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Structural Damage Monitoring of Harbor Caissons with Interlocking Condition

Thanh-Canh Huynh*, So-Young Lee*, Khac-Duy Nguyen* and Jeong-Tae Kim*†

Abstract The objective of this study is to monitor the health status of harbor caissons which have potential foundation damage. To obtain the objective, the following approaches are performed. Firstly, a structural damage monitoring(SDM) method is designed for interlocked multiple-caisson structures. The SDM method utilizes the change in modal strain energy to monitor the foundation damage in a target caisson unit. Secondly, a finite element model of a caisson system which consists of three caisson units is established to verify the feasibility of the proposed method. In the finite element simulation, the caisson units are constrained each other by shear-key connections. The health status of the caisson system against various levels of foundation damage is monitored by measuring relative modal displacements between the adjacent caissons.

Keywords: Structural Damage Monitoring, Harbor Caisson Structure, Interlocking Condition, Submerged Condition, Relative Motion

1. Introduction

Most of harbor caissons are designed as gravity-type structures which are stabilized on foundation mounds by their self-weights. Caissons are partially submerged into water to dissipate wave energy from open sea, to reduce the wave influence on coastlines, and to protect them from erosion and flooding. Existing harbor caisson structures have frequently experienced extreme breaking waves caused by strong typhoons. As a result, the foundation of the caisson system is exposed against local failures such as erosion, seabed scour at beneath seaward, and scour at shoreward edges [1]. Furthermore, those local damage types may be resulted in the global structural damage under the effect of frequent waves. Therefore, there is a need to develop structural health monitoring techniques for the harbor caisson structure to assess the local damage in the structure-foundation interface.

Over the last decades, many researchers have investigated the global structural failure of caisson-type breakwaters. The problems related to overturning, sliding distance and bearing capacity have been examined in numerical as well as experimental model tests [2-5]. Also, a few researchers have attempted to monitor the health status of harbor caisson structures with local damages. Lee et al. [6] studied vibration responses of a lab-scaled harbor caisson under structure-foundation interface damage. Jabbari et al. [7] used artificial neural networks to estimate scour depth around a vertical breakwater. Lee et al. [8] investigated local scour in an impermeable submerged breakwater. However, those studies have examined only behaviors of mono-caisson systems. Only a few researchers have studied the vibration responses of multiple contacted caisson units [9-10]. Despite of their attempts, there is a need to examine the effect of foundation damage on the interaction between adjacent caisson units.

The objective of this study is to monitor the health status of harbor caisson systems using

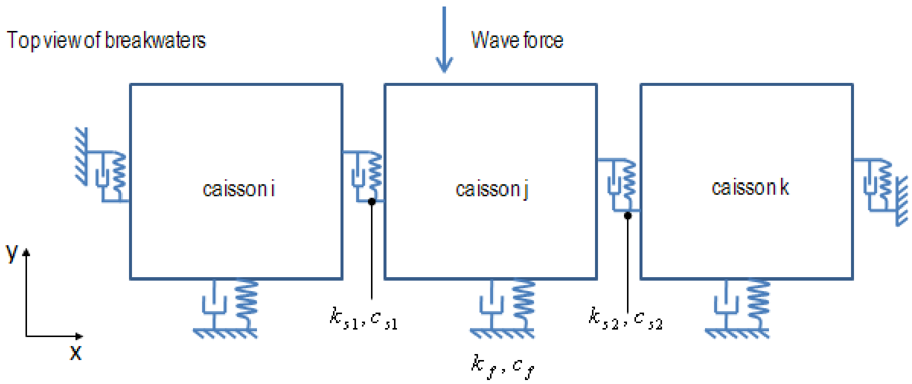
[Received: November 2, 2012, Revised: December 7, 2012, Accepted: December 10, 2012] *Department of Ocean Engineering, Pukyong National University, Busan 608-737, Korea †Corresponding Author: idis@pknu.ac.kr

relative modal displacements. To obtain the objective, the following approaches are performed. Firstly, a structural damage monitoring (SDM) method is designed for interlocked multiple-caisson structures. The SDM method utilizes the change in modal strain energy to monitor the foundation damage in a target caisson unit. Secondly, a finite element model of a caisson system which consists three caisson units is established to verify the feasibility of the proposed method. In the finite element simulation, the caisson units are constrained each other by shear-key connections. The heath status of the caisson system against various levels of foundation damage is monitored by measuring relative modal displacements between the adjacent caissons.

