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Abstract

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Keywords

Observations, propagating, vortex, tidal, current

Disciplines

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TECHNICAL COMMUNICATIONS

Observations of a Propagating Vortex in a Tidal Current

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ABSTRACT

While observing the hydrodynamics and geomorphology of the entrance to Burrill Lake, a small estuary on the south coast of New South Wales, Australia, a striking vortex phenomenon was observed. This vortex is described and interpreted.

Additional Index Words: tidal current, vortex, hydrodynamics, wave group

OBSERVATIONS

Burrill Lake is located 200 kilometers south of Sydney on the New South Wales south coast. The lake has a water surface area of 4.1 square kilometers and is linked to the sea through a constricted entrance, through which the tides propagate with some attenuation. River inflow, although important ecologically, is unimportant hydrodynamically except in times of flood. The observations were made at approximately 1100 EST on July 1, 2003. For this period, the recorded tide at Jervis Bay 55 kilometers to the north were: high tide at 0925 EST, 1.61 meters, and low tide at 1450 EST, 0.92 meters. Thus, the tide was ebbing, relatively weakly, through the inlet at the time of observation.

Conditions on the day and the preceding night had been windy, with squally rain showers. A strong surf was running and the Department of Public Works and Services (DPWS) recorder operating offshore from Batemans Bay (50 km to the south in water of depth 73 m) recorded a significant wave height, H_s, of 2.6 meters and a spectral peak period of 13.5 seconds.

The tidal lagoon is connected to the sea via a 2.5-kilometer-long inlet channel of *ca.* 3 meters depth and 80–150 meters width, which terminates at the seaward end in a constriction. The entrance constriction at the time of observation was approximately 25 meters wide, 1.5 meters deep, and just under 200 meters long. It is bounded on its north side by a barrier dune underlain by rock that forms a vertical wall along the north side of the channel. This bank extends horizontally to the north and slopes seaward; it was overtopped by larger waves and surges.

On a first inspection, the flow was observed to be ebbing smoothly through the entrance constriction, but quite suddenly, an intense vortex appeared and propagated upstream against the ebbing current, as shown in Figure 1. The vortex persisted for several minutes, finally decaying after it had propagated upstream into the wider entrance channel. At intervals of a couple of minutes, a new vortex appeared and followed the same history. The vortices varied a little in strength, but their characteristic dimensions were approximately the same and their sense of rotation was always counterclockwise. The dimensions of the stronger vortices are listed in Table 1.

An unusually strong long-period surge was present at the time and contributed to the generation of the vortices through overwash across the shallow bank flowing into the ebbing current in the channel, as sketched in Figure 1.

The water surface elevation was observed to fall toward the center of the vortex, but a reliable estimate of the maximum surface depression could not be made, first, because the maximum depression lowered the surface below the point from which it was visible from the far bank, and second, because the whole surface of the vortex rapidly became covered with choppy wavelets of wavelength about 200 millimeters and height about 100 millimeters. Their presence suggests that turbulence of scale *ca.* 100–200 millimeters was significant and would act to diffuse vorticity across the vortex and to entrain the ambient tidal current into the vortex. The rate of

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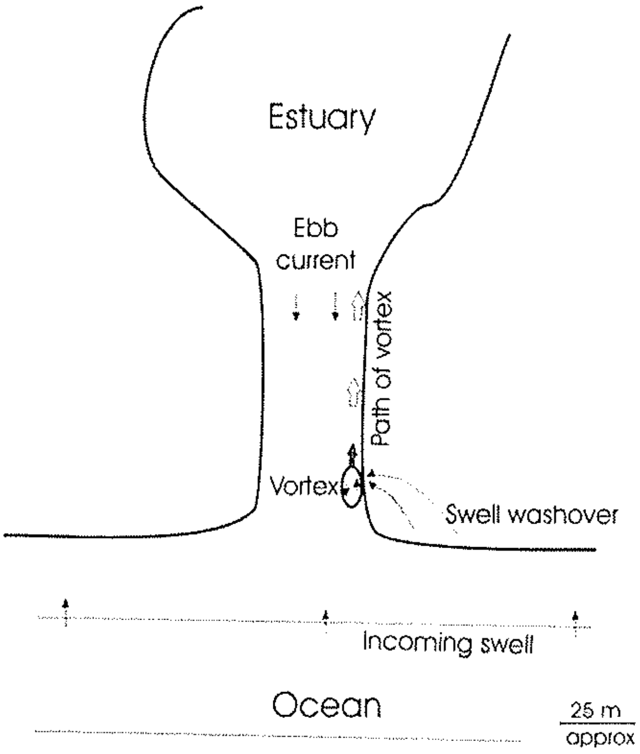

Figure 1. Schematic of vortex generation and path.

growth of the vortex diameter as it propagated upstream through the entrance constriction was small and could not be reliably estimated.

