Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Effect of Grout Filling Condition on Corrosion of Prestressing Steel in Existing Prestressed Concrete Bridges

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ABSTRACT

In the existing prestressed concrete bridges, remarkable corrosion and breakage of prestressing steels, which in turn reduces strength of the bridges themselves or may cause protrusion of tendon and injure pedestrian, due to imperfect grout is reported. Clarification of the mechanism of this kind of deterioration regarding grout quality is necessary in order for prestressed concrete technology to contribute to maintenance and development of infrastructure. In this paper, the effect of grout filling condition on corrosion of prestressing steel is studied through dissection research.

Keywords. Prestressed concrete, Dissection research, Grout filling, Chloride attack, anticorrosive effect

INTRODUCTION

Prestressed concrete (hereafter, abbreviated as PC), in which high strength concrete is used and cracks are controlled by prestressing force, can create infrastructures with high durability. On the other hand, due to imperfect grout filling in portions of PC bridges constructed in the past, cases where load carrying capacity was degraded by corrosion or breakage of PC steel, or where third person injuries could have taken place by protruded prestressing steel bars have been reported. For the PC technology to contribute to the maintenance and advancement of the infrastructures in the future, it is necessary to clarify the damage mechanism arising from grout filling, and to facilitate enhancement of the grout filling investigation method and/or enhancement of the degradation prevention technology of unfilled parts.

In response to this current state, “Study using Demolished Bridge" (Hanai, 2010) has been conducted to estimate factors that causes imperfect grout filling based on investigation for demolished PC bridges, and at the same time to verify the damage mechanism caused by grout filling conditions.

This paper discusses the effect of grout filling condition on corrosion of PC steel in existing PC bridges based on dissection research conducted for PC bridges with undamaged PC steel despite of imperfect grout filling and PC bridges with heavily corroded PC steel under chloride attack environment.

INVESTIGATION OF DEMOLISHED PC BRIDGES

Table 1 shows the results of the investigation of actual conditions conducted for PC bridges demolished due to degradation by chloride attack and others, in Japan. These are the bridges that had been constructed before publishing of "Manual for PC Grouting" edited by Japan Prestressed Concrete Contractors Association in 1986 to propose standardization of grout injection operation, and it is considered that grouting for these bridges was performed in accordance with "Proposed PC Grouting Guide" (hereafter, called 1961 Proposed Guide) published by Japan Society of Civil Engineers in 1961.

Table 1. Research results of actual conditions of demolished PC bridges

Bridge	A bridge	B bridge	C bridge	D bridge	E bridge
Year completed	1965	1972	1967	1972	1965
Bridge type	Road bridge	Pedestrian bridge	Road bridge	Bridge for bicycle	Road bridge
Structural type	Post-tensioned simple PCT girder				
Maximum span	39.9m	29.2m	27.3m	23.2m	22.8m
Number of spans	5	3	5	2	5
Number of main girders	6	2	5	2	3
Impact of the chloride attack	Along coastline	60m from coastline	80m from coastline	200m from coastline	No impact
Presence of upper deck anchorage	Yes	Yes	No	Yes	Yes
Condition of PC steel	Occurrence of breakage	Occurrence of breakage	Occurrence of breakage	Occurrence of breakage	No breakage

The PC bridges constructed before 1961 were mainly built by simple girder systems with a span of about 30m or less. However, while the continuous girders and cantilever erections increased during the 1960's and the 1970's, 1961 Proposed Guide only called to attention that "grout injection shall be performed continuously until enough amount of grout with uniform consistency flows out from all outlets". Thus, the grouting work and its quality control at that time could have not been adequate. In this research, certain amounts of defective grout filling parts have been found for all bridges, including "imperfect grouting" in which certain amounts of voids were found in some parts, and "unfilled grouting" in which PC steel was exposed in some parts.

