Numerical and Experimental Study on the Steel-Concrete Connection for Supporting Structure of Current Power System

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Abstract—**Tidal current energy is recently regarded as a vital source of ocean energy, because it is not only reliable and renewable but also its capacity is predictable compared to the other ocean energy sources including offshore wind and wave. Since the tidal current power systems are commonly installed at the rapid flow water area, it requires the safe and reliable supporting as well as the steady and high-efficiency current power generator. In addition, the rational construction and maintenance methods should be prepared to reduce the total cost of tidal current power generation systems. Until now, various types of current power structures have been developed such as pile-type, gravity-type, and jacket-type and so on, considering performance for construction work as well as soil and marine conditions.**

Among these, the gravity-type is regarded as the most cost-effective and reliable one, since there is no need to use large scale marine equipments such as pile driving vessels, cranes and so on. Generally, the structure of gravity-type is composed of a steel column supporting, the current power generator and a concrete basement providing the structural stability of the whole system due to its self-weight. The most failures of support structures occur at the steel-concrete connection part due to the shear forces and the fatigue loads. Therefore, the safety of steel-concrete connection is the most important to secure the overall safety of supporting structure.

In this study, the structural details and failure mode of steel-concrete connections for the gravity type have been investigated. Also, the numerical analysis and the static loading test for the scaled model have been carried out to evaluate the structural behaviors according to connection details. The analysis and test results indicate that the connection detail using circular ribs is more effective to resist against the tensile forces than the other connection details. Thus, it is concluded that this connection detail can be usefully applied to the supporting structures subjected to the thrust forces induced by blades as well as the horizontal current forces.

Keywords— Current Power Structure, Gravity-type, Steel-Concrete Connection, Structural Loading Test

I. INTRODUCTION

Due to global warming, the necessities of an alternative clean energy development are increased. Tidal current power is now recognized as one of the clean power resources in Korea, where there are many strong current regions on the west and south coasts [1]. From now on, three projects for tidal current power have been demonstrated in Korea. First project is the Uldolmok tidal current power plant located in south-west coasts where the maximum current velocity is approximately 7m/s. It was composed of a 1MW vertical axes turbine and a hexagonal jacket support structure. In order to overcome the rapid current velocity in this area, several heavy concrete blocks had been laid on the top of a jacket structure. After laying jacket structure at the designated location, six piles in the edges were installed in order to fix the whole structure [2].

Second project is the Daebang-channel tidal current power plant located in the south coast of Korea. It was composed of a 100kW horizontal current power and a floating type support structure. This floating type structure was consists of the steel structure supporting current power and two submerged pontoon providing buoyancy of whole system. And this structure is anchored by two heavy concrete blocks [3].

Third project is the Jangjook-channel tidal current power plant located in near the Uldolmok. It was composed of an 110kW horizontal current power and a gravity type support structure having 850ton self-weight [4]. This gravity type structure was lifted, moved, and installed by a 2,000ton class heavy lifting crane.

As mentioned previously, Korea has good resources for a tidal current power. Many efforts to develop this clean ocean energy has been carried out and it is expected that the large tidal current power complex would be constructed in Korea in the near future.

II. CAISSON TYPE SUPPOTING STRUCTURE

The representative supporting structures of the offshore wind power have been carried out [5], [6] and test and analysis of the gravity type of it also have performed [7], [8]. But it is not easy to find out the study on the supporting structures for the tidal current power.

The essential success points of the tidal current power project are cost-effective and reliable supporting structures as

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well as efficient current power devices. In addition, the rational construction and maintenance methods should be prepared to reduce the total cost of tidal current power generation systems. Until now, various types of current power structures have been developed such as pile-type, gravity-type, and jacket-type and so on, considering the performance for construction work as well as soil and marine conditions. Among these types, the gravity-type is estimated as a relatively more economical and reliable type of current power systems, since it does not have to use marine heavy equipments such as pile driving vessels, cranes and so on.

