Atlantic sediment cores. In: Suess E and Thiede J (eds) *Coastal Upwelling: 1st Sediment Record B*, pp. 365–398. New York: Plenum Press.
Paytan A and Kastner M (1996) Benthic Ba fluxes in the central equatorial Pacific, implications for the oceanic Ba cycle. *Earth and Planetary Science Letters* 142: 439–450.
Perks HM (1999) *Climatic and Oceanographic Controls on the Burial and Preservation of Organic Matter in Equatorial Pacific Deep-sea Sediments*. PhD thesis, University of California, San Diego.
Perks HM and Keeling RF (1998) A 400 kyr record of combustion oxygen demand in the western equatorial Pacific: Evidence for a precessionally forced climate response. *Paleoceanography* 13: 63–69.
Sarnthein M, Pflaumann U, Ross R, Tiedemann R and Winn K (1992) Transfer functions to reconstruct ocean paleoproductivity, a comparison. In: Summerhayes CP, Prell WL and Emeis KC (eds) *Upwelling Systems: Evolution Since the Early Miocene*. Geology Society Special Publication 64: 411–427.
Schneider RR (1991) *Spätquartäre Produktivitätsänderungen im östlichen Angola-Becken: Reaktion auf Variationen im Passat-Monsun-Windsystem und in der Advektion des Benguela-Küstenstroms*. Reports, Fachbereich Geowissenschaften, Universität Bremen.
Wefer G and Fischer G (1993) Seasonal patterns of vertical particle flux in equatorial and coastal upwelling areas of the eastern Atlantic. *Deep-Sea Research* 40: 1613–1645.
Wefer G, Berger WH, Siedler G and Webb D (eds) (1996) *The South Atlantic. Present and Past Circulation*. Berlin: Springer-Verlag.
Wefer G, Berger WH, Richter C *et al*. (1998) Proceedings Ocean Drilling Program Initial Reports Leg 175. College Station, TX (Ocean Drilling Program).
Wefer G, Berger WH, Bijma J and Fischer G (1999) Clues to ocean history: a brief overview of proxies. In: Fischer G and Wefer G (eds) *Use of Proxies in Paleoceanography. Examples from the South Atlantic*, pp. 1–68. Berlin: Springer-Verlag.

SEICHES

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Introduction

Seiches are resonant oscillations, or 'normal modes', of lakes and coastal waters; that is, they are standing waves with unique frequencies, 'eigenfrequencies', imposed by the dimensions of the basins in which they occur. For example, the basic behavior of a seiche in a rectangular basin is depicted in **Figure 1**. Each panel shows a snapshot of sea level and currents every quarter-period through one seiche cycle. Water moves back and forth across the basin in a periodic oscillation, alternately raising and lowering sea level at the basin sides. Sea level pivots about a 'node' in the middle of the basin at which the sea level never changes. Currents are maximum at the center (beneath the node) when the sea level is horizontal, and they vanish when the sea level is at its extremes.

Seiches can be excited by many diverse environmental phenomena such as seismic disturbances, internal and surface gravity waves (including other normal modes of adjoining basins), winds, and atmospheric pressure disturbances. Once excited, seiches are noticeable under ordinary conditions because of the periodic changes in water level or currents associated with them (**Figure 1**). At some locations and times, such sea-level oscillations and currents produce hazardous or even destructive conditions. Notable examples are the catastrophic seiches of Nagasaki Harbor in Japan that are locally known as 'abiki', and those of Ciutadella Harbor on Menorca Island in Spain, called 'rissaga'. At both locations extreme seiche-produced sea-level oscillations greater than 3 m have been reported. Although seiches in most harbors do not reach such heights, the currents associated with them can still be dangerous, and for this reason the study of coastal and harbor seiches and their causes is of practical significance to harbor management and design. In this article we place emphasis on marine seiches, especially those in coastal and harbor waters.

History

In 1781, J. L. Lagrange found that the propagation velocity of a 'long' water wave (one whose wavelength is long compared to the water depth h) is given by $(gh)^{1/2}$, where g is gravitational acceleration. Merian showed in 1828 that such a wave, reflecting back and forth from the ends of a closed rectangular basin of length L, produces a standing wave with a period T, given by

