current regime can be understood. However, if the currents are not enough to mobilize the oil, the it may take an extra burst of energy to mobilize oil on the bottom, and once mobilized, the oil can move with the ambient currents. As discussed above, depending on the frequency of waves and the water depth, wave motion can drive substantial oscillating currents near the ocean floor that may serve to mobilize the oil. The mobilization energy will be function of the water depth and energy in wave spectrum at the surface.

The total energy required to mobilize a given oil is not well understood, but we can draw understanding from the substantial literature on sediment transport under waves (Simecek-Beatty 2007). In the case of sediments, the mobilization energy can be determined by determination of the critical shear stress, as represented by the Shields parameter:

$$\frac{\tau}{(\rho_s - \rho)gD} \tag{9}$$

where τ is the shear stress at the bed, ρ_s is the density of the sediment, ρ is the density of the water, g is the acceleration of gravity, and D is the diameter of the sediment grains. In the case of oil, there is no grain diameter, but we expect that the mobilization will be a function of shear stress at the bed, relative density of the oil, and perhaps the viscosity and surface tension of the oil in place of the sediment diameter. While additional research is needed to determine those relationships, we do expect that the mobilization of a particular oil will be a function of the sheer stress, which is directly related to the kinetic energy available from the flow, or, in this case, form the oscillatory motion of the waves. Thus we may be able to determine the wave climate required for mobilization of oil in a particular case from observations.

5 Examples

5.1 S.S. Jacob Luckenbach

For a couple of years in the early 2000s, there were periodic reports of "mystery spills", often manifested by the discovery of a number of oiled birds washing up on the coast of California, south of San Francisco Bay. These events generally occurred in the winter months, and were usually accompanied by strong onshore winds. However, not every onshore wind event was followed by the discovery of oiled birds. The events were similar enough that it was likely that they were connected, but the connection was unclear. During one of these events, a source was identified.

The S.S. Jacob Luckenbach collided with her sister ship and sank on July 14, 1953. This vessel, was loaded with 457,000 gallons of bunker fueland sank in 180 feet of water approximately 17 miles west-southwest of San

Francisco. It turns out it had been leaking sporadically over the years and was associated with several of the identified "mystery spills" in 2002 and earlier. On May 2, 2002, an oil removal plan was accepted by the Unified Command and oil removal operations commenced on May 25, 2002, and were complete by the end of that summer.

Once identified, it was fairly clear that the Luckenbach was the source of oil in these events. However, it was not leaking consistently, nor did it correlate directly with particular wind conditions. What might have caused the vessel to leak at these particular times?

The vessel was resting on the bottom at a depth of 54 meters. Could waves be reaching down this far and disturbing the vessel? As discussed above, the depth at which the motion of the waves interacts with the bottom is a function of the wave length of the waves – the motion of the waves tends to reach down to about 1/2 the wavelength of the waves. So waves with a wavelength longer than about 100 meters might be able to disturb the vessel on the bottom. From equation 2 it can be determined that in that water depth, waves with a frequency of less than 0.7 s_{-1} (or a period longer than 8.4 seconds) could have an effect on the ship. Only about 4% of the energy from an 8 second wave would be felt at the bottom, but for waves with longer periods, there could be substantial movement. Particularly when there are winter storms in the north pacific, substantial swell with longer periods are fairly common in that region.

For example, on February 26th of 2002, there was a significant wave event, recorded by a wave buoy situated off Pt Reyes, CA, operated by the Scripts Institute of Oceanography (`http://cdip.ucsd.edu/?nav=historic&sub=data&stn=029&stream=p1`). Examining the peak wave period data from that location reveals a peak period of around 20 seconds. Looking at the wave spectrum data at that time, the energy in the 18-22 second band was as high as 2252 cm^2. This corresponds to a surface wave height of about 1.34 meters, with a period of 20 seconds, and a wave length of 418 meters in 54 meters of water, the depth at the Luckenbach.

This wave would be felt on the bottom, by the ship, as a sloshing back and forth with a movement of .88 meter, over the 20 second period of the wave. The maximum velocity reached would be about .14 m/s (about .3 knot). This is probably enough motion to rock the ship, perhaps enough to stimulate it to release some fuel. It is likely that the periodic releases from the S.S. Luckenback were caused by such wave events.

5.2 DBL 152

On November 11, 2005, the tank barge DBL 152 allided with a drilling rig that sank during Hurricane Rita. As a result, the barge spilled an estimated 70,000 bbls (close to 3 million gallons) of "slurry oil", an oil with an unusual combination of properties (high density, low viscosity) compared with oils more commonly encountered in spills.[1] A large portion of the released oil sank to the sea floor to form large discrete mats in many areas and smaller globules in others. Observational data suggest that oil remained in two areas of heavier concentration until a series of storms apparently redistributed the oil (Beegle-Krause, Barker, Watabayashi, and Lehr 2006).

Events at the T/B DBL 152 site have given us useful insight into how waves affected the oil on the bottom. Observations on November 20th indicated a couple of large pools of oil on the bottom, including oil in the trench scoured by the barge after the accident. Observations on November 30th indicated that much of the oil had either moved or dissipated. It is likely that the oil was mobilized by wave energy.

In the location of the wreck, the water depth is about 15 m (50 feet), as waves are felt down to a depth of about 1/2 the wavelength, we can apply eq. 2, and determine that waves with a period of greater than about 4.5 seconds will effect the bottom. NOAA National Data Buoy Center (NDBC) wave buoys report the wave energy spectrum at the surface. These data indicate how much energy is in the waves for each period band at a given time, are available in real time, and have been archived for a number of years.