Considering three structures demonstrated in Korea, the steel jacket was relatively expensive but easy to lift and transport, compare to a concrete gravity type. And the floating structure was hard to control the motion of the structure related to the whole stability and safety, compare to a concrete gravity type. If the 110kw current power were scaled up as 1MW, the weight of the concrete gravity structure also would be increased as approximately 2,000tons. The amount of weight cannot be controlled only with only a heavy lifting crane, which can be the crucial limit to use a gravity type supporting structure.

Due to these reasons, the caisson type supporting structure has been considered in this study as shown in Fig. 1. It is expected that this caisson supporting structure can be easily controlled by small tug boats on the ocean surface without a large lifting crane because it uses the buoyancy of caisson. This caisson structure with a current power is the new concept, but it has been commonly applied to quay walls and breakwaters in many harbor construction sites. The concrete caissons can be serially manufactured at the special factory and delivered to the site, consequently making the construction period shorten and the concrete quality guaranteed.

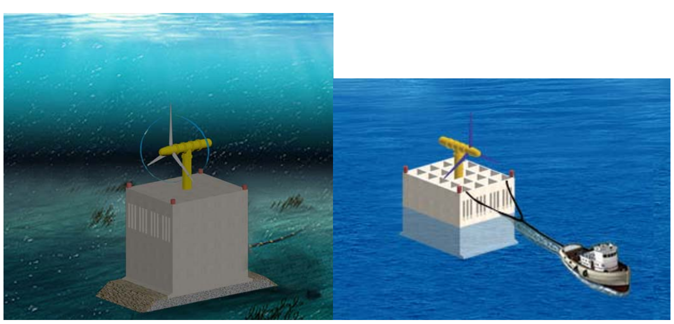


Fig. 1 Caisson type tidal current power

In this study, the structural details and failure mode of steel-concrete connections for the gravity type and the caisson type have been investigated. Also, the numerical analysis and the static loading test for the scaled model have been carried out to evaluate the structural behaviors according to connection details.

III. Failure Modes of Steel-Concrete Connections

Generally, the failure modes of the steel-concrete connection are classified as concrete failure modes and steel failure modes. And each failure mode is divided into tensile failure and shear failure [9].

The concrete can present various failure modes in the steel-concrete connections caused by tensile and shear forces. And concrete failure easily can take place before the yield or failure of steel members because the ultimate strength of steel is much higher than that of concrete. Therefore, it is important how to define the failure surface of the concrete and estimate the nominal strength. ACI code [9] assumed the failure surface as a square and the failure volume as a pyramid as show in Fig. 2.

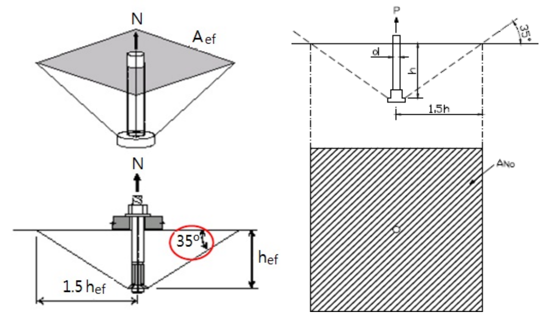


Fig. 2 Failure suirface of concrete

Fig. 3 shows that the flexural-shear test results for the steel column having group studs [10]. It clearly presents that the failure surface assumed by ACI code [9] can be different as a real failure surface since the assumed failure surface was only considered as a tensile force but the tensile force in the real structure can be induced by the moment. It is expected that the steel column joint in gravity type supporting structure would show a similar behavior due to drag and lift forces caused by rapid current flow. Therefore, in order to verify the safety and reliability of a whole current power system, the structural details and failure mode of steel-concrete connections for the gravity type have been examined in this study.