$$T = \frac{2L}{n(gh)^{1/2}} \qquad [1]$$

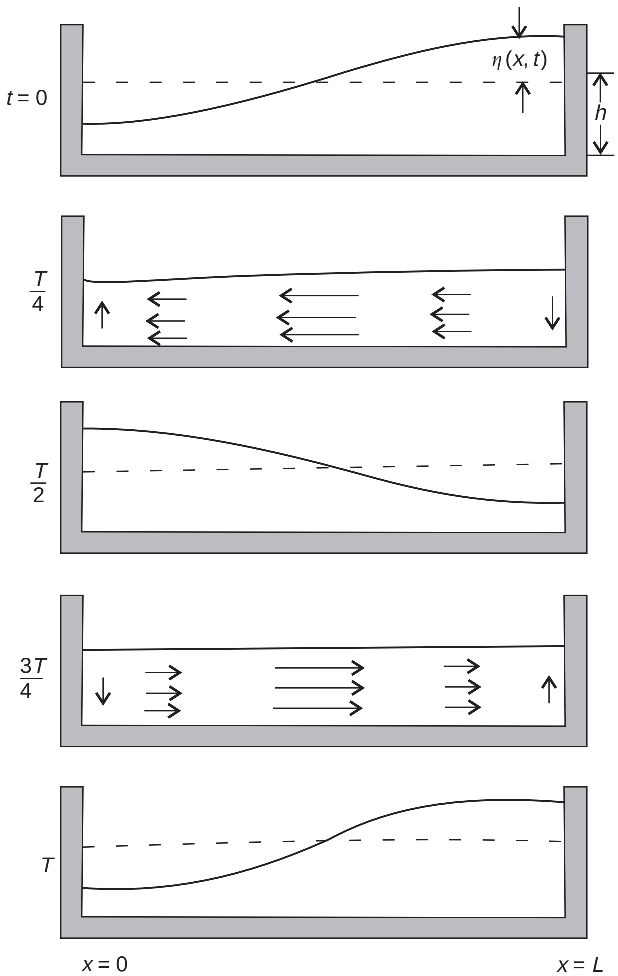

Figure 1 Diagram of a mode-one seiche oscillation in a closed basin through one period *T*. Panels show the sea surface and currents (arrows) each quarter-period. The basin length is *L*. The undisturbed water depth is *h*, and the deviation from this depth is denoted by η. Note the node at $x = L/2$ where the sea surface never moves (i.e. $\eta = 0$).

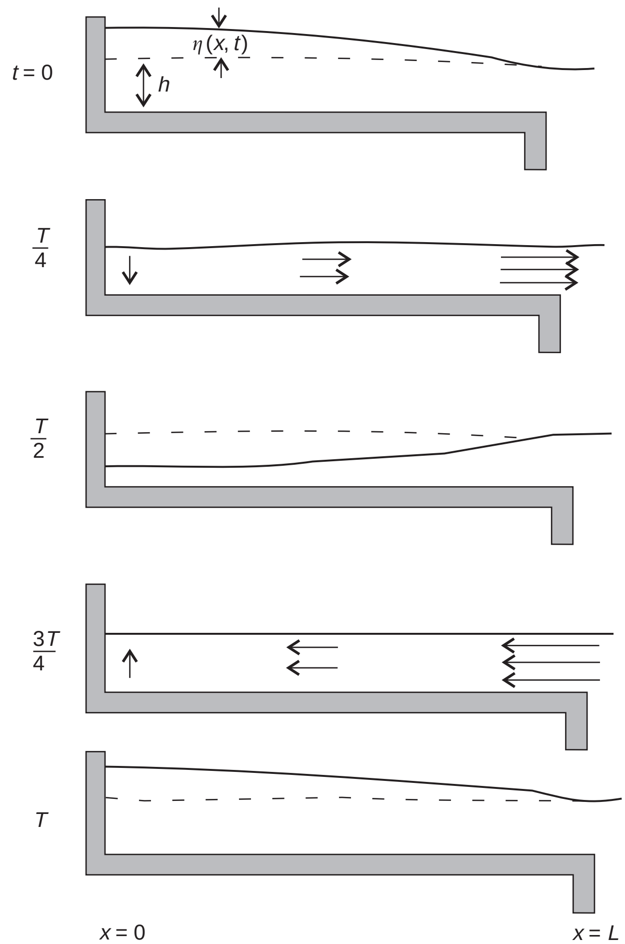

Figure 2 Diagram of a seiche oscillation in a partially open basin through one period *T*. Panels show the sea surface and currents (arrows) each quarter-period. The basin length is *L* with the open end at $x = L$. The undisturbed water depth is *h*, and the deviation from this depth is denoted by η. Note that the node (where $\eta = 0$) is located at the open end.

where $n = 1, 2, 3, \ldots$ is the number of nodes of the wave (**Figure 1**) and designates the 'harmonic mode' of the oscillation. Eqn [1] is known as Merian's formula.

