論文の要旨

題　目: Study on Tidal Current Distribution in the Bali Strait Using Coastal Acoustic Tomography

（沿岸音響トモグラフィーを用いたバリ海峡の潮流分布に関する研究）

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A ferry boat was tilted and sunk on March 4th, 2016, while crossing Bali Strait from Gilimanuk port to the Ketapang port. A study on tidal current distribution in the Bali Strait is needed to prevent more disastrous events caused by the strong currents. The ferry route of the Bali Strait is categorized as a heavy shipping traffic area. The conventional current measurement, such as shipboard ADCP, moored ADCP, and many other acoustic technologies, are not supported and prohibited by many countries from measuring ocean properties around heavy shipping traffic areas. Moreover, it is particularly difficult to make measurements in the upper 30 m or so, not only because of the interference and biofouling but also because of the possibility of contamination by surface waves. In a surface wave field, the vertical motion of the mooring or rotor-pumping of Savonious rotor-type instruments leads to an erroneous overestimation of currents. Coastal acoustic tomography (CAT) is proposed to apply OAT technology in shallow water and coastal seas. Compared with other current-field measurement conventional methods, CAT is an observational method suited to use in the Bali Strait with strong and highly variable currents. By reconstructing the vertical and horizontal tidal current distribution, analysis and clarification of the tidal current characteristic could be done. Those results could be helpful to estimate a better and safe ferry route to avoid the disastrous currents.

A CAT measurement with four acoustic stations was attempted during June 1-3, 2016, at the northern part of the Bali Strait, where a vital route of ferries is severely disturbed by a strong current varying rapidly in one hour. The models and methods used for the Bali Strait case are ray simulation, range-average current, north-east current component, and horizontal-slice inversion. The ray simulation was done by using the one-point 2014 CTD data. After that, the first arrival peak could be identified to calculate the differential and summation of travel time by using the ray simulation result. Furthermore, by using those travel time data, the range-average current, the north-east current component could be calculated. The sea surface height data was obtained by put a pressure sensor at S7 station. Finally, the horizontal-slice inversion could be done by using tapered least-square accompanied with the L-curve method to solve the second order of Fourier Function method of the current velocities.

Four land-based CAT systems (S1, S3, S5, S7) were deployed on both sides of the strait. One-minute interval data resampled at 10-min interval data were decomposed into two period-ranges, > 6h using a 6-hour low pas filter (LPF) to retrieve M2-tide which has 12-h period, and 10min-6h using a 10min-6h band pass filter (BPF). The range-average current results for every transmission line showed the characteristic of a tidal wave in Bali Strait is mix semidiurnal tides. The M2 and M8 oscillations peaked at the low water of SSH data and diminished around the high water. And the phase relation between SSH and current showed that potential energy from SSH variation served to generate not only M2 current, but also M8 current. Furthermore, the M8 oscillation is embedded in the envelope oscillation of the semidiurnal period. It provides a big possibility that the nonlinear interaction of semidiurnal and diurnal tides generated the M8 oscillation. However, the reason why the M8 component rather than M3, M4, and M6 was dominated is not found yet. Generally, the M8 overtide of period 3.17-hours is usually much weaker than M2 tide. The strong and highly variable 3-h oscillation, which occurs in the northern part of the Bali Strait and causes problems with ferry operation, was measured for the first time using a CAT array.

The spatiotemporal tidal current fields were reconstructed by the inverse method of CAT data. The accuracy of the spatiotemporal current fields, based on RMSD between the observed RACs and the inverted RACs is 40% underestimation. And the accuracy of the inversion result indicated by the current velocity error of inversion. It showed less than 0.01 ms^{-1}. The inversion result showed a satisfactory accuracy.

The characteristic of the strong current in the north of Bali Strait is dominate by the northward current. The eastward current was very weak compared to the northward current in the M2 band. The clockwise and counter-clockwise vortex formed at the lateral side of Java Island when the northward current is strong in the central strait. The suggestion for a better ferry route to prevent and reduce ship accidents is shifted 10 km to the southern side of the experiment site.

The more comprehensive inverse method of CAT could be done for further works is three-dimensional inversion. This inversion is combining horizontal-slice inversion with vertical-slice inversion. The ray simulation result could be used for the vertical-slice inversion. Every RACs result of the vertical-slice inversion is used to reconstruct the horizontal-slice inversion for every depth of the vertical-slice inversion layer. The inverted results from all the horizontal-slice inversions are pilled up to construct a 3D structure of current. The three-dimensional structure results could better understand the generation of the 3-hour oscillation in the tomography domain.

Next future work that could be done is data assimilation. Kalman Filter was initially proposed by Kalman (1960) to simplify the Bayesian estimate for the linear model. It is an efficient data assimilation (DA) method that can explicitly account for the dynamic propagation of errors in the linear model. The ensemble Kalman filter (EnKF) is a sequential data assimilation scheme that integrates observation data into a dynamical system obeying Kalman filter theory and Monte Carlo method. This technique is the extended Kalman filter scheme which enables an application to nonlinear systems. The differential travel time and the travel time summation, proportional to range-average current and sound speed, are CAT observation data to be assimilated into an ocean model. As a result, the spatial resolution, which is a weak point in CAT measurement, is primarily improved through a dynamic interpolation for grids between the transmission lines. The DA could do forecasting the tidal current distribution in the ferry route of the Bali Strait. This forecasting model is useful for better ferry routes and schedules to avoid the disastrous current.