Numerical Analysis of a Single Large-diameter Cofferdam under Offshore Loadings

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***Abstract*—A new type of steel cofferdam for offshore structures is presented and analyzed in this paper. This new cofferdam is a single body with a large double sleeve cross-section, in contrast with the conventional one which is assembling steel sheet piles, and is filled with water inside. To evaluate its structural behaviors and safety against offshore loadings, several numerical analyses were conducted using ANSYS Mechanical. For each construction stage of the cofferdam, three-dimensional finite element models were used to simulate the cofferdam under offshore loadings including wave and wind which is corresponded to Southern-west Sea of Korea. Results show that suction and hydrostatic pressure is dominant across the board during installation. Also, earth pressure and hydrodynamic wave forces mainly affected stress increases during penetration and dewatering.**

***Index Terms*—cofferdam, double sleeve cross section, hydrostatic pressure offset, sequential hydrodynamic-structural analysis, construction stage**

I. Introduction

Temporary works for offshore structures are often required to provide a safe workplace and to install deep or shallow foundations. The steel cofferdam is widely used among several temporary structures in offshore environments, and this causes increases of construction cost and period rather than the onshore due to equipment and manpower; it would be due to assembling and welding many steel plates of the conventional cofferdam. Particularly for a large offshore workplace, the conventional cofferdam requires additional support members such as bracing frames to resist external forces, and this aggravates workability involved in installing piles.

Several types of cofferdam have been applied to offshore constructions: sheet pile and precast house types. The former can be categorized with braced, double-walled sheet pile, and cellular cofferdams [1]. They are the most conventional and are flexible to various construction conditions. Also, light-weight cranes are enough to construct them. However, the method requires many manpower and is consequently vulnerable with respect to safety and costs. The latter applies prefabricated steel or concrete structure to temporary structures. This makes on-site works minimized; thus, construction period and constructability are improved [2]. However, the cofferdam by the precast house method is expensive due to the use of high capacity cranes. Several problems have been also reported that the joint between piles and a foundation slab in precast house has defects related to exposal to saltwater during curing [3]. Characteristics of each cofferdam are briefly described in Table 1. The above review of conventional offshore cofferdams shows that there are rooms for improvement of the structures by applying an alternative type.

TABLE I. Types of Cofferdam [1,2]

Type		Characteristics
Sheet pile	Braced	• Single wall • requirement of bracing members
	Double-walled	• Double walls • Stiffness increase by filling with granular materials and connecting two walls with tie rods
	Cellular	• No necessity of bracing • Resistance to lateral forces by its own circumferential forces
Precast house	Steel	• Lightweight and high workability • Expensive and easy to corrode
	Concrete	• Less expensive than a steel precast house • Addition of bracing members

This study introduced a single large steel cofferdam with double circular sleeve cross section and analyzed its structural behaviors under offshore loadings. The proposed cofferdam is designed to offset hydrostatic pressures on outer and inner sleeves; during installation, seawater is filled with in the space between the two sleeve walls. Also, by adopting the double sleeve cross section, external forces can be distributed. For example, inner sleeve is mainly subjected to hydrostatic pressures while the outer is loaded by hydrodynamic forces. Several studies have been conducted for offshore cofferdams. Lefas and Geogiannou [4] were proposed a simplified two-dimensional model for a large diameter sheet pile cofferdam reinforced with concrete ring beam. Zhang et al. [5] investigated structural behaviors of a cofferdam created by conversion construction method. Xu et al. [6] proposed a numerical solution for collapse and landslide shape of cofferdam under wave loadings and conducted parametric studies. Kim et al. [7] investigated structural behaviors of cylindrical cofferdams with plane and corrugated cross sections.

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Although these studies provided insights into the behaviors of single wall cofferdams, they were not for double wall type of cofferdams filled with water. To estimate the structural performance of the proposed cofferdam, sequential hydrodynamic-structural analyses were conducted. First, offshore loadings were clarified for each construction stage and were evaluated corresponding to Southern-west Sea of Korea. Stress profiles were then examined after calculating wave pressures from hydrodynamic analyses.

