The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Stage analysdeckis for deck erection of single-pylon suspension bridge

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ABSTRACT

Suspension bridges are one of the most flexible structures, and the flexibility of the structures may develop some problems while the bridges are under construction. Especially, in the case of asymmetrical suspension bridges, the construction sequence will be very critical to the structural safety and stability. Dandeung bridge is an asymmetrical suspension bridge which has a main span with the length of 400m and a single pylon with the height of 100m. Because of the bridge's structural features, the construction of the stiffening deck for main span is planned by 3-D numerical analysis and simulation considering many cases of sequence for the deck erection. In this paper, the suitable construction sequence for main span is suggested in the case of single-pylon and single-span suspension bridges.

1. INTRODUCTION

Generally, suspension bridges are one of the most flexible structures, and the flexibility of the structures may develop static and dynamic problems exceptionally while the bridges are under construction. Thus, for successful completion of suspension bridge, the detail planning, structural analysis, and simulation are very important. In this paper, as the behavior of suspension bridges under stiffening deck erection is considered by stage analysis and simulation, it is suggested that the optimized construction stage can minimize some construction error and problems on site(Choi 2011).

In this paper, a single pylon suspension bridge with an only main span of 400m is adopted as an example. Structural behavior of a single pylon suspension bridge with one span is different from other ordinary suspension bridges with two pylons and three spans. For stage analysis, the RM V8i program of Bentley Systems was used, and the specific structural modeling method is adopted. Especially, when the stiffening decks are erected, the gap between the bottom surfaces of the deck blocks can be calculated

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by modeling additional spring elements at the nodes on the ends of deck elements. Also, the sliding of tower saddle for the balance of cable tension at the top of the pylon and the deck setback and pull-down can be adapted to the stage analysis by using some spring elements. This is very beneficial to plan the erection sequence for stiffening deck in advance. Through this paper, the construction sequence for single pylon with one span suspension bridge is optimized and the construction error can be decreased significantly during the construction.

2. SINGLE PYLON SUSPENSION BRIDGE

2.1 State of the art

After the Brooklyn Bridge in New York City has been completed, most of suspension bridges in the world have been designed and constructed as similar features with two pylons and three spans. In past times, because the economic efficiency to construct bridges was the first issue, suspension bridges had been designed as a long-span bridge. However, at present, as the technique of design and analysis has been developed, new trial for the design of suspension bridge has been appeared. For one of them, there are four suspension bridges with single pylon for traffic in the world.

(a) Elche Bridge (1999, Spain)

(b) Liede Bridge (2009, China)

(c) Oakland Bay Bridge (2013, USA)

(d) Jiangxinzhou Bridge (2012, China)

Fig. 1 Single pylon suspension bridges

The bridges in Fig. 1 have single pylon and one or two spans, and the maximum main span length is 385m at the main span for the Oakland Bay Bridge. Also, all of the bridges have the spatially supported cables, and the cable system for all of the single pylon suspension bridge has designed as spatially self-anchored type with the exception of the Elche bridge(Table. 1).

2.2 Structural features

Single pylon suspension bridges have similar features about the structural behavior in service in comparison to the two pylon suspension bridges. However, both spans behave like side spans of two pylon suspension bridges. Especially, as the cable has the small sag, the sag sensitivity for cable length and temperature change is too high under construction.

Table. 1 Single pylon suspension bridge

Name	Location	Completion	Cable System	Span Length	Lanes
Elche Br.	Spain	1999	Spatial, Earth-anchored	165m	4
Liede Br.	China	2009	Spatial, Self-anchored	219+167m	6
Oakland Bay Br.	USA	2013 (expected)	Spatial, Self-anchored	385+180m	8
Jiangwinzhou Br.	China	2012	Spatial, Self-anchored	248+60m	6

Also, single pylon suspension bridges tend to have spatially supported cable system because the pylon is only one and the construction cost for slender and one-legged structure may be less than the cost for two-legged structure. As a result, the cables should be supported spatially and twisted by erecting hanger ropes, and there are some problems for twisted cables about the secondary stress, deformation due to temperature change and fatigue.

