3. Repair and Rehabilitation Methods

3.1 General

One of the characteristics of port facilities is that they are exposed to harsh marine environments, where loads such as wave forces and seismic forces act in combination with complex environmental effects. As a result, various forms of deterioration occur, leading to a decline in different performance functions. Because these structures are placed in marine environments, they are particularly vulnerable to salt damage (chloride-induced corrosion of steel materials), and repair or strengthening due to salt damage deterioration is another notable feature.

The relationship between the deterioration caused by various actions acting on port facilities and its effects on performance is referred to as a deformation chain. Understanding this deformation chain is extremely important when selecting inspection and investigation items, estimating causes of deterioration, and selecting repair or strengthening measures. **TCVN13330:2021** provides useful reference on this deformation chain.

The basic flow of maintenance for port facilities is shown in **Figure 3.1.1**. Based on comprehensive evaluations of various inspection and diagnostic results, it is necessary to select appropriate and rational countermeasures.

Although detailed methods of inspection and investigation for deterioration of different types of structures are described in **Chapter 2**, this section discusses countermeasures for confirmed deterioration. The countermeasures described here are based on extensive knowledge accumulated in Japan. However, in Vietnam, external forces acting on port structures, ground and soil conditions, water quality, and other factors differ from those in Japan, which may cause different impacts on the structures. Therefore, when using this manual, it is essential to properly understand the various factors affecting structures under Vietnamese conditions.