F. A. Forel, between 1869 and 1895, applied Merian's formula with much success to Swiss lakes, in particular Lake Geneva, the oscillations of which had long been recognized by local inhabitants who referred to them as 'seiches', apparently from the Latin word 'siccus' meaning 'dry'. Forel's seiche studies were of great interest to scientists around the world and by the turn of the century many were contributing to descriptive and theoretical aspects of the phenomenon. Perhaps most noteworthy was G. Chrystal who, in 1904 and 1905, developed a comprehensive analytical theory of free oscillations in closed basins of complex form.

By the end of the nineteenth century, it was widely recognized that seiches also occurred in open basins, such as harbors and coastal bays, either as lateral oscillations reflecting from side-to-side across the basin, or more frequently, as longitudinal oscillations between the basin head and mouth. Longitudinal harbor oscillations are dynamically equivalent to lake seiches with a node at the open mouth (**Figure 2**), and a modified version of Merian's formula for such open basins gives the period as

$$T = \frac{4L}{(2n - 1)(gh)^{1/2}} \qquad [2]$$

where $n = 1, 2, 3, \ldots$. The dynamics leading to both eqns [1] and [2] are discussed below.

Interest in coastal seiches was fanned by the development of highly accurate mechanical tide recorders (*see* **Tides**) which frequently revealed surprisingly regular higher-frequency or 'secondary' oscillations in addition to ordinary tides. Even greater motivation was provided by F. Omori's observation, reported in 1900, that the periods of destructive sea waves (*see* **Tsunamis**) in harbors were often the same as those of the ordinary 'secondary waves' in those same harbors. This led directly to a major field, laboratory, and theoretical study that was carried out in Japan from 1903 through 1906 by K. Honda, T. Terada, Y. Yoshida, and D. Isitani, who concluded that coastal bays can be likened to a series of resonators, all excited by the same sea with its many frequencies of motion, but each oscillating at its own particular frequencies – the seiche frequencies.

Most twentieth century seiche research can be traced back to problems or processes recognized in the important work of Honda and his colleagues. In particular, it became widely accepted that most coastal and harbor seiching is forced by open sea processes. A. Defant developed numerical modeling techniques which modern computers have made very efficient, and B. W. Wilson applied the theory to ocean engineering problems. Many others have made major contributions during the twentieth century.

Dynamics

The dynamics of seiches are easiest to understand by considering several idealized situations with simplified physics. More complex geometries and physics have been considered in seiche studies, but the basic features developed here apply qualitatively to those studies.

In a basin in which the water depth is much smaller than the basin length, fluid motions may be described by the depth-averaged velocity u and the deviation of the sea surface from its resting position η. Changes in these quantities are related through momentum and mass conservation equations:

$$\frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} - ru \qquad [3]$$

$$\frac{\partial \eta}{\partial t} + h\frac{\partial u}{\partial x} = 0 \qquad [4]$$

in which h is the fluid depth at rest, r is a coefficient of frictional damping, g is gravitational acceleration, x is the horizontal distance and t is time (see **Figure 1**). Nonlinear and rotation effects have been neglected, and only motions in the x direction are considered. Eqn [3] states that the fluid velocity changes in response to the pressure gradient introduced by the tilting of the sea surface, and is retarded by frictional processes. Eqn [4] states that the sea-surface changes in response to convergences and divergences in the horizontal velocity field; that is, where fluid accumulates ($\partial u/\partial x < 0$) the sea surface must rise, and vice versa. Eqns [3] and [4] can be combined to form a single equation for either η or u, each having the same form. For example,

$$\frac{\partial^2 u}{\partial t^2} + r\frac{\partial u}{\partial t} - gh\frac{\partial^2 u}{\partial x^2} = 0 \qquad [5]$$

Closed Basins

The simplest seiche occurs in a closed basin with no connection to a larger body of water, such as a lake or even a soup bowl. **Figure 1** shows a closed basin with constant depth h and vertical sidewalls. At the sides of the basin, the velocity must vanish because fluid cannot flow through the walls, so $u = 0$ at $x = 0$ and L. Solutions of eqn [5] that satisfy these conditions and oscillate in time with frequency ω are

$$u = u_0 e^{-rt/2}\cos(\omega t)\sin\left(\frac{n\pi}{L}x\right) \qquad [6]$$

where u_0 is the maximum current, $n = 1, 2, 3, \ldots$, and $\omega = [gh(n\pi/L)^2 - r^2/4]^{1/2}$. The corresponding sea-surface elevation is

$$\eta = -\frac{u_0 \omega L}{gn\pi} e^{-rt/2}\left[\sin(\omega t) - \frac{r}{2\omega}\cos(\omega t)\right]\cos\left(\frac{n\pi}{L}x\right) \qquad [7]$$

Eqns [6] and [7] represent the normal modes or seiches of the basin. The integer n defines the harmonic mode of the seiche and corresponds to the number of velocity maxima and sea-level nodes (locations where sea level does not change) which occur where $\cos(n\pi x/L) = 0$.

