HENRY
Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

Conference Paper, Published Version

Sim, Ju-Yeol; Jung, Tae-Hwa; Yoo, Jeseon; Cho, Yong-Sik

Decomposition of Incident and Reflected Regular Wave Using One Moving Wave Gage

Zur Verfügung gestellt in Kooperation mit/Provided in Cooperation with:
Kuratorium für Forschung im Küsteningenieurwesen (KFKI)

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/110163

Vorgeschlagene Zitierweise/Suggested citation:
Sim, Ju-Yeol; Jung, Tae-Hwa; Yoo, Jeseon; Cho, Yong-Sik (2008): Decomposition of Incident and Reflected Regular Wave Using One Moving Wave Gage. In: Wang, Sam S. Y. (Hg.): ICHE 2008. Proceedings of the 8th International Conference on Hydro-Science and Engineering, September 9-12, 2008, Nagoya, Japan. Nagoya: Nagoya Hydraulic Research Institute for River Basin Management.

Standardnutzungsbedingungen/Terms of Use:

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

DECOMPOSITION OF INCIDENT AND REFLECTED REGULAR WAVE USING ONE MOVING WAVE GAGE

Ju-Yeol Sim[1], Tae-Hwa Jung[2], Jeseon Yoo[3] and Yong-Sik Cho[4]

[1] Graduate Student, Department of Civil Engineering, Hanyang University
17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea, e-mail: simjuyul@hanyang.ac.kr
[2] Post-doctoral Researcher, River & Coast Research Division, Korea Institute of Construction Technology
2311 Daehwa-dong, ilsanseo-gu, Goyang-si, Geyeonggi-do 411-712, Korea, e-mail: togye176@kict.re.kr
[3] Post-doctoral Researcher, Department of Civil Engineering, Hanyang University
17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea, e-mail: jeseonyoo@hanyang.ac.kr
[4] Corresponding Author, Department of Civil Engineering, Hanyang University
17 Haengdang-dong, Seongdong-gu Seoul 133-791, Korea, e-mail: ysc59@hanyang.ac.kr

ABSTRACT

A method splitting harmonic wave into incident and reflected waves using a single movable wave gage is introduced. After measuring water surface elevation at different locations and times, the reflection and transmission coefficients are calculated by using fast Fourier transformation and least square method. The present method is validated by testing under regular wave condition.

Keywords: wave decomposition, fast Fourier transformation, wave gage

1. INTRODUCTION

The prediction of wave transformation such as a wave reflection is very important to design and prevent the coastal structure from oceanic wave attack. In laboratory experiments for the analysis of wave reflection, several methods are already established to determine the incident and reflected waves (Goda and Suzuki, 1976; Mansard and Funke, 1980; Suh et al., 2001; Lin and Huang, 2004). These methods utilize anywhere from two to four wave gage.

When considering the decomposition of waves due to complex geometries (for instance, a combination of a submerged structure and sloping breakwater or a submerged structure and a sloping beach), it is reported that at least two pairs of wave gage are required, one upwave region and downwave region of the submerged structure. However, the installation of multiple wave gages can be problematic. First of all, the cost of a wave gage is not a negligible expense. Secondly, the presence of multiple wave gages can cause serious signal noise problem, affecting the reliability of the results.

In this study, a simple method which decomposes the incident and reflected waves from regular or irregular harmonic waves is developed using one moving wave gauge. This method extended the Lin and Huang's method (2004) to consider different measuring time. By moving one wave gauge, time series of water surface elevation was obtained from different locations and times. Then, the incident and reflected wave amplitudes can be calculated from that data using fast Fourier transform and the least square method. If two different locations and times are selected, the singular condition for distance is identical to that of Goda and Suzuki (1976). Applying to numerical model shows the validation of model.