II. Single Large Cofferdam

A. Construction Procedure

The proposed cofferdam consists of several large cylindrical segments to be lifted by a conventional floating crane; each segment is manufactured near fabrication yard and towed to a target area. The cofferdam is constructed as follows. First, a segment is placed on the seabed and a lid plate is connected on the top of the segment. Next, the segment is penetrated into the seabed by suction, and the lid is then removed. Subsequently, another segment is placed and connected repeatedly. After completing the installation of the cofferdam, dewatering is conducted, and a foundation is constructed in the cofferdam (Fig. 1). Among several construction stages, the following stages, which might be critical to design, were selected to examine structural behaviors of the cofferdam: 1) initial penetration of the lowest segment, 2) penetration completion of the segment, and 3) dewatering.

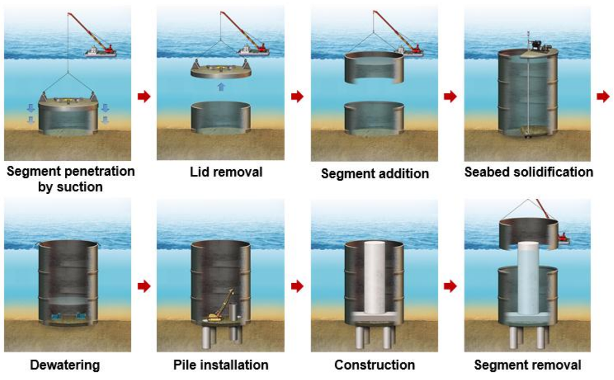

Figure 1. Construction procedure of offshore single large cofferdam

B. Mono-cofferdam with Double Sleeve Cross Section

The proposed cofferdam for offshore bridge construction was targeted for the seabed in Southern-west Sea of Korea; the mean sea level of this area is 10m, and the range of the wave period is approximately 6~12 sec.

The cofferdam had been fabricated to minimize offshore works and to reduce construction period. Its diameter and height are 20m and 27m including penetration depth of 10m, respectively. Although the large dimension is to ensure enough construction space for construction, it could cause to install many bracings and support members in the cofferdam. To prevent the temporary member installation that leads to work inefficiencies, two ways can be considered: increasing the wall thickness of the cofferdam and designing cross-section to be subjected to small external forces.

The proposed cofferdam adopted a double sleeve cross section as shown in Fig. 2. The space between two walls is fully or partially filled with seawater; the inner water play a role to offset the hydrostatic pressures on the outer and inner walls. The distance between the walls is 20cm, and each wall is connected with circumferential and vertical support members. The angle between each vertical support is 15 degrees, and the distance of each circumferential support is 3m. Total weight of the cofferdam is approximately 4450 kN. The overall specific dimensions of the cofferdam are listed in Table II.

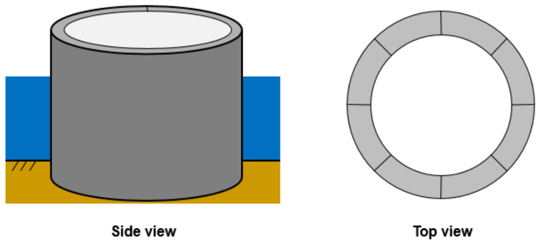

Figure 2. Cofferdam with double sleeve cross section

TABLE II. Dimensions of Cofferdam

Part	Diameter (m)	Height (m)	Width (cm)	Thickness (mm)
Outer sleeve	20.0	27.0	-	16.0
Inner sleeve	19.6			
Vertical support	-		20.0	
Circumferential support				

C. Evaluation of Enviormental Loadings

Environmental loadings of the sea were calculated by referring to an offshore design code and a design report including on-site investigation; the design report [8] is based on international and Korean design codes such as DNV-OS-J101, IEC61400-3, and concrete design code of Korea. Based on data such as in-situ test results for the seabed and wind/wave history, representative design parameters were determined and used to evaluate the loads. The wave and current loadings were calculated by numerical hydrodynamic analyses. The seabed was assumed as saturated weak clay; the geostatic pressure was applied, and effects of active/passive earth pressures were considered by Winkler spring with a subgrade modulus. An average wind pressure was applied on the cofferdam surface exposed to air. The applied forces are specified as shown in Table 3. In the table, notice that different occurrence frequencies were applied for the two former construction stages and other. According to DNV-OS-H101, wave conditions with 10-year occurrence frequency are recommended for offshore temporary structures. However, the period for penetration of the cofferdam is short; it is known that a suction bucket can be penetrated into the clay ground for several hours. Thus, the wave condition would be excessive. Thus, the 1-year occurrence frequency of wave conditions were applied for starting and ending of penetration stages.

