ANALYSIS OF WAVE SPECTRA FOR SHALLOW WATER WAVES USING VIDEO IMAGES TECHNIQUE

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本研究では、まず、デジタルビデオカメラによる撮影画像をもとに海岸に来襲する波浪の周波数スペクトルを求め、超音波式波高計による観測結果との比較により、画像解析手法の妥当性について検討した。ビデオ映像は茨城県波崎海岸に設置されたビデオカメラ観測装置により撮影されたもので、連続画像から画素の輝度の時間変動データを取得してスペクトルを求める。波高計による観測結果は、港湾空港技術研究所波崎海洋研究施設（HORS）の観測用桟橋で得られたものである。両者の比較から、画像解析により得られたスペクトルのピーク周波数が観測結果によく一致することが確認された。次いで、撮影画像から方向スペクトルの推定を試みた。得られた方向スペクトルは、方向集中度が高く周波数分布も狭い、鋭い形状のスペクトルであった。

Key Words: Video image, wave spectra, shallow water, wave characteristic

1. INTRODUCTION

Since first developed in 1980, the capability of video remote sensing techniques have been used and developed into a very useful tool for monitoring coastal changes in the nearshore environment area. These capabilities include to study sand bar morphology, foreshore beach slope, wave runup, wave phase to estimate bathymetry, directional wave spectra and etc.

The basic idea of the remote sensing of video camera is to take a snapshot image of the instantaneous wave pattern in coastal area with assumption that the color variations of the snapshot image reflect the wave characteristics. Since successive images data from video camera were collected at a specific period, temporal changes of the wave field can be studied. In this video image technique, the pixel brightness on the snapshot image can be considered proportional to the intensities of the light reflected from the water surface.

After we have successfully extracted wave number components and derived bathymetry in shallow water area with video images data from Hasaki beach in Japan, the applicability of video images from Hasaki beach have to be investigated more further to study wave characteristic in coastal area. The measurement of water wave characteristics in coastal area is important for variety of coastal and marine engineers for planning and designing process of many coastal works. Wave spectra are common ways to characterize a complicated sea surface. Spectral techniques certainly represent a powerful and advance research tool for marine or coastal engineering studies. Wave spectra allow a more detailed description of real waves compare to regular wave theory.

Therefore, it is important to examine the representation for shallow water wave spectra to study wave characteristics. This paper presents the comparison of wave spectra between video images and in-situ measurement in assessing the accuracy of video images technique to derive wave spectra.
with the actual wave field. Directional wave spectrum derived from pixel brightness on video images in shallow water area was also provided.

2. FIELD SITE

This research study was investigated with video camera 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 below. 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.

![Fig.1 Location of the Hasaki site](image)

3. MEASUREMENT DATA

The actual surface fluctuations in the Hasaki site were recorded using several ultrasonic wave gauges. The ultrasonic wave gauges were installed on the pier with position \(x = 378\) m, \(x = 230\) m, and \(x = 145\) m from the shoreline. The HORS pier is located at \(x = 0\) m where in-situ wave pressure gauges installed. Water surface fluctuations were recorded as 60 minutes segment, each of which contains approximately 7200 data points, at a sampling rate of 2 Hz.

Meanwhile, image data were collected by using single camera installed in HORS pier at Hasaki beach, Japan in 2006. The digital video camera with the resolution of 640 x 420 pixels was used to acquire snapshot images. This video camera was mounted 10 m high above the ground level. The video images data was recorded for 15 minutes duration at every one hour interval with frequency sampling interval of 1 Hz. Fig. 2 shows the example of snapshot images recorded by video camera system around pier area at Hasaki site.

4. IMAGE ANALYSIS

In order to collect qualitative data, firstly, rectification of the image must be carried out in order to extract quantitative data from a sequence of snapshot images. Rectification involves photogrammetric transformations, which convert image coordinates \((u, v)\) into the real world coordinates \((x, y, z)\) as shown in Fig. 3. This transformation was based on the standard photographic method as described by Holland et al.\(^8\).

\[
\begin{align*}
\frac{u}{v} &= \frac{L_1 x + L_2 y + L_3 z + L_4}{L_5 x + L_6 y + L_7 z + 1} \\
\frac{v}{u} &= \frac{L_8 x + L_9 y + L_{10} z + L_{11}}{L_{12} x + L_{13} y + L_{14} z + 1} 
\end{align*}
\]  