2. THEORETICAL BACKGROUND

The water surface elevation at any location and time $(x_m,\ t_m)$ can be expressed as follows:

$$\begin{aligned}\eta(x_m,\ t_m) &= \eta_i(x_m,\ t_m) + \eta_r(x_m,\ t_m) \\ &= \frac{H_i}{2}\cos(kx_m - \omega t_m + \delta_i) + \frac{H_r}{2}\cos(kx_m + \omega t_m + \delta_r) + \varepsilon_m\end{aligned} \tag{1}$$

where η_i and η_r are the incident and reflected waves, respectively; H_i and δ_i are the incident wave height and phase angle; H_r and δ_r are the reflected wave height and phase angle; ε_m is error caused by signal; ω is the angular frequency; and k is the wavenumber calculated by linear dispersion relationship:

$$\omega = \sqrt{gk \tanh kh} \tag{2}$$

where g is the gravitational acceleration and h is the water depth. The individual wave component can be extracted by applying the water surface elevation to fast Fourier transformation as follows:

$$\tilde{\eta} = \frac{\omega}{2\pi}\int_0^{(2\pi/\omega)} \eta(x_m, t_m)\exp(-i\omega t)dt \tag{3}$$

Measuring at two different locations

First, water surface elevations at (x_0, t_0) and (x_1, t_1) are measured by moving a wave gage as shown in Fig. 1.

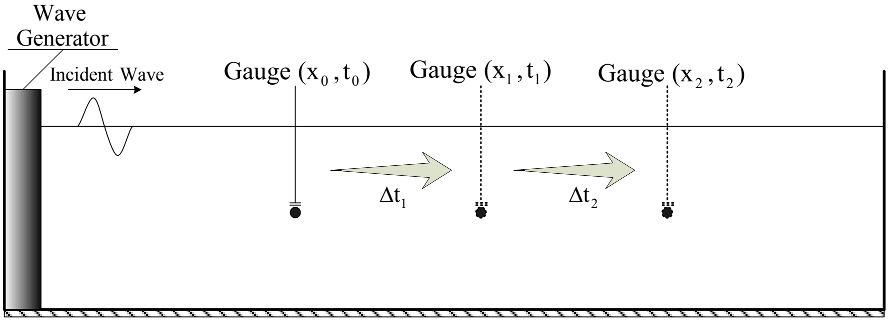

Figure 1 Definition sketch of wave flume using one moving wave gauge.

Each water surface elevation can be express as follows:

$$\eta(x_0, t_0) = \frac{H_i}{2}\cos(kx_0 - \omega t_0 + \delta_{i,0}) + \frac{H_r}{2}\cos(kx_0 + \omega t_0 + \delta_{r,0}) + \varepsilon_0 \tag{4}$$

$$\eta(x_1, t_1) = \frac{H_i}{2}\cos(kx_1 - \omega t_1 + \delta_{i,1}) + \frac{H_r}{2}\cos(kx_1 + \omega t_1 + \delta_{r,1}) + \varepsilon_1 \tag{5}$$

Substituting Eq. 4 and 5 into 3 gives

$$\tilde{\eta}(x_0) = X_1\tilde{\eta}_I + X_2\tilde{\eta}_R + E_0 \tag{6}$$

$$\tilde{\eta}(x_1) = X_1\tilde{\eta}_I + X_2\tilde{\eta}_R + E_1 \tag{7}$$

where E_0 and E_1 are the fast Fourier transform of errors, and

$$\tilde{\eta}_I = \frac{H_i}{2}\exp[-i(kx_0 + \varepsilon_0)] \tag{8}$$

$$\tilde{\eta}_R = \frac{H_r}{2}\exp[i(kx_0 + \varepsilon_0)] \tag{9}$$

$$X_1 = X_2 = \frac{1}{2} \tag{10}$$

$$X_3 = \frac{1}{2}\exp[-i(k\Delta x_1 - \omega\Delta t_1)] \tag{11}$$

$$X_4 = \frac{1}{2}\exp[i(k\Delta x_1 + \omega\Delta t_1)] \tag{12}$$

where $\Delta x_1 = x_1 - x_0$ and $\Delta t_1 = t_1 - t_0$

To minimize the errors, E_0 and E_1, in the Eq. 6 and 7, least square method is used.

$$\frac{\partial}{\partial\tilde{\eta}_I}\sum_{m=0}^{1}[E_m]^2 = \frac{\partial}{\partial\tilde{\eta}_R}\sum_{m=0}^{1}[E_m]^2 = 0 \tag{13}$$