2.3 Construction method

Single pylon suspension bridges have similar features about the structural behavior in

3. STAGE ANALYSIS FOR AN EXAMPLE BRIDGE

3.1 Stage analysis

Construction methods and sequence for anchorages, pylon and cables of single pylon suspension bridges is very similar to the ordinary suspension bridges with two pylons. However, there are some special features to the method of stiffening deck erection. If the cable system may be designed by self-anchored type like Liede Bridge and Oakland Bay Bridge, the stiffening decks will be erected on the temporary supporting structures and the hanger ropes should be pulled in the fixing frame on the stiffening deck’s top. In case of single pylon suspension bridge with an earth-anchored cable system, stiffening decks should be erected sequentially by divided block as a unit. Then, the engineer has to plan the erection sequence to concern with various structural conditions – deformation, stress, and balance of structures.

3.2 Example bridge

In this paper, a single pylon suspension bridge with an only main span of 400m is adopted as an example - the Dandeung bridge. The single pylon suspension bridge connecting Sinsi-do and Munyeo-do in South Korea, is due to be constructed in the second section of connecting road works of the Gogunsan islands in Jeollanamdo. The construction of this bridge has been planned to make traffic for inhabitants of the islands convenient, to promote local development, and to improve the international marine tourism circumstance. The bridge is designed to have one pylon and asymmetric main cable configuration. At present, suspension bridges with single pylon are located in Spain, China, and USA. All of 4 bridges are completed in the 2000s. The main span length of Dandeung bridge is 400m which will be the world’s longest one among suspension bridges with 1-pylon. Also, the span composition of cable system is 425m+280m in length(Table. 2).

Fig. 2 Aerial view of Dandeung bridge

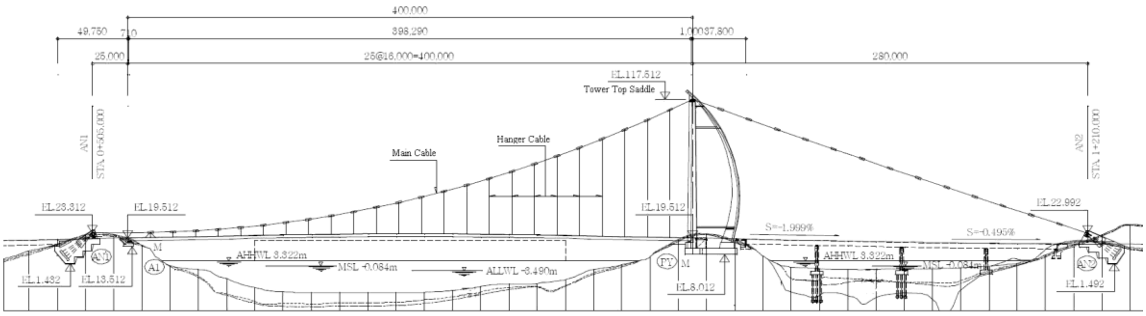


Fig. 3 Elevation view of Dandeung bridge

In this paper, a stage analysis for stiffening deck erection has been performed, and the optimized sequence has been planned. The process and result will be described below.

3.3 Modeling for numerical simulation

In the analysis of long span bridges, especially in the case of cable suspended bridges, the geometrical on-linear factors caused by large displacements have to be taken into account. Large displacements are caused by applied load, the cables’ self-weight, and the influence of the cable’s rigidity caused by the initial stress of the constant load. Therefore, geometrical non-linear analysis should be performed for construction stage analysis of suspended bridge. To perform a non-linear calculation with large displacements in RM V8i, the calculation type “Large displacements” is chosen from the calculation option.