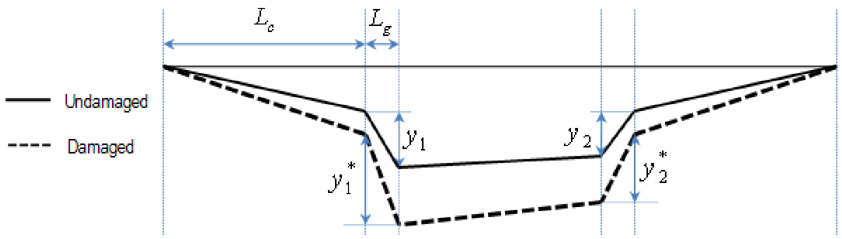
2. Damage Monitoring Method

Dynamic behaviors of a harbor caisson system are very complicated since a caisson unit in the system interacts not only with its foundation but also with its adjacent contacted units via shear-keys. Based on the previous studies [11-12], an 1-D dynamic series model of three caisson units i, j and k considering motion in wave direction (y direction) is proposed as shown in Fig. 1(a). In the model, the three caisson units are treated as rigid bodies. Each unit is constrained by its adjacent units through shear-keys, and by its foundation. For the middle caisson unit (i.e., caisson j), it is connected to caisson i by the left shear-key's spring (k_{s1}) and damper (c_{s1}), and to caisson k by the right shear-key's spring (k_{s2}) and damper (c_{s2}). Caisson j is also supported by the foundation spring (k_f) and damper (c_f).

For the static problem, when caisson j is subjected to a y-axis static load, the caisson system can be deformed as shown in Fig. 1(b). Depending on the load location, the relative displacement between caisson j and caisson i (y_1) may be different from that between caisson



(a) 1-D dynamic series model of 3 caisson units



(b) Y-directional displacement under static force

Fig. 1 1-D dynamic series model of 3 caisson units in static problem j and caisson k (y_2). Next, it is assumed that damage happens at caisson j's structural components (shear-keys or foundation), that results in reductions of the shear-key's spring constants (k_{s1}, k_{s2}) or the foundation stiffness (k_f). As a result, the relative displacements (y_1,y_2) between caisson j and its adjacent caisson units are increased to y^*_1, y^*_2, respectively.

Also, strain energies of the shear-key connections would be changed due to the structural changes. The strain energy shift of the left shear-key of caisson j is illustrated in Fig. 2. As shown in the figure, the strain energy of the left shear-key of caisson j (U_1) is changed to U_1* due to the changes in the shear-key's stiffness and the relative displacement between caisson j and caisson i

The post-damage spring stiffness of the left shear key of caisson j, k_{s1}^*, and the post-damage relative displacement between caisson i and caisson j, y_1^*, can be expressed as:

$$k_{s1}^* = k_{s1} + \Delta k_{s1} \tag{1}$$

$$y_1^* = y_1 + \Delta y_1 \tag{2}$$

where Δk_{s1} is the stiffness reduction of the left shear-key of caisson j and Δy_1 represents the increment of the relative displacement between caisson j and caisson i. The strain energy shift in the left shear-key of caisson j is given by:

$$\frac{\Delta U_1}{U_1} = \frac{U_1^* - U_1}{U_1} = \frac{k_{s1}^*(y_1^*)^2 - k_{s1}(y_1)^2}{k_{s1}(y_1)^2} \tag{3}$$

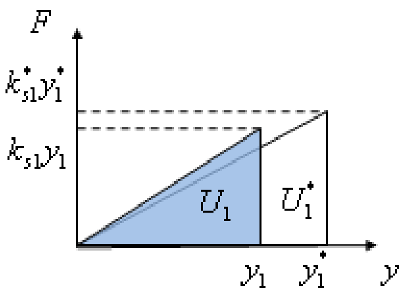


Fig. 2. Strain energy shift in caisson j's left shear-key due to damage

where $\triangle U_1$ is the strain energy change of the left shear-key of caisson j.

Substituting Eqs. (1) and (2) into Eq. (3), neglecting second-order terms, Eq. (3) can be rewritten as:

$$\frac{\Delta U_1}{U_1} = \frac{\Delta k_{s1}}{k_{s1}} + \frac{2\Delta y_1}{y_1} \tag{4}$$

Suppose that only the structure-foundation interface of caisson j is damaged, and the spring constant of its shear-key remains unchanged, the strain energy shift of the left shear key of caisson j is simplified as:

$$\frac{\Delta U_1}{U_1} = \frac{2\Delta y_1}{y_1} \tag{5}$$

For the dynamic problem, the real displacement of the structure is the integration of its mode shapes via the modal supperposition method. Therefore, the strain energy shift of the left shear-keys of caisson j for the mth mode would be computed as:

