Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 7 Issue 11, November-2018

Numerical Investigation on Buckling Behavior of Suction-installed Cofferdam

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***Abstract*—This paper conducted buckling analyses of a new type of large offshore cofferdam. The present cofferdam consists of upper and lower modules; each module has a role to prevent water and to obtain bearing capacity of soil, respectively; the lower module is penetrated by pressure difference between interior and exterior of the module (suction). Because the suction pressure induces large compressive stresses in the module, there exist possibilities of the global and local buckling failures. Particularly, the present cofferdam has joint interfaces due to assembly of upper and lower module, and complex behaviors of interface consequently affects buckling characteristics of the structure. For this reason, this paper investigated buckling behaviors of the lower cofferdam module. Considering several boundary loading conditions, buckling loads and modes were estimated.**

Keywords—Cofferdam; buckling; suction bucket foundation; finite element analysis; eigen buckling analysis

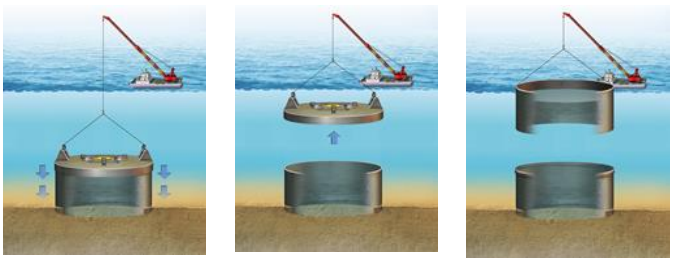
I. INTRODUCTION

Offshore constructions are a representative extreme work. Facilities and structures are exposed to wave loads, and the construction can be tough because they are built at the center of the ocean. Especially, the construction only is allowed for good weather and marine conditions; this causes tremendous construction costs. To extend possible working days at the offshore site, many offshore projects for near-shore site adopts a cofferdam as a temporary structure to make dry condition when a main structure is installed. The cofferdam conventionally consists of many steel sheet-piles that are assembled with each other and play a role to prevent water and soils during construction. Because the assembly work requires many manpower and period, a prefabricated cofferdam has been recently applied to offshore projects (Fig. 1).

A new type of the prefabricated cofferdam is briefly introduced in this paper. Unlike conventional prefabricated cofferdams, the present cofferdam consists of several modules as shown in Fig. 2 to minimize assembly works and to be installed by conventional offshore cranes with normal lifting capacity. Among several modules of the cofferdam, the lowest module plays a role as an anchor foundation and is penetrated by pressure difference between interior and exterior of the module; this pressure is called as suction pressure. To penetrate the module into seabed by suction, the top open end of the module has to be enclosed by a stiff lid plate to seal the interface between the lid and the module wall in order to prevent air, water getting in or out. After completing the penetration of the module, others are placed and assembled.

(a) Plate type (b) Corrugated type (c) Double plate type

Fig. 1. Prefabricated circular body cofferdams



(a) Module installation by suction (b) Lid plate removal (c) Other module installation

Fig. 2. Installation of the lowest module

In structural design view of the lowest module, the suction pressure is the most critical load. The pressure depends on soil bearing capacity and the depth. The module with the lid plate is subjected to suction pressure which is uniformly distributed on the inner surface of the wall the lid. The pressure causes high flexural and compressive stresses in the module wall due to bending and lateral forces from the lid plate. On the other hand, the wall should be slender because of weight and manufacture issues. As increasing the required thickness of the wall, the lifting capacity of offshore cranes is higher and the manufacture of curved plate with desired curvature becomes difficult. High compressive stresses in a slender

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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structural member are easily buckled locally and globally. Thus, the buckling analysis has to be conducted for areas where the high compressive stresses are expected. In addition, for the lowest module, the joint behaviors between the lid and the wall should be considered because high compressive stresses are expected. However, contact conditions at the joint are not clear. The condition affects stiffness of the module, consequently results of the buckling analysis.

Many studies on suction foundation are related to evaluation on the bearing capacity of soil: vertical, lateral, and pull-out resistances of the foundation [1-4]. On the other hands, few researchers investigated suction foundations with respect to structural analysis [5, 6]; particularly, Madsen et al. (2013) conducted numerical buckling analysis of large suction caissons. However, their analyses were bounded to the single caisson, without the joints between the lid and the skirt wall. In this study, considering behaviors at the interface between the lid and the skirt, a linear buckling analysis of the suction foundation for the present cofferdam was conducted applying various boundary and loading conditions. From the numerical results by using finite element models, changes in buckling loads and modes of the structure subjected to suction pressure were investigated.