At the process of the structural modeling, it is very important to evaluate and model the behavior of saddle slip and field joint between the divided deck blocks. Here, the modeling concept for saddle and field joint is described below(Fig. 4, Fig. 5,Choi 2011). The saddle and field joint between deck segments can be substituted by spring elements.

Table. 2 Structural data and design condition

Component		Design
Span composition		Cable : 425 + 280 = 705m Deck : 400m
Deck Type		Edge box deck
Slope	Longitudinal	2%
	Transverse	2%
Design Traffic Speed		60km/h
Width		20.0m
Live Load		DB-24, DL-24*
Design Wind Speed		34.4m/s
Seismic Load		Seismic Grade 1*

* Guideline for the design of cable supported steel bridge, Korea (2006)

Table. 3 Cable design and cross section composition

Component		Specification
Wire	Material	KS D 3059
	Diameter	5.35mm
	Area	22.48mm2
	Tensile Strength	1,960MPa
	Elastic Modulus	200,000MPa
Strand	Number of wires	336EA/strand
	Arrangement	16x21 wires
Cable	Number of strands	12strands
	Number of wires	4,032EA/cable
	Diameter	379.8mm
	Diameter (at band)	375.2mm
	Weight	6.979kN/m
	Allowable Tension	71,062kN

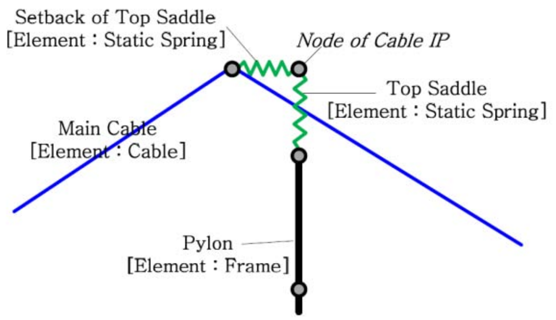


Fig. 4 Modeling of saddle

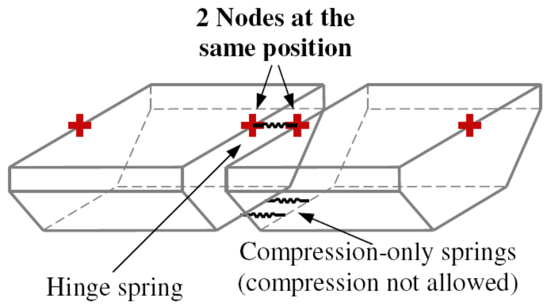


Fig. 5 Modeling of field jointbetween deck segments

3.4 Sequence of stiffening deck erection

Dandeung bridge has only one span and single pylon, and when a stiffening deck segment is erected at a unit, the configuration of cable and erected deck segments will be deformed largely. In general, in case of two pylon suspension bridges, stiffening deck segments are erected firstly at the middle point of main span to avoid excessive deformation of structure. However, in case of single pylon suspension bridge, as the difference of elevation at both cable ends of the main span is too large and sag sensitivity is too high, symmetric erecting method for deck segments may be unfavorable. As a result, at the planning process, the deck erection will be go along from the end of the deck to the opposite end sequentially.

Dandueng bridge, an example for this paper, has a main span of 400m in length, and the diameter of main cables is 380mm which is consisted of 4,032 wires per cable with the tensile strength of 1,960MPa(Table. 3). Also, the deck is separated into 26 segments. Fig. 6 shows the plan of deck erection sequence.

