Seiche

A short-period oscillation in an enclosed or semienclosed body of water, analogous to the free oscillation of water in a dish. The initial displacement of water from a level surface can arise from a variety of causes, and the restoring force is gravity, which always tends to maintain a level surface. Once formed, the oscillations are characteristic only of the geometry of the basin itself and may persist for many cycles before decaying under the influence of friction. The term "seiche" appears to have been first used to describe the rhythmic oscillation of the water surface in Lake Geneva, which occasionally exposed large areas of the lake bed that are normally submerged. *See* WAVE MOTION IN LIQUIDS.

Behavior. The most straightforward example of a surface seiche is that occurring in a long, narrow lake of uniform depth; in this case the water surface elevations have a simple physical analogy with the vibrations of a plucked string. Since the wave length is long relative to the water depth, seiche behavior conforms to the theory of shallow water waves. Thus the velocity is given by $\sqrt{gh}$, where g is the acceleration of gravity and h is the water depth. A standing wave can be represented by the sum of two waves traveling in opposite directions, each being reflected at the ends of the basin. The natural period of oscillation of a uniformly deep, completely enclosed rectangular basin is given by Merian's formula (1), where

$$T = \frac{2L}{n\sqrt{gh}} \qquad (1)$$

L is the length of the basin and n is the number of nodal lines present, one for the fundamental or uninodal seiche, two for the binodal seiche, and so forth (**Fig. 1**). However, the formula is only approximate, and calculation of the higher modes of oscillation starts to depart seriously from that given by Eq. (1) due to the importance of nonuniformity of the basin shape.

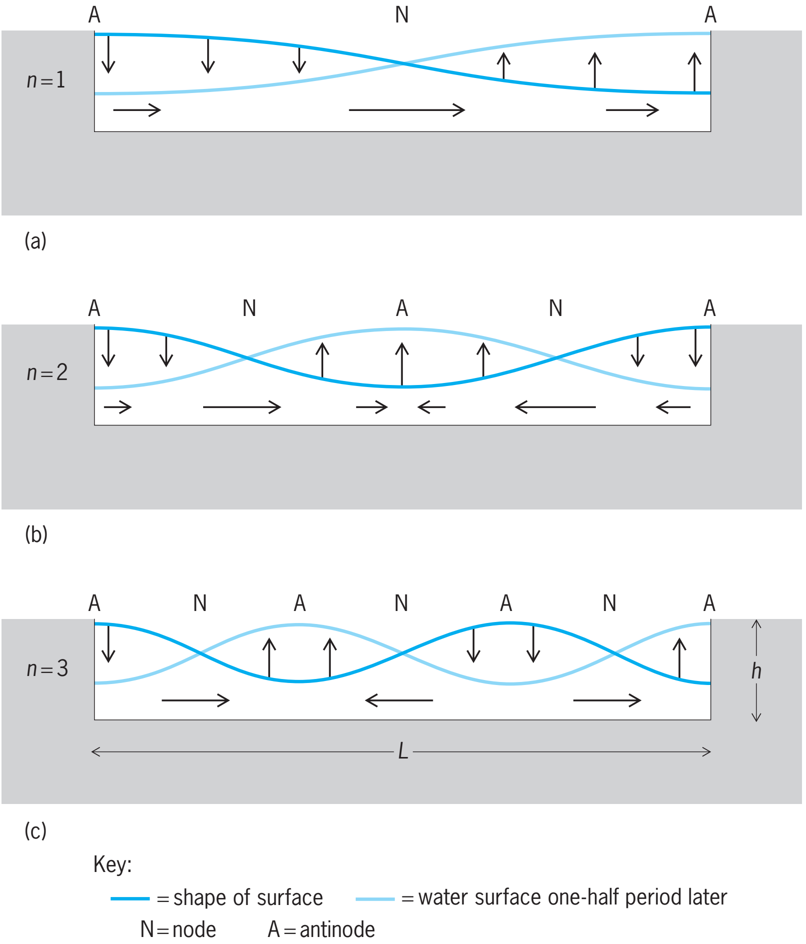

Fig. 1. Schematic diagram of a (*a*) uninodal, (*b*) binodal, and (*c*) trinodal seiche in a rectangular basin. Vertical and horizontal vectors show the direction of flow corresponding to the indicated change of water surface. Vertical movements are greatly exaggerated.

