BATHYMETRY INVERSION USING VIDEO IMAGE IN SHALLOW WATER

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日本の沿岸では，港湾空港技術研究所により，海岸過程を把握する目的でビデオモニタリングシステムが2006年から導入されている．記録されたビデオ映像から画像解析手法により，波の情報と海底地形を推定することができる．解析の手順は，まず，ビデオ映像において岸沖方向のラインを設定し，ライン上の画素の輝度を読み取る．これをもとに，波の進行の様子が表わされるタイムスタック画像を作成する．タイムスタック画像から，画像解析により浅海域における波の特性を調べることができる．本研究の目的は，クロススペクトルと相関を利用した方法を開発し，タイムスタック画像から波数を精度良く推定すること，さらに，波の分散モデルを利用して波の情報から海底地形を逆推定することである．波崎海岸におけるビデオ映像記録に本手法を適用した結果，本手法により，来襲波の波数を精度良く推定でき，汀線付近や砕波帯周辺における海底地形を推定することが可能であると示された．

Key Words: *video image, wave number,bathymetry inverse, timestack*

1. INTRODUCTION

The nearshore is a region where several human activities take places, like recreation, fishing, navigation, etc. This area is known as the dynamic zone which characterized by a dynamic interaction between waves and underlying bathymetry. The breaking waves and current induce sediment transport updating the bed level condition. Then, the new update bathymetry provides feedback to the wave field and modifying the wave characteristic and induces more morphology change to the nearshore bathymetry. These bathymetry changes can occur on temporal time scale (hours to decades) and spatial scales (meters to kilometers) with different degree of complexity. Thus, it is important to understanding the coastal process in the nearshore zone.

Good quality bathymetry information is hence required in order to identify correctly the physical processes that are taking place. However, bathymetric data collection by in situ measurement is not easy task. Combination of traditional in situ survey method and advanced techniques such as global position systems and modern ship vehicles are expensive in labour, time and money. Added, in situ survey measurements have limitation on spatial and temporal resolutions.

Recently, the invention of new digital technology of images form video camera systems 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 compare with in-situ traditional measurement.

This video camera program (Argus system) is first initiated by the Coastal Imaging Lab of Oregon State University, USA in 1980. Since then, video image technique have been used and developed into very useful tool for monitoring coastal processes in the nearshore environment area[1].

Related with bathymetry prediction, in the video image data it is possible to see the interaction of the incident wave field with the bathymetry (i.e. wave shoaling and refraction); from this information, then it can be used to obtain estimates of bathymetry. The approach for estimating bathymetry is based on wave kinematics utilize the depth dependence of the wave speed (or, equivalently, the wave length and frequency via $c=f/k$, where c is the wave phase speed, f is the wave frequency and k is the wave number = $1/L$, and L is the wave length). Overall, this approach requires image sequence (or time series of intensity at discretely sample locations).

The underlying methodology to extract of wave characteristic problem has taken on number of different form. These include finding wave celerity from time series of cross-shore pixel intensities using cross-spectral scheme[2)] and determining wave phase speed from coastal video observation system using cross-correlation analysis technique[3)] as opposed to the cross-spectral technique developed by Stockdon and Holman[2)].

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 implies to the bathymetry estimation derived from video images.

Thus, the objective of this study is to determine wave number estimate based on cross-spectral correlation technique 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.

2. FIELD SITE

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 for 2006 period were obtained from NOWPHAS wave measurement data at Kashima site location (35°55'37" N and 140° 44'00" E). The wave record located in 22m water depth.