TABLE III. INPUT PARAMETERS OF ENVIRONMENTAL LOADINGS

Loading type	Specification		
	Initial penetration	Penetration completion	Dewatering
Hydrostatic pressure	Unit weight of seawater: 10.06 kN/m^3		
Hydrodynamic pressure	Regular wave[*] - Height: 1m - Period: 6 sec. - Phase: 90 °		Ultimate wave[**] - Height: 11m - Period: 9 sec. - Phase: 135 °
Tidal current	0.176 m/s[*]		1.056 m/s
Earth pressure	- Unit weight of saturated clay: 18 kN/m^3 - Lateral geostatic coefficient: 1.0 - Subgrade modulus: 5,000 kN/m^3		
Wind	-		30.37m/s[**]

[*]1-year occurrence frequency
[**]10-year occurrence frequency

III. NUMERICAL SIMULATIONS

A. *Numerical Model Descriptions*

Numerical simulations of the proposed cofferdam were conducted to analyze structural behaviors and factors affecting stress increases during construction; three-dimensional finite element models consisting of shell elements were used to investigate stresses of the cofferdam. The models were created using ANSYS Mechanical. ANSYS AQWA and Wind loading extension were also used to calculate hydrodynamic wave and wind pressures, respectively.

In the models for each construction stage, external forces were applied to the cofferdam to reproduce the environmental conditions and the effects of filled water in the cofferdam, as shown in Fig. 3. For initial penetration due to self-weight of the cofferdam, the space between the two circular walls is partially filled with water because of the difference between the water depth and the segment height; effects of the hydrostatic pressures were partially removed for inner and outer sleeves. The ground spring were attached to the wall surface exposed to marine clay. Wave pressures considering tidal current from hydrodynamic analysis were also applied to the submerged part. The inner sleeve and the lid were also subjected to the suction pressure of 100 kPa; the load is caused by water pumps, which makes pressure differences between inside and outside of the cofferdam.

For the penetration completion stage, the segment is considered to be completely penetrated, but is assumed to be still subjected to the suction pressure. Because the body is fully submerged in the sea, effects of the cofferdam due to hydrostatic pressures on bending behaviors of the segment can be ignored.

For the dewatering stage, inside of the cofferdam was assumed to be fully dewatered. The surface of the cofferdam exposed to air was loaded by wind pressure, and hydrostatic pressures on the inner wall were considered.

For all stages, the gravitational loading was considered. For reference, same loading conditions with those for the initial penetration were not mentioned again in the descriptions of the last two stages.

Vertical displacements at the bottom of the cofferdam were fully constrained. Ground springs were imposed on the surfaces of outer and inner sleeves; lateral displacements in the radial direction can occur. From starting to ending of penetration, the lid is connected to the walls for sealing. For suction penetration of the bottom segment and installation of other segments, the lid should be not only possible to be attached but detached. As a result, the rigidity of the joint between the walls and the lid is indefinite. For this reason, three contact conditions were considered as shown in Fig. 4: rigid connection (case 1), normal-shear contact (case 2), and normal contact only (case 3). The rigid connection can transfer bending moments of the lid to the sleeve, while forces in the normal direction only affect the lid and the sleeves for the last contact condition. Because the pressure of 100 kPa on the lid with a diameter of 20m, the use of a lid without reinforcements cannot resist to the pressure and lead to large bending of the lid that affect the sleeve wall deformation. Consequently, many radial stiffeners were used to support the lid, and a circumferential support was added to reduce stress concentration due to the direct contact between the inner sleeve and the stiffeners.