Analysis of these data from NDBC wave buoys in the region indicates that there were two substantial wave events between the grounding of the vessel and November 30th: November 14-19th and November 26-29th. The November 29th incident was the larger of the two. As the oil was in place on November 20th, but had moved or dissipated substantially by November 30th, we conclude that the wave energy during the earlier event was not enough to mobilize the oil, and the energy in the later event exceeded the threshold for mobilizing the oil.

To assess the wave energy at the bottom, the surface spectrum is transformed by scaling each frequency according to how it decays with depth, and then adding up the individual energy totals to obtain the total wave energy at the bottom.

The kinetic energy scales with the square of the amplitude of the oscil-

---

[1] A slurry oil is a low API gravity, low viscosity oil created by mixing different slurry oils "in line" to meet a product API gravity. The destination tank is filled from the bottom and the lightest oil in the mixture is added last to aid in mixing (NOAA 2005).

lation, so energy at the bottom is:

$$E_b = \frac{E_s}{\sinh(kh)^2} \tag{10}$$

where E_b is the energy at the bottom, and E_s is the energy at the surface. E_s is provided for each wave period band by the NDBC wave spectrum data. By scaling the energy in each wave period bin in a spectrum according to the appropriate wave number for that period and the water depth, and summing the results, we get an estimate for the total wave kinetic energy at the bottom.

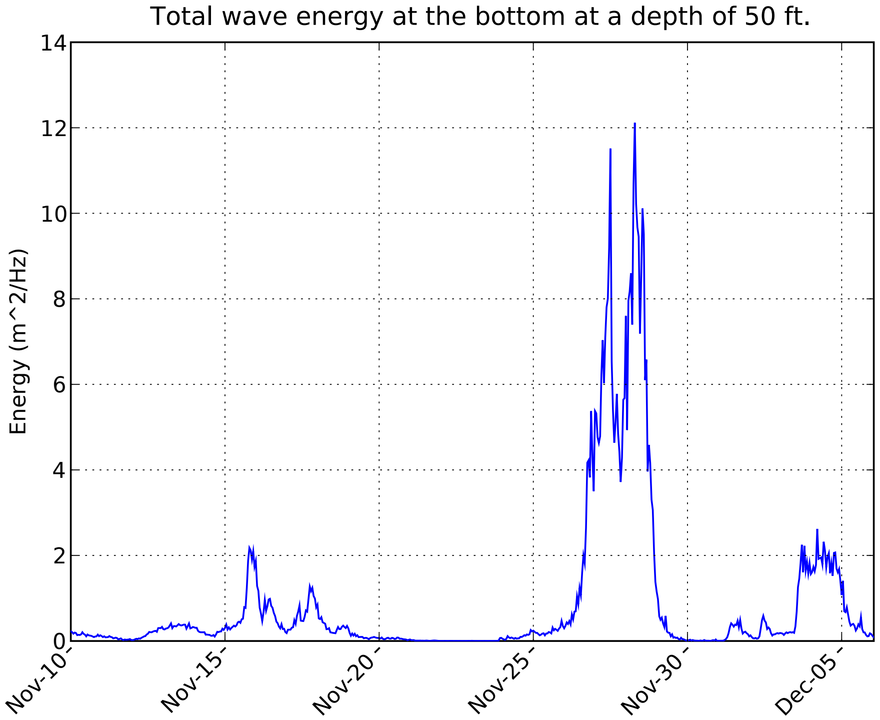


Figure 5: Bottom wave energy based on NDBC Buoy 42035 for November 2005 transformed to the depth of grounded vessel (50 ft)

This analysis has been done for the month of November 2005 and for the archived data from 2004. The data are from the most representative buoy available, NDBC buoy 42035, just south of Galveston Bay. That buoy is about 30 miles west of the incident site, and 15 miles closer to shore, in about 45 feet of water. We expect the wave conditions there to be similar, though it may report less wave energy from north winds. As the North winds have smaller fetch, they tend to result in less energy at longer periods, and thus have less effect at the bottom. A plot of the wave energy at the bottom in 50 feet of water is given in Fig. 5.2.

Two wave events are clear, one between November 14th and 19th, and a second one between November 26th and 29th. This indicates that a bottom energy of 2 m^2/Hz (square meters per hertz) was not enough to mobilize the oil, but an energy between 2 and 12 m^2/Hz was enough to mobilize the oil. The exact required energy is unknown, but from the plot we have estimated that 6 m^2/Hz was exceeded for a substantial period of time and may be a reasonable estimate for the energy level required to break up and mobilize the oil.