It was noticed that behind the vortex the water level in the entrance constriction commenced to rise and rose rapidly for about 1 minute then fell for about 1 minute. A new vortex was generated at the seaward end as the water level commenced to rise there but outran the incoming surge, propagating into the outflowing current from the previous surge combined with the tidal outflow. The larger surges observed on the day had a trough to crest height of 600 millimeters and a typical period of 120 seconds. Even the smallest of the surges exceeded 300 millimeters in height. The surges became visible at the shoreward side of the breaker zone, a few meters seaward of the mouth of the entrance constriction. They propagated upstream through the entrance constriction and also rose over the barrier spit on the northern side of the estuary draining off that structure and into the entrance constriction. They propagated into the wider entrance channel with a height of about 150 millimeters.

The vortices were generated by the water flowing off the spit and into the entrance constriction at its downstream end. Because of the details of the shape of the side wall and the general downstream movement of water through the constriction, the flow generated a vortex with upstream flow against the northern channel wall and downstream flow toward midchannel.

To confirm that the surges were generated by the strong offshore wave action described above, the surge height and period are estimated from the wave record in the next section. In the final section, potential flow is used to examine the relation between the speed of propagation and dimensions of the vortex.

Table 1. *Observed characteristics of vortex.*

Property	Magnitude
Length (m)	4.5–5
Width (m)	2.5–3
Maximum speed of rotation (m/s)	3–4
Speed of propagation (m/s)	0.5
Tidal current speed (m/s)	1
Width from bank to center of rotation (m)	1–1.5

SURGE PERIOD AND HEIGHT

Because a strong swell was breaking offshore, it was assumed that the wave group setdown was driving the observed surge. Data supplied by the DPWS from the offshore wave recorder at Batemans Bay were used to estimate the surge period and height. A comprehensive treatment of wave groups by TUCKER (1991), largely based on the work of LONGUET-HIGGINS (1984), was followed. Tucker's expression for the interval between groups of waves of height equal to or exceeding H_s gave a period of 89 seconds compared with the observed 120 seconds. The choice of H_s as the reference height, also made by Tucker, is arbitrary, as is the number of high waves used to define a wave group with $n \geq 2$ giving excessively long periods. The methods of GODA (1976) and OCHI and SAHINOGLOU (1989) suffer from the same uncertainty.

To overcome the uncertainties resulting from the definition of a wave group, an envelope analysis was then performed on the water level time series data after first band-pass filtering the data about the spectral peak frequency (LONGUET-HIGGINS and STEWART, 1964). The band-passed data and envelope are shown in Figure 2. The spectrum of the envelope

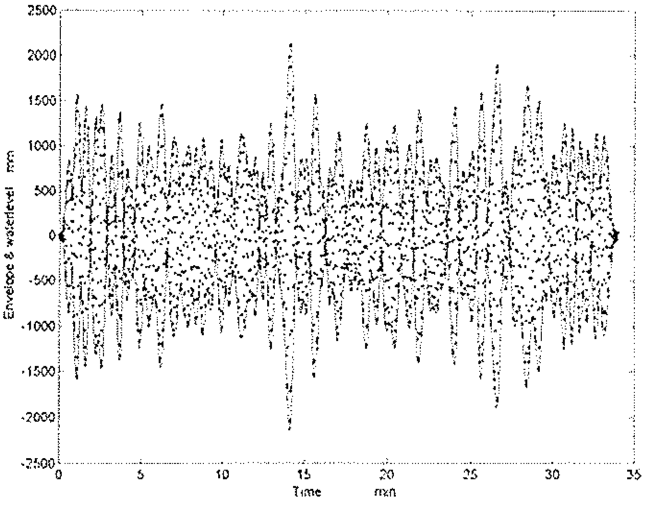

Figure 2. Envelope of offshore wave record after band-passing.

showed a broad peak at 0.12 hertz (*i.e.*, a period of 80 s). The same period was found by filtering the time series with successively longer filters to eliminate the swell while retaining all longer period wave energy. The reason for the difference between these estimates and the observed period is not known. A resonance is suspected, although there is no obvious topographically constrained basin or shelf mode with the correct period.