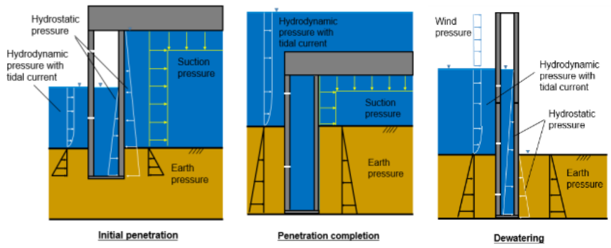

Figure 3. Applied load diagrams

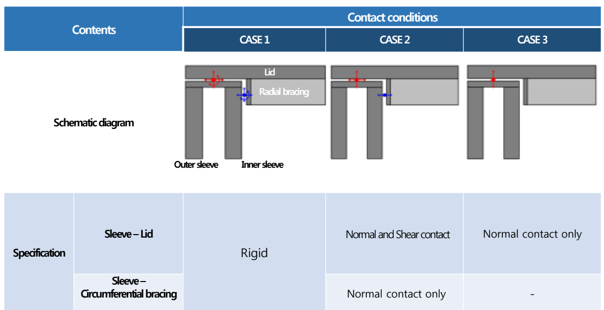

Figure 4. Comparison between contact conditions

B. *Stress Profile Analysis*

Stress distributions were examined for each loading case. First of all, to investigate basic behaviors, the lowest segment connected with the lid subjected to only suction and hydrostatic pressures was analyzed. Except applying different loadings, others were identical to those of the model for initial penetration stage. Stresses in the sleeves were observed along the wall height. As shown in Fig. 5, stress changes are complex for Cases 1 and 2 due to the contact between the walls and the circumferential support. Note that stress jump indicated near the contact area and then disappeared sharply. The stiff stress increase of the area would be mostly caused by lateral contact forces from the radial stiffeners. The stress increases were also contributed by bending of the lid; this fact can be checked by comparing with lines with circle (blue) and asterisk marks (red) and lines for the outer and inner sleeves near the vertical support. Based on changes in stress, the inner sleeve seems to be governed by bending of the lid because smoother stress changes in the outer sleeve were overall observed. In the submerged part, inflection points of stress curves occurred due to the circumferential support between the walls.

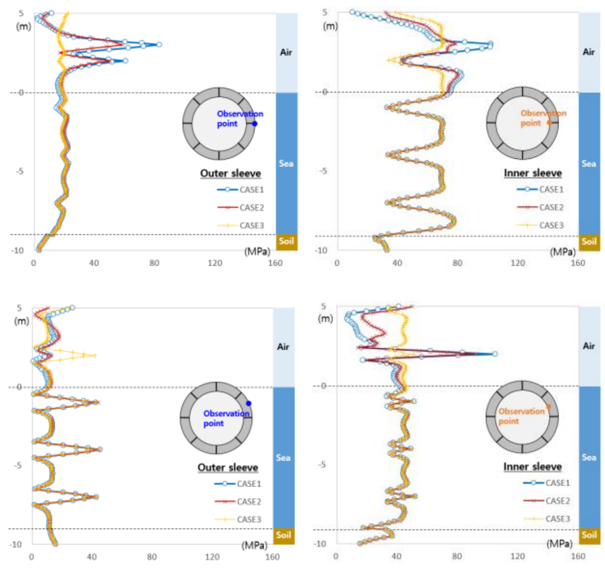

Figure 5. Stress profiles (bottom segment, only confinement loadings)

The stress profile for the initial penetration stage was examined. As shown in Fig. 6, results of the initial penetration model are considerably similar to those of the model for basic behavior analysis of the cofferdam; especially, more similar stress patterns in the outer and inner sleeves along the vertical support were observed. The bottom part also showed sharp stress changes. This is caused by applying earth pressures and lateral loadings such as hydrodynamic wave pressures. Alike the results for the initial penetration, suction and hydrostatic pressures mainly affect stress changes of the cofferdam. Wave and tidal current were minor factors in the stage; although the symmetry of stress distributions disappeared because of lateral loadings, similar stress profiles were observed along any vertical lines on the sleeve.

For the penetration completion, stress profiles are shown in Fig. 7. Severe changes in stresses in the upper part were caused by the suction and the bracing members of the lid, while passive and active earth pressures resulted in stress increases in penetration region. Remind that hydrostatic pressures were not included in the analysis due to the pressure offset. Earth pressures was closely related to stress increases in the penetration region. Nevertheless, the increases were also related to suction pressure because the pressure caused large radial deformation of ground springs.

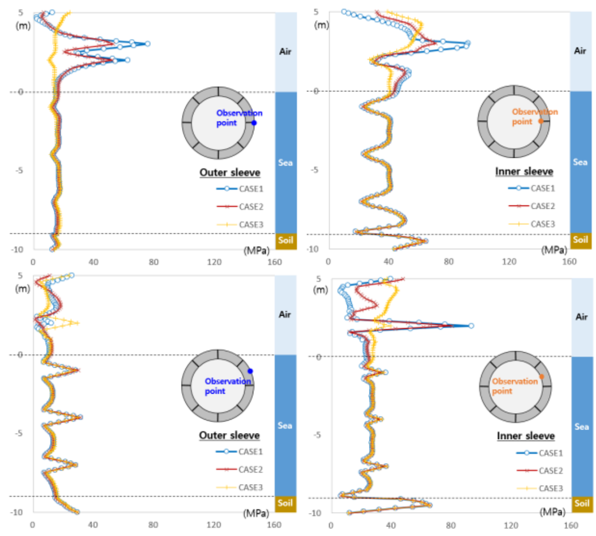

Figure 6. Stress profiles (bottom segment, initial penetration)