Next, those PC bridges that corresponded to the purpose of dissection research were selected from **Table 1**. (A and B bridges where the impact of chloride attack was more significant than grout quality were excluded.) The investigation of PC bridges in which PC steel remained undamaged even with imperfect grout filling was intended to understand the effect of grout filling condition on corrosion and breakage of the PC steel, and only E bridge that was not subject to chloride attack met this objective. The investigation of PC bridges with PC steel significantly corroded under chloride attack environment was intended to understand the degree of severity of the chloride attack effect in case of excellent grout filling, and C bridge was considered to meet the condition.

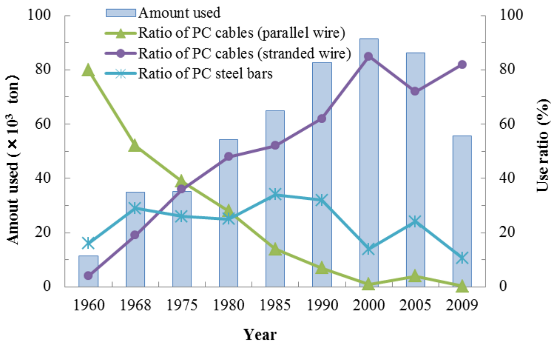

Figure 1. Amount of PC steel used and use ratio in Japan (JPCCA, From 1960 to 2009)

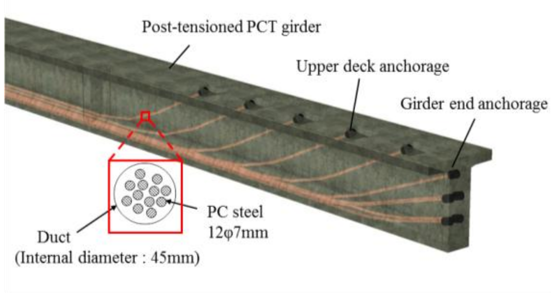

Figure 2. Schematic diagram of PC steel layout for PCT girder bridge

Additionally, a parallel wire with a diameter of 7 mm was commonly used in the form of 12 wires in one cable (represented as 12φ7 mm, for example.) at that time (**Figure 1**), and its capacity of about 60 tons (in case of 12φ7 mm) was small. Therefore, all of required numbers of PC cables could not be anchored in the girder end, and some of them were placed at the upper deck of girders. Anchoring at upper deck of girder was identified in four bridges except C bridge in this investigation. (**Figure 2**)

DISSECTION RESEARCH

PC Bridge with Undamaged PC Steel that was Intact Even Under Imperfect Grout Filling

E bridge is a 5-span simple post-tensioned PCT girder bridge completed in 1965. While each span length is 22.8 m and 45 years has passed since its completion, it is maintained in a relatively good condition without any visible damages such as cracking and delamination. In the investigation, grout filling condition of 342 PC cables that were located in two cut planes for each main girder (total of 30 cut planes) that was cut at arbitrary locations during removal operation, were visually examined. Here, the determination of grout filling conditions was performed by contrasting them with the sample photographs as shown in **Table 2**.

Table 2. Classification of grout filling condition

Classification	Grout filling condition		Note
Filling level 1	Grout is completely filled.		Bond and corrosion protection of PC steel are secured.
Filling level 2	While some voids exist, PC steel is almost covered completely with grout.		
Filling level 3	Grout filling is inadequate, and PC steel is exposed.		Bond and corrosion protection of PC steel are not secured.
Filling level 4	Grout is not filled.		