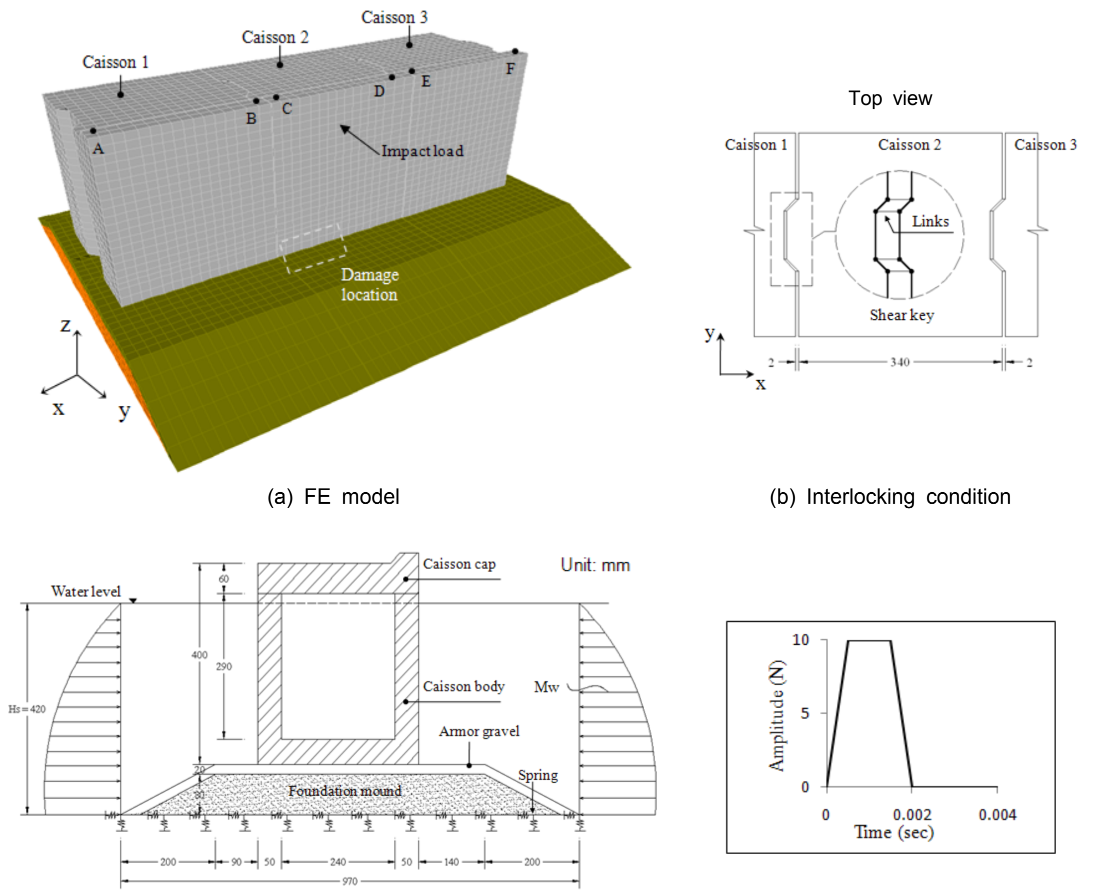
$$\frac{\Delta U_{m1}}{U_{m1}} = \frac{2\Delta \phi_{m1}}{\phi_{m1}} \tag{6}$$

where $\triangle U_{m1}/U_{m1}$ is the shift in the mth modal strain energy of the left shear-key of caisson j due to damage, and $\triangle \phi_{m1}/\phi_{m1}$ is the change in the relative mth modal displacement between caisson j and caisson i due to damage. Using Eq. (6), the foundation damage can be detected by the change in the modal strain energy of the shear-key connection.

3. Numerical Verification

3.1 Finite Element Model

In order to verify the proposed SDM method, a numerical model of three caisson units was established using SAP2000 software as shown in Fig. 3. The finite element(FE) model