II. NUMERICAL APPROACHES FOR BUCKLING ANALYSIS

Numerical buckling analysis can be conducted by two approaches. One is the geometrically nonlinear analysis and the other is based on eigenvalue analysis. In the section, the two methods are briefly introduced. Detailed theoretical backgrounds can be referred in references [7-9].

A. Geometrically nonlinear analysis

The analysis can consider finite deformation effects of the structure which are included in formulating a finite element equation for the equilibrium, as in Eq. (1)

$$[\mathbf{K}_s+\mathbf{K}_g][\delta\mathbf{\Delta}] = \delta\mathbf{P} \qquad (1)$$

In Eq. (1), each notation is as follows: $\mathbf{K}_s$: tangent stiffness matrix, $\mathbf{K}_g$: geometric stiffness matrix, $\delta\mathbf{\Delta}$: incremental nodal displacement vector, and $\delta\mathbf{P}$: incremental nodal force vector. The powerful advantage of geometrically nonlinear analysis is that the method can produce destabilization, such as P-Δ, of structures; bifurcation of the load path due to buckling behavior can be simulated: gradual hardening and softening. However, the approach can only provide asymptotic convergence to a buckling critical value, instead of a determinant value. Also, nonlinear solution techniques are required in the approach; the solution can be calculated applying the incremental equation form and nonlinear solvers should be used to loading path throughout pre- and post-peak behaviors of the structure due to buckling.

B. Eigenvalue analysis

The elastic critical buckling load can be also determined from eigenvalue analysis of an idealized elastic model of the structure. In eigenvalue analysis, the eigenvalue and the eigenvectors mean the buckling load and the shape when the structure is buckled, respectively. Eq. (2) is the matrix equation to determine the critical load and its shape:

$$[\mathbf{K}_s + \lambda\mathbf{K}_{gg}]\,[\mathbf{\Delta}] = \mathbf{0} \qquad (2)$$

In Eq. (2), each notation is as follows: $\mathbf{K}_{gg}$: generalized geometric stiffness matrix, λ: loading multiplier, $\mathbf{\Delta}$: nodal displacement vector, and $\mathbf{0}$: zero vector. Although the pre-buckling statics is required to estimate generalized stresses and $\mathbf{K}_{gg}$, which is calculated using nodal displacement components considered boundary conditions, the approach is simpler and computationally light. During pre-buckling statics, the nodal displacements are affected by the load vector. As a result, unlike modal analysis for structural dynamics, the eigenvalue analysis for buckling analysis are affected displacement boundary conditions as well as load conditions.

For the presented suction-installed cofferdam module, the pair of the buckling loads and the shape vector is important, not the loading path that is affected by destabilization; it would be interested in real design process with respect to the buckling safety and the stiffener location. For this reason, this study applied the eigenvalue analysis for buckling to the module with different contact conditions. However, the eigenvalue buckling analysis cannot be combined with nonlinearities such as nonlinear material and contact problems. Thus, instead of contact conditions, the rigid-connection assumption was applied at the interface.

III. NUMERICAL MODEL

A. Model description

To implement numerical buckling analysis of the suction-installed module, ANSYS Mechanical (ver.15) was used. The module has a large double sleeve cross-section with the outer and the inner sleeve diameter of 20m and 19.6m, respectively, and the height is 15m (Fig. 3a). The sleeves have the thickness of 16mm. In addition, the diameter of the lid plate is also 20m. The lid is subjected to uniform pressure throughout all the bottom surface of the lid. Because the lid with the large diameter is only supported by the tip of the module at the perimeter of the lid, excessive bending and vertical displacement are expected, consequently excessive stresses in the lid and the sleeves. To reduce these stresses and deflections, radial stiffeners are also added to the bottom surface of the lid, as well as the use of thick plates. A circumferential stiffener is also attached to the end of the radial stiffeners as shown in Fig. 3b; the number of the radial stiffeners is 24 and the thickness is 0.03m. Numerical models were created for the penetration depth of 10m in the seabed, using shell elements for all components of the module.

B. Load parameters

As mentioned before, the critical load is effected by boundary conditions and load condition. In real, an offshore cofferdam is subjected to several loads: hydrostatic and hydrodynamic pressures, self-weight of the cofferdam, suction pressure, suction-induced-seepage, and earth pressure. However, this study only considered suction pressure and earth pressure as an external load because these forces was the most influential to stress increases in the preliminary structural

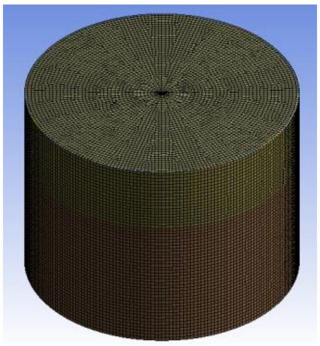
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 7 Issue 11, November-2018

analysis and they mainly cause confined stresses in the sleeves; the hydrodynamic force is related to lateral force and flexural stress. The hydrostatic pressure is also a type of confining load but the pressure is offset by the water in the space between the inner and the outer sleeves.