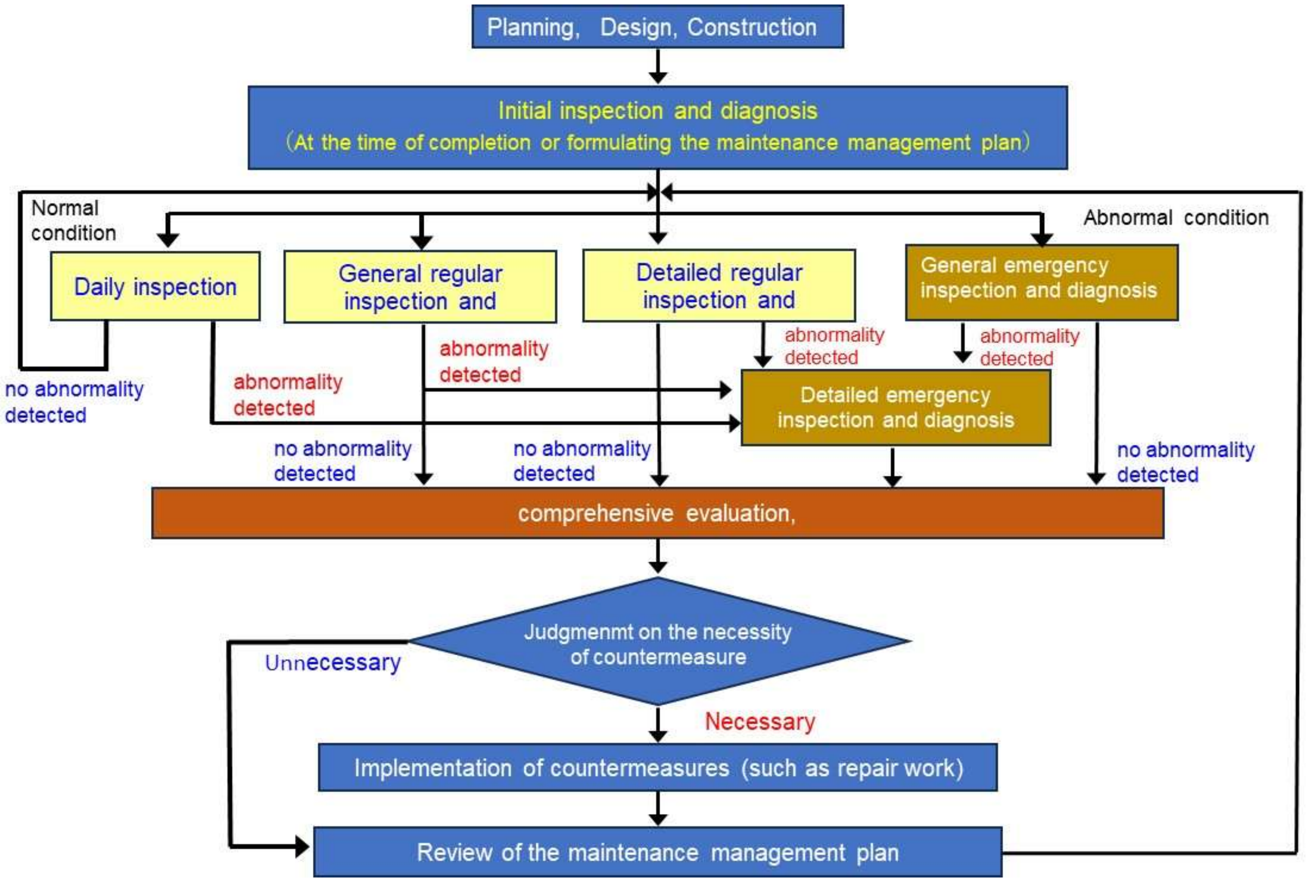


Figure 3.1.1 Flow of maintenance and management of port facilities

3.2 Types and selection of countermeasures

In port facilities, inspections and investigations are carried out during the maintenance stage, and various countermeasures are taken based on the results. Such countermeasures include general repair and strengthening, monitoring, restriction or suspension of facility use, and other measures. It is necessary to select an appropriate method based on various criteria such as the degree of deterioration of the structure, the importance of the facility, and economic considerations. **Table 3.2.1** shows the classification of countermeasures. In addition, depending on the usage conditions of the facility in question and its surrounding facilities, measures such as restricting or suspending facility use and prohibiting entry may also be included as countermeasures.

Table 3.2.1　Classification of Countermeasures

Type of countermeasure	Details of the Countermeasures
Follow-up observation	When inspection items and frequency remain unchanged, and will continue as before
Rearrangement of the inspection and diagnosis plan	When inspection items and frequency are to be modified
Repair	When restoring performance and durability to the original level
Strengthening	When improving performance and durability beyond the original level
Usage Restrictions	In cases where the use of the facility is restricted or suspended, or access is prohibited.
Upgrade	When replacement is more reasonable than repair or reinforcement
Removal	When the facility is no longer needed

It can be considered one of the countermeasures to decide not to carry out any particular repair or reinforcement work and instead continue periodic inspections and diagnoses, on the grounds that the deterioration of the structure has not progressed. At this time, it is necessary to determine, based on the results of the most recent periodic inspection and diagnosis, whether there is a need to change the inspection items or frequency.

When deciding on repair or reinforcement methods, or when determining the scope of structures to be subjected to countermeasures, if the information obtained from periodic inspection and diagnosis alone is insufficient, it is necessary to conduct a separate detailed investigation.

3.3 Countermeasures for waterways and basins

3.3.1 General

In order to secure the necessary water depth for water area facilities, it is essential to understand tendencies of siltation and other related phenomena through appropriate inspection and diagnosis, and to implement timely and proper countermeasures.
For the inspection of navigation channels and anchorages, the siltation mechanisms should be carefully considered, and appropriate inspection methods and implementation timing should be selected so that signs of water depth reduction caused by seabed siltation can be detected as early as possible.
If the inspection results indicate a potential risk of insufficient water depth due to siltation, the causes should be thoroughly investigated, the state of siltation should be analyzed, and suitable countermeasures should be implemented, considering the degree of impact and economic feasibility.
In particular, for facilities where a clear tendency of siltation is observed, it is desirable to carry out siltation progression forecasts and appropriately determine the timing and frequency of inspections and diagnoses.
Since the siltation mechanisms vary depending on each facility, it is recommended to combine the data obtained through inspection and diagnosis with proper numerical simulations to perform siltation progression forecasting.
The causes of siltation in navigation channels and anchorages can be summarized as follows:

1. Intrusion and accumulation of drifting sand due to waves or currents
2. Sedimentation and accumulation of sediment carried by rivers
3. Intrusion and accumulation of wind-blown sand
4. Movement of sediment and variation in the deposition area caused by disturbances inside the port (such as slope failure of channel banks, formation of sand waves, and sediment movement caused by ship navigation)

For water area facilities located inside harbors sheltered by breakwaters and other structures, the process of siltation occurrence and development has been organized as a chain of deterioration phenomena, as shown in Figure 3.3.1. As indicated in the figure, since the state of siltation differs depending on its causes, this should be fully considered when planning and selecting countermeasures.