This procedure gives an algebraic linear matrix equation:

$$\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}\begin{bmatrix} \tilde{\eta}_I \\ \tilde{\eta}_R \end{bmatrix} = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \tag{14}$$

where

$$C_{11} = (X_1^2 + X_3^2) = \frac{1}{4} + \frac{1}{4}\exp[-2i(k\Delta x_1 - \omega\Delta t_1)] \tag{15}$$

$$C_{12} = C_{21} = (X_1X_2 + X_3X_4) = \frac{1}{4} + \frac{1}{4}\exp[2i\omega\Delta t_1] \tag{16}$$

$$C_{22} = (X_2^2 + X_4^2) = \frac{1}{4} + \frac{1}{4}\exp[2i(k\Delta x_1 + \omega\Delta t_1)] \tag{17}$$

$$D_1 = X_1\tilde{\eta}(x_0) + X_3\tilde{\eta}(x_1) \tag{18}$$

$$D_2 = X_2\tilde{\eta}(x_0) + X_4\tilde{\eta}(x_1) \tag{19}$$

After solving the matrix equation, the unknown incident and reflected wave heights can be obtained from

$$H_i = 2|\tilde{\eta}_I| \tag{20}$$

$$H_r = 2|\tilde{\eta}_R| \tag{21}$$

The singularity for solving Eq. 14 occurs when the determinant of matrix diverges.

$$C_{11} \cdot C_{22} - C_{12} \cdot C_{21} = 0 \tag{22}$$

This equation can be simplified as follows

$$\begin{aligned} &\cos(2k\Delta x_1 + 2\omega\Delta t_1) + i\sin(2k\Delta x_1 + 2\omega\Delta t_1) + \cos(2k\Delta x_1 - 2\omega\Delta t_1) \\ &- i\sin(2k\Delta x_1 - 2\omega\Delta t_1) - 2\cos(2\omega\Delta t_1) - 2i\sin(2\omega\Delta t_1) = 0 \end{aligned} \tag{23}$$

The condition satisfying Eq. 23 is given by

$$\Delta x_1 = n\frac{L}{2} \qquad (n = 1,\ 2,\ 3,\ \cdots) \tag{24}$$

It should be noted that the singularity for solving Eq. 14 is equivalent to the limitation of the two-point method suggested by Goad and Suzuki (1976). For the three measuring points, same procedure from Eq. 4 to Eq. 24 can be applied and also same result of Mansard and Funke (1980) is obtained.

3. VERIFICATION

A numerical simulation was carried out for cases of regular waves to verify the results of the present method. Since it has been previously shown that the use of two wave gages gives rise to large errors at $\Delta x_1 / L = n/2 \ (n = 0,\ 1,\ 2,\ \cdots)$, the numerical test was performed with data measured at three different points.

The numerical were conducted using the following conditions: $H_i = 0.1m$, $H_r = 0.05m$, and $h = 1.0m$. First, letting $\Delta x_1 = h$, $\Delta x_2 = 2\Delta x_1$, $\Delta t_1 = 2.0T$, and $\Delta t_2 = 2\Delta t_1$ with a sampling rate of 256 Hz, the incident and reflected wave heights were calculated. The incident wave period was varied so as to consider a broad range of relative water depth. Thus, the relative water depth varied from a shallow water limit $(kh = 0.314)$ to a deep water limit $(kh = 3.14)$. Fig. 2 shows a comparison between the target and predicted incident and reflected wave heights. The results are in good agreement for all relative water depths.

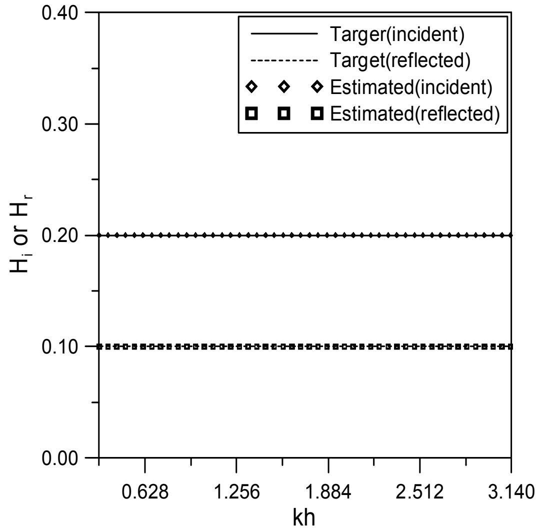

Figure 2 Comparison of wave heights between target and estimated values of incident and reflected waves for different relative water depth.

Fig. 3 shows the incident and reflected wave heights calculated by changing Δx_1 from $\Delta x_1 = 1.0h$ to $\Delta x_1 = 5.0h$. The other condition remained the same as those in Fig. 2. As shown in Fig. 3, the decomposition of the fundamental harmonic waves is successfully achieved regardless of the location of the second and third measurements.