The **table** gives examples of observed periods of surface seiches in different lakes. Figure 1 shows profiles of a standing wave in a closed basin of the fundamental, binodal, and trinodal seiche. Below the nodes there is maximum horizontal and no vertical motion; below the antinodes there is maximum vertical and no horizontal motion. **Figure 2** shows simultaneous records of water height near each end of Lake Vättern during a uninodal seiche. The two measurements show opposite movement of the water at each antinode. When several different seiches occur in a basin, their effects are superposed. Thus it is quite possible, for example, for a vessel to be located at the node of the fundamental seiche but at the antinode of the binodal seiche. The amplitudes of

Observed surface seiche periods in typical lakes and observed decay rates

	Observed periods of oscillation, min						Fractional decrease in amplitude of free uninodal seiche over each successive period
Lake and location	T_1	T_2	T_3	T_4	T_5	T_6	
Geneva (Switzerland–France)	74.0	35.5					.030
Garda (Italy)	42.9	28.6	21.8	15.0	12.1	9.9	.045
Loch Earn (Scotland)	14.5	8.1	6.0	4.0	3.5	2.9	
Erie (United States–Canada)	858.0	542.3	350.9	250.5			.322
Königssee (Germany)	11.6						.204
Vättern (Sweden)	179.0	97.5	80.7	57.9	48.1	42.6	.113
Yamanaka (Japan)	15.6	10.6	5.5				.099
Baikal (Russia)	278.2						

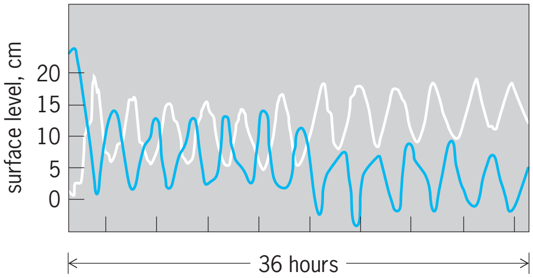

Fig. 2. Simultaneous recordings taken near each end of Lake Vättern during a uninodal seiche. The reading at one end is a mirror image of the observed displacement at the other end. 1 cm = 0.4 in. (*After A. Defant*, *Physical Oceanography*, *vol. 2*, *Pergamon*, *1961*)

the different harmonics are determined by the initial disturbance.

It is also possible for transverse seiches to exist together with the longitudinal seiche. The appropriate generalization of Merian's formula for a deep, rectangular basin of length L and breadth B is given by Eq. (2), where $\alpha = L/B$ and m and n define the harmonic nodes in the transverse and longitudinal directions, respectively. However, the earlier comments regarding nonuniformity of basin shape still apply, and Eq. (2) cannot be generally applicable to natural basins.

$$T_{mn} = \frac{2L}{\sqrt{gh}}\,(\alpha^2 m^2 + n^2)^{-1/2} \qquad (2)$$

Seiches are also a common feature of semienclosed basins such as bays, gulfs, and harbors, the natural period for an open-end rectangular basin of uniform depth being twice that of the same-size basin closed at both ends. The node and antinode occur at the open and closed ends, respectively. A problem of great practical significance is the oscillation of water in harbors, which can generate strong and unpredictable currents affecting the safety of ships entering or leaving the harbor; under extreme conditions these can also cause damage to moored vessels.

Generation and decay. Seiches can be generated when the water is subject to changes in wind or atmospheric pressure gradients or, in the case of semienclosed basins, by the oscillation of adjacent connected water bodies having a periodicity close to that of the seiche or of one of its harmonics. Other, less frequent causes of seiches include heavy precipitation over a portion of the lake, flood discharge from rivers, seismic disturbances, submarine mudslides or slumps, and tides. The most dramatic seiches have been observed after earthquakes.

The amplitude and persistence of the resulting seiche depend not only on the magnitude of the energy source but also on the energy losses within the water body. Such losses include dissipative effects resulting from friction on the sides or bottom of the basin. For semienclosed basins, energy can also be lost by the radiation of waves away from the mouth. If the seiche is generated by an impulsive event such as a sudden change in atmospheric pressure gradient, the seiche amplitude is seen to decay by a nearly constant fraction with each succeeding period. The table shows, for example, that in Lake Geneva the decay has been estimated to be about 3% with each seiche period, whereas in Lake Erie it is 32%. In general, the rate of decay is greater for basins that are shallow or have narrow constrictions and complex topography.