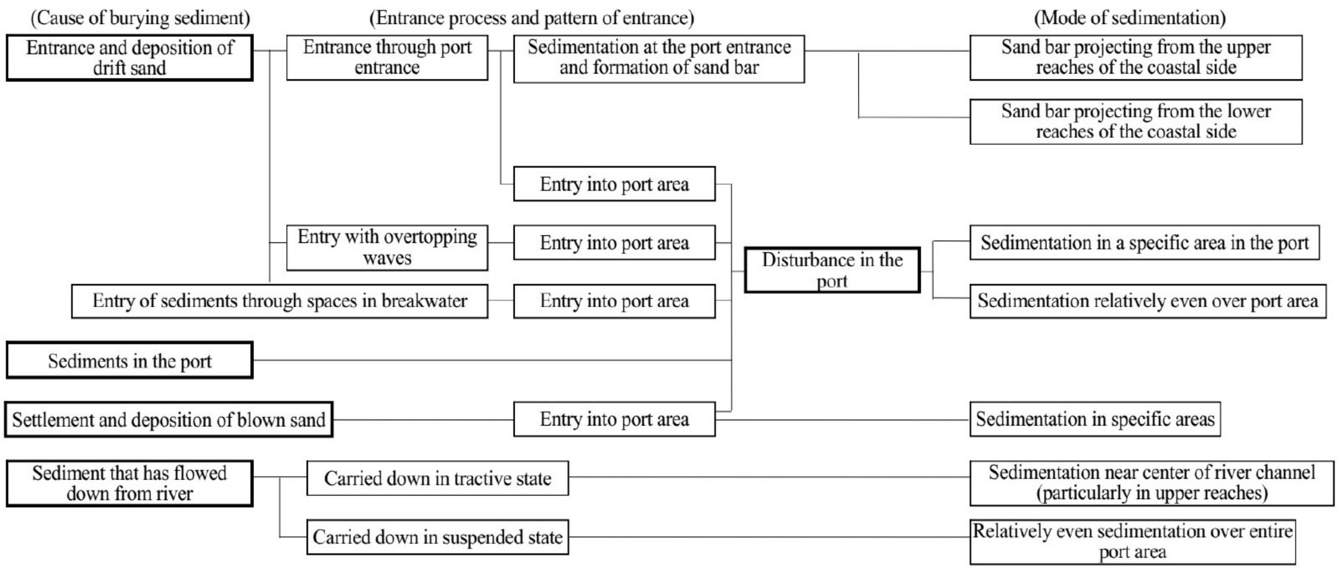


Figure 3.3.1 Deterioration chain for burial affecting waterways and basins [1)]

With regard to shoaling in typical unprotected water areas outside harbors, the following forms can be identified:

1) When waves are the main external force and the seabed consists of sandy soil or sandy mud, in relatively shallow-dredged channels, shoaling often occurs accompanied by scouring of the adjacent surrounding areas (see Fig. 3.3.2(a)).
2) When the seabed consists of soft mud and the dredged depth of the channel is relatively shallow, shoaling tends to occur uniformly, including on the side slopes (see Fig. 3.3.2(b)).
3) In channels where the dredged depth is deeper compared to the surrounding areas, shoaling tends to be significant at the bottom (see Fig. 3.3.2(c)).
4) In straits and similar areas where natural sand bars have been cut through to create dredged channels, shoaling often occurs in a manner that restores the original sand bar topography.
5) In channels dredged through seabeds where sand waves naturally exist, the sand waves tend to reappear at the channel bottom.