The spatial structure of the lowest or fundamental mode seiche ($n = 1$) is shown schematically in **Figure 1** through one period and was described above. Sea level rises and falls at each sidewall, pivoting about the node at $x = L/2$. The velocity vanishes at the sidewalls and reaches a maximum at the node. Sea level and velocity are almost 90° out of phase; the velocity is zero everywhere when the sea level has its maximum displacement, whereas the velocity is maximum when the sea level is horizontal.

The effect of friction is to cause a gradual exponential decay or damping of the oscillations and a slight decrease in seiche frequency with a shift in phase between u and η. If friction is weak (small r), the seiche may oscillate through many periods before fully dissipating. In this case, the frequency is close to the undamped value, $\omega \approx (gh)^{1/2} n\pi/L$ with period ($T = 2\pi/\omega$) given by Merian's formula, eqn [1]. If friction is sufficiently strong (very large r), the seiche may fully dissipate without oscillating at all. This occurs when $r > 2(gh)^{1/2} n\pi/L$, for which the frequency ω becomes imaginary.

The speed of a surface gravity wave in this basin is $(gh)^{1/2}$, so the period of the fundamental seiche ($n = 1$) is equivalent to the time it takes a surface gravity wave to travel across the basin and back. Thus, the seiche may be thought of as a surface gravity wave that repeatedly travels back and forth across the basin, perfectly reflecting off the sidewalls and creating a standing wave pattern.

Partially Open Basins

Seiches may also occur in basins that are connected to larger bodies of water at some part of the basin boundary (**Figure 2**). For example, harbors and inlets are open to the continental shelf at their mouths. The continental shelf itself can also be considered a partially open basin in that the shallow shelf is connected to the deep ocean at the shelf edge. The effect of the opening can be understood by considering the seiche in terms of surface gravity waves. A gravity wave propagates from the opening to the solid boundary where it reflects perfectly and travels back toward the opening. However, on reaching the opening it is not totally reflected. Some of the wave energy escapes from the basin into the larger body of water, thereby reducing the amplitude of the reflected wave. The reflected portion of the wave again propagates toward the closed sidewall and reflects back toward the open side. Each reflection from the open side reduces the energy in the oscillation, essentially acting like the frictional effects described above. This loss of energy due to the radiation of waves into the deep basin is called 'radiation damping.' Its effect is to produce a decaying response in the partially open basin, similar to frictional decay.

In general, a wider basin mouth produces greater radiation damping, and hence a weaker resonant seiche response to any forcing. Conversely, a narrower mouth reduces radiation damping and hence increases the amplification of fundamental mode seiches, theoretically becoming infinite as the basin mouth vanishes. However, seiches are typically forced through the basin mouth (see below), so a narrow mouth is expected to limit the forcing and yield a decreased seiche response. J. Miles and W. Munk pointed out this apparent contradiction in 1961 and referred to it as the 'harbor paradox.' Later reports raised a number of questions concerning the validity of the harbor paradox, among them the fact that frictional damping, which would increase with a narrowing of the mouth, was not included in its formulation.

The seiche modes of an idealized partially open basin (**Figure 2**) can be found by solving eqn [5] subject to a prescribed periodic sea-level oscillation at the open side; $\eta = \eta_0 \cos(\sigma t)$ at $x = L$ where σ is the frequency of oscillation. For simplicity, friction is neglected by setting $r = 0$. The response in the basin is

$$\eta = \eta_0 \cos(\sigma t) \frac{\cos(kx)}{\cos(kL)} \qquad [8]$$

$$u = \eta_0 (g/h)^{1/2} \sin(\sigma t) \frac{\sin(kx)}{\cos(kL)} \qquad [9]$$

where the wavenumber k is related to the frequency by $\sigma = (gh)^{1/2} k$. The response is similar to that in the closed basin, with the velocity and sea level again 90° out of phase. The spatial structure (k) is now determined by the forcing frequency. Notice that both the velocity and sea-level amplitudes are inversely proportional to $\cos(kL)$, which implies that the response will approach infinity (resonance) when $\cos(kL) = 0$. This occurs when $k = (n\pi - \pi/2)/L$, or equivalently when $\sigma = (gh)^{1/2}(n\pi - \pi/2)/L$ where $n = 1, 2, 3 \ldots$ is any integer.