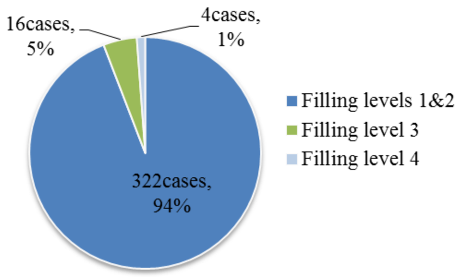

Figure 3. Investigation results of grout filling level (E bridge)

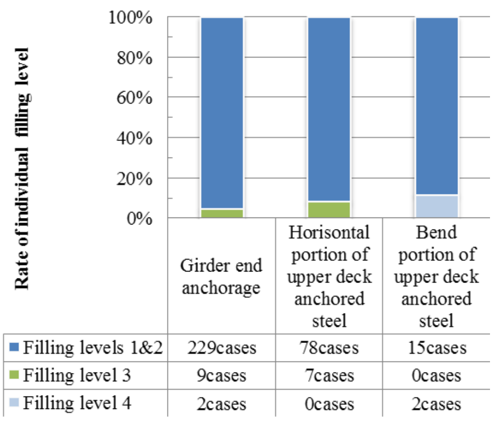

Figure 4. Grout filling level by locations (E bridge)

Results of confirmation of grout filling conditions are shown in **Figure 3** and **Figure 4**. Among 342 cases investigated, filling levels 1 & 2 and filling levels 3 & 4 accounted for 322 cases (94%) and 20 cases (6%), respectively. While the ratio of cases with filling levels 3 & 4 found in cables anchored at upper deck was relatively high (particularly in the bend portion), there were also some cases involving cables anchored at girder end. Additionally, grout filling condition with a focus on cables anchored at upper deck is shown in **Figure 5**. According to this, filling level 4 was located at up to 0.5 m below the upper deck. In addition, as grout stuck to the duct, it was found that the void cavity ran further back. (**Figure 6**) By contrast, the grout was filled in the upward bend portioning section of the opposite side. Based on such a condition, the effect of bleeding is unlikely, and it is inferred that an unfilled part was left along the down grade line of the grout injection side (due to rapid injection of grout with high fluidity) where the grout flowed too fast.

Additionally, it was confirmed that for the total of 342 cases investigated, the main cable of this bridge has nearly no corrosion, and no trace of water penetration was confirmed in the duct of cable anchored at upper deck where unfilled grout was confirmed.

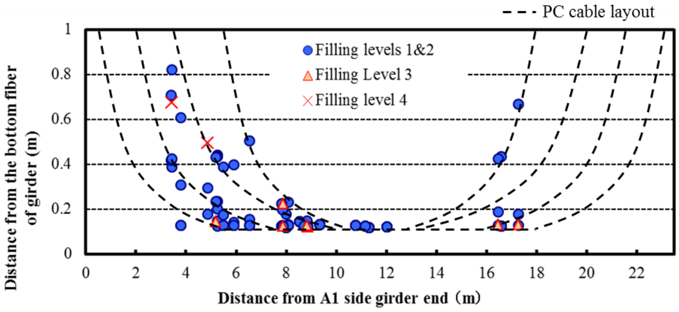

Figure 5. Grout filling condition of cable anchored at E bridge upper deck

Figure 6. Condition of filling level 4 in E bridge

PC Bridge with PC Steel with Significant Corrosion Under Chloride Attack Environment

C bridge is a 5-span simple post-tensioned PCT girder bridge placed in service in 1967. Since the main cable using "24φ7 mm" has about twice the capacity of "12φ7 mm" which was commonly used at that time, four cables were anchored only at girder end for each main girder. It was constructed at a location adjacent to the Sea of Japan coast line, and because deteriorations such as cracking and delamination due to corrosion of the steel became significant after having been exposed to severe chloride attack environment for long time period, its service was finished in September, 2010 (at 43 years of service) on the premise of reconstruction. (**Figure 7**) Removal of this bridge was performed by cutting each girder into 6 or 7 pieces longitudinally after cutting the cast-in-place deck slabs between the main girders. Grout filling investigation was performed for the main girder cut planes. Additionally, steel corrosion investigation was performed, with a focus on the first span with the most severe damages identified as shown in **Figure 8**, for G1 girder (region where reduction of the section was identified for about half of PC steel in the past investigation), G3 girder (region where reduction of the section of entire PC steel of C3 cable and some breakages were identified in the past investigation), and G4 girder (region where damages have occurred after 40 years of service without having past damage/repair history), and for G4 girder of the fourth span which shows second-worst damage.