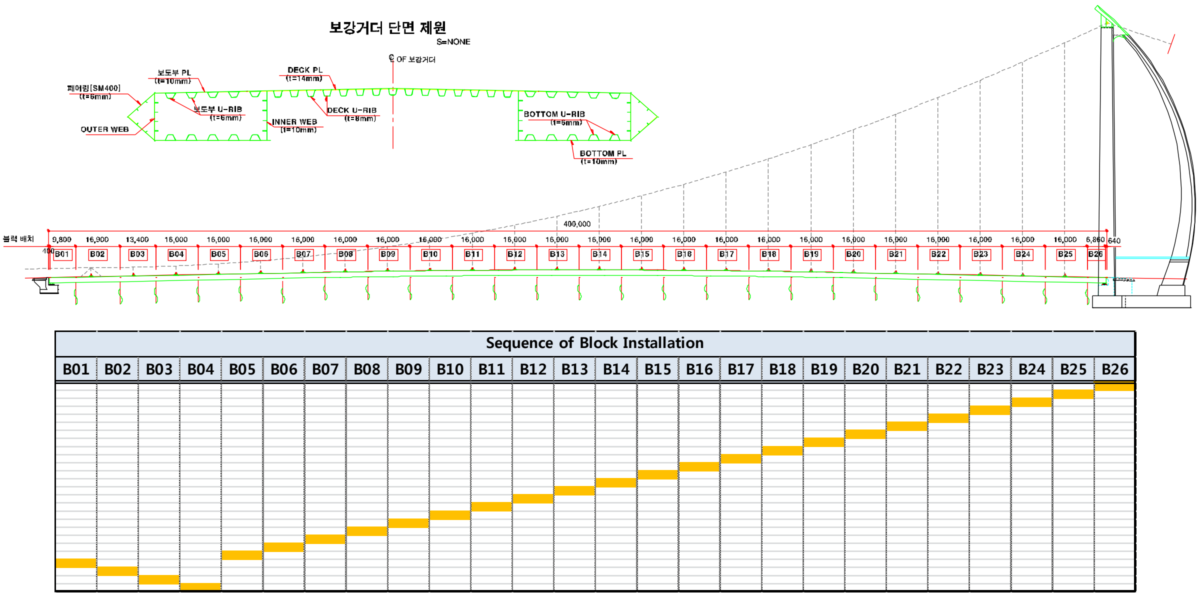


Fig. 6 Deck erection sequence

4. RESULT OF STAGE ANALYSIS

4.1 Behavior of main cable

During the cable erection works, the pylon saddle should be set toward the side span to secure the stability of saddle sliding, and the quantity of set-back for Dandueng bridge's saddle is 1,188mm. And then, as the deck erection work is progressing, the saddle will be sliding in four phases with satisfying the stable state of saddle behavior(Table. 4). About the cable movement, two kinds of safety should be satisfied. Those are safety factor of cable slip(f_{s1}) on the saddle and safety factor of saddle slip(f_{s2}) on the saddle base. Designed minimum safety factor is f_{s1} = 1.5 and f_{s2} =1.0.

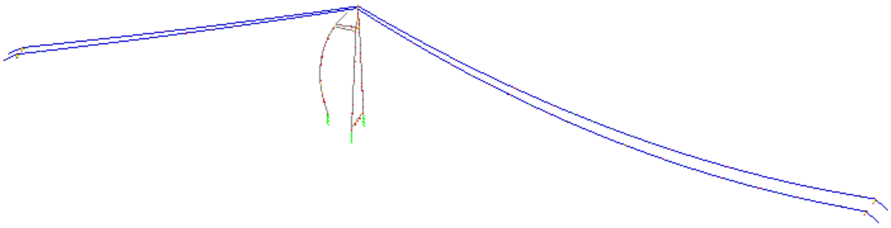
$$f_{s1} = \frac{\mu_s \theta}{\ln\left(T_{side} / T_{center}\right)} \qquad (1)$$

$$f_{s2} = \frac{\mu_c N}{H_{side} - H_{center}} \qquad (2)$$

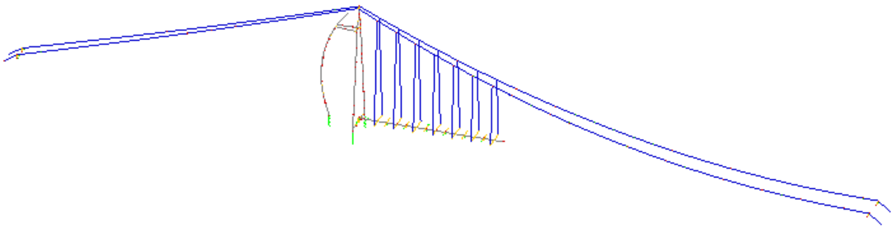
The coefficient of friction between cable wire and saddle surface, μ_s, is commonly adopted as 0.15 and the coefficient of friction between saddle and saddle basement, μ_s, is about 0.04.