(1)

![Fig.3 Relation between image coordinate \((u, v)\) and real world coordinate \((x,y,z)\)](image)
where the coefficients $L_1$ to $L_{11}$ are linear functions of the camera orientations $(\tau, \phi, \sigma)$, the camera position $(x_c, y_c, z_c)$ and the effective focal length $(f)$, which directly relates to the camera horizontal field of view $\delta$. Three camera orientations, namely the tilt $(\tau)$ which represents the rotation with respect to the vertical $z$-axis, azimuth $(\phi)$ which represents the orientation in the horizontal $xy$-plane and roll $(\sigma)$ represents of the focal plane with respect to the horizon, respectively.

The inverse transformation from image coordinates to field coordinates results in a system of two equations with three unknowns. The $z$-coordinates are assumed in this transformation to match a certain horizontal reference level or the tidal water level. Rectified images result from snapshot images is presented in **Fig. 4** below.

![Fig. 4 Rectified image time series from snapshot images on 18 August 2006 at 09.00 around pier area.](image)

5. WAVE FREQUENCY SPECTRUM

From a sequence of rectified images, time series of pixel brightness intensity at specific point where the wave gauge is located then can be formed. **Fig. 5** shows the examples of time series at $x = 230$ m (outside breaking area) from the wave gauge and pixel brightness on video images sequence which correspond to the nearest location of the wave gauge. The time series of pixel brightness on video images may have introduced possible some source of error corresponding to the pixel resolution resulting from rectification procedure, because the actual area occupied by a pixel in the image will increase with increasing distance from the camera as shown in **Fig. 6**.

![Fig. 6 Scale distortion from rectification of snapshot image](image)

**Fig. 6 Scale distortion from rectification of snapshot image**

In this study, wave frequency spectra were calculated based on Fourier transform in combination with overlapped, segmented and averaging procedure as given in Bendat and Piersol9). Due to the short time series used in the video images data (around 15 minutes), the time series of 512 points data were used in the analysis.

The time series of 512 points sampled at 1.0 second were first standardized using zero mean and subdivided into 128-points segment with 50% overlap for spectral estimation. This process of analysis resulted in 7 segments of data with spectral resolution of 0.0078 Hz. Fast Fourier Transform was implemented with each Hanning-window segment and averaged to calculate wave frequency spectrum.

Video images recorded on 18 August 2006 were used in the spectral analysis. In this day, the observed significant waves height based on NOWPHAS data base were below 1.0 m and the wave direction was approach from NE direction. The results of wave spectrum of pixel brightness on video image are shown in **Fig. 7**.

![Fig. 7 Comparison time series of wave profile from a wave gauge with sampling frequency 0.5 Hz and pixel brightness on video images with sampling frequency 1.0 Hz](image)
Comparison of wave spectrum between time series of pixel brightness on video images and in-situ measurement is shown in Fig. 8. It can be seen that the normalized spectral are similar in shape. The figure shows narrow band spectrum with major sharp peak at frequency 0.117 Hz, which corresponds to peak period of 8.5 seconds. This peak frequency corresponds with peak period from offshore measurement \((T_{1/3} = 8.2 \text{ seconds})\). Meanwhile multiple weaker peaks appear at higher frequency from 0.2 Hz to 0.4 Hz. These multiple weaker peaks are presence due to nonlinear wave component which is a typical characteristic of shallow water spectrum. Also, the spectrum shape from wave gauge is smoother because the frequency resolution is less than of the pixel brightness on video images. Below 0.05 Hz and above 0.4 Hz, the white noise decreases due to band-pass filter with a high pass filter and a low pass filter.

Figure 9 shows another example of comparison between the wave spectra from video images and in-situ measurement on 18 August 2006. In the figures, the peak frequency was very close in both wave spectra. While in some cases, for example at 11.00 h and 15.00 h, the video images and in-situ spectra presented different peak frequency. This variability is because the accuracy of wave spectrum from video images which represent the sea surface elevation dependent on wave slope and other phenomena such as sea ripples, wave breaking, sun glitter, etc. On the other hand, the wave gauges data is represent as true water surface elevations.