In bays and gulfs a dominant source of energy is the tide. Since there is quite a rich array of tidal frequencies, it is sometimes possible to determine the natural seiche frequency of a bay simply by observing the amplification of different tidal components. If the tidal period is close to that of the seiche period for the bay, resonance increases the tidal amplitude. An example of this is the Bay of Fundy (Canada), where the tide can exceed 45 ft (15 m). The bay has a fundamental mode seiche period of about 13.3 h, close to the semidiurnal lunar tidal period of 12.4 h. A similar, near-resonance exists in the Gulf of Mexico, where the period of the fundamental seiche mode is close to 24 h, with resulting amplification of the diurnal tide. In smaller bays and harbors the generation of seiches has been attributed to surf beats. This effect is due to the coupling of radiation stress, in effect the thrust of the waves on the coast, with rhythmic changes in the height of the wind waves or swell. Since the swell can originate from distant storms, the existence of seiches is not necessarily closely correlated with local meteorological conditions. Coastal seiches can also be generated by traveling fronts or pressure disturbances, especially when the atmospheric disturbance travels at a speed close to that of the gravity wave ($\sqrt{gh}$). A less frequent but often important generation mechanism in harbors is the tsunami or seismically formed ocean wave. *See* TSUNAMI.

Effect of rotation. The response of large bodies of water is significantly influenced by the Coriolis effect produced by the rotation of the Earth. The effective period of the rotation decreases with latitude and is given by $^1/_2\ \tau/\sin\lambda$, where τ is the period of rotation of the Earth (24 h) and λ the latitude. The Coriolis force acts at right angles to the direction of motion of the water, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The Coriolis force introduces a transverse slope to each of the traveling waves that combine to form a standing wave pattern, or seiche. The transverse motion, added to the motion along the channel, results in the movement of water in an elliptical path rotating once with each seiche period. The transverse motion has the effect of shrinking the nodal lines of zero vertical motion to small areas known as amphidromic points.

In the plan views of **Fig.** 3*a* and *b*, arrows show surface currents at one-fourth and three-fourth cycles, respectively. After high water at the channel head, Coriolis deflection, indicated by broken arrows, causes an increase of water level in the right half of the current in both Fig. 3*a* and *b*, with a corresponding decrease to the left. The broken line is

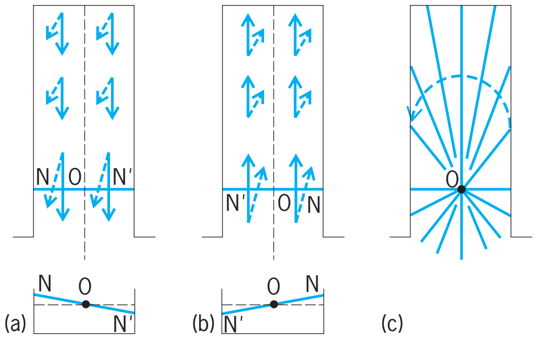

Fig. 3. **Schematic representation of transverse oscillations in a bay in the Northern Hemisphere leading to the development of an amphidromic point. (*a*) Ebb current. (*b*) Flood current. (*c*) Cotidal lines.**

one of mean level with respect to the deflection. Water profiles along nodal lines are shown beneath Fig. 3*a* and *b*. Point O, the amphidromic point, is thus the only position of no water level change. Line O-N (O-N′) connects points having simultaneous high (low) water. Other such cotidal lines are shown in Fig. 3*c* for different phases of one seiche oscillation. The superposition of the transverse motion on the primary longitudinal motion causes this line to rotate counterclockwise (dotted arrow) for one complete oscillation in the Northern Hemisphere. *See* CORIOLIS ACCELERATION; TIDE.

Internal seiches. Internal seiches are standing waves that occur in water that has vertical variations in temperature or salinity resulting in a vertical density stratification. The waves produce vertical movements of water at depth, with very little vertical motion at the surface. They are typically generated by the piling up of water at one end of the lake by wind, although in semienclosed basins they may be forced by oscillations in the density structure at the mouth of the basin. **Figure** 4 shows the measurements of two isotherm depths in Lake Alpnach (Switzerland) generated by a wind pulse as well as by diurnal wind forcing. The oscillations decay by one-third over about 1 day. As for surface seiches, the residence time of the energy varies, depending on the excitation (tens to hundreds of joules per square meter) and the depth of the basin, from less than 1 day up to several weeks.

Since the relative density differences within the water column are much smaller than the density difference at the air-water interface, the same amount of energy produces internal seiches of much greater amplitude than the corresponding surface seiche. However, the internal wave speed is much slower than the surface wave. The relative density difference in lakes during the summer is typically of the order of 0.002, so that wind effects, which might produce surface seiches of only a few centimeters, can produce internal seiches of meters to tens of meters (Fig. 4). In the Great Lakes of North America and the long and deep Rift valley lakes of Baikal and East Africa, amplitudes can reach almost 100 m with periods of many weeks to months.