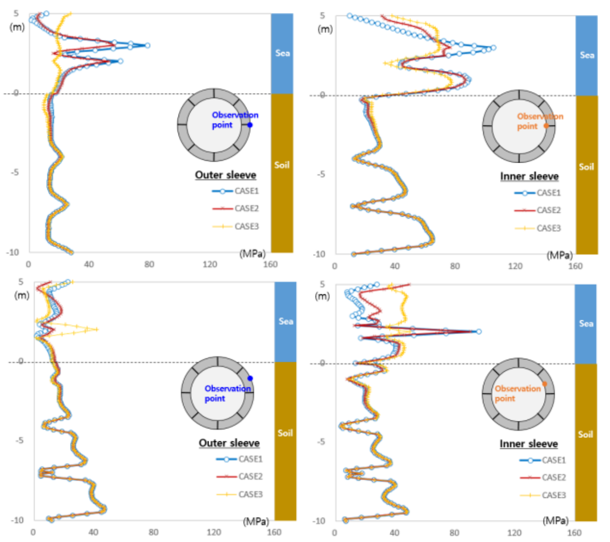

Figure 7. Stress profiles (bottom segment, penetration completion)

Finally, for the dewatering completion stage, stress profiles are shown in Figs. 8, 9 and 10. Unlike previous stages, effects of hydrodynamic wave and wind on the cofferdam behavior were remarkable; this resulted from the removal of suction pressure and the area exposed to these pressures became large. Because of wave and wind pressures, axisymmetric behaviors of the cofferdam disappeared; furthermore, because the ratio of the cofferdam diameter to the wave length is greater than 0.2, wave diffraction effects cannot be ignored. For this reason, stress profiles at front, side, and back against the wave direction were shown in Figs. 8 and 10, respectively. Because the lid was removed, rapid stress jumps were not shown. However, the stress increase and decrease occurred repeatedly due to the circumferential support connecting between outer and inner sleeves. Although there are differences between stress profiles, Figs. 8, 9, and 10 show clear differences in structural roles between outer and inner sleeves. Hydrodynamic waves with tidal current were resisted by the outer sleeve, while hydrostatic pressures mainly leaded to stress increases of the inner sleeve. Unexpectedly, effects of wind were small, compared with other load factors. In addition, the stress patterns in the penetration region differed from those of the previous. The reason why the stress decreased along the depth of the seabed could be due to disappearance of the suction pressure and the removal of the lid; the suction pressure that was applied on the large area was tremendous than other loading factor, and considerable bending of the lid due to the pressure caused large bending deformation of the sleeves. The above analysis seems to be reasonable because the difference between stress patterns obviously appears for the inner sleeve, rather than the outer sleeve. Finally, in design view, it was examined that stresses were also within the allowable stress of the structural steel applied with safety factor of 1.25.

IV. Discussions

A. *Joint Conditions bewteen Lid and Sleeve Wall*

For the two former construction stages, three joint connection conditions were applied on the surfaces between the lid reinforced with bracings and double sleeve walls. As shown in Figs. 6 and 7, effects of the contact conditions are effective to the top of the sleeves and the area exposed to the bracings of the lid. Strong bending of the lid due to suction was transferred to sleeve for Cases 1 and 2, while only vertical forces due to suction affect the sleeves for Case 3. A way to reduce the stress is increasing the thickness of the lid or the number of bracings. However, this will cause to increase construction costs and to aggravate constructability. The results for Case 3 show that the stress jump can be dramatically reduced, or even removed, by placing the bracings in a different way. As mention above, stress jumps were caused by the lid bending and contact between the bracings and the sleeve; the bracings are necessary to prevent excessive bending of the lid. Placement of the bracings above the lid, not below the lid, can be an effective alternative because the way can basically remove the contact problem between the sleeve and the bracings.