a) Before chipping
(G3 girder of the first span)

b) After chipping of the same place shown left
(breakage of C3 cable)

Figure 7. Condition of C bridge (40 years of bridge age)

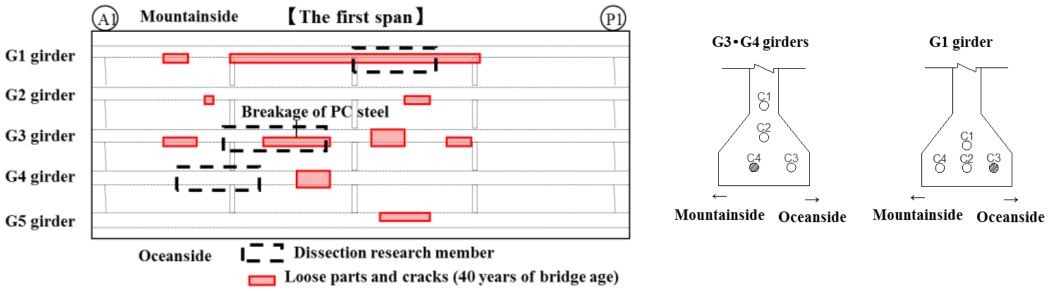

Figure 8. Damage condition of C bridge main girder bottom flange and member sampling location (left), and cable layout (right)

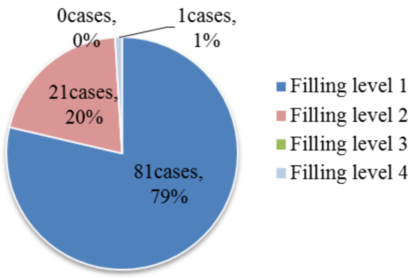

Figure 9. Investigation results of grout filling level (C bridge/ the first span)

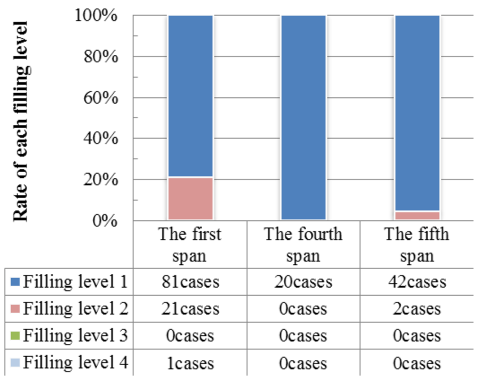

Figure 10. Grout filling level by locations (C bridge)

Grout filling condition. Figure 9 shows grout filling investigation results in the first span, and **Figure 10** shows the grout filling levels of the first, fourth, and fifth spans as grout filling level by locations. The investigation in the first span covered 103 cables located in each individual main girder cut plane, and identified 102 cases (99%) of filling levels 1 and 2, 0 case of filling levels 3, and 1 case (1%) of filling levels 4. Focusing on filling levels 1 and 2, while many localized voids were found in the first span, grout filling was excellent for a large majority of locations. The area near C3 cable of G3 girder in the first span, where breakage of PC steel was confirmed, was the only location where unfilled grout was confirmed.