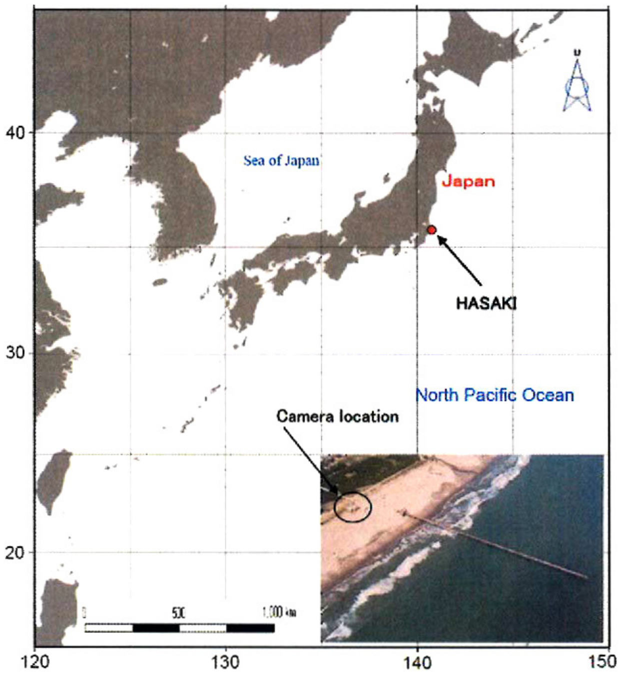

Fig. 1 Location of the Hasaki site

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. METHODOLOGY

This research study is to develop a video-image based depth inversion technique to inversely compute water depths from depth induced wave number which can be evaluated from nearshore video image sequences. These video images can provide high resolution wave signals in the nearshore in the time and space domains.

Methodology of the present research is shown in the **Fig 2**. Figure 2 shows four steps for nearshore bathymetry estimation derived from video images which consist of 1) data collection; 2) image processing analysis; 3) wave number analysis and 4) estimation of local water depth. The purpose of data collection is to collect hydrographic data of study area (for example wave height, wave period, tidal range, and bathymetry) and also video images.

In the image processing step, the procedure consists of four analyses which are image analysis, image rectification, timestack image and image filtering. The main aim of the image processing is to obtain physical information from timestack images.

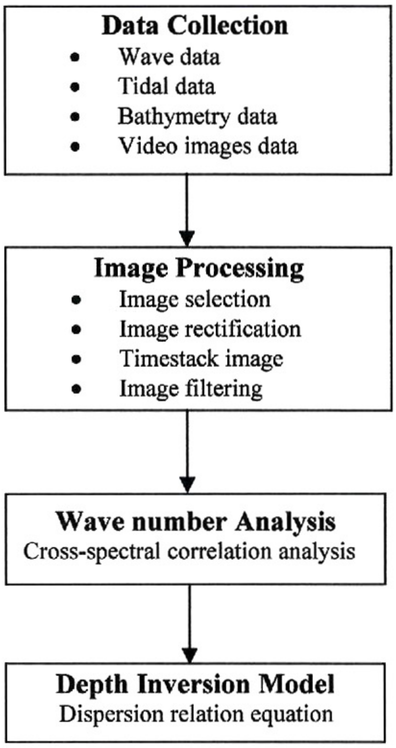

Fig.2 Methodology for depth inversion using video images

After generation of the timestack images along cross-shore arrays and longshore arrays from rectified image, the next analysis is to extract wave number estimation from timestacks. Then using estimation of wave number value, the nearshore bathymetry can be predicted by the wave dispersion relation equation.

(1) Video Camera System

The video camera system in Hasaki site was first installed on August 16, 2006. The 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[4]. In this video camera system, snapshot images and 10 minutes average time exposure images were collected every hours using single camera as shown in **Fig 3** and **Fig 4** below.

From **Fig 4**, we can see white foams appear on the figure which indicate the location of breaking waves. These location of breaking waves can be used to indicate the position of sand bar where the water is shallow enough to cause wave breaking.

(2) Image Processing

In the Hasaki site, the camera took successive pictures of surface water fluctuations around hasaki pier at interval 1 second. An example of snapshot image taken by camera around Hasaki pier is shown in **Fig 3**. 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[5] was used. Figure 5 shows image rectification from snapshot picture

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 (timestack) for cross-shore at y = 120 m and for longshore array at x = 185 m are presented **in Fig 6.**

Fig 3. Snapshot image around pier area

Fig 4. Time-average image

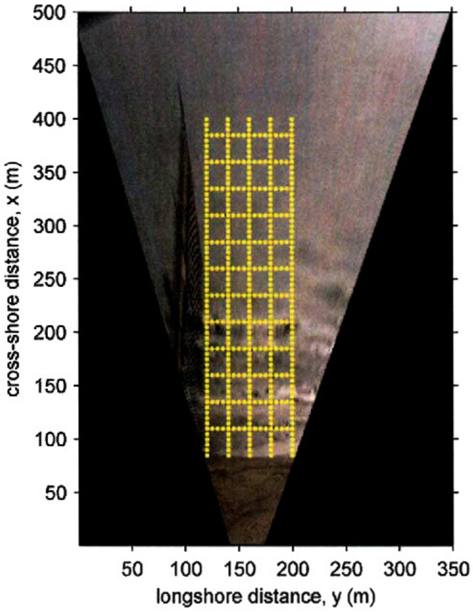

Fig. 5 Rectified image from snapshot image on 25/08/2006 at 07.00 around pier area with five cross-shore arrays and twelve long-shore arrays (shown with dots pixel)