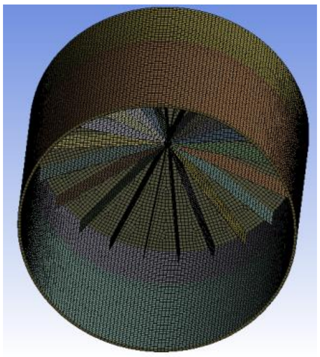
For suction pressure, 100kPa was applied to the inner surfaces of the lid and the wall, respectively. The vertical displacements at the bottom of the wall were fully constrained and the weak springs were imposed to the inner surface of the wall. Next, the geostatic earth pressures were applied to the outer and the inner surfaces below seabed. In real, the area of the sleeves surrounded by soil would be subjected to greater earth pressures because of lateral deflection of the sleeve: soil-structure interaction. However, active and passive earth pressures were too large because they were based on the limit equilibrium state. So, to supplement the use of the geostatic pressure only to represent the earth pressure on the sleeve, ground springs were applied to the same area. The springs contributes to both the model stiffness (as an element) and the forces (as a boundary condition) that applied to the sleeves. However, with respect to numerical analysis strictly, the ground springs are only an element in the model; their contribution is limited to the stiffness in the numerical analysis. In summary, on the earth pressure, the coefficient of the lateral earth pressure of 1.0 under geostatic state and the submerged unit weight of 8kN/m^3 were applied to calculate the earth pressure.

C. Boundary condition parameter

Assuming the tip of the skirt reaches to a hard soil layer, three boundary condition cases were imposed to the bottom of the sleeves: clamped, hinged, and roller constraints. For all the cases, the ground springs were also applied. The subgrade modulus of the soil was assumed to be 5000 kN/m^3.



(a) Outer sleeve



(b) Inner sleeve and lid plate

Fig. 3. Finite element model

IV. NUMERICAL RESULTS

For numerical model imposed by the fixed support under suction pressure and earth pressure, respectively, the buckling load multiplier are listed in Table 1. Unexpectedly, as the buckling mode became higher, there were no remarkable changes in the buckling shape for each case; although the number of the buckling mode increase to 40 (of course, this is not practical and not necessary) to observe different buckling shape modes, for suction pressure, the buckling occurred in upper areas of the outer and the inner sleeves; the area is not directly supported by vertical supports connecting with the sleeves. The suction pressure when the buckling initiated was 136 kPa.

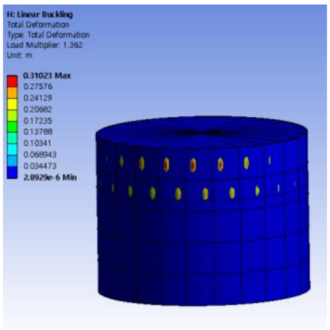
For earth pressure, the buckling occurred in lower areas of the sleeves. To initiate the buckling by the earth pressure, the lateral earth pressure coefficient has to be increased to 3.67 (Table 2). When the fixed boundary condition was applied, the load multiplier at the mode 1 increased to 3.72.

TABLE I. LOAD MULTIPLIER: LOADING CONDITIONS (ROLLER)

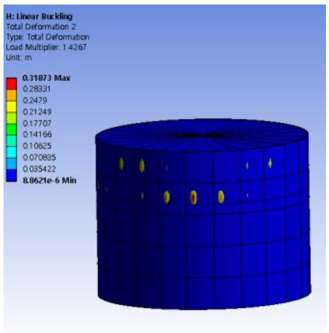
Load	Load multiplier			
	Mode 1	*Mode 10*	*Mode 30*	*Mode 40*
Suction	1.36	1.43	1.60	1.71
Earth pressure	3.67	3.75	4.08	4.21

TABLE II. LOAD MULTIPLIER: BOUNDARY CONDITIONS (SUCTION)