These resonances correspond to the fundamental seiche modes for the partially open basin. They are sometimes called 'quarter-wave resonances' because their spatial structure consists of odd multiples of quarter wavelengths with a node at the open side of the basin ($x = L$). The first mode ($n = 1$) contains one-quarter wavelength inside the basin (as in **Figure 2**), so its total wavelength is equal to four times the basin width L, and its period is $T = 2\pi/\sigma = 4L/(gh)^{1/2}$. Other modes have periods given by eqn [2].

Despite the fact that these modes decay in time owing to radiation damping, they are expected to be the dominant motions in the basin because their amplitudes are potentially so large. That is, if the forcing consists of many frequencies simultaneously, those closest to the seiche frequencies will cause the largest response and will remain after the response at other frequencies has decayed. Furthermore, higher modes ($n \geq 2$) have shorter length scales and higher frequencies, so they are more likely to be dissipated by frictional forces, leaving the first mode to dominate the response. This is much like the ringing of a bell. A single strike of the hammer excites vibrations at many frequencies, yet the fundamental resonant frequency is the one that is heard. Finally, the enormous amplification of the resonant response means that a small-amplitude forcing of the basin can excite a much larger response in the basin.

Observations in the laboratory as well as nature reveal that seiches have somewhat longer periods than those calculated for the equivalent idealized open basins discussed above. This increase is similar to that which would be produced by an extension in the basin length, L, and it results from the fact that the water at the basin mouth has inertia and therefore is disturbed by, and participates in, the oscillation. This 'mouth correction', which was described by Lord Rayleigh in 1878 with respect to air vibrations, increases with the ratio of mouth width to basin length. In the case of a fully open square harbor, the actual period is approximately one-third greater than in the idealized case.

In nature, forcing often consists of multiple frequencies within a narrow range or 'band'. In this case, the response depends on the relative strength of the forcing in the narrow band and the resonant response at the seiche frequency closest to the dominant band. If the response at the dominant forcing frequency is stronger than the response at the resonant frequency, then oscillations will occur primarily at the forcing frequency. For example, the forcing frequency σ in eqns [8] and [9] may be different from any seiche frequency, and the energy in the forcing at the resonant seiche frequency may be so small that it is not amplified enough to overwhelm the response at the dominant forcing frequency. In this case, the observed oscillations, sometimes referred to as 'forced seiches', will have frequencies different from the 'free seiche' frequencies discussed above.

Generating Mechanisms and Observations

Seiches in harbors and coastal regions may be directly generated by a variety of forces, some of which are depicted in **Figure 3**: (1) atmospheric pressure fluctuations; (2) surface wind stress (*see* **Storm Surges**); (3) surface gravity waves caused by seismic activity (*see* **Tsunamis**); (4) surface gravity waves formed by wind (*see* **Wave Generation by Wind**); and (5) internal gravity waves (*see* **Internal Waves** and **Internal Tides**). It should be kept in mind that each of these forcing mechanisms can also generate or enhance other forcing mechanisms, thereby indirectly causing seiches. Thus, precise identification of the cause of seiching at any particular harbor or coast can be difficult.

To be effective the forcing must cause a change in the volume of water in the basin, and hence the sea level, which is usually accomplished by a change in the inflow or outflow at the open side of the basin. The amplitude of the seiche response depends on