However, in general, it can be concluded that the
video images and in-situ spectra show similar form with the frequency peaks positioned very close to each other as indicated in Fig. 10. The figure shows the single peak frequency observed from video images and in-situ measurement varied between 0.09 Hz and 0.13 Hz. The average of peak frequency from video images and in-situ are 0.09 Hz and 0.10 Hz, respectively. The average of peak frequencies agreed well with a difference of only 0.01 Hz between video images and in-situ spectra.

6. DIRECTIONAL WAVE SPECTRUM

Two estimation methods of directional wave spectrum have been used in this work. First method is Extended Maximum Likelihood Method (EMLM), developed by Isobe et al. The EMLM is popularly used because it can provide high directional resolution and capable to handle various kind of wave property. The equation for the EMLM method is given by

\[ \hat{S}(f, \theta) = \kappa \left[ \sum_{m} \sum_{n} \Phi_{mn}^{-1}(f) H_{m}(f, \theta) \right] \]

where \( \hat{S}(f, \theta) \) is the estimate of the directional spreading function, \( \Phi_{mn}^{-1} \) is an \( mn \) element of the inverse cross spectral matrix \( \Phi^{-1} \) and \( \kappa \) is the constant to normalize the directional spectrum energy, \( H_{m}(f, \theta) \) is the matrix consisting of transfer functions between the surface elevation and any other combination of wave properties (e.g. pressure, velocity or acceleration) and the symbol * is the conjugate complex.

The second method is the Bayesian Directional Method (BDM), introduced by Hashimoto et al. Generally, the BDM provides the highest resolution in estimating the directional wave spectrum. In the BDM, the estimation of a directional wave spectrum can be considered as a regression analysis to find the most suitable model from limited data. The directional spreading function is expressed as a piecewise constant function over each segment of the directional range from 0 to \( 2\pi \). Since the directional spreading function always greater than or equal to zero, then it can be approximated as

\[ G(\theta | f) \approx \sum_{k=1}^{K} \exp\{x_k(f)\} I_k(\theta) \]

where

\[ I_k(\theta) = \begin{cases} 1: (k-1)\Delta\theta \leq \theta < k\Delta\theta \\ 0: \text{otherwise} \end{cases} \]

Generally, the directional spreading function \( G(\theta | f) \) is assumed a smooth continuous function with respect to the wave direction. This is mathematically expressed by the following relationship between three consecutive values of the estimate.

\[ \sum_{k=1}^{K} (x_k - 2x_{k-1} + x_{k-2})^2 \approx 0; (x_0 = x_K, x_{-1} = x_{K-1}) \]

The optimal estimate of \( G(\theta | f) \) is obtained by maximize the likelihood function with respect to \( \{x_k\} \) within the range where equation (5) does not become too large. These criteria can be formulated using an appropriate parameter \( u^2 \). The most suitable value of the hyperparameter \( u^2 \) and the estimate of variance \( \sigma^2 \) can be obtained by minimizing the Akaike Bayesian Information Criterion (ABIC) given by:

\[ \text{ABIC} = -2\ln L(x, \sigma^2) p(x | u^2, \sigma^2) dx \]

In this work, a star array design from pixel brightness on video images data was used to estimate directional spectra in shallow water. The examples of directional wave spectrum estimate using the EMLM and BDM are provided in Fig. 11 and Fig. 12, respectively.

In general, Fig. 11 and Fig. 12 show that directional wave spectrum estimated by the EMLM and BDM had narrower directional spreading and shown clear peaks. The figures indicate that the energy peak of the BDM is higher than energy peak estimated by the EMLM. Fig. 13 shows comparison on directional width of spectrum at peak frequency of 0.109 Hz. The figure indicated that both methods estimate similar mean direction about 94 degree from shoreline which indicating the wave approach perpendicular to the shoreline.

Fig. 11 Directional wave spectrum of swell on 18 August 2006 at 09.00 h using the EMLM
Specifically, directional wave spectrum derived from the BDM has narrower directional spreading compare to the EMLM. Also, energy leakage is presence on directional spreading estimated by the EMLM. It is clearly shown that the directional spectrum estimate has been improved by using the BDM method.

7. CONCLUSIONS

Wave spectra analysis in shallow water from pixel brightness on video images was presented. The comparison of wave frequency spectra obtained from video images and in-situ measurement showed that the peak frequencies estimated from pixel brightness on video images well correspond with the signal of in-situ measurement. This study also indicated that video images data could be used to estimate directional spectra in the shallow water area. It is shown that video images method can be very useful technique to understanding the behavior of the wave field in coastal area.

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