The surge height was taken as the maximum onshore setup, which was possibly an overestimate but not unreasonable in the light of the envelope shape. The onshore wave setup, ζ, was estimated in terms of the height of the swell at breaking, H_b. For the significant wave, the design software in the *Coastal Engineering Manual* (VERI-TECH, 2001) gives H_b = 3.5 meters and ζ = 0.77 meter. Alternatively, following TUCKER (1991) and largely according to LONGUET-HIGGINS and STEWART (1964),

$$\zeta = \frac{5}{16}\gamma H_b,$$

where γ is the breaker index for which LONGUET-HIGGINS and STEWART (1964) used 0.64. For H_b = 3.7 meters, ζ = 0.74 meters, which is in good agreement with the *Coastal Engineering Manual*. Taking this value as the surge height gives agreement with the observed height.

POTENTIAL FLOW MODEL

Potential flow provides an explanation for the propagation of the vortex. The wall on the northern side of the entrance constriction provides a vertical plane behind which an image vortex is located. The image vortex and the actual vortex form a vortex pair, which then propagate into the oncoming current. To test this model and the self-consistency of the observations, the velocities and dimensions of an appropriate potential flow are developed.

Consider a vortex pair of strength K traveling along the x-axis in a uniform flow of velocity U in the x direction. The vortices considered are point or line vortices with vorticity concentrated in the core. Let $z = x + iy$ be the complex coordinate, $w = \phi + i\psi$ the complex potential (ψ is the stream function), and $dw/dz = u - iv$ the complex conjugate of the velocity. Then

$$w = Uz + iK\ln\left(\frac{z - ia}{z + ia}\right), \tag{1}$$

where $2a$ is the spacing of the cores of the vortex pair. The zone moving with the vortex cores is limited by the upstream and downstream stagnation points $(x_s, 0)$ and $(-x_s, 0)$ and by the bounding streamline through them. To evaluate these dimensions, set the velocity to zero, then

$$\text{substituting} \quad \left.\frac{dw}{dz}\right|_s = 0 \quad \text{in Equation (1)},$$

$$x = x_s = a\sqrt{\frac{2K}{aU} - 1}, \tag{2}$$

and by symmetry, the maximum width of the vortex zone from the x-axis is given by $\psi_s = 0$, $(0, y_m)$.

Substitute into the imaginary part of Equation (1)

$$\psi_s = Uy + \frac{K}{2}\ln\left[\frac{x^2 + (y - a)^2}{x^2 + (y + a)^2}\right] = 0, \tag{3}$$

and at $(0, y_m)$,

$$\psi_s = Uy_m + \frac{K}{2}\ln\left[\frac{(y_m - a)^2}{(y_m + a)^2}\right] = 0.$$

To solve, let

$$Y = \frac{y_m}{a}, \qquad \beta = \frac{Ua}{K}.$$

Then,

$$0 = \beta Y + \ln\left(\frac{Y - 1}{Y + 1}\right), \tag{4}$$

from which y_m can be found numerically.

By using the data in Table 1 for maximum speed and radius to maximum speed, the vortex strength can be found. By adding the speed of propagation to the tidal current speed, the relative speed of propagation can be found. With these data, the overall dimensions of the vortex were calculated as length = $2x_s$ = 5.2 meters and y_m = 3.1 meters. These dimensions are compatible with the observed dimensions, confirming that the potential flow model provides a model of flow consistent with all observed quantities. There might be substantial errors in the observed quantities; however, the gross dimensions of the observed vortex and its speed of propagation were fairly accurately determined, and their evaluation from the potential theory uses all observed quantities, providing some confidence in those estimates.

CONCLUSIONS

Vortices generated by wave group surges were observed to form and propagate upstream against the ebb current in the mouth of Burrill Lake. A simple potential flow model provides a consistent description and explanation of the vortices. The vortices significantly increase local velocities along their route and could contribute to both bank and bed erosion, although not to significant sediment transport.

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