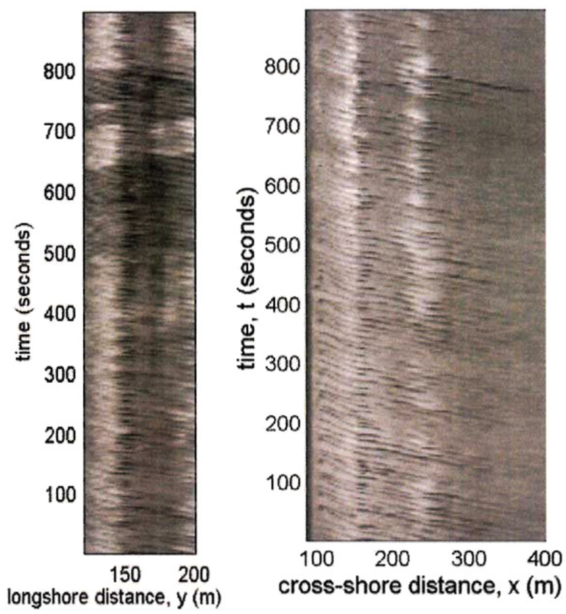

Fig. 6 Timestack images on 25/08/2006 along longshore array at x = 185 m (left) and along cross-shore array at y = 120 m (right) and along. The slope of the wave traces can be used to calculate the approximate speed of the shoreward progression of waves

(3) Wave number Model

In this research, 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[6]. We assume that time delay information is available from the spatially separated pixels such that

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

In 1-Dimension (x-direction), time delay equation can be expressed as described by Bendat and Piersol[7])

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

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:

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

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 (wave direction) and c (wave celerity) as unknown model parameters.

To utilize the time delay equation with remotely sensed imagery, one 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:

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

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

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

where the tilde indicate the Fourier transform, the asterisk indicates complex conjugate, angle bracket 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 $\Phi_{i,j,f} = f\Delta t_{i,j,f}$, replace Δ_t with the right hand side of (2) and replace Φ in (5) to get a model for cross-spectral correlation equation:

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

While the time delay equation is linier in the cross-shore wave number ($k_{m,f}$ cos($\alpha_{m,f}$)), the cross-spectral correlation equation is nonlinear function of wave number. Since the wave number is nonlinearly related to the cross-spectral correlation, a nonlinear inversion approach Levenberg-Marquardt (LM)[8] 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, $\gamma_{i,j,f}$.

Because the wave rarely approach from directly offshore, the longshore wave number must be determined. 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, not only the wave number can be determined but also the wave direction.

(4) Depth Inversion

The depth inversion method based on timestack method is computing water depth by relating wave number parameters using a suitably accurate dispersion equation. Water depth, h is related to local wave number, k and frequency, f through the linier dispersion equation[9]

$$(2\pi f)^2 = gk\tanh(kh) \quad (9)$$

where g is gravitational acceleration and h is the local water depth. From (9) the local water depth can be derived with

$$h = \frac{\tanh^{-1}\left(\dfrac{(2\pi f)^2}{gk}\right)}{k} \quad (10)$$

Due to hyperbolic tangent in equation above makes the equation is complicated to solve. Given a value for f (sample wave frequencies) and h (an initial depth), this equation can be solved iteratively for wave number.

4. RESULT

To apply this technique, we will use data timestack 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 resolution the wave will give strong signal for the analysis of pixel intensity time series. In 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 estimation method was applied to the sample cross-spectral correlation at each frequency over entire array. **Fig 7** shows the wave number estimate results from the highest coherence at frequency of 0.10 Hz. This frequency correspond with the peak wave period offshore measurement. It also show that the wave direction most perpendicular to the shoreline when approaching near shoreline. **Fig 7** also shows the distribution of the predicted errors which reflected the quality of data.

After calculate wave number estimate, the local water depth is then inversely estimated using dispersion equation. The result of water depth estimated is shown in **Fig 8**. The bathymetry estimation by invert 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 predicticted errors are small.