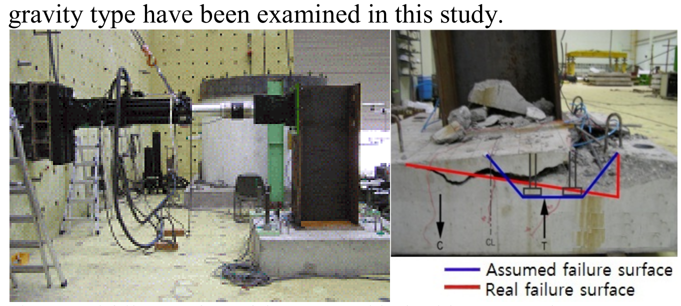


Fig. 3 Real failure surface of the concrete block with group studs

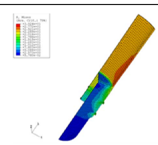
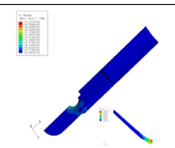
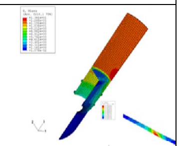
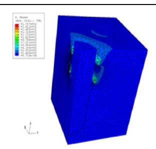
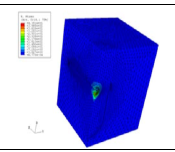
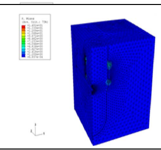
IV. Pullout Test for Steel Column Connections

A. *Pre-anlaysis for steel column connections*

In order to find out the proper connection details efficiently resisting to drag and lifting forces, three connection types were considered and analyzed in this study as shown in Table 1. The first type was composed of a connection plate and a circular rib round the steel column, and the second type had a connection plate transversely connected to a long rod instead of a circular rib. The last type had combined the first and second types. The analyses for three types had only focused on the stress distribution since it is hard to precisely model the interface between concrete and steel surfaces. Therefore, the interface between two materials is separately modeled so that it can be delaminated according to the loading conditions

Analyses results showed that the ultimate loads of the first and the last types with a circular rib were approximately over 30kN, while that of the second type was approximately 9.8kN. And the maximum displacements of the first and the last types were 0.094mm and 0.082mm respectively while that of the second type was 0.123mm. From these results, it is regarded that the circular rib can resist the tensile force favorably compared to that a connection hole and a rod type is not.

TABLE I. ANALYSIS RESULTS OF SUPPORTING STRUCTURES

Index	Connection Type		
	[1] :Circular Rib	*[2]: Hole + Rod*	*[3] : [1]+[2]*
Steel			
Concrete			
max. displacemet [mm]	0.0936	0.12280	0.0818
Ultimate Load [kN]	30.19	9.80	30.99

B. *Pulout loading test for connection details*

Fig. 4 shows the schematic diagram for a gravity type supporting structure of a horizontal current power. It is mainly composed of four parts; blades, a power generator, a circular steel column, and a concrete basement. This pullout loading test only focused on the steel-concrete connection. From the pre-analysis for three connection types, it is clear that the circular rib can effectively resist to the tensile force.

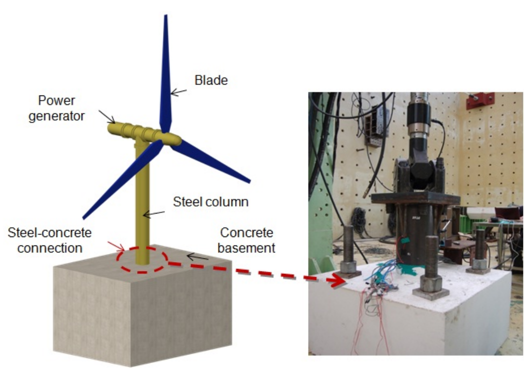


Fig. 4 Pullout test set-up

However, it is hard to design circular ribs since it isn`t known the resisting force of circular ribs and it is difficult to precisely analysis them since the interface modeling between concrete and steel ribs` surfaces is very complicated. Therefore, the simple pullout loading test according to the rib details were carried out in this study.