Table. 4 Set-back and sliding plan for pylon saddle

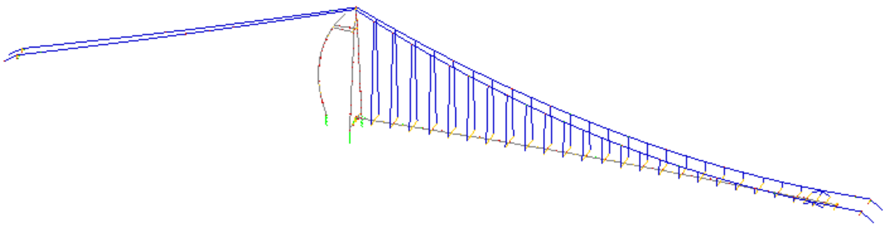
Sequence	PY	Stage
Setback	1.118m	Before cable erection
1st Sliding	0.118m	Deck erection 15%
2nd Sliding	0.200m	Deck erection 23%
3rd Sliding	0.300m	Deck erection 38%
4th Sliding	0.500m	Deck erection 73%



(a) After cable works



(b) Under deck segments erecting works



(c) After completion

Fig. 7 Structural analysis model

Fig. 8 shows the result of numerical simulation for deck erection by RM V8i. The safety factor for two saddle behavior – friction between saddle and cable, saddle sliding – is plotted through the progress rate of deck erection work. During all stages, two safety factors are over the designed minimum value. Also, it can be confirmed that the value of safety factor is increased after the saddle sliding work following Table. 4.