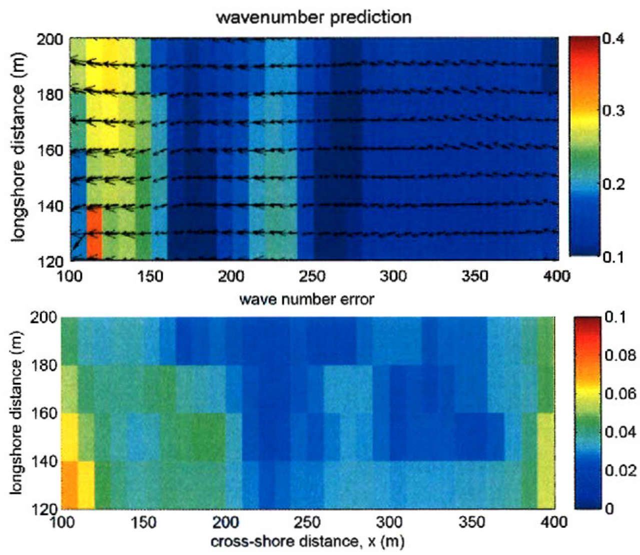

Fig. 7 The value of wave numbers estimate, k (top) with wave angle distribution (arrows sign) and error estimate (bottom) from image 25/08/2006.

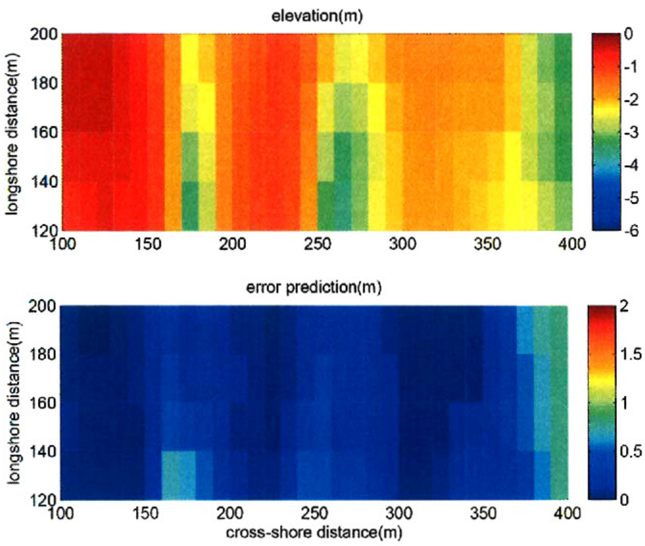

Fig. 8 Batymetry inverse result from video image at 25 August 2006 (top) and error prediction (bottom)

To verify the bathymetry invert model, the result is compare with the survey measurement data. The accuracy of the bathymetry invert was tested using image data collected over 1 month period on August 2006. Figure 9 shows comparison between measured beach profile and mean estimated profile based video images collected over one month period 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 10-20 cm. Meanwhile, seaward direction (x > 270 m) the bathymetry less accurate. In general, the rms error accros the entire profile of measured compare to estimated water depth was 0.44 m rms-error

The possibility of inaccuracy in seaward direction likely due to the limitation of the camera system for example because of the distance and position of camera video which give influence on the accuracy of image rectification. Another limitation of video camera system can be related with environmental condition during time of sampling such as rain, fog, poor lighting which can distrub the quality of the image.

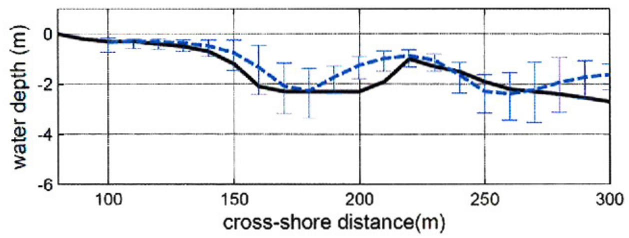

Fig. 9 Cross-shore profile between survey observation (thick line) and bathymetry inverse from video images (dash line) along with standard deviation error bars

5. 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 analysis which based on cross-spectral correlation technique and bathymetry inverse which based on wave dispersion model. The result indicated that the cross-spectral correlation approach have capability to derive wave number estimate from time series of pixel intensities to estimate bathymetry near shoreline and breaking area. The method provides reasonable accurate depth estimate near shoreline area through bathymetry inverse method with rms error 0.44. However, the bathymetry inversion has a number of possible sources of error since we do not know the true answer. If we compare to the traditional survey technique, the cost and time savings of depth measurement will make the depth inversion technique useful in many situations.

ACKNOWLEDGMENT: The authors wish to thank Port and Airport Research Institute (PARI), Japan for their data support during this study

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