In natural waters, the two-layer approximation, as depicted for surface seiches in Fig. 1, is a simplification, and in nature the density varies continuously with depth. Subsequently, the density structure allows several vertical modes, with characterizing vertical wavelengths, to exist. Such an example is given in Fig. 4 where, beside the fundamental seiche period of about 8 h, a second vertical mode with a 24-h periodicity is prominently displayed. The characteristic of the second vertical mode is the periodic widening and thinning of the middle layer (between 11 and 17°C in Fig. 4). The fluid of the lighter top layer (above 17°C) and the fluid in the heavier deep layer (below 11°C) move in phase, whereas the fluid in the middle layer has the exactly opposite direction. Higher vertical resolution (by dividing the water column in more homogeneous layers) leads to even more vertical modes, generally expressed by $VpHq$, where p indicates the p-th vertical mode, and q the q-th horizontal mode. According to Eq. (2), the horizontal modes are combinations of the two horizontal coordinates (modes m, n). The Earth's rotation also alters the structure of internal seiches since

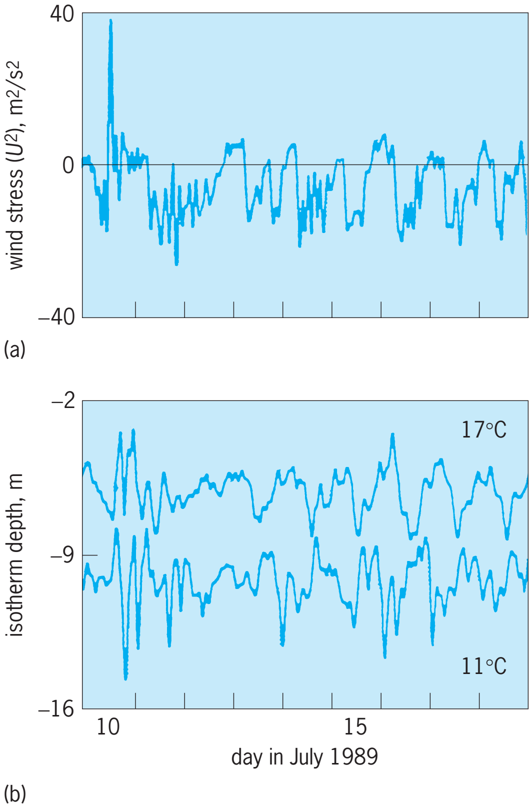

Fig. 4. **Seiche measurements in Lake Alpnach, in Switzerland. (*a*) Time series of the lake-parallel component of the square of the wind speed (proportional to the wind stress) over the lake (maximum depth = 35 m). (*b*) Times series of the two selected isotherms of 11 and 17°C. The fluid layer between the two lines shows a strong second vertical mode characteristics of 24-h periodicity (V2H1). The fundamental mode (V1H1) of an 8 h period is also prominent. (*After M. Münnich, A. Wüest, and D. M. Imboden, Observations of the second vertical mode of the internal seiche in an alpine lake, Limnol. Oceanogr., 37:1705–1719, 1992*)**

the transverse slope of the internal interface induced by the Coriolis force is greatly increased for internal seiches.

Which modes are excited, and to what extent, in a particular water body depends on the forcing and the stratification, but is almost impossible to predict. As in the case of surface seiches, internal seiching is a mechanism that selectively extracts energy from the forcing (mostly wind) at a frequency close to that of the internal seiche. For example, as shown in Fig. 4, the second vertical mode in Lake Alpnach is resonantly forced at a 24-h period by the local diurnal wind.

The latter example demonstrates that the amplitude of internal seiches can reach a significant fraction of the basin depth. This enormous amplitude results in a distortion of the smooth sinusoidal perturbation of the interface predicted by linear theory, and the peak and trough of the wave travel at slightly different speeds. In addition, interaction with the topography and bottom friction leads to turbulence and the generation of short-period internal waves radiated into the water body. Especially in large basins and lakes, where resonant seiching is difficult to reach, most internal energy is contained in progressive short-period waves. Internal shear, bottom friction, and wave breaking leads to damping of the internal seiche energy. As a rule, the decay rate of the energy is about 1 day per 40 m of water depth (40 days in Lake Baikal). However, for very weak and almost linear seiching, damping may reduce the decay rate.

The enormous amplitude of internal seiches results in a distortion of the smooth sinusoidal perturbation of the interface predicted by linear theory. In effect, the peak and trough of the wave travel at slightly different speeds, resulting in steepening of a portion of the interface. Under the right conditions, the steepened interface can break down into a series of shorter waves, possibly accompanied by turbulence and mixing and usually referred to as an internal surge.

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