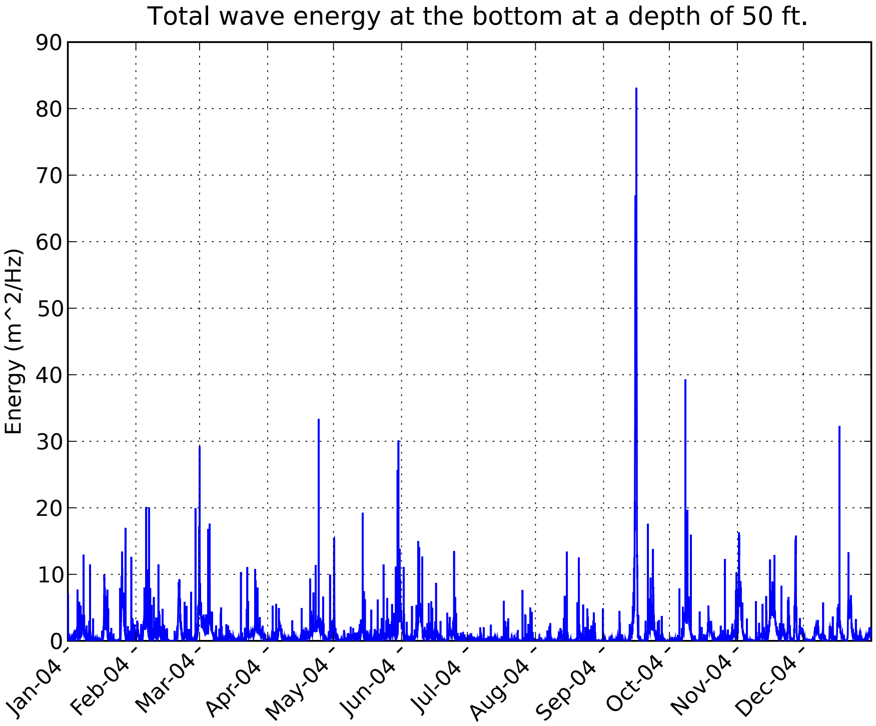


Figure 6: Bottom wave energy based on NDBC Buoy 42035 transformed to depth of grounded vessel (50 ft) for the year 2004

The bottom energy for the entire year 2004 can be seen in Fig. 5.2. Clearly energy levels above 6 m^2/Hz are quite common. (The large en-

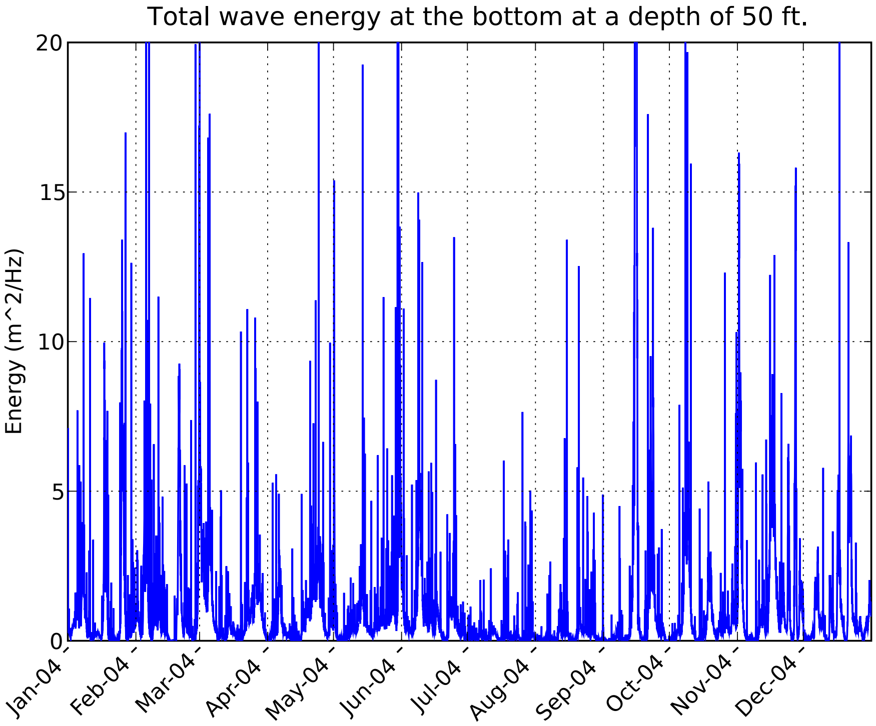


Figure 7: Bottom wave energy based on NDBC Buoy 42035 transformed to depth of grounded vessel (50 ft) for the year 2004. This is a close-up of the lower energy levels in Fig. 5.2

ergy spike in September is Hurricane Ivan.) Lastly, Fig. 5.2 is the 2004 data scaled to see the lower energy events better. This plot clearly indicates periods of bottom wave energy level exceeding 6 m^2/Hz (or even 12 m^2/Hz) are very common. In 2004, the energy level was above 6 m^2/Hz for a total of 240 hours (about 3% of the time). This particular value is specific to the DBL-152 oil – oils with different properties may require different energies to mobilize. However, this analysis indicates that over the course of a year, there are likely to be many wave events large enough to mobilize and distribute oil on the bottom in this depth of water.

6 Conclusion

There are a number of reasons for oil spill responders to be concerned about the effects of ocean waves near the bottom of the sea. A understanding of wave mechanics, and how the effects of waves are changed by water depth and wave frequency can help guide our understanding of two important classes of events important to the response community.

There is growing concern about historical wrecks that may start to leak oil – these wrecks may be effected by the wave climate under certain conditions. Depending on the depth at which the wreck sits, and the wave climate in the region, the wrecks may be periodically jostled by the waves, leading to otherwise unexplained intermittent "mystery spill" events. This appears to have been the case with the S.S. Jakob Luckenbach. Assessment of the wave forces on wrecks should be a part of the analysis of the threat from other wrecks being considered.

In addition to wrecks, there are more and more heavy fuel oil products being used and shipped throughout the world. These oils may well sink, challenging the response community to develop effective methods of response (CRRC 2007). Effectiveness of response efforts will be hampered or aided by our understanding of the mobilization and transport of oil on the bottom. Clearly wave action plays a role in such mobilization, and the analysis presented here provides a framework for thinking about the issues.

The example of the DBL-152 incident provided a way to scale the wave energy required to mobilize that particular oil in that particular incident. However a framework for assessing any other future incident is still not available: How much wave energy does it take to mobilize oil on the bottom? How is the energy effected by the oil type, specifically density, viscosity, and surface tension? Is the nature of the bottom a significant consideration as well? The response community would be well served by future research into these issues.

References

Airy, G. B. (1849). Tides and waves. In *Encyclopaedia Metropolitania*, pp. 241–396. London: J.J. Griffin. Re-issue, initially published in 1845.

Beegle-Krause, C., C. H. Barker, G. Watabayashi, and W. Lehr (2006). Long-term transport of oil from t/b dbl-152: Lessons learned for oils heavier than seawater. In *Proceedings of the Twenty-Ninth Arctic and Marine Oil spill Program (AMOP) Technical Seminar*, Ottawa, ON. Environment Canada.