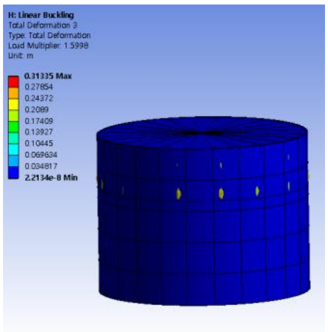
Load	Load multiplier			
	Mode 1	*Mode 10*	*Mode 30*	*Mode 40*
Fixed B.C.	1.36	1.43	1.60	1.71
Hinged B.C.	1.36	1.43	1.60	1.71
Roller B.C.	1.36	1.43	1.60	1.71



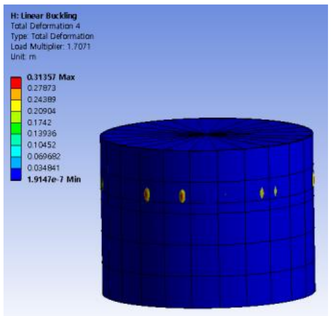
(a) Mode 1



(b) Mode 10



(c) Mode 30



(d) Mode 40

Fig. 4. Buckling load multiplier and shape (suction pressure, roller B.C.)

On the other hand, changes in boundary conditions rarely affect buckling loads as shown in Table 2. This means that ground springs strongly constrain to lateral deflections of the sleeves. Also, the results show that buckling failure of the module could be caused by the suction pressure rather than earth pressure. There was no change in load multiplier for suction pressure, while the load multiplier for earth pressure slightly increased to 3.73 when the fixed boundary condition was applied.

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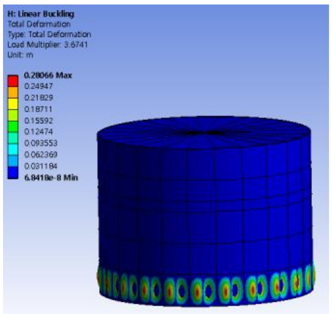
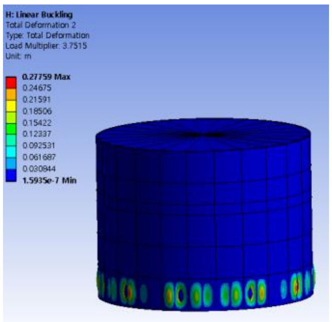
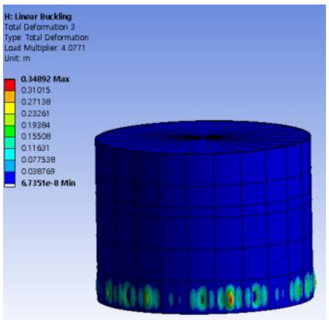


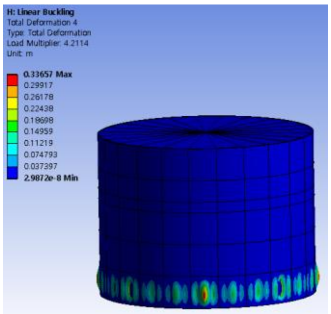
(a) Mode 1



(b) Mode 10



(c) Mode 30



(d) Mode 40

Fig. 5. Buckling load multiplier and shape (Earth pressure, roller B.C.)

V. CONCLUSIONS

This paper briefly introduced the concept of the suction-installed cofferdam and explained the necessity of buckling analyses for the lower module of the cofferdam. Numerical approaches to estimate buckling behaviors of structures were then described and compared with each other: geometrically nonlinear analysis and eigenvalue analysis. To investigate effects of loading and boundary conditions on buckling loads and their mode shape, finite element models were used to conduct buckling eigenvalue analyses, several conclusions were drawn from the results as follows:

- The confining loads such as suction and earth pressures causing the buckling of the module were applied, respectively. The results show that suction pressure easily enables the module to be buckled rather than earth pressure.
- The buckling failures occurred at the sleeves near the joint between the lid and the sleeves for suction pressure, while the failures were shown at the lower part of the sleeves for earth pressure.
- Changes in boundary conditions at the tip of the skirt rarely affects the buckling loads. These were different unlike expected results; for slender column, the buckling load and the mode shape are strongly dependent on the boundary condition at the ends. The confliction with them can be explained due to ground springs. The springs were not weak and were imposed on the surface of the sleeves corresponding to penetration depth. As a result, they played a role like a strong boundary condition and the effect was greater than that of the point boundary condition at the tip of the skirt.
- From the above buckling analyses, additional stiffeners should be added to the area near the skirt ends.

ACKNOWLEDGMENT

This study was supported by the Ministry of Land, Infrastructure and Transport, Project No: 16SCIP-B119960 (Development of Life-Cycle Engineering Technique and Construction Method for Global Competitiveness Upgrade of Cable Bridges).

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