B. *Suction Pressure*

In the study, the pressure gradient due to suction was assumed to be a constant and uniform pressure. This way is simple and proper to design. However, the pressure gradient causes seepage of seawater. As a result, water pressures on the sleeve which hydrodynamic terms are excluded in differ from hydrostatic pressures calculated by the conventional formula; particularly for soil, incremental water pressures due to seepage should be considered. In the soil inside the cofferdam, the upward seepage occurs, and water pressures are greater than hydrostatic pressure. If the pressure gradient due to suction is large, the difference becomes large and leads to overestimated designs of the cofferdam. Thus, a suction pressure estimation would be required by seepage analysis to reproduce more reasonable results from the numerical analysis.

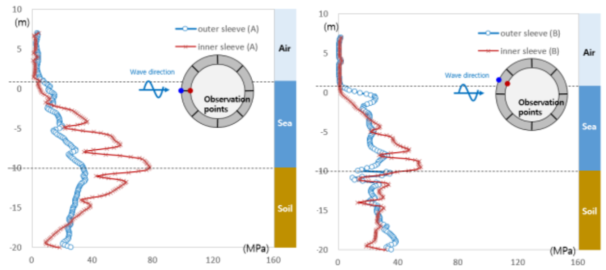

Figure 8. Stress profiles (dewatering, front)

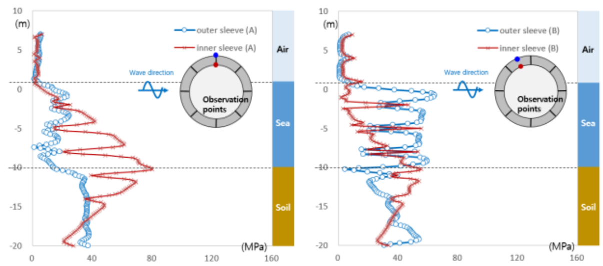

Figure 9. Stress (dewatering, side)

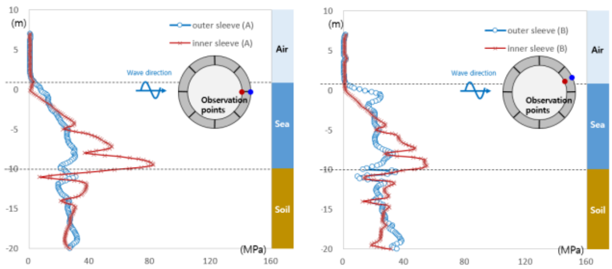

Figure 10. Stress profiles (dewatering, rear)

C. *Stress Changes During Penetration*

Stress profiles of the lower segment were compared for the penetration depths of 1m, 5m, and 10m; the depths of 1m and 10m are corresponded to the stages of initial penetration and penetration completion, respectively. Changes in stress profiles on the inner sleeve during penetration are more prominent. Also, except stress jump regions, stresses for the deeper depth were not always greater than those for the lower depth. Thus, assuming several construction stages, structural analyses should be conducted for each stage in design.

D. *Effects of Double Sleeve Cross Section*

The study adopted the double sleeve cross section filled with seawater and conducted several numerical analyses. However, this is not meant for the proposed cross section to be valid. In the mechanical view, although effects of hydrostatic pressures on bending were expected to fully or partially disappear due to offset, the role of the filled water and the offset effect is not clarified; the offset of hydrostatic pressures due to filled water is literally an assumption. Thus, further studies are required to verify the effects. Nevertheless, if the offset effect is validly hold, the proposed cofferdam is definitely superior to conventional temporary structures with respect to cost and constructability.

V. Conclusions

The preceding sections have introduced the essential concept of the proposed cofferdam and have conducted its stress analyses. Structural behaviors of the cofferdam during penetration and after dewatering were studied in detail based on analyzing stress profiles. Effects of the joint connection were also investigated by assuming several different contact conditions. Finally, several assumptions and results of the simulation were critically discussed, and the restriction of the paper were pointed out.

It is shown that when the cofferdam is installed by pressure gradient (suction), lateral loadings such as hydrodynamic wave pressure and wind were not considerably contributed to stress increases. Suction pressure and collateral contact loads transferred from the bending of the lid were major loading factors. The joint connection effects were limited to the upper part of segment sleeves. Although there are stress jumps at the contact area between inner sleeve and the circumferential and the radial bracings of the lid, the proposed cofferdam could be improved by bracing placement changes.

It is concluded that a cofferdam, subjected to offshore and geostatic loadings, with the double sleeve cross section filled with seawater provides an efficient and cost-saved temporary works during penetration and dewatering. By adopting the double sleeve cross section, effective load distribution of each sleeve was derived and this would eventually lead to cost reduction as well as constructability.

Acknowledgment

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