CRRC (2007). Submerged oil state of the practice and research needs. Technical report, Coastal Response Research Center, Durham, NH. `http://www.crrc.unh.edu/sites/crrc.unh.edu/files/media/docs/Workshops/submerged_oil/submerged_oil_workshop_report.pdf`.

Dean, R. G. and R. A. Dalrymple (1991). *Water Wave Mechanics for Engineers and Scientists*. World Scientific.

NDBC (2013, February). How are spectral wave data derived from buoy motion measurements? National Data Buoy Center web site: `http://www.ndbc.noaa.gov/wave.shtml`.

NOAA (2005). Interview with Joe Dwyer of the Houston Fuel Oil Terminal Co. regarding T/B DBL-152 oil loading history and density. personal communication. NOAA Incident News: `http://incidentnews.noaa.gov/entry/1997`.

Simecek-Beatty, D. (2007, June). A proposed method for computing resuspension of submerged oil. In *Proceedings of the Thirtieth Arctic and Marine Oil spill Program (AMOP) Technical Seminar*, Edmonton, Alberta, pp. 755–768. Environment Canada, Ontario, Canada.

Symons, L., J. Wagner, and D. Helton (2013). Risk assessment for potentially polluting wrecks in u.s. waters. Technical report, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries and Office of Response and Restoration, Silver Spring, MD. `http://sanctuaries.noaa.gov/protect/ppw/pdfs/2013_potentiallypollutingwrecks.pdf`.

Subsurface Oil and Waves in The Coastal Zone

Christopher H. Barker

Chris.Barker@noaa.gov

NOAA | Office of Response and Restoration | Emergency Response Division

Introduction

Over the last few years, there have been more and more oil spill responses effected by subsurface waves in the coastal zone. These have ranged from oil leaking from sunken ships to heavy oils that have sunk to the bottom. A primary example is the T/B DBL 152 incident on the Gulf of Mexico coast in November, 2006. The incident resulted in approximately 70,000 barrels of Slurry Oil (API 4) being released and sinking to the bottom. Waves played a significant role in the mobilization of the oil on the bottom, in addition to effecting sediment loading in the subsurface, often restricting visibility and making ROV operations difficult.

Waves can also play a major role in disturbing sunken ships, and evidenced by the SS Jacob Luckenbach, sunken off San Francisco during WWII. The ship was a source of occasional incidents of oiled birds washing ashore after certain winter storms. The oil on the ship was removed as part of a major remediation effort in the summer of 2002.

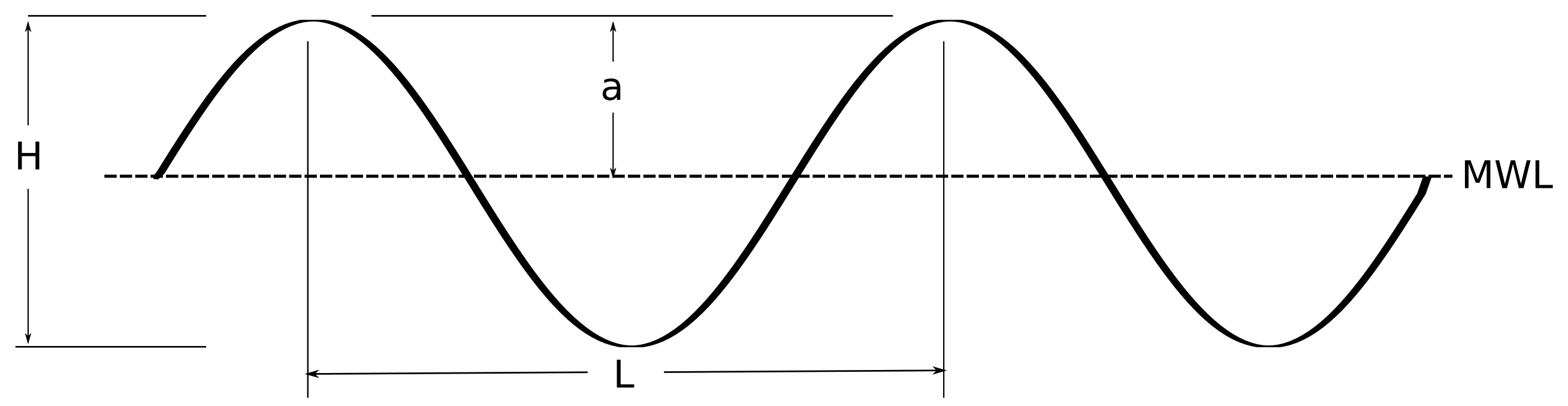


Figure 1. Schematic of a steady wave

Linear Wave Theory

Making the assumptions above for a wave train in water leads to a simplified solution to the physics of the wave known as linear wave theory.

The form of the water surface from linear theory is a simple cosine function:

$$\eta(x,t) = a\cos(kx - \omega t)$$

where η is the water surface, x is the horizontal dimension, a is the wave amplitude, t is time, k is the wave number ($2\pi/L$), and ω is the wave frequency ($2\pi/T$). This wave form satisfies the governing physics if and only if the wave frequency and wave number have the following relationship, know as the “dispersion relationship”:

$$\omega^2 = gk\tanh(kh)$$

where g is the acceleration of gravity, and h is the water depth. This equation defines the relationship between the period of the wave and the wave length, and how that relationship is governed by the water depth. The velocites as the wave passes by are given by:

$$u(x,z,t) = a\omega\frac{\cosh(k(h+z))}{\sinh(kh)}\cos(kx - \omega t)$$

where u is the horizontal component of the velocity, and z is the vertical coordinate (zero at the mean water level and positive-up).

$$v(x,z,t) = a\omega\frac{\sinh(k(h+z))}{\sinh(kh)}\sin(kx - \omega t)$$

where v is the vertical velocity. These expressions can tell us a great deal about how the water moves under waves, and how it may influence oil on or near the bottom. The time dependence is a cosine for the horizontal velocity, and a sine for the vertical, thus producing an ellipsoidal motion in the water as the wave passes over. The vertical velocity’s dependence on z is the hyperbolic sin function, which goes to zero as z approaches h. The dependence on z for the horizontal motion is governed by hyperbolic cosine, which has a value of one when z approaches h: there is a horizontal motion at the bottom, governed by the $sinh(kh)$ term in the numerator – i.e. depending on the water depth.