The four scaled specimens were designed and fabricated according to the number and the thickness of circular ribs as shown in Table 2. The width and the length of the concrete basement for four specimens were same as 800m, and the depth of it was 520mm. The diameter and the thickness of the steel column were 200mm and 8mm respectively as shown in Fig. 5. The design standard strength of concrete was 40MPa and all steels were SS400 having the ultimate strength of 400MPa.

TABLE II. SPECIMEN DETAILS

Circular Rib Details	Index			
	R0	*1R20*	*2R10*	*2R20*
No. of Ribs [EA]	-	1	2	2
Width of Ribs [mm]	-	20	10	20

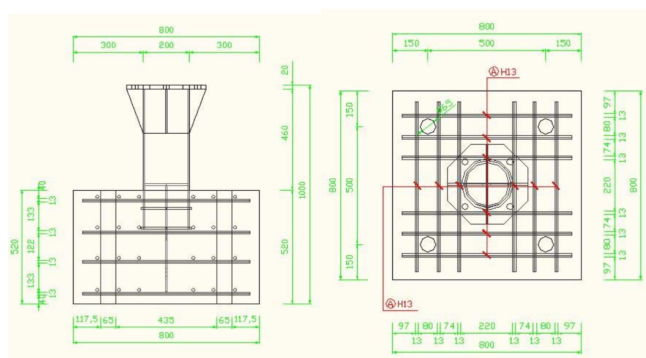


Fig. 5 Dimensions of specimens

C. *Test results*

Fig. 6 shows the load-displacement relation for each specimen. The ultimate strength of R0 specimen without ribs was approximately 300kN while those of other specimens such a 1R20, 2R10, and 2R20 were over 400kN. And all specimens without R0 specimen present the ductile behaviors after they reach the yield state. Also It is said that the number of ribs can be more important factor than the width of them, since the ultimate strength of 2R20 specimen was higher than that of 2R10.

Fig. 7 shows the crack patterns for each specimen. Many radial cracks were founded around the four fixed supports except for R0 specimen. It is reasons that the ultimate strength of R0 specimen was low compared to other specimens with ribs and physical interlocking reactions between ribs and re-bars as well as the frictional force between the surfaces of an embedded steel column and those of concrete might resist to the tensile force.

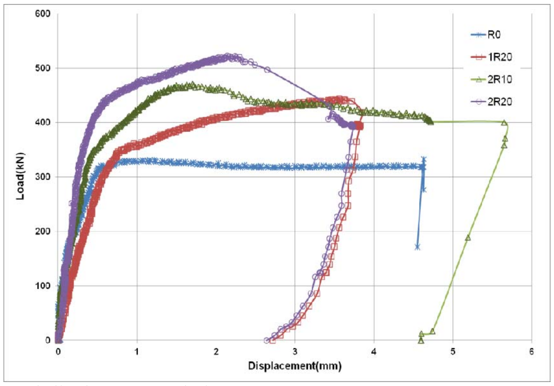


Fig. 6 Load-displacement relations

Fig. 7 Carck pattern of specimens

From these test results, it is concluded that the circular rib can effectively resist to the tensile force and the number of ribs can be more important factor than the width of them governing the ultimate strength of structures. Also the further study should be performed in order to verify the structural actions of circular ribs more in detail.

V. CONCLUSION AND FUTHER STUDY

In this study, the structural details and failure mode of steel-concrete connections for the gravity type have been investigated. Also, the numerical analysis and the static loading test for the scaled model have been carried out to evaluate the structural behaviors according to connection details. The conclusions are as below;

[1] The caisson supporting structure may be the best alternative supporting structure for the tidal current power since it is easily controlled by small tug boats on the ocean surface using the buoyancy of caisson without a large lifting crane.

[2] It is found that the circular rib can effectively resist the tensile force compared to a connection hole and a rod, from the analyses results.

[3] It is concluded that the circular rib can effectively resist the tensile force and the number of ribs can be more important factor than the width of them governing the ultimate strength of structures, from the pullout test results.

[4] Also the further study should be performed in order to more clearly verify the structural actions of circular ribs. And another flexural and shear test for gravity type supporting structures will be conducted.

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