Steel corrosion investigation. Figure 11 shows conditions of duct, grout, and PC wire of the C4 cable that was demolished from G3 girder in the first span as a duct conduit piece and then broken up. Only minor corrosion cases were found in some parts of the duct. As for grout filling condition, filling levels were 2 that had some voids gaps in the cut plane, but the main cable was still covered by grout. However, the grout of upper side was brittle, and crush of some portions during removal of the duct, bubbles, and traces of settling were confirmed as well. While this cable was collected from the location near the area (breakage of C3 cable at the same location was confirmed) where the most significant damage was found in this bridge, it was confirmed that corrosion of PC wire was minor. That is, it can be determined that the PC steel corrosion can be controlled as long as grout is mostly filled even under a significant chloride attack environment.

a) Cross section (ocean side in the right)

b) Appearance of grout inside ducts

c) PC wire inside duct (upper side)

Figure 11. Dissection research of C4 cable of G3 girder of the first span in C bridge

Mass reduction rate. Figure 12 shows the mass reduction rate of C1 thru C4 cables collected from the same material when the first span G3 girder was cut and demolished. Based on this, although the mass reduction rate exceeded 35% and breakage of 13 steel wires were identified for C3 cable, the mass reduction rate was 10% or less and no breakage was identified for the rest of cables.

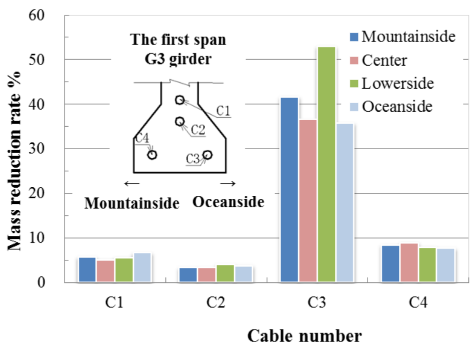

Figure 12. Relation between cable location and corrosion amount (Comparison among the same members of C bridge)

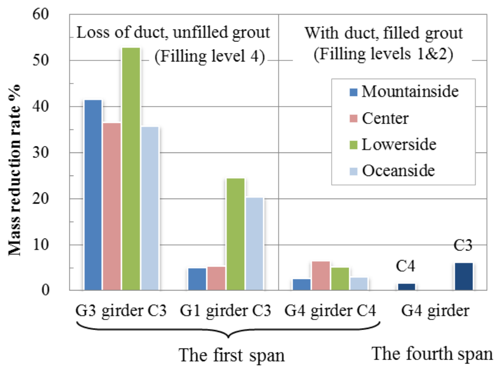

Figure 13. Relation between damage condition and amount of cable corrosion (Comparison among members having the same covering in C bridge)

a) Vicinity of G4 girder C4 cable in the first span **b) Condition before chipping for G4 girder in the fourth span** **c) After chipping of the same place shown left (breakage of C3 cable)**

Figure 14. Damage condition at the part with filled grout (C bridge)

Additionally, **Figure 13** shows the mass reduction rates of G3 girder C3 cable in the first span (which has the most significant damage), and cables having the same covering in the first span including G1 girder C3 cable (which has the second most significant damage), G4 girder C4 cable (which used to be an undamaged sound part, but newly damaged), and G4 girder C3 and C4 cables (which has the highest damage outside of the first span) in the fourth span. This time, the mass reduction rate exceeded 10% where cracking was significant enough to separate concrete in areas with loss of duct and unfilled grout (or, it fell off during duct sheath removal) as shown in the above **Figure 7**. However, the mass reduction rate was 10% or less, averaging about 4%, where the extent of cracking remained in the longitudinal direction axial cracks at the bottom surface of lower flange as shown in **Figure 14**.

SUMMARY

Actual conditions of grout filling and effect of grout filling level on corrosion of PC steel were investigated for PC bridges of 40 years or older that are going to be demolished. Followings were confirmed as a result.

(1) When grout filling is in an excellent condition, while there were cases that PC steel corroded under severe chloride attack, the mass reduction rate at the outermost edge was 4% or less on the average, demonstrating a considerable anticorrosive effect.

(2) Even when grout filling was imperfect, corrosion of PC steel was not identified in situations where water was not penetrated. On the other hand, under conditions subject to severe chloride attack, significant corrosion of PC steel (10% or higher in terms of mass reduction rate) and strand breakages were confirmed where grout filling was imperfect.

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