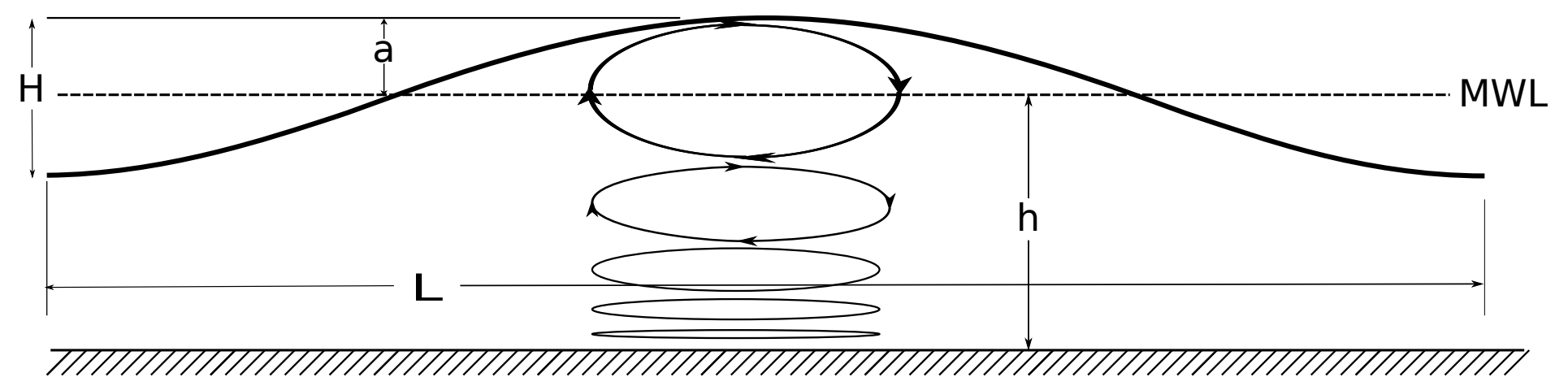


Figure 2. Orbital velocities under a shallow water wave

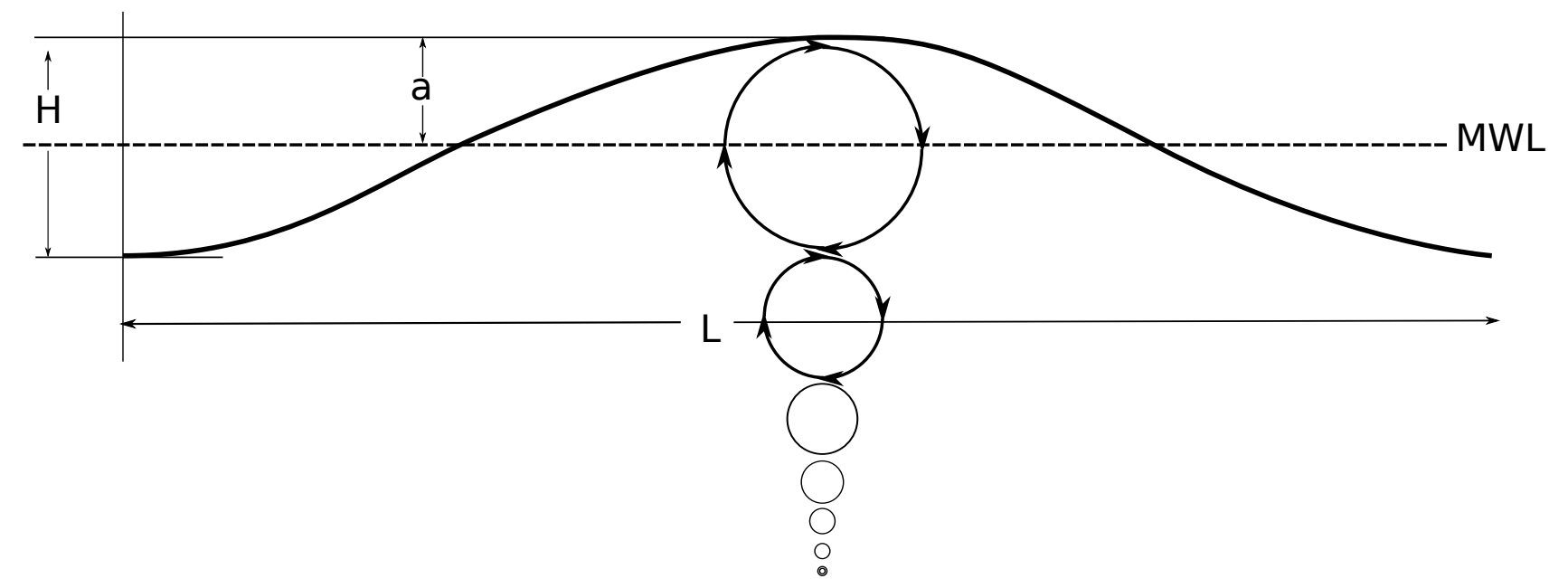


Figure 3. Orbital velocities under a deep water wave

Effects of Depth

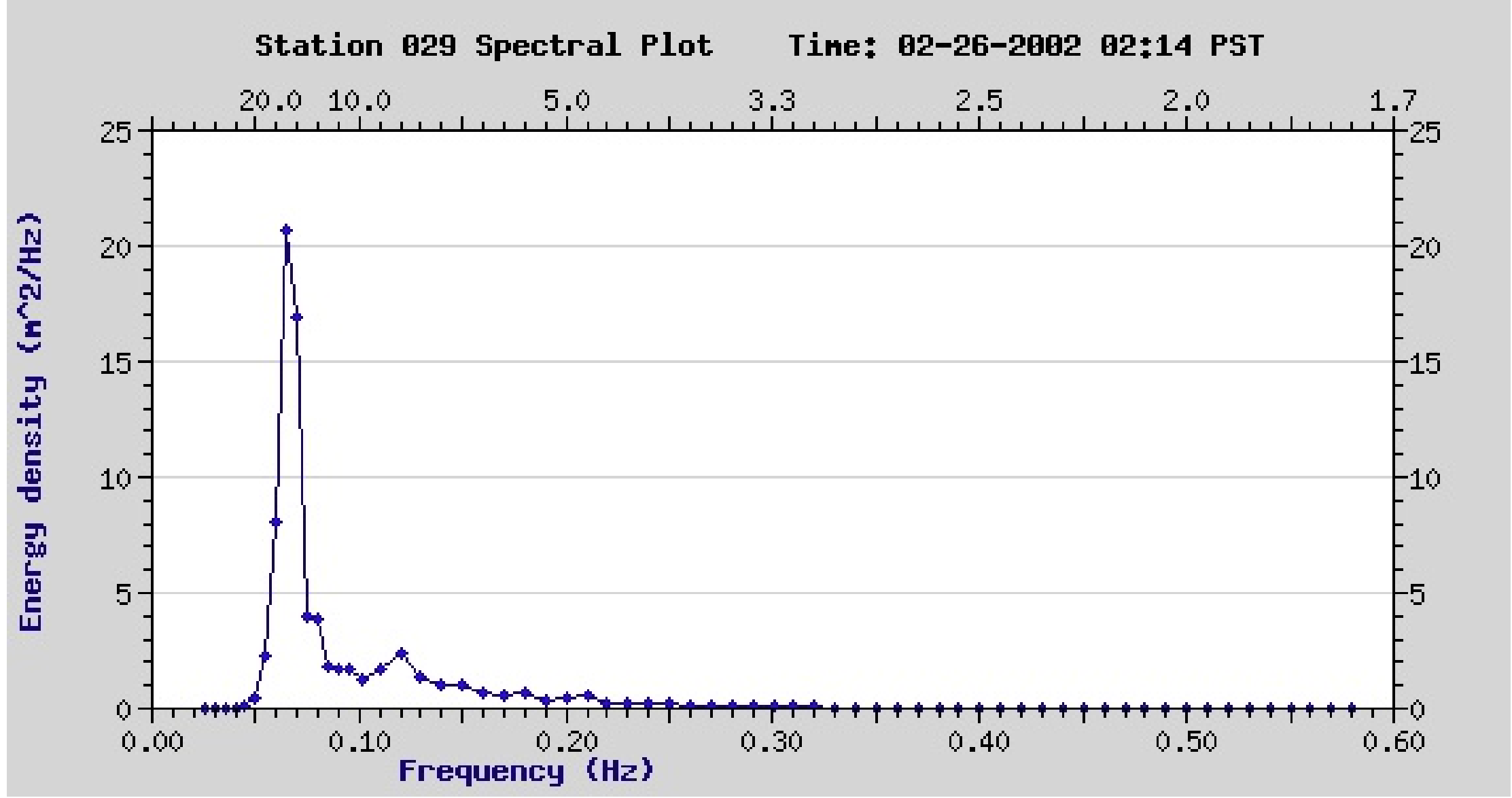
In deep water, the water velocities decay rapidly with depth. In shallow water, the vertical velocity decays rapidly as it approaches the bottom, but the horizontal velocity remains fairly constant.

In shallow water, the horizontal motion is fairly constant with depth, but the vertical motion is damped by the bottom. Note also that the range of the horizontal motion, and thus the maximum velocity is scaled by the wave height.

In deep water, the waves do not “feel” the bottom, and the motions remain circular, but decay in amplitude with depth. Below about one half of a wavelength in depth, there is virtually no motion.

Most important is that “deep” and “shallow” are relative terms, scaled by the wavelength of the waves. So a “deep” wave will behave as a shallow wave as it approaches shallower water. The wave begins to “feel” the bottom when h/L is less than about 1/2.

Figure 4. Wave specturm near the Luckenback: Feb 26, 2002. Note the peak at close to 20 s. period.



S.S. Jacob Luckenbach

The S.S. Jacob Luckenbach sank on July 14, 1953, loaded with 457,000 gallons of bunker fuel. It had been leaking sporadically over the years resulting in several identified “mystery spills” near San Francisco Bay in 2002 and earlier. What might have caused the vessel to leak at these particular times?

The vessel was resting on the bottom at a depth of 54 meters. Could waves be reaching down this far and disturbing the vessel? Waves with a wavelength longer than about 100 meters might be able to disturb the vessel on the bottom. In that water depth, waves with a frequency of less than 0.7 s^{-1} (or a period longer than 8.4 seconds) could have an effect on the ship. Only about 4% of the energy from an 8 second wave would be felt at the bottom, but for waves with longer periods, there could be substantial movement. Particularly when there are winter storms in the North Pacific, substantial swell with longer periods are fairly common in that region.