(a) FE model (b) Interlocking condition

(c) Cross section (d) Impact load

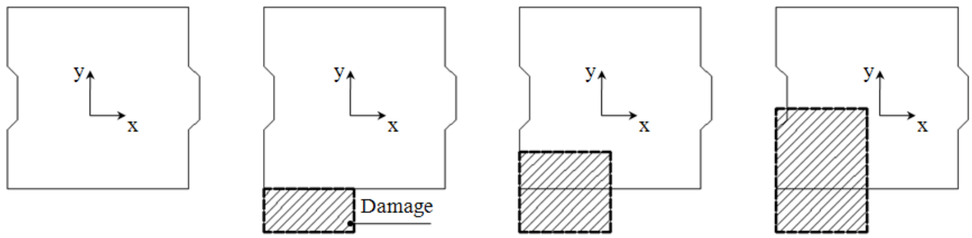
Fig. 3 Finite element model of three caisson units

includes 3 concrete caisson units (i.e., Caisson 1-3) standing on a foundation mound which is covered by an armor gravel layer. In the FE simulation, the foundation was supported by an area spring system, which represents the rest of the foundation mound. The spring stiffness was selected as 31.25(MN/m/m^2) [13]. Interlocking conditions were simulated by y-directional 1-D links at the shear-keys as shown in Fig. 3(b). The stiffness of the links were assumed as 25 (MN/m/m^2). This value was determined by matching the natural frequencies of the FE model with those of the lab-scaled model. By simulating the shear-key connections, y-directional vibrations of the middle unit (i.e., Caisson 2) could be propagated to the adjacent units. Detailed geometric information of the FE model is shown in Fig. 3(a) and (c). Based on the foundation analysis by Bowles [13], material properties of the FE model are given in Table 1.

Table 1 Material properties of FE model

	Caisson	Armor gravel	Foundation mound
Mass density (kg/m^3)	2,500	2,100	2,000
Elastic modulus (MPa)	20,000	10	15
Poisson's ration	0.18	0.3	0.3

Considering the fact that harbor caissons are partially submerged into sea water, the submerged condition was simulated by adding



(a) Undamaged (b) Damage 1 (c) Damage 2 (d) Damage 3

Fig. 4 Foundation damage scenarios of Caisson 2

effective mass to the numerical caisson system as shown in Fig. 3(c). The added mass of water was calculated by Westergaard's hydrodynamic water pressure equation [14]:

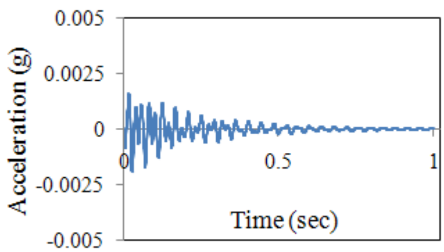
$$M_w = \int_{h_1}^{h_2} \frac{7}{8} \rho \sqrt{H_w . h}\, dh \tag{7}$$

where M_w is the hydrodynamic pressure; ρ is the water density; H_w and h are the depth from water level to the foundation and that to the acting point of hydrodynamic pressure, respectively.

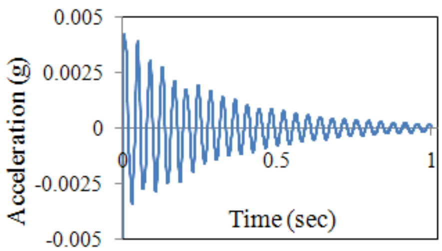
In order to obtain mode shapes of the caisson system, a y-directional impact force was applied on Caisson 2 as denoted in Fig. 3(a) and (d). According to limited accessibility of real submerged caissons, the y-directional acceleration responses of each caisson unit were measured at 2 points on its top surface and along its length, as shown in Fig. 3(a).

It was supposed that the foundation of Caisson 2 was scoured under frequent wave actions. As described in Fig. 4, three levels of foundation damage were simulated by removing armor gravel elements. In Damage 1, about 1.2% of the armor gravel was removed as incipient stage. In Damage 2, the loss of the armor gravel was about 2.3% as moderate damage stage. Damage 3 was the most significant damage in which 3.8% of the armor gravel was lost. It is noted that the damaged area was expanded to the foundation-caisson contact region of Caisson 2 in Damage 2 and Damage 3.

The y-directional acceleration responses of Caissons 1 and 2 at the undamaged scenario are shown in Fig. 5. It can be seen that Caisson 1 was vibrated due to the impact on Caisson 2. This implied that the vibration of Caisson 2 was propagated into Caisson 1 via the shear-key connections between the two caissons. Also, the vibration amplitude of the excited unit is about three times larger than the adjacent unit. This relation was similar as the experimental result reported by Lamberti et al. [12].



(a) Caisson 1



(b) Caisson 2

Fig. 5 Y-directional acceleration

3.2 Damage Monitoring in FE Model

The proposed SDM method was employed to monitor the health status of the caisson model. Natural frequencies and y-directional mode shapes of the caisson system were extracted using the frequency domain decomposition method[15]. The first two natural frequencies of the caisson system at the healthy and damaged states are summarized in Table 2. The corresponding y-directional modal displacements are shown in Fig. 6.