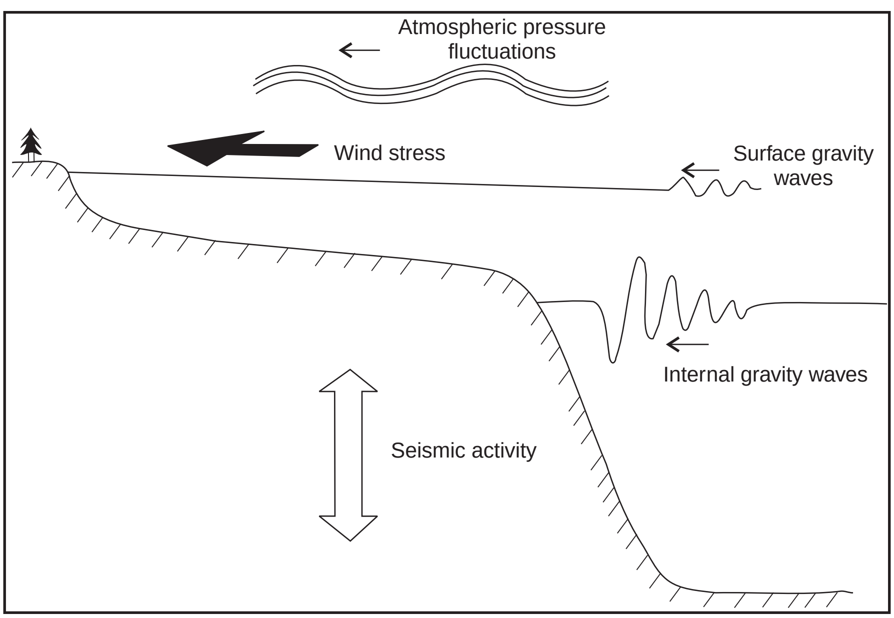

Figure 3 Sketch of various forcing mechanisms that are known to excite harbor and coastal seiches. Arrows for atmospheric pressure fluctuations, surface gravity waves, and internal gravity waves indicate propagation. Arrows for wind stress and seismic activity indicate direction of forced motions.

both the form and the time dependence of the forcing. The first mode seiche typically has a period somewhere between a few minutes and an hour or so, so the forcing must have some energy near this period to generate large seiches.

As an example, a sudden increase in atmospheric pressure over a harbor could force an outflow of water, thus lowering the harbor sea level. When the atmospheric pressure returns to normal, the harbor rapidly refills, initiating harbor seiching. However, although atmospheric pressure may change rapidly enough to match seiche frequencies, the magnitude of such high frequency fluctuations typically produces sea-level changes of only a few centimeters, so direct forcing is unlikely though not unknown. Several examples of direct forcing of fundamental and higher-mode free oscillations of shelves, bays, and harbors by atmospheric pressure fluctuations have been described. In the case of the observations at Table Bay Harbor, in Cape Town, South Africa, it was noted that 'a necessary ingredient … was found to be that the pressure waves approach … from the direction of the open sea.'

In lakes, seiches are frequently generated by relaxation of direct wind stress, and since wind stress acting on a harbor can easily produce an outflow of water, this might seem to be a significant generation mechanism in coastal waters as well. However, strong winds rarely change rapidly enough to initiate harbor seiching directly. That is, the typical timescales for changes in strong winds are too long to match the seiche mode periods. Nevertheless, wind relaxation seiches have been observed in fiords and long bays such as Buzzards Bay in Massachusetts, USA.

Tsunamis are rare, but they consist of large surface gravity waves that can generate enormous inflows into coastal regions, causing strong seiches, especially in large harbors. The resulting seiches, which may be a mix of free and forced oscillations, were a major motivation for early harbor seiche research as noted earlier (*see* **Tsunamis**). Direct generation of seiches by local seismic disturbances (as distinct from forcing by seismically generated tsunamis) is well established but very unusual. For example, the great Alaskan earthquake of 1964 produced remarkable seiches in the bayous along the Gulf of Mexico coast of Louisiana, USA. Similar phenomena are the sometimes very destructive oscillations excited by sudden slides of earth and glacier debris into high-latitude fiords and bays.

Most wind-generated surface gravity waves tend to occur at higher frequencies than seiches, so they are not effective as direct forcing mechanisms. However, in some exposed coastal locations, wind-generated swells combine to form oscillations, called 'infragravity' waves, with periods of minutes. These low-frequency surface waves are a well-known agent for excitation of seiches in small basins with periods less than about 10 minutes. Noteworthy are observations of 2–6 min seiches in Duncan Basin of Table Bay Harbor, Cape Town, South Africa, that occur at times of stormy weather. In 1993, similar short period seiches were reported in Barbers Point Harbor at Oahu, Hawaii, and their relationship to local swell and infragravity waves was demonstrated (*see* **Surface, Gravity and Capillary Waves**).

Perhaps the most effective way of directly exciting harbor and coastal seiches is by internal gravity waves. These internal waves can have large amplitudes and their frequency content often includes seiche frequencies. Furthermore, internal gravity waves are capable of traveling long distances in the ocean before delivering their energy to a harbor or coastline. In recent years this mechanism has been suggested as an explanation for the frequently reported and sometimes hazardous harbor seiches with periods in the range of 10–100 min. There is little or no evidence of a seismic origin for these seiches, and their frequency does not match that of ordinary ocean wind-generated surface waves. Their forcing has often been ascribed to meteorologically produced long surface waves. For example, it has been suggested that the 'abiki' of Nagasaki Harbor and the 'Marrobbio' in the Strait of Sicily may be forced by the passage of large low-pressure atmospheric fronts. In 1996, evidence was found that the hazardous 10-minute 'rissaga' of Ciutadella Harbor, Spain, and offshore normal modes are similarly excited by surface waves generated by atmospheric pressure oscillations, and it was proposed that the term 'meteorological tsunamis' be applied to all such seiche events.