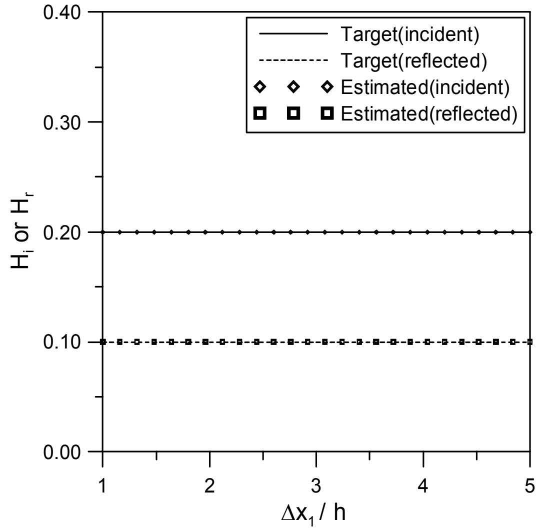

Figure 3 Comparison of wave heights between target and estimated values of incident and reflected waves for different location gap.

4. CONCLUSION

A simple method separating the incident and reflected waves from a harmonic wave was developed. The newly developed method may reduce the cost and increase the reliability of performing wave characteristic measurements. The number of wave height measured in this method is flexible, and the measurement can be performed exactly as in Goda and Suzuki (1976) and Mansard and Funke (1980) depending on the number of measuring point.

Verification of this method was performed using a numerical model simulating regular wave condition. The amplitude and incident and reflected waves of targeted and estimated values were compared at various relative wave depth and location. It was shown that the estimated values are identical to the target ones irrespective of the values of relative water depth and location.

Since the measurement of the wave heights is time-dependent, the method presented in this study may not work well when re-reflection caused by a laboratory wave generator is significant. However, recently developed wave generators are equipped with a wave gage at their nose to minimize the effects of re-reflection during laboratory experiments. Under such conditions, this method can be worked effectively.

ACKNOWLEDGMENTS

The financial support of the Korea Research Foundation(KRF-2007-313-D00827) is gratefully acknowledged.

REFERENCES

Battjes, J.A. (1974), Surf similarity, *Proc. 14th Coastal Engineering Conference*, 38, pp.167-176.

Brossard, J., Hemon, A. and Rivoalen, E. (2000), Improved analysis of regular gravity waves and coefficient of reflexion using one or two moving probes, *Coastal Engineering*, 39, pp.193-212.

Gaillard, P., Gauthier, M. and Holly, F. (1980), Method of analysis of random wave experiments with reflecting coastal structures, *Proc. 17th Coastal Engineering Conference*, ASCE, Reston VA, USA, pp.201-220.

Goda, Y. (2000), Random Seas and Design of Maritime Structures, *World Scientific,* Singapore.

Goda, Y. and Suzuki, Y. (1976), Estimation of incident and reflected waves in random wave experiments, *Proc. 15th Coastal Engineering Conference*, ASCE, Honolulu, pp.828-845.

Hughes, S.A. (1993), Laboratory wave reflection analysis using co-located gauges, *Coastal Engineering,* 20, pp.223-247.

Kubota, S., Mizuguchi, M. and Takezawa, M. (1990), Reflection from swash zone on natural beaches, *Proc. 22nd Coastal Engineering Conference*, ASCE, Reston VA, USA, pp.570-583.

Lin, C,Y. and Huang, C,J. (2004), Decomposition of incident and reflected higher harmonic waves using four wave gauges, *Coastal Engineering*, 51, pp.395-406.

Park, W.S., Oh, Y.M. and Chun, I.S. (1992), Separation technique of incident and reflected waves using least squares method, *Journal of Korean Society Coastal Ocean Engineering*, 4, pp.139-145 (in Korean, with English abstract).

Suh, K.D., Park, W.S. and Park, B.S. (2001), Separation of incident and reflected waves in wave-current flumes, *Coastal Engineering*, 43, pp.149-159.

Tatavarti, R.V., Huntley, D.A. and Bowen, A.J. (1988), Incoming and outgoing wave interactions on beaches, *Proc. 21st Coastal Engineering Conference*, ASCE, Reston VA, USA, pp.136-150.

Walton, T.L. (1992), Wave reflection from natural beaches, *Ocean Engineering*, 19, pp.239-258.