For example, on February 26th of 2002, there was a significant wave event, recorded by a wave buoy situated off Pt Reyes, CA, operated by the Scripts Institute of Oceanography. Examining the peak wave period data from that location (fig. 4) reveals a peak period of around 20 seconds. The energy in the 18-22 second band was as high as 2252cm^2. This corresponds to a surface wave height of about 1.34 meters, with a period of 20 seconds, and a wave length of 418 meters in 54 meters of water, the depth at the Luckenbach.

This wave would be felt on the bottom, by the ship, as a sloshing back and forth with a movement of .88 meter, over the 20 second period of the wave. The maximum velocity reached would be about .14 m/s (about .3 knot). This is probably enough motion to rock the ship, perhaps enough to stimulate it to release some fuel. It is likely that the periodic releases from the S.S. Luckenback were caused by such wave events.

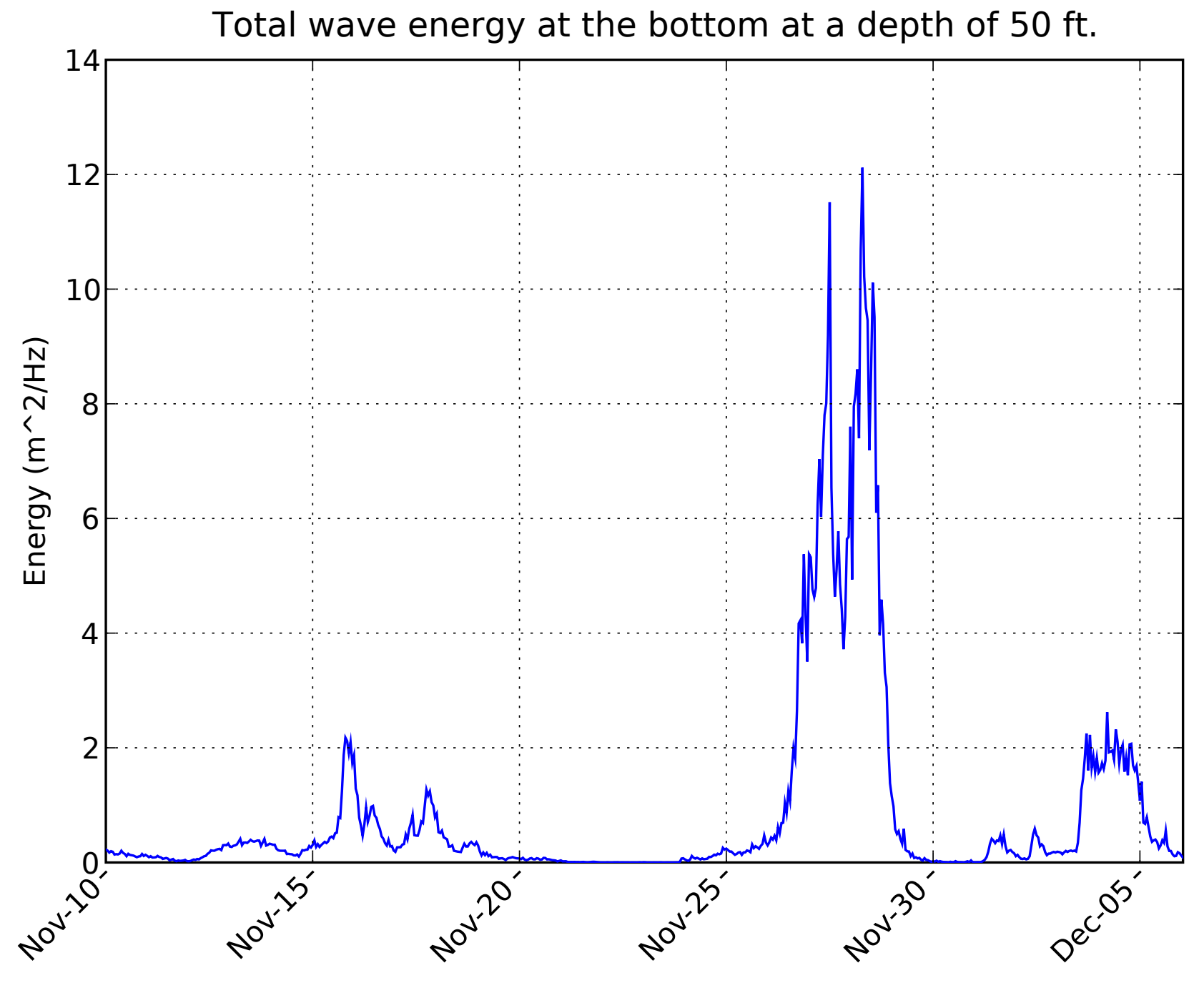


Figure 4. Bottom wave energy based on NDBC Buoy 42035 for November 2005.

