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# A practical scheme of vibration monitoring and modal analysis for caisson breakwater

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ABSTRACT

In this study, a practical vibration analysis approach to obtain the dynamic characteristics of an *in-situ* caisson breakwater under the ambient wave load is presented. Firstly, a scheme of vibration monitoring and modal analysis is designed for the caisson breakwater. The limits of vibration monitoring on the caisson system is examined based on sensor placement and excitation source. An output-only modal analysis approach which combines the time-domain stochastic subspace identification method and the frequency domain decomposition method is designed to estimate modal parameters from wave-induced ambient vibration signals. Secondly, in-situ tests on a real caisson breakwater are described. Acceleration signals recorded under ambient wave-induced excitation are experimentally analyzed for a few caisson units under sea-level variation. Finally, experimental modal analyses are performed on the measured acceleration signals to evaluate the practicality of the proposed scheme. The numerical modal analysis of the caisson-foundation system was also conducted to support the experimental mode identification result. Relative modal responses of three adjacent caisson units are analyzed to estimate relative differences in dynamic characteristics due to their structural conditions. Also, the effect of water-level variation on modal parameters such as natural frequencies, modal damping and mode shapes is analyzed from the in-situ vibration records of a single caisson unit.

## 1. Introduction

Gravity-type caisson breakwaters stand on a foundation mound above seabed and stabilized by its own weight. The breakwaters transmit wave forces to the foundation and reflect or dissipate the wave energy from the sea. Upon repeatedly experiencing wave forces, the caisson system is inevitably damaged due to local and global variations of geometric and boundary properties deviated from its as-built states (Takagi, 2015). The structural instability results in weakening the structural performance against settlement, overturning and sliding which are mainly attributed to local defects in the caisson-foundation system (Oumeraci and Kortenhaus, 1994; Goda, 1994; Lamberti et al., 1999).

Recently, the safety of the caisson breakwater system becomes a more important issue due to the frequent occurrence of extreme events. There were severe failure events of breakwaters (Oumeraci and Kortenhaus, 1994; Franco, 1994; Tanimoto and Takahashi, 1994; Takayama and Higashira, 2002; Maddrell, 2005). Typhoon Maemi, which hit the southern part of Korean Peninsula in 2003, resulted in the failure of many caisson breakwaters. The tsunami caused by the Great East Japan Earthquake in 2011 destroyed many breakwaters in Japan. Many researchers have investigated on the damaged breakwaters and their failure mechanisms to clarify the instabilities of those breakwaters under the tsunami attacks (Takagi, 2015; Marinski and Oumeraci, 1992; Oumeraci et al., 2001; Arikawa et al., 2012). For safety and maintenance reasons, therefore, the structural performance of the breakwater should be adequately assessed to predict its lifetime serviceability.

Dynamic characterization has been adopted as a promising tool to assess the integrity of civil infrastructure (Stubbs et al., 1992; Doebling et al., 1998; Sohn et al., 2003; Ko and Ni, 2005; Gul and Catbas, 2011; Park et al., 2016; Huynh et al., 2016). Vibration test and modal identification play an important role in the validation of the structural design and the characterization of the structural performance. Most research studies have focused on structural health monitoring of inland structures like bridges, but only a few research efforts have been made to harbor structures (e.g., pier and wharf) (Inaudi et al., 2000; Lobedan et al., 2002; Del Grosso et al., 2007; Boroschek et al., 2011). Del Grosso et al. (2007) presented some experiences on structural health monitoring of harbor piers in the Port of Genoa, Italy. Boroschek et al. (2011) performed an experimental evaluation of the dynamic properties of a wharf structure. For the caisson breakwater, the identified modal parameters can be used

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for the condition assessment of the caisson-foundation system. The identified modal parameters can be further utilized for the estimation of the structural responses of the caisson under particular loading and boundary conditions.

In spite of those research efforts, the application of vibration-based techniques to the caisson breakwater has received little attention because of the limited accessibility for vibration measurement, the high-power excitation source for the forced-vibration test, and the difficulty in vibration response analysis. Recent research attempts have shown the possibility of the vibration-based approach for structural health monitoring of upright breakwaters (Smirnov and Moroz, 1983; Gao et al., 1988; Lamberti and Martinelli, 1998; Martinelli and Lamberti, 2011; Huynh et al., 2012, 2013; Lee et al., 2013a, 2015). Gao et al. (1988) investigated vibration responses of a caisson breakwater using forced vibration tests. Lamberti and Martinelli (1998) performed impact tests to examine the relative movement of excited caissons and its adjacent ones in the array. Yi et al. (2013) evaluated dynamic characteristics like natural frequency and modal damping of a caisson breakwater using tugboat impact tests.

Although those experimental results made good indications of natural frequencies and damping ratios, forced vibration tests (e.g., tugboat collision) are not always applicable for large-scale caisson breakwaters due to the requirement of high-energy excitation and the potential danger in its performance. Lee et al. (2013a) applied the so-called 'ambient vibration test' to measure vibration responses of the lab-scaled caisson-foundation system. Lee et al. (2015) performed lab-scaled tests on a caisson breakwater model to identify structural parameters of the tested model using vibration records. Despite those research attempts on lab-scaled models of caisson breakwaters, real conditions have not been simulated accounting for uncertain ambient parameters. Also, the practicality of vibration test under natural solicitation has not been evaluated for the real caisson-foundation system.