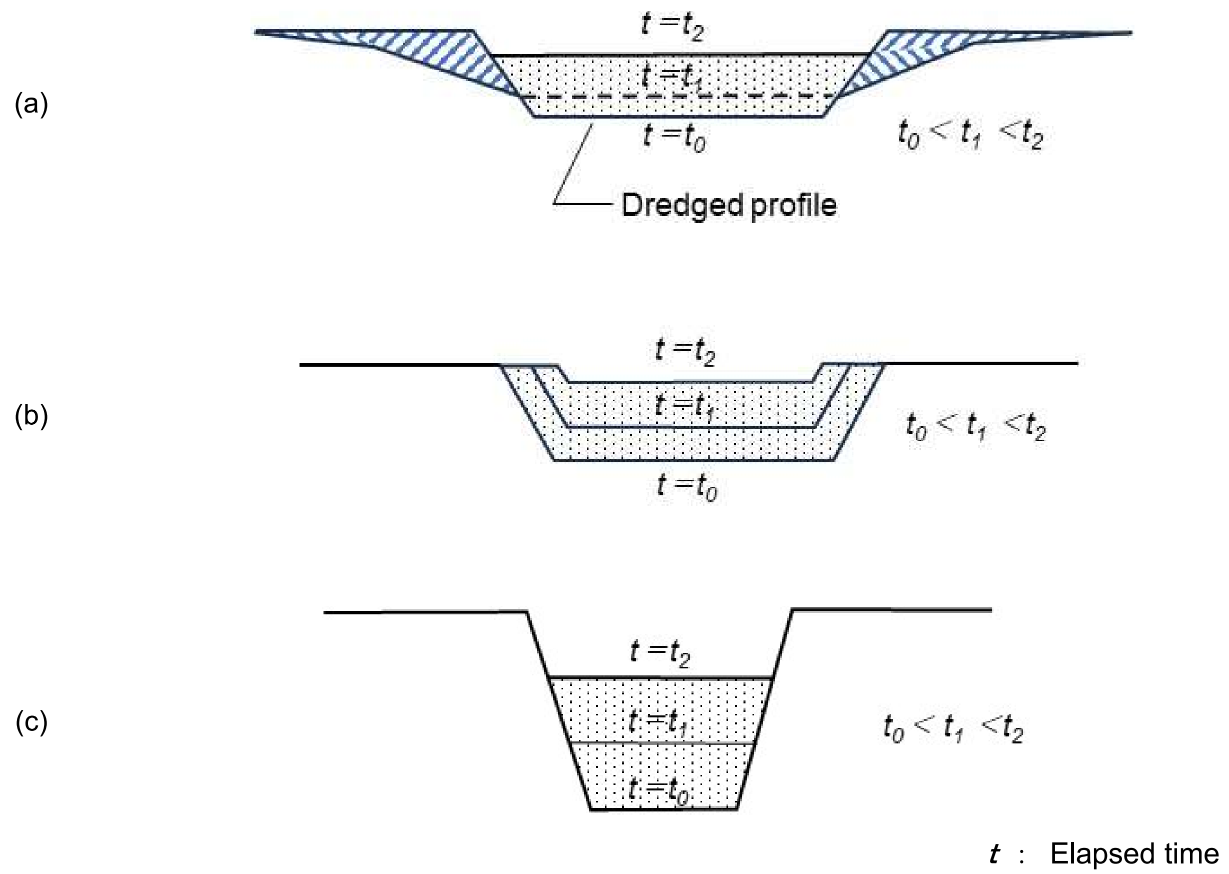


Figure 3.3.2 Forms of Shoaling in Unprotected Water Areas [3)]

3.3.2 **Countermeasures against Shoaling in Navigation Channels and Anchorages**

When the results of inspection surveys, such as depth sounding of navigation channels and anchorages, indicate a concern for insufficient water depth due to shoaling, the causes of shoaling should be thoroughly examined and the forms of shoaling analyzed. Furthermore, in selecting appropriate countermeasures, comprehensive consideration should be given to the various impacts induced by the countermeasures, their economic feasibility, and the effectiveness of performance recovery.

The following three methods can be considered as countermeasures against shoaling. In selecting among these methods, it is important to fully understand the mechanism and actual conditions of shoaling, and to refer to past case studies and results of model experiments. In addition, sufficient attention must be paid to the potential impacts of the countermeasures on the surrounding environment.

1. Methods that permanently or semi-permanently prevent shoaling by constructing facilities such as breakwaters (Table 3.3.1)
2. Methods that effectively capture sediments through over-dredging or pocket dredging, combined with maintenance dredging
3. Implementation of maintenance dredging as necessary

Table 3.3.1 Structures Used as Semi-Permanent Countermeasures against Shoaling

Countermeasure against longshore sediment transport	Prevention of sand intrusion from the harbor entrance	Breakwater, Groin (training jetty)
	Prevention of sand intrusion due to overtopping waves	Raising of a breakwater
	Prevention of sand intrusion through the breakwater	Sand control structure
River erosion control facility	Increase in river sediment transport capacity	River training wall
	Prevention of river sediment	Division levee
	Reduction of river sediment	Diversion weir
Wind-blown sand prevention work	Reduction of wind-blown sand	Planting, Sand protection forest
	Prevention of wind-blown sand intrusion	Sand fence

In cases where maintenance dredging is not considered on a semi-permanent basis, specific countermeasures against shoaling may be referred to by consulting the shoaling countermeasure facilities described in *the Technical Standards and Commentary for Port and Harbