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ANALYSIS OF WAVE NUMBER USING VIDEO IMAGES TO STUDY NEARSHORE BATHYMETRY

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Video camera monitoring system has been installed since 2006 by Port and Airport Research Institute for the purpose to study nearshore coastal processes in Hasaki beach, Japan. In present study, the cross-spectral correlation approach has been used to estimate wave number from video images. This approach based on pixel array analysis that utilizes a non linear inverse method Levenberg-Marquardt to invert images data into wave number estimate. The method was tested using image data collected at Hasaki beach, Japan. The result indicated that the cross-spectral correlation approach have capability to derive wave number estimate from multiple array time series of pixel intensities to estimate bathymetry. The method provides reasonable accurate depth estimate near shoreline and breaking area through bathymetry inverse method.

Key Words : *Wave number, video image, nearshore, bathymetry, inverse technique*

1. INTRODUCTION

Bathymetry information is very important for variety of coastal engineers to understanding the coastal process in the nearshore area. Some nearshore activities like recreation, fishing, navigation, beach nourishment and dredging require the knowledge of bathymetry. Good quality bathymetry information is hence required in order to identify correctly the physical processes that are taking place. However, combination of traditional in situ survey method and advanced techniques such as global positioning system and modern ship vehicles are time consuming, expensive, especially in shallow coastal water where survey swaths are narrow.

Recently, the invention of new digital technology of images form video camera system now can provide and improve the additional capability of automated data collection. This invention of new digital technology of images from video camera system can provide information of the shoreward of wave. This automated data collections have much greater range of time and spatial scales. Also, this technology is suitable for hazardous coastal areas such as surf zone area, where the operations of ship vehicle have limitation on maneuvers.

Some methodologies have been proposed to estimate bathymetry in nearshore area by establishing the relationship between wave characteristic derived from video image sequences and known water depth. The underlying methodology to extract wave characteristic problem from video images has taken on number of different forms. These include finding wave celerity from time series of cross-shore pixel intensities using cross-spectral scheme[1)] and determining wave phase speed from coastal video observation system using cross-correlation analysis technique[2)] as opposed to the cross-spectral technique developed by Stockdon and Holman[1)].

Both methodologies above are designed to extract wave speed component at select frequency from video imagery. However, the wave phase speed estimates near shoreline and at the location where the wave signal change significantly due to present of wave breaking was poorly estimated. This problem has implication on the bathymetry estimation result derived from video images.

Thus, the objective of this study is to determine wave number estimate based on cross-spectral correlation technique that utilizes a non linear inverse method to estimate bathymetry using video images. For this research, the Hasaki beach as one of beach in Japan will be used to generate further research in the shallow water area. In the following sections, we will first review about data conditions in Hasaki beach area. Next, we summarize mathematical formation of wave number model and inversion model. Finally, we examine and analyze our application model results and then draw some conclusions.

2. STUDY AREA

This research study was investigated with camera video observation from Hasaki beach, Japan. The Hasaki beach is located on 120 km east of Tokyo facing the North Pacific Ocean as shown in **Fig 1**.

In general, Hasaki beach is known as straight sandy coast stretching from north to south with length around 17 km long. Since 1986, many coastal studies have been conducted in this location especially around the pier which is known as HORS (Hasaki Oceanographical Research Station).

Wave data were obtained from NOWPHAS wave measurement data at Kashima site location (35°55'37" N and 140° 44'00" E). The wave gauge is located in 22 m water depth. During 2006, the yearly average significant wave height ($H_{1/3}$) is about 1.06 m with corresponding wave period ($T_{1/3}$) of 8.4 seconds. In normal condition, waves approach the coast most often from the East and South East directions. The average of the tidal range is about 1.60 m

3. WAVE NUMBER MODEL

The estimation of wave celerity, c (or, equivalent to wave number, k) is determined by using nonlinear inversion method related to the cross-spectral correlation as proposed by Plant et al[3]. We assume that time delay information is available from the spatially separated pixels such that

$$I(x_i, y_i, t) = I(x_j, y_j, t + \Delta t_{i,j,n}) \tag{1}$$

In 1-Dimension (x-direction), time delay equation can be expressed as described by Bendat and Piersol[4]

$$\Delta t_{i,j,n} = \int_{xi}^{xj} \frac{\cos(\alpha_n[x])}{c_n[x]} dx = \int_{xi}^{xj} \frac{\cos(\alpha_n[x])k_n[x]}{f_n} dx \tag{2}$$

where α_n is the direction of the n^{th} wave component, f_n is wave frequency and c_n is the celerity of the wave component. The wave field can be described in discrete spatial domain, with spacing, Δx and then the discrete time delay equation becomes:

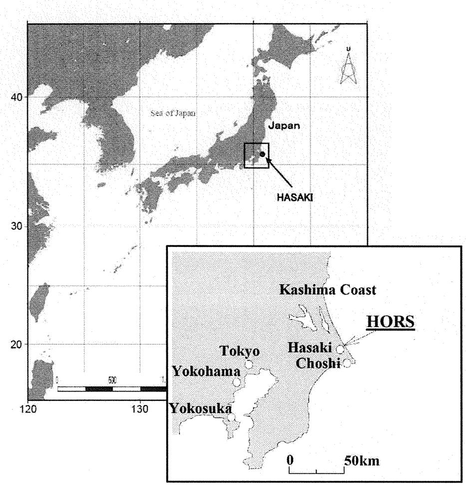

Fig. 1 Location of the Hasaki site

$$\Delta t_{i,j,n} = \Delta x \sum_{m=1}^{M} D_{i,j,m} \frac{\cos(\alpha_n[x_m])}{f_n} k_n[x_m] \tag{3}$$

where D is design matrix defined on both the sample domain (x_i, x_j), and x_m is the estimation of domain and α_n (wave direction) and c_n (wave celerity) as unknown model parameters.

To utilize the time delay equation with remotely sensed imagery, we first must estimate time lag, Δ_t, associated with the propagation of the visible wave signal. The time lag will differ for all sensor pairs. This requires some sort of a search for Δ_t that corresponds to a maximum in the cross correlation function (r_{ij}) as described by:

$$r_{i,j}(\Delta t) = W(\Delta t) * \langle I(x_i, t) I(x_j, t + \Delta t) \rangle \tag{4}$$

where W is a band-passed filter that is convolved against the cross correlation and the angle brackets indicate an ensemble average over all observation times. Since it is natural to work with wave processes in the frequency domain, a discrete Fourier transform is applying to the observation to compute the cross-spectra between two sensors pair. The time delay equation can be described as:

$$C_{i,j,f}^{OBS} = \langle \tilde{I}(x_i, f) \tilde{I}^*(x_j, f) \rangle = \gamma_{i,j,f} \exp\{\sqrt{-1}\Phi_{i,j,f}\} \tag{5}$$

where the tildes indicate the Fourier transform, the asterisk indicates complex conjugate, angle brackets indicate ensemble or band averaging, γ is the coherence, and Φ is the phase shift between two sample locations x_i and x_j. Since the phase shift between two sensors is $\Phi_{i,j,f} = 2\pi f \Delta t_{i,j,f}$, replace Δ_t with the right hand side of (3) and replace Φ in (5) to get a model for cross-spectral correlation equation:

$$C_{i,j,f}^{MODEL} = \exp\left\{2\pi\Delta x\sqrt{-1}\sum_{m=1}^{M} D_{i,j,m}k_{m,f}\cos\left(\alpha_{m,f}\right)\right\} \quad (6)$$

4. NON LINEAR INVERSE METHOD

When the wave number is nonlinearly related to the cross-spectral correlation, a non-linear inversion method Levenberg-Marquardt (LM)[5] is used to minimize the weighted squared difference between successive estimated of the model and the observations:

$$\Delta C_{i,j,f}^{\tau} = \left\{\gamma_{i,j,f} C_{i,j,f}^{MODEL(\tau)} - C_{i,j,f}^{OBS}\right\} \quad (7)$$

where, at each iteration τ, the model-observation mismatch is weighted by the observed coherence, $\gamma_{i,j,f}$. An iterative procedure starts with an initial value $k_{f,m}^{o}$ and new estimate of wave number model are obtained with:

$$k_{f,m}^{\tau+1} = k_{f,m}^{\tau} + \Delta k_{f,m}^{\tau} \quad (8)$$

where the variation $\Delta k_{f,m}^{\tau}$ calculated from

$$\Delta k_{f,m}^{\tau} = \left(\left[R^{\tau}\right]^{T} R^{\tau} + \lambda^{\tau} I\right)^{-1} \left[R^{\tau}\right]^{T} \Delta C_{i,j,f}^{\tau} \quad (9)$$

where λ^{τ} is the damping parameter, I is the identity matrix and R is sensitivity matrix for the cross-spectral correlation as describe:

$$R^{\tau} = \gamma_{i,j,f}\sqrt{-1}D_{i,j,m}C_{i,j,f}^{MODEL(\tau)}\Delta x \quad (10)$$

The iterative procedure of sequentially calculating $\Delta k_{f,m}^{\tau}$ and $k_{f,m}^{\tau+1}$ from Eqs (8) and (9) is continued until the convergence criterion $\left|\Delta k_{f,m}^{\tau}\right| < \varepsilon$ is satisfied, where ε in this model is 10^{-6}

Fig. 2 Snapshot image around pier area

In 2-dimension, the longshore wave number is determined by a similar analysis of cross-spectral correlation for longshore timestack. By calculated the cross-shore and longshore wave number estimate, the wave direction distribution can be examined.

5. RESULTS

(1) Video Camera System

The video camera system in Hasaki site was first installed on August 16, 2006. The data sets of video images were collected from single camera network Canon VB-C50iR on 10 m height above ground level to generate images with resolution 640 x 480 pixels[6]. In this video camera system, snapshot images were collected at interval 1 second every hours using single camera as shown in **Fig 2.**

(2) Image Processing

To extract pixel lines from successive images, the image coordinate of pixel (u,v) on the image need to convert on the real coordinate system (x,y,z). In this rectification, the relationship between image coordinate and real coordinate as described by Holland et al[7] was used. The result of rectification image from snapshot image is shown in **Fig 3**.

Then timestack images were collected hourly at each point in the array which can be expressed as $I(x_i, y_i, t)$, where x_i, y_i are the spatial coordinate of the i^{th} image pixel, and t are discrete sampling times. An example of time series of pixel intensities image for cross-shore at y = 120 m and for alongshore array at x = 185 m and 285 m are presented in **Fig 4**.

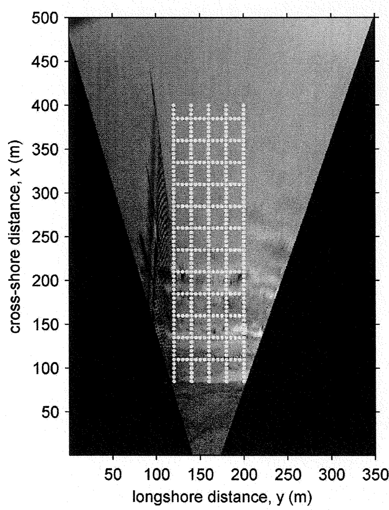

Fig. 3 Rectified image from snapshot image on 25/08/2006 at 07.00 around pier area with five cross-shore arrays and twelve long-shore arrays (shown with dots pixel)

(3) Analysis of Wave number, *k*

To apply this technique, we were used timestack data collected on August 25, 2006. Using this timestack, the wave number estimate was computed at a series of wave frequencies ranging from 0.08 Hz to 0.12 Hz. It is expected from those wave frequencies resolutions; the wave will give strong signal for the analysis of pixel intensity time series. On this date, the peak wave period based on field measurement was 9.1 sec; the wave direction was approach from 81 degree from North direction; and the significant wave height was 1.11 m.

Using the measured bathymetry and the tide level at the time of the image collection, the wave number was compute for each frequency. The nonlinear inverse Levenberg-Marquardt method was applied to the sample cross-spectral correlation at each frequency over entire array. **Fig 5** shows the wave number estimate results from the highest coherence at frequency of 0.10 Hz. This frequency corresponds with the peak wave period offshore measurement. The direction of wave approach generally close to shore normal with the median direction was -5 degree. **Fig 5** also shows the distribution of the predicted errors which reflected the quality of data.

(4) Depth Inversion

The depth inversion method based on timestack method computes water depth by relating wave number parameters using a suitably accurate dispersion equation. Water depth, *h* is related to local wavenumber, *k* and frequency, *f* through the linear dispersion equation[8)]

$$(2\pi f)^2 = gk\tanh(kh) \qquad (11)$$

where *g* is gravitational acceleration and *h* is the local water depth. Given a value for *f* (sample wave frequencies) and *h* (an initial depth), this equation can be solved iteratively for wave number. Again, we used the Levenberg-Marquardt nonlinear inverse method to minimize error between the wave number predicted by (12) and the estimated form images (7).

The result of water depth estimated map is shown in **Fig 6**. The bathymetry estimation by inverted all frequency shows that the Hasaki beach have sand bar at *x* = 200-250 m. At near shoreline and wave breaking area, the bathymetry estimate is accurate with predicted errors are small.

To verify the bathymetry invert model, the result is compare to the survey measurement data. The accuracy of the bathymetry invert was tested using image data collected on August 2006. Figure 7 shows comparison between measured beach profile and mean estimated profile based video images at y = 200 m. It shows that the prediction is most accurate near shoreline and sand bar, where the differences between estimated and survey water depth is less than 10-30 cm. **Fig 7** also indicates that the region around x = 250 m is associated with the slope break before the shoreface of wave will start to break. Then waves will break again near shoreline around x = 150 m. Estimated of water depth were varied in these regions which shown by positive and negative difference errors in the **Fig 7**.

Meanwhile, for seaward direction (x > 270 m) the estimate bathymetry shows large error with positive difference error around 1.5-2 m.