However, attributing the cause of remotely generated harbor seiches to meteorologically forced surface waves does not account for observations that such seiches are frequently associated with ocean tides. In 1908 it was noted that in many cases harbor seiche activity occurs at specific tidal phases. In the 1980s, a clear association was found between tidal and seiche amplitudes and it was suggested that tide-generated internal waves could be a significant agent for excitation of coastal and harbor seiches. In 1990, a study of the fundamental theoretical questions concerning transfer of momentum from internal waves to seiche modes and the wide frequency gap between tides and harbor seiches indicated that the high-frequency energy content of tide-generated internal solitary waves is sufficient to account for the energy of the recorded seiches, and

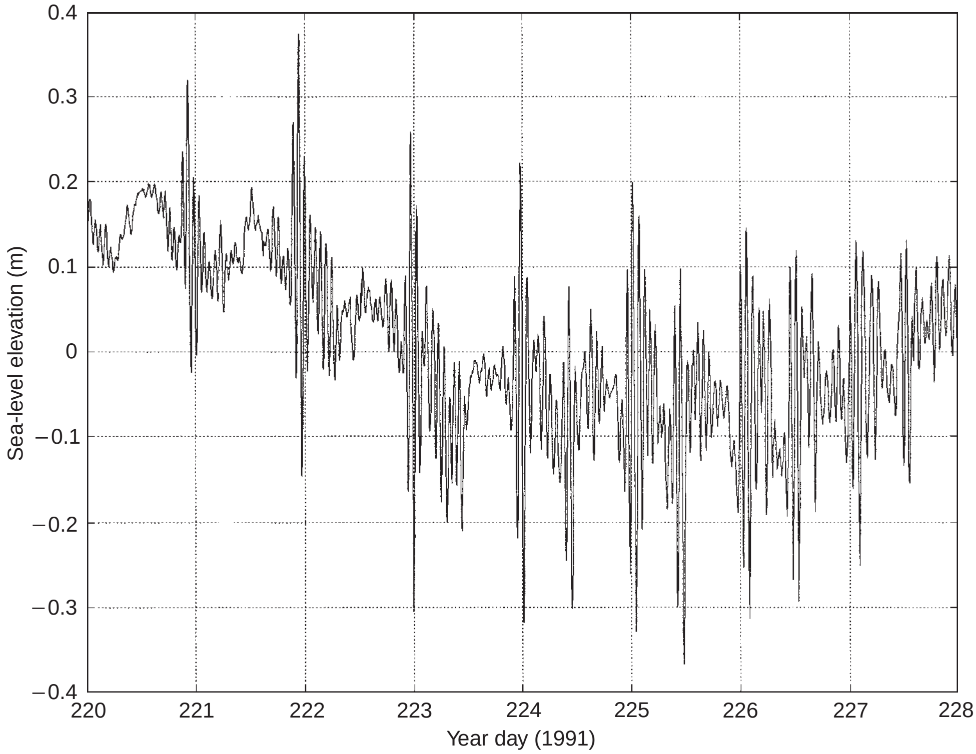

Figure 4 An example of harbor seiches from Puerto Princesa at Palawan Island in the Philippines. The tidal signal has been removed from this sea-level record to accentuate the bursts of 75-min harbor seiches. The seiches are excited by the arrival at the harbor mouth of internal wave packets produced by strong tidal current flow across a shallow sill some 450 km away.

a dynamical model for the generating process was published.

Observations at Palawan Island in the Philippines have demonstrated that harbor seiches can be forced by tide-generated internal waves and, as might be expected, there was also a strong dependency between seiche activity and water column density stratification. Periods of maximum seiche activity are associated with periods of strong tides, an example of which is given in **Figure 4**, which shows an 8-day sea-level record from Puerto Princesa at Palawan Island with the tidal signal removed. Bursts of 75-min harbor seiches are excited by the arrival at the harbor mouth of internal wave packets produced by strong tidal current flow across a shallow sill some 450 km away. The internal wave packets require 2.5 days to reach the harbor, producing a similar delay between tidal and seiche patterns. As an illustration, note the change in seiche activity from a diurnal to a semidiurnal pattern that is evident in **Figure 4**. A similar shift in tidal current patterns occurred at the internal wave generation site several days earlier.

More recent observations at Ciutadella Harbor in Spain point to a second process producing internal wave-generated seiches. Often the largest seiche events at that harbor occur under a specific set of conditions – seasonal warming of the sea surface and extremely small tides – which combine to produce very stable conditions in the upper water column. It has been suggested that under those conditions, meteorological processes can produce internal waves by inducing flow over shallow topography and that these meteorologically produced internal waves are responsible for the observed seiche activity.