Relative to the high-power excitation source for forced vibration tests, such as tugboat impact load, the ambient wave load can be considered as a simple and practical excitation source to induce oscillations of the gravity-type caisson breakwater. The objective of this study is to propose a practical vibration analysis approach for estimating the dynamic characteristics of in-situ caisson breakwater under the ambient wave load.

Firstly, a scheme of vibration monitoring and modal analysis is designed for the caisson breakwater. The limits of vibration monitoring on the caisson system is examined based on sensor placement and the excitation source. An output-only modal analysis approach which combines the time-domain stochastic subspace identification (SSI) method and the frequency domain decomposition (FDD) method is designed to estimate modal parameters from wave-induced ambient vibration signals.

Secondly, in-situ tests on a real caisson breakwater are described. Acceleration signals recorded under ambient wave-induced excitation are experimentally analyzed for a few caisson units under sea-level variation.

Finally, experimental modal analyses are performed on the measured acceleration signals to evaluate the practicality of the proposed scheme. The numerical modal analysis of the caisson-foundation system was also conducted to support the experimental mode identification result. Relative modal responses of three adjacent caisson units are analyzed to estimate relative differences in dynamic characteristics due to their structural conditions. Also, the effect of water-level variation on modal parameters such as natural frequencies, modal damping and mode shapes is analyzed from the in-situ vibration records of a single caisson unit.

## 2. Vibration monitoring and modal analysis of caisson breakwater

Vibration tests and modal identification can play important roles to validate the structural design and the characterization of the structural performance. For the caisson breakwater, the identified modal parameters can be used to assess the structural condition of the caisson-foundation system. The identified modal parameters can be further utilized for estimating the structural responses of the caisson under particular loading and boundary conditions.

### 2.1. Vibration monitoring condition of caisson breakwater

The limits of vibration monitoring of caisson breakwaters is outlined with respect to the sensor placement and the excitation source. The caisson breakwater is designed to protect the port from the effect of incident waves. A vertical composite caisson breakwater, which is placed on a rubble mound foundation and armored by a protection unit, receives pulsating wave pressure from incident waves (Oumeraci et al., 2001), as shown in Fig. 1. Since the caisson breakwater is submerged under seawater, being subjected to buoyancy, hydrostatic pressure and wave force, only the top of the caisson is accessible for the field measurement which requires a dry condition.

A structural system is represented by structural dynamics characteristics such as stiffness, mass, and damping properties. Its acceleration responses depend on the structural characteristics and it can be defined as

$$\ddot{\boldsymbol{u}}_t = [\mathrm{M}]^{-1}\left(\{F\} - \dot{\boldsymbol{u}}_t[\mathrm{C}] - \boldsymbol{u}_t[\mathrm{K}]\right) \tag{1}$$

in which $\boldsymbol{u}_t$, $\dot{\boldsymbol{u}}_t$ and $\ddot{\boldsymbol{u}}_t$ represent the displacement, velocity, and acceleration vectors, respectively; [M], [K] and [C] represent the mass matrix, stiffness matrix, and damping matrix, respectively; and $\{F\}$ is the vector of external force.

The acceleration response provides the information on the dynamic characteristics that can be used for structural health monitoring. In this study, piezoelectric accelerometers are utilized to measure the acceleration responses. The piezoelectric material in the sensor acts as a spring and connects the base of the accelerometer to a seismic mass. When an input is introduced to the base, a force is created on the piezoelectric element that is proportional to the applied acceleration and the size of the seismic mass.

For the forced response of a damped structural system, the general frequency response function (FRF) can be simplified in a complex form as follows (Ewins, 2000):

$$[\mathrm{FRF}(\omega)] = \left[\mathrm{K} + i\omega\mathrm{C} - \omega^2\mathrm{M}\right]^{-1} \tag{2}$$

in which the FRF is defined as a force to displacement response ratio in the frequency domain. As Eq. (1) can be equivalently interpreted as Eq. (2), the system's dynamic characteristics can be estimated via modal parameters such as natural frequency, modal damping and mode shape.

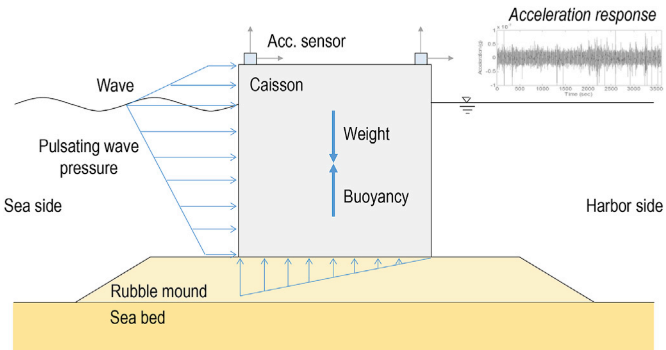


Fig. 1. Vibration monitoring condition of caisson breakwater.