As described in Table 2, the natural frequencies tended to decrease with the damage growth. It is found that the first frequency was more sensitive to the damages than the second one. As shown in Fig. 6, the three caisson units had only positive transverse motions in the first

Table 2 Natural frequency shift of the caisson system under foundation damage.

Damage case	Mode 1 (Hz)	Mode 2 (Hz)
Undamaged	25.42	46.77
Damage 1	25.25 (-0.68%)	46.75 (-0.045%)
Damage 2	24.58 (-3.32%)	46.66 (-0.24%)
Damage 3	24.35 (-4.21%)	46.64 (-0.28%)

*Parentheses indicate variation (%) of natural frequencies with respect to undamaged case.

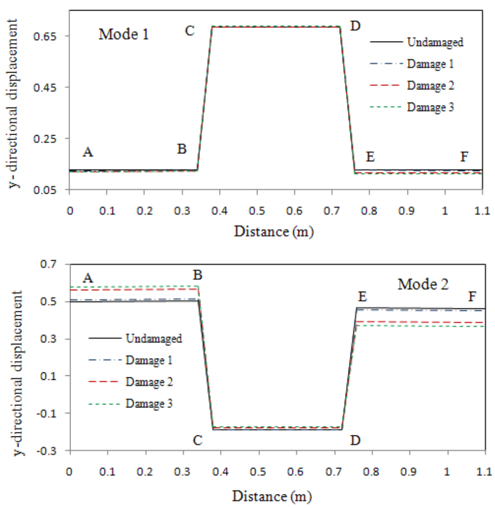


Fig. 6 Y-directional mode shape of FE model

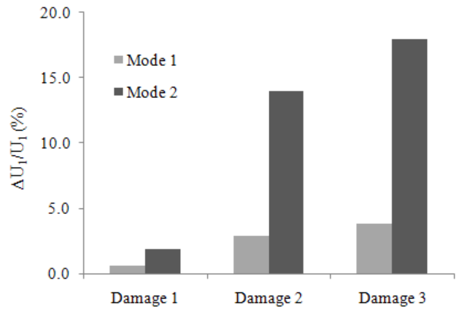


Fig. 7 Strain energy shift in Caisson 2's shear key versus damage in foundation's interface

mode. Meanwhile, both positive and negative transverse motions were observed in the second mode. Also, the changes in the relative modal displacements of the second mode were larger than those of the first mode.

As illustrated in Fig. 6, the modal displacements were increased or decreased depending on sensor locations. This phenomenon came from the normalization of mode shapes. Since the increase of the displacement physically represents foundation damage, the positive variation in relative motion was utilized in this study to monitor foundation damage of the caisson system.

For damage evaluation, the modal strain energy shift in the shear-key connection was computed by Eq. (6). Fig. 7 shows the modal strain energy shift of the left shear key of Caisson 2 due to the damage in the structure-foundation interface. As illustrated in Fig. 7, the modal strain energy shift in the left shear-key of Caisson 2 was proportional with the damage growth. In Damage 1, the modal strain energy shifts were only 0.6% and 1.8% for the first and second modes, respectively. In Damage 2, however, the modal strain energy shifts were risen significantly for both modes. They were accounted for about 3.0% for mode 1 and nearly 14.0% for mode 2. In Damage 3 which represents the most severe damage, the increments of modal strain energies were the largest. They reached to about 3.8% and approximate 18% of the undamaged modal strain energies for modes 1 and 2, respectively. It is found that the above significant changes were related to the expansion of damaged area to the foundation caisson contact region in Damage 2 and Damage 3.

4. Conclusions

In this study, a structural damage monitoring method was presented to evaluate the health status of harbor caissons which have potential foundation damage. Firstly, a structural damage monitoring (SDM) method was designed for interlocked multiple-caisson structures. The SDM method utilized the change in modal strain energy to monitor the foundation damage in a target caisson unit. Secondly, a finite element model of a caisson system was established to verify the feasibility of the proposed method. In the finite element simulation, the caisson units were constrained each other by shear-key connections. The health status of the caisson system against various levels of foundation damage was monitored by measuring relative modal displacements between the adjacent caissons.

From the numerical analysis, the following conclusions have been made:

(1) The strain energy shift in the shear-key connection was successfully utilized to monitor the heath status of the caisson system.

(2) The proposed SDM methodology is promising since it is simple and easy to be applied to real harbor caisson structures.

On reviewing the results of this study, there still exist several research needs on harbor caisson structures. First, the relationship between the damaged area of the caisson-foundation interface and the strain energy shift of the shear-key should be generalized to predict damage severity. Second, the feasibility of the proposed SDM method needs to be verified by experimental studies.

Acknowledgements

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