See also

Internal Tides. Internal Waves. Storm Surges. Surface, Gravity and Capillary Waves. Tides. Tsunamis. Wave Generation by Wind.

Further Reading

Chapman DC and Giese GS (1990) A model for the generation of coastal seiches by deep-sea internal waves. *Journal of Physical Oceanography* 20: 1459–1467.

Chrystal G (1905) On the hydrodynamic theory of seiches. *Transactions of the Royal Society of Edinburgh* 41: 599–649.

Defant A (1961) *Physical Oceanography*, vol 2. New York: Pergamon Press.

Forel FA (1892) *Le Leman (Collected Papers)*, 2 vols. Lausanne, Switzerland: Rouge.

Giese GS, Chapman DC, Collins MG, Encarnacion R and Jacinto G (1998) The coupling between harbor seiches at Palawan Island and Sulu Sea internal solitons. *Journal of Physical Oceanography* 28: 2418–2426.
Honda K, Terada T, Yoshida Y and Isitani D (1908) Secondary undulations of oceanic tides. *Journal of the College of Science, Imperial University, Tokyo* 24: 1–113.
Korgen BJ (1995) Seiches. *American Scientist* 83: 330–341.
Miles JW (1974) Harbor seiching. *Annual Review of Fluid Mechanics* 6: 17–35.
Okihiro M, Guza RT and Seymour RT (1993) Excitation of seiche observed in a small harbor. *Journal of Geophysical Research* 98: 18 201–18 211.
Rabinovich AB and Monserrat S (1996) Meteorological tsunamis near the Balearic and Kuril islands: descriptive and statistical analysis. *Natural Hazards* 13: 55–90.
Wilson BW (1972) Seiches. *Advances in Hydroscience* 8: 1–94.

SEISMIC STRUCTURE

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Introduction

Seismic exploration of the oceans began in earnest in the 1950s. The early seismic experiments were refraction in nature using explosives as sources. The principal data were first arrival, P-wave travel times, which were analyzed to produce primarily one-dimensional models of compressional velocity as a function of depth. Within a decade, the results of these experiments had convincingly demonstrated that the crust beneath the ocean crust was much thinner than continental crust. Moreover, the structure of the deep ocean was unexpectedly uniform, particularly when compared with the continents. In light of this uniformity it made sense to talk of average or 'normal' oceanic crust. The first compilations described the average seismic structure in terms of constant velocity layers, with the igneous crust being divided into an upper layer 2 and an underlying layer 3.

Today, the scale and scope of seismic experiments is much greater, routinely resulting in two- and three-dimensional images of the oceanic crust. Experiments can use arrays of ocean bottom seismographs and/or multichannel streamers to record a wide range of reflection and refraction signals. The source is typically an airgun array, which is much more repeatable than explosives and produces much more densely sampled seismic sections. Seismic models of the oceanic crust are now typically continuous functions of both the horizontal and vertical position, but are still principally P-wave or compressional models, because S-waves can only be produced indirectly through mode conversion in active source experiments.

In spite of their greater resolving power, modern experiments are still too limited in their geographic scope to act as a general database for looking at many of the questions concerning oceanic seismic structure. The main vehicle for looking at the general seismic structure of the oceans is still the catalog of one-dimensional P-wave velocity models built up over approximately 40 years of experiments. The original simple layer terminology, with slight elaboration, is by now firmly entrenched as the means of describing the principal seismic features of the oceanic crust; despite the fact that the representation of the underlying velocity structure has changed significantly over time. The next section discusses the evolution of the velocity model and the layer description. Subsequent sections discuss the interpretation of seismic structure in terms of geologic structure; the seismic structure of anomalous crust; and the relationship of seismic structure to such influences as spreading rate and age.

Normal Oceanic Crust

Table 1 reproduces one of the first definitions of average or 'normal' oceanic crust by Raitt (1963). Even in this era before plate tectonics, Raitt excluded from consideration any areas such as oceanic plateaus that he thought atypical of the deep ocean. Today, compilations count as normal crust formed at midocean ridges away from fracture zones. The early refraction experiments typically consisted of a small set of widely spaced instruments. They were analyzed using the slope-intercept method in which a set of straight lines was fitted to first arrival travel times. This type of analysis naturally leads to stair-step or 'layer-cake' models consisting of a stack of uniform velocity layers separated by steps in velocity. Although their limitations as a description of the earth were recognized, these models provided a simple and convenient means of comparing