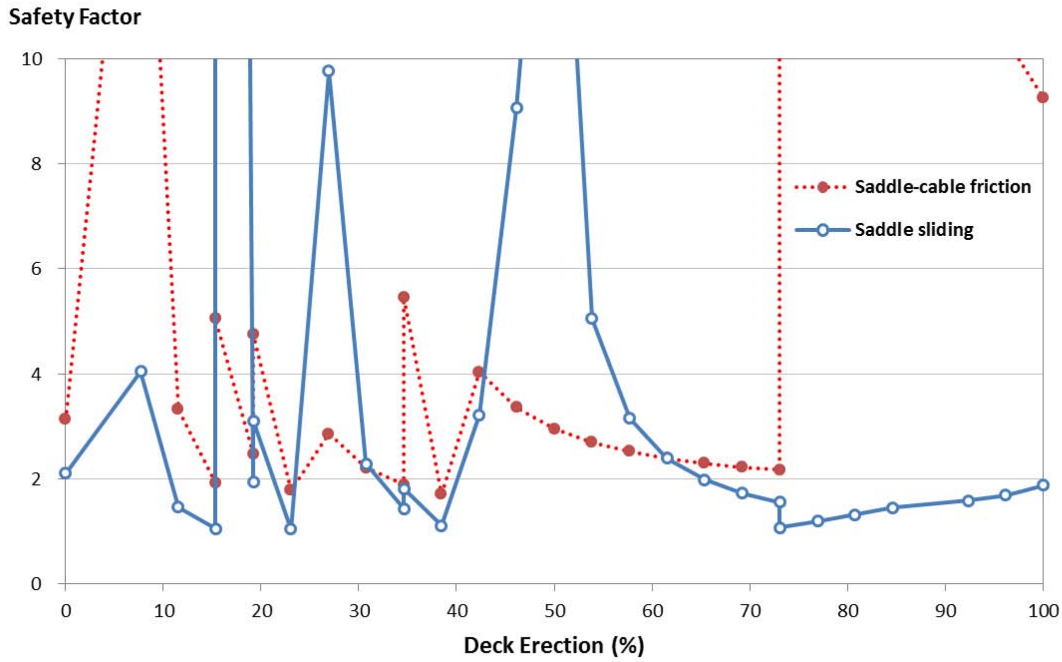


Fig. 8 Safety factor for behavior of pylon saddle

4.2 Behavior of deck segment

According to the stage analysis, the configuration change of erected deck segments can be calculated numerically with the large displacement effect. Especially, at the beginning of deck erection, the erected deck segments behaves with a wide variation of the elevation because the main cable has low tension force and low stiffness compared to the final stage(Choi 2011).

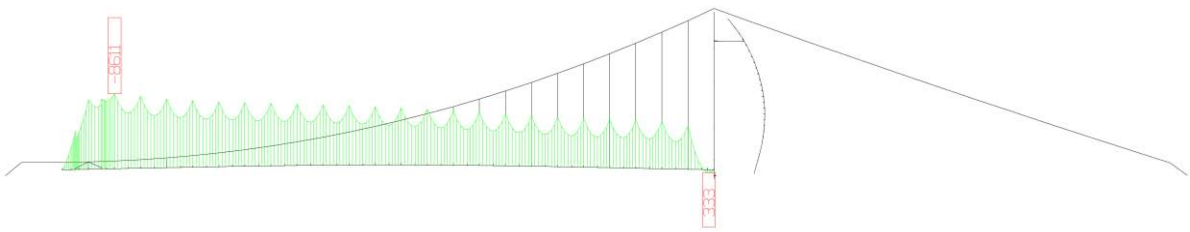


Fig. 9 Maximum moment distribution for deck pull-down work

Also, under deck erection work, the stress distribution in the cross section is appeared differently in comparison with the service stage of the bridge. For Dandueng bridge, there are no link shoe or buffer which can accommodate the large angle change and horizontal displacement at the girder ends, and there are only spherical shoes to support the girder reaction. Thus, when the last deck segment – key segment – is installed, girder set-back work to expand the space for segment installation cannot be performed. As a result, the first deck near the pylon is fixed on the spherical shoe, and then the opposite side deck will be erected without the vertical and horizontal fix and the pull-down work of deck segment will be performed to fix on the spherical shoe. At the process, the section moment and stress may increase sharply(Fig. 9, Fig. 10). The maximum stress is developed at the deck pull-down work, and the stress is about 34 MPa which is less than the allowable stress 190 MPa(Fig. 10).

As the deck segments are erected sequentially, the deck segments are connected at the top of the cross section by temporary joints which is available to rotate, and the gap between segments will be developed necessarily at the bottom surface. The gap has maximum value 160mm at the first field joint near the pylon, and the gap is decreasing slightly as the location of joint go toward the anchorage.