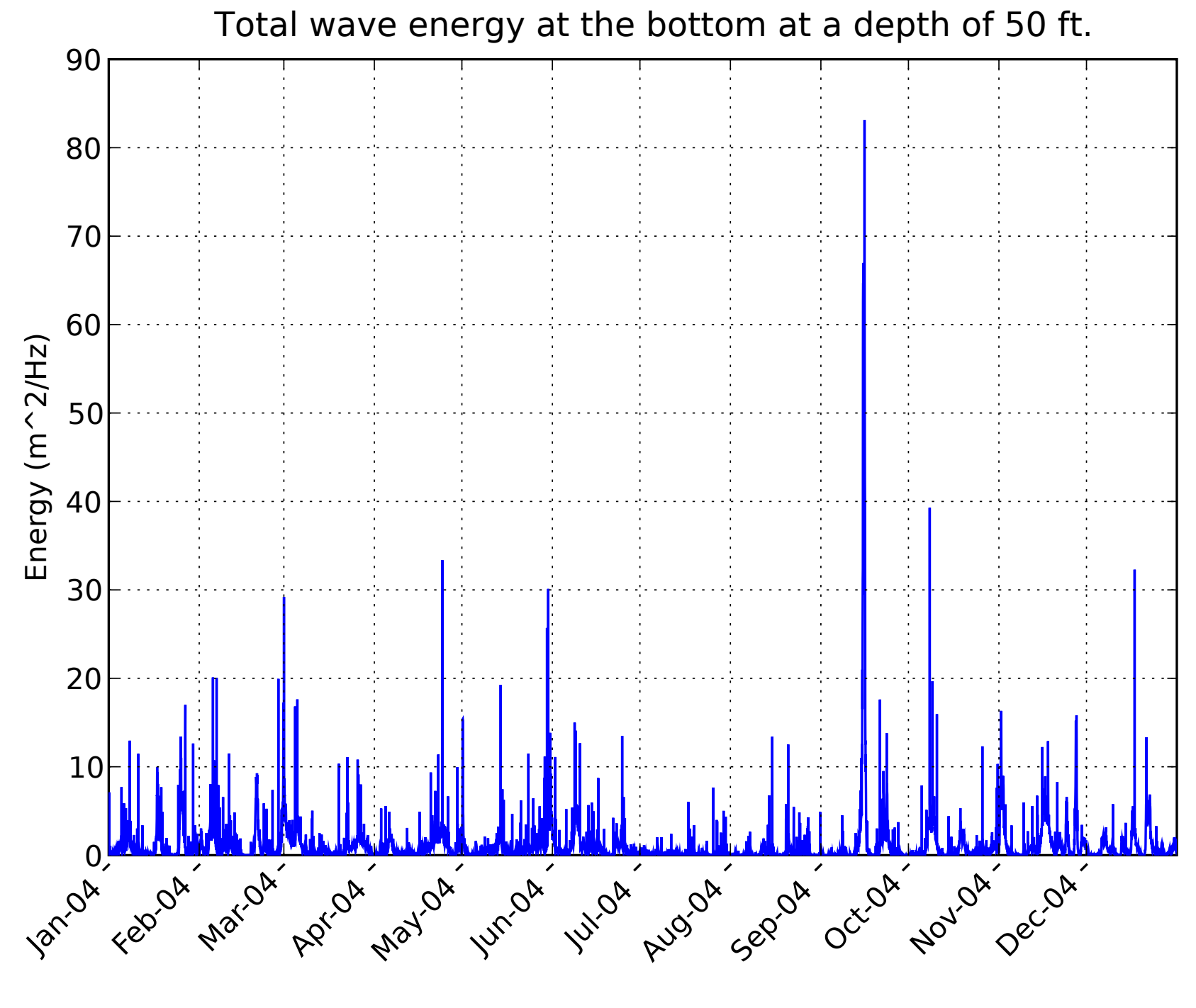


Figure 5. Bottom wave energy based on NDBC Buoy 42035 for the year 2004

DBL 152

On November 11, 2005, the tank barge DBL 152 allided with a drilling rig that sank during Hurricane Rita, spilling 70,000 bbls of “slurry oil”, an oil with high density but low viscosity. The oil sank to the sea floor, with observational data suggesting that oil remained in two areas of heavier concentration until a series of storms redistributed the oil.

Observations on November 20th indicated a couple of large pools of oil on the bottom. By November 30th much of the oil had either moved or dissipated. It is likely that the oil was mobilized by wave energy. In the location of the wreck, the water depth is about 15 m. As wave motion extends to a depth of about 1/2 the wavelength, waves with a period of greater than about 4.5 seconds will effect the bottom.

Analysis of wave spectrum data from NDBC wave buoys in the region indicate that there were two substantial wave events between the grounding of the vessel and November 30th: November 14-19th and November 26-29th (fig. 4). The November 29th incident was the larger of the two. As the oil was in place on November 20th, but had moved or dissipated substantially by November 30th, we conclude that the wave energy during the earlier event was not enough to mobilize the oil, but the energy in the later event exceeded the threshold for mobilizing the oil.

The kinetic energy in waves scales with the square of the amplitude of the oscillation, so energy at the bottom is:

$$E_b = \frac{E_s}{\sinh(kh)^2}$$

where E_b is the energy at the bottom, and E_s is the energy at the surface. E_s is provided for each wave period band by the NDBC wave spectrum data. Scaling the energy in each wave period bin in a spectrum according to the appropriate wave number for that period and the water depth, and summing the results, provides an estimate for the total wave kinetic energy at the bottom. This analysis has been done for the month of November 2005 and for the archived data from 2004. The data are from the most representative buoy available, NDBC buoy 42035, just south of Galveston Bay.

A plot of the wave energy at the bottom in 50 feet of water is given in fig. 4. Two wave events are clear, one between November 14th and 19th, and a second one between November 26th and 29th. This indicates that a bottom energy of 2 m^2/Hz (square meters per hertz) was not enough to mobilize the oil, but an energy between 2 and 12 m^2/Hz was enough to mobilize the oil. The exact required energy is unknown, but from the plot we have estimated that 6 m^2/Hz was exceeded for a substantial period of time and may be a reasonable estimate for the energy level required to break up and mobilize the oil.

The bottom energy for the entire year 2004 can be seen in fig. 5 (The large energy spike in September is Hurricane Ivan). In 2004, the energy level was above 6 m^2/Hz for a total of 240 hours (about 3% of the time). This particular value is specific to the DBL-152 oil – oils with different properties may require different energies to mobilize. However, this analysis indicates that over the course of a year, there are likely to be many wave events large enough to mobilize and distribute oil on the bottom in this depth of water.