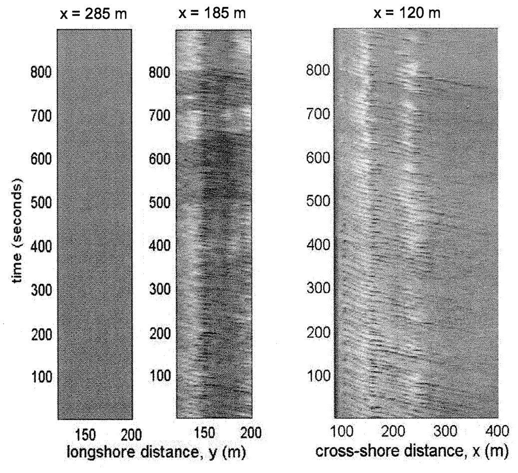

Fig. 4 Timestack images along alongshore array at x = 285 m (left) and x = 185 m (middle). Right figure is for cross-shore timestack at y = 120 m. The speeds of the shoreward progression of waves are calculated by using the slope of the traces of wave crests as shown in images above. Unfortunately, for alongshore timestack at x = 285 m, the trace of wave crest can not be indentify.

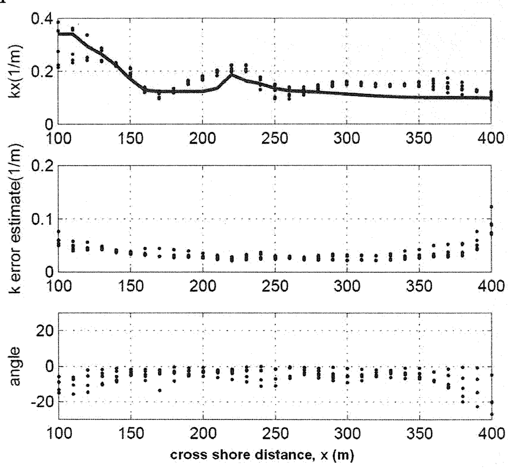

Fig. 5 Wave number estimate (dots) compared to linear wave theory (line) (top), (2nd) rms error prediction and (3rd) wave angle

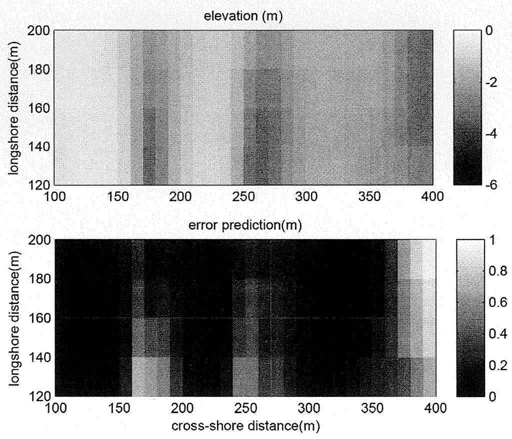

Fig. 6 Bathymetry inverse result from video image at 25 August 2006 (top) and error prediction (bottom)

Large errors which were found outside breaking area seem related to poor information on the alongshore timestack image (at $x = 285$ m) as shown in **Fig 4** (left image) which causing poor water depth estimate result on the model.

This poor information of wave signal on alongshore timestack likely attributed to the limitation of the camera system where performance of video imaging of waves is degrading with increased distance from the camera and with viewing angle. As the result, the pixel resolution of image rectification will decrease as the consequence of increasing distance of camera.

6. CONCLUSIONS

This research presents a method to estimate bathymetry in the shallow water area using wave number derived from video images. The method consists of wave number model which based on cross-spectral correlation technique and bathymetry inverse which based on wave dispersion model. The results indicated that the cross-spectral correlation approach have capability to derive wave number estimate from time series of pixel intensities to estimate bathymetry. The model provides reasonable accurate depth estimate near shoreline and breaking area. Meanwhile, the large errors which found outside breaking area was mainly associated with poor information of wave signal on alongshore timestack, which resulting poor depth estimate.

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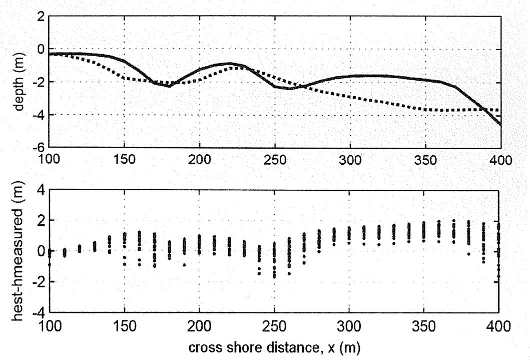

Fig. 7 Comparison between measured depth (dots) and average mean depth estimated (line) (top) and estimated depth error compared to measured depth for August 18-31, 2006 (bottom).

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