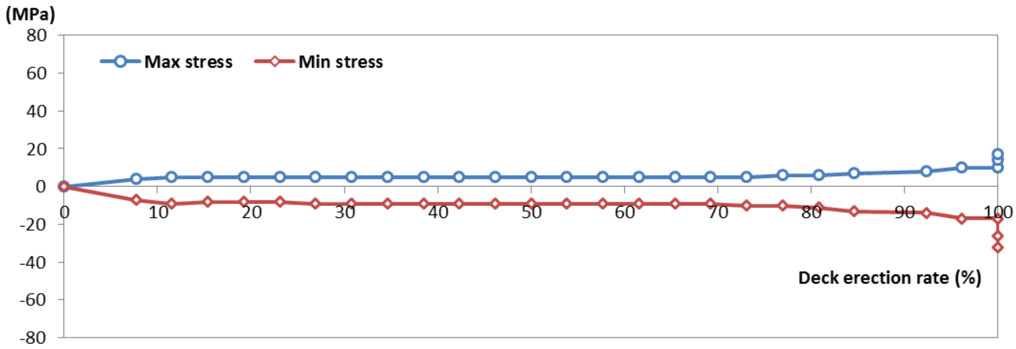


Fig. 10 Maximum stress in cross sections to the deck erection

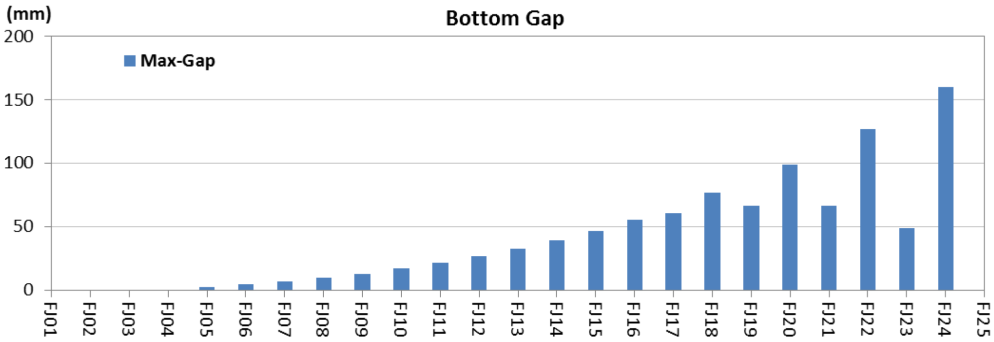


Fig. 11 Gap at the bottom of field joints

5. PLANNING OF DECK ERECTION FROM THE STAGE ANALYSIS

According to the stage analysis, the deck erection work for Dandueng bridge is planned. The deck will be divided and fabricated by 16m in length at a unit, and the segments are installed by lifting gantry on the main cables. Due to the spatially supported cable system, the lifting gantry has been developed thoroughly and the new gantry has no crossbeam connecting both the machine on cables.

The deck erection will progress from the pylon side to the opposite side near the anchorage, and the key-segment is located at the fourth position from the anchorage. Also, temporary supporting systems will be built necessarily on both ends of deck because the depth of sea is very shallow near both ends of deck(Fig. 12). And, the welding of field joints will be conducted after all deck segments are erected.

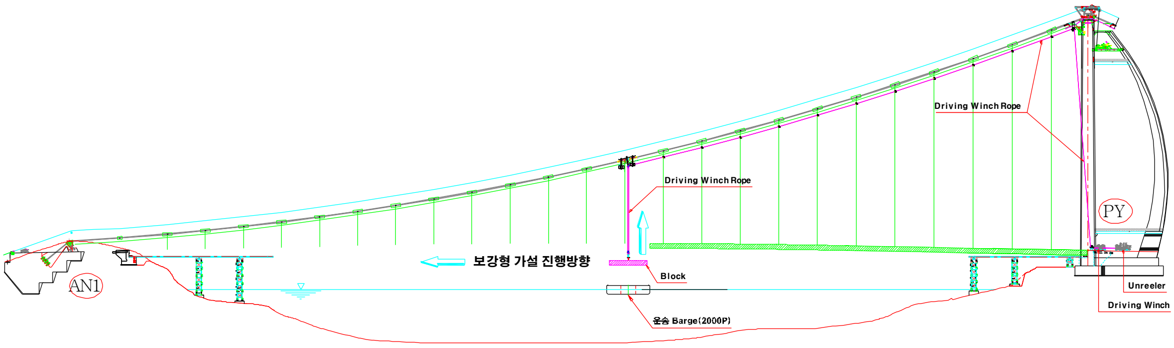


Fig. 12 Sequence for stiffening deck erection of Dandeung bridge

6. CONCLUSIONS

In this paper, stage analysis and simulation has been performed for a single pylon suspension bridge with concern to saddle slip action and deck bottom gap. As a result of the example bridge, some important problems on behavior of saddle and deck have been checked. Especially, sequence for deck erection has been optimized to overcome unfavorable conditions because of some structural features of single pylon.

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