

## Appendix-5: Repair and Reinforcement of Steel Sheet Pile Quay Walls with Reduced Strength Due to Corrosion

### 1. Introduction

At present, in Japan, the corrosion protection method for port steel structures is, in principle, to apply cathodic protection below the mean low water level, and to apply coating protection above 1 m from the mean low water level.<sup>1)</sup> Nowadays, many facilities are provided with such appropriate corrosion protection measures. However, there are still some steel structures that remain without protection, or where proper maintenance has not been carried out, and the reduction in strength due to corrosion has become apparent.

This paper presents a case study of the repair and reinforcement of a steel sheet pile quay wall whose strength has decreased due to corrosion. The method introduced here is a “new reinforced concrete reinforcement method using underwater stud welding,” called the CRUS method (New Reinforced Concrete System with the Underwater Welding-Stud).<sup>2)</sup>

### 2. Overview of the Structure and Defects

The structure subject to repair and reinforcement here is a steel sheet pile revetment constructed around 1975. By the time of the survey, nearly 40 years had passed since its construction, and deterioration had progressed. A standard cross-sectional drawing is shown in Figure 1.

In this structure, reinforced concrete for the superstructure was placed above L.W.L. +0.7 m. Although cathodic protection was applied to the underwater portion, it was assumed that the structure had experienced a long period in the past without any corrosion protection. In addition, because subsidence behind the revetment due to the outflow of backfill soil had occasionally occurred, a corrosion condition survey of the steel sheet piles was conducted approximately 40 years after construction.

The remaining thickness of the steel sheet piles was measured using an ultrasonic thickness gauge (Photo 1). Typical measurement results of the remaining thickness at representative positions are shown in Figure 2.

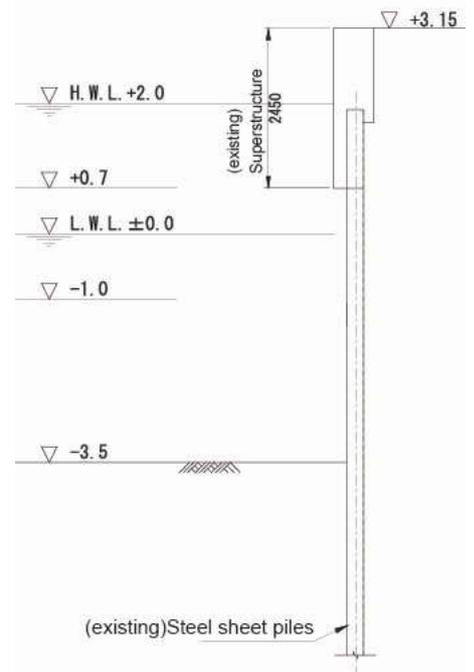


Figure 1 Cross Section of Quaywall



Photo 1 Measurement of Steel Sheet Pile



Photo 2 Hole due to Corrosion

In the legend of this figure, B-1 to B-7 indicate the block numbers of the quay wall, and the symbols in parentheses (S, Z) indicate the type of sheet pile cross-section. It should be noted that when the average thickness is 5 mm or less, the residual bearing capacity is regarded as zero,<sup>3)</sup> and therefore the thickness limit of 5 mm is indicated by a broken line in the figure.

At B2-4, B3-1, B3-2, B6-5, and B7-1, a tendency for localized corrosion was observed between L.W.L. +0.5 m and –

0.5 m. Furthermore, a detailed visual inspection conducted by divers confirmed that numerous large perforations due to corrosion had formed in the sheet piles (Photo 2).

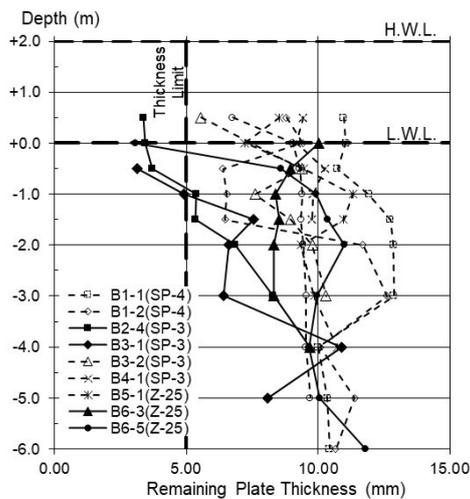


Fig.2 Measurement Results of Thickness

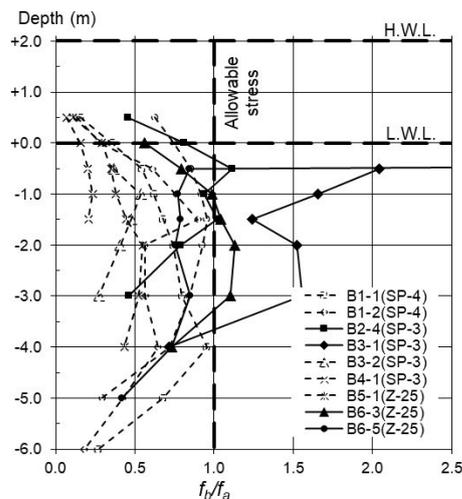


Fig.3 Stress Ratio of Sheet Pile ( $f_b/f_a$ )

### 3. Diagnosis of Structural Soundness and Consideration of Countermeasures

#### 3.1 Diagnosis of Structural Soundness

The quay wall is divided into several types (blocks), with differences in the type of steel sheet piles and design water depths. Therefore, for each quay wall type, a comparison was made between the external forces, such as earth pressure from the backfill, and the current load-bearing capacity of the corroded sheet piles, using the allowable stress design method.

Figure 3 shows the ratio of the bending stress of the sheet pile ( $f_b$ ) to the allowable stress ( $f_a$ ), expressed as  $f_b/f_a$ . In this figure, where  $f_b/f_a$  is greater than 1, it indicates that the sheet piles have insufficient strength, and for the portions shown as solid lines, repair and reinforcement were judged necessary to secure load-bearing capacity. On the other hand, the portions shown as dashed lines still retain the required capacity against external forces, but it was judged appropriate to apply corrosion protection methods in order to prevent future strength reduction and maintain durability.

The total length of the target section was approximately 195 m, of which about 118 m was judged to require repair and reinforcement. The remaining 77 m was designated for corrosion protection only, in order to suppress deterioration.

#### 3.2 Selection of Repair Method

##### (1) Types of Repair Methods

The two main methods applicable for the repair and reinforcement of steel sheet piles are: the reinforced concrete covering method (Figure 4) and the steel plate welding method (Figure 5)<sup>4</sup>.

The CRUS method, which is a reinforced concrete covering method, involves welding and installing studs onto the surface of steel sheet piles or steel pipe piles, as shown in Figure 4. By means of these studs, the structural members such as steel sheet piles are integrated with the reinforced concrete that functions as the covering and repair material. In the CRUS method, the studs play an important role in transferring stresses between the steel members and the reinforced concrete. This method can be applied even to structures with complex shapes, and due to the corrosion protection effect of the alkalinity of concrete on the steel, a durability of approximately 30 years or more can be expected.

The steel plate welding method, as shown in Figure 5, involves welding slit steel plates onto steel sheet piles or steel pipe piles to secure the required welding length. This method can reduce initial costs when the repair area is small. However, it has drawbacks, such as the difficulty of ensuring quality when welding underwater onto severely corroded steel members, and uncertainties regarding the durability of underwater welds. Furthermore, if the steel plate welding method alone is used, corrosion tends to progress significantly due to the heat generated during welding; therefore, it is

necessary to apply coating protection or cathodic protection methods in combination.

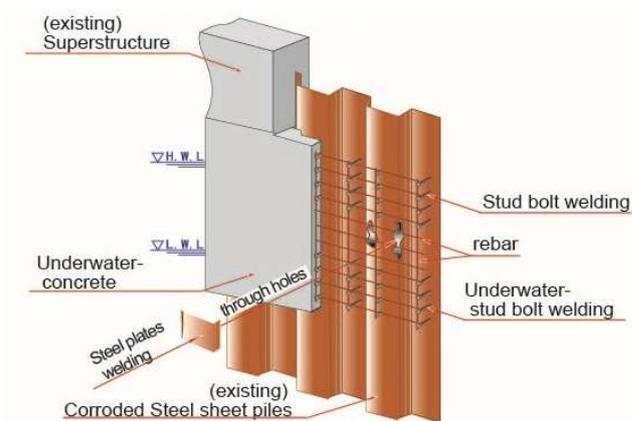


Fig.4 CRUS Method

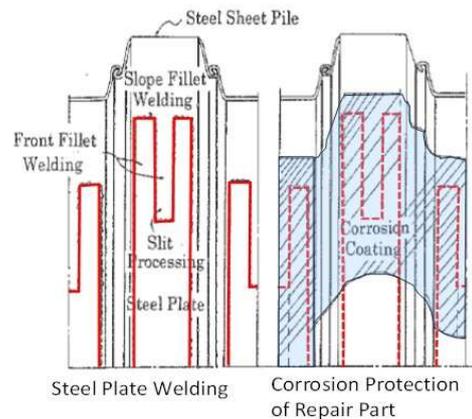
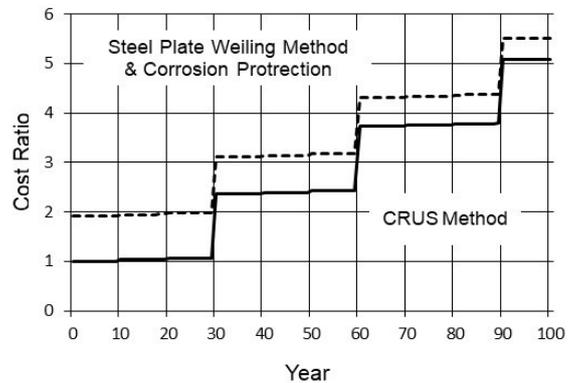


Fig.5 Steel Plate Welding Method

## (2) Comparison of Life-Cycle Costs

In selecting the repair method, life-cycle cost (LCC) calculations were carried out by evaluating both the initial repair cost and the maintenance cost, assuming a future service life of 100 years. Figure 6 shows the comparison of the LCC of the two methods, taking the initial cost of the CRUS method as 1. Since the initial cost of the steel plate welding method is higher, the LCC of the CRUS method turned out to be smaller.



The following conditions were applied in calculating the LCC:

- For the steel plate welding method, the petrolatum coating method is used in combination as a coating corrosion protection method.
- Below the coating area, both methods apply cathodic protection (service life: 30 years).
- In CRUS method, all elements are removed and newly installed every 30 years.
- For the steel plate welding method, the petrolatum coating is completely removed and reapplied every 30 years.
- For maintenance costs, a detailed inspection is conducted once every 10 years. In years other than construction, repair, or detailed inspection, a general visual inspection is carried out once a year.

## 4. Implementation of Repair and Reinforcement Methods

As a result of the study on constructability and life-cycle costs (LCC), the CRUS method, a reinforced concrete covering method, was adopted as the repair and reinforcement measure for this sheet pile structure.

### 4.1 Overview of the CRUS Method

For sections where the load-bearing capacity of the steel sheet piles was insufficient due to corrosion, the CRUS method structure shown in Figure 7 was applied. In other sections, in order to protect the sheet piles from corrosion, reduce costs, and maintain an overall sense of uniformity in appearance, the CRUS method (for corrosion protection) was also applied above L.W.L. -1.0 m (Figure 8).

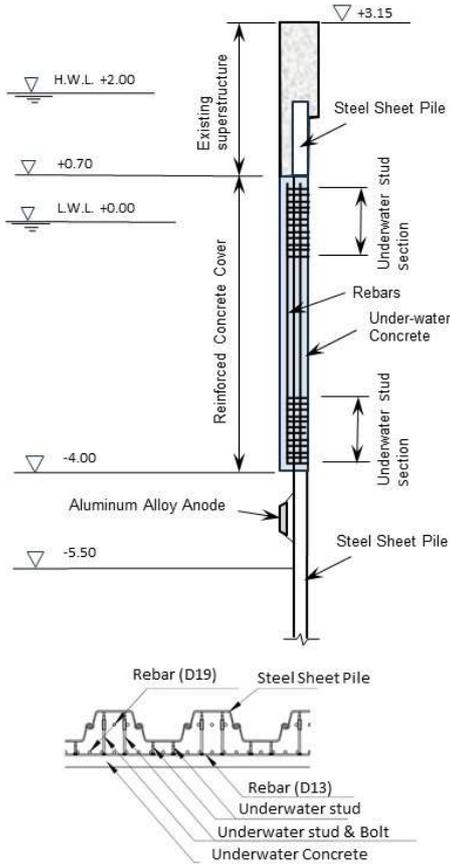


Fig.7 Cross-section of Repair & Reinforcement Section

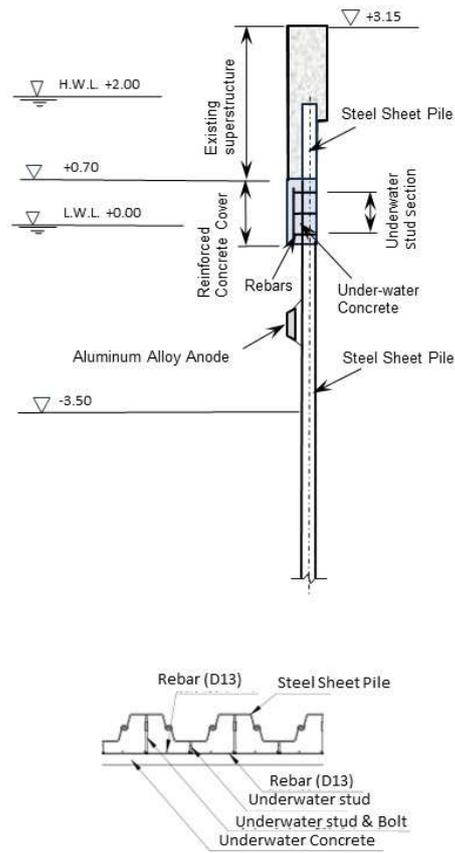


Fig.8 Cross-section of Corrosion Protection Section

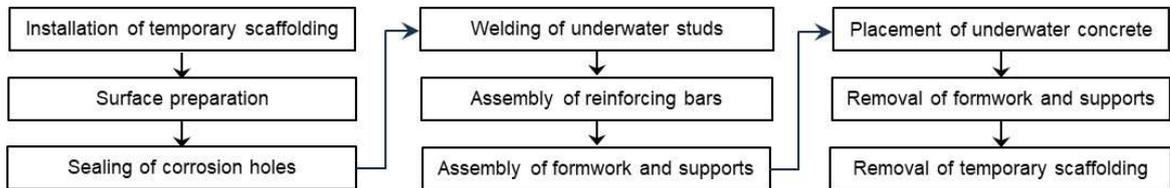


Fig.9 Construction Procedure of the CRUS Method

## 4.2 Construction Procedure of the CRUS Method

The standard construction procedure (construction flow) of the CRUS method is shown in Figure 9. Among these, the key processes of this method are underwater stud welding and underwater concrete, which are described below.

### (1) Characteristics of CRUS Method

Stud welding is a method of attaching bolts to the base material by welding using a special welding gun. The CRUS method is an improved version designed to eliminate the influence of water so that this welding technique can be applied to underwater structures such as port facilities. The minimum required plate thickness of the base material for stud welding is one-third of the stud shank diameter and not less than 5 mm. Therefore, in design, it is necessary to take into consideration the welding area of the studs and the stud shank diameter.

### (2) Materials for CRUS Method

The stud materials used for underwater stud welding have mechanical properties equivalent to those used for land-based stud welding. In the CRUS method, materials conforming to JIS B 1198:2011 "Headed Studs" or former JIS B 1197:1987 "Threaded Studs" are used (Table 1).

Table1 Mechanical Properties of Threaded Welding Studs ( Former JIS B 1197)

Strength grade : Section 4.8			
Tensile strength	N/mm <sup>2</sup>	minimum : 392	maximum : 539
Hardness <sup>(1)</sup>	Brinell hardness	HB	minimum : 110 maximum : 170
	Rockwell hardness	HRB	minimum : 62 maximum : 88
Yield point or Yield strength <sup>(2)</sup>	N/mm <sup>2</sup>	minimum : 314	
Elongation	%	minimum : 14	

Note : (1) Hardness shall conform to either Brinell hardness or Rockwell hardness.

(2) For materials with a distinct yield point, that value shall be used. For those without a distinct yield point, the 0.2% yield stress (permanent elongation) shall be used.

In this case, studs with a standard shank diameter of 16 mm (M16) were used. In the CRUS method, it is necessary to weld the reinforcing bars to the studs in order to reliably transfer the stresses occurring in the steel sheet piles to the reinforcing bars within the covering concrete. Since there is a gap of several hundred millimeters between the recess of the sheet pile and the reinforcing bars, underwater stud bolts approximately 100 mm in length with threaded heads were installed. Long nuts and bolts were then connected to the threaded heads to achieve the connection with the reinforcing bars.

### (3) Construction of CRUS Method

The welding areas for underwater stud welding were surface-prepared using tools such as air sanders. If rust or other foreign substances are mixed into the underwater stud welds, welding defects can easily occur and sufficient strength cannot be obtained. Therefore, after surface preparation, the underwater studs were welded as quickly as possible. Photo 3 shows the Completion of underwater stud installation



Photo 3 Underwater stud welding

### (4) Quality Control of Underwater Stud Welding

Prior to construction, tensile tests and bending tests using specimens were conducted in accordance with JIS B 1197:1987 to confirm the strength and bending ductility of the welds. The results of the bending test are shown in Photo 4. In addition, during construction, the welding current was measured, and the welding quality was evaluated for all studs based on the current waveform to determine pass or fail.

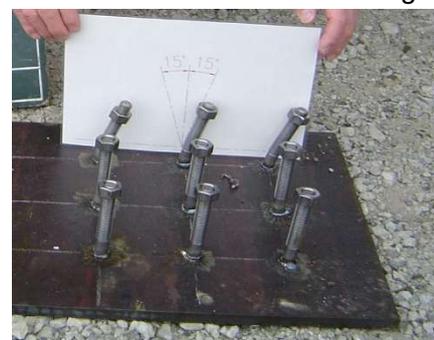


Photo 4 Specimen after bending test

## 4.3 Antiwashout Underwater Concrete

### (1) Characteristics of Antiwashout Underwater Concrete

Since the covering concrete is placed underwater inside the formwork, antiwashout underwater concrete with high flowability and resistance to material segregation was used.

In the CRUS method, from the time of its development in 1983, the standard construction procedure has been to inject concrete from the inlet at the bottom of the formwork installed underwater. This minimizes contact with seawater and makes it possible to construct high-quality concrete structures.

### (2) Mix Proportion of Antiwashout Underwater Concrete

In the CRUS method, it is common to set the design standard strength of concrete at 24 N/mm<sup>2</sup>; however, in this construction, the design standard strength was set at 33 N/mm<sup>2</sup>. The target slump flow was 500 ± 50 mm, and the maximum size of coarse aggregate was 20 mm. The mix proportion of the concrete is shown in Table 3, while the placement condition and the condition after completion are shown in Photos 5 and Photo 6.

Table 3 Mix Proportion of Antiwashout Underwater Concrete

W/C (%)	s/a (%)	Unit Volume (kg/m <sup>3</sup> )						
		C	W	S	G	Ad① <sup>※1</sup>	Ad② <sup>※2</sup>	Ad③ <sup>※3</sup>
38.9	40.0	553	215	586	910	2.0	5.53	13.83

※1 Ad①:Antiwashout admixture for underwater concrete

※2 Ad②:air-entraining and water-reducing admixture (standard type I )

※3 Ad③ : superplasticizer (standard type I )



Photo 5 Placement of Underwater Concrete



Photo 6 After Completion

## 5. Conclusion

Since its development in 1983, the CRUS method has been applied to numerous marine and port steel structures throughout Japan. Furthermore, in the long-term field exposure tests of the CRUS method, conducted as part of joint research on corrosion protection methods for steel pipe piles with the Port and Airport Research Institute and other organizations, its long-term durability is still being verified.

Awareness of the necessity of applying corrosion protection methods to steel structures in port facilities and similar environments has increased compared with the past. However, many marine and port steel structures still remain in need of repair and reinforcement. The repair and reinforcement method described here is expected to be useful for such port steel structures.

## References

- 1) Coastal Development Institute of Technology: “*Manual for Corrosion Protection and Repair of Port Steel Structures (Revised Edition)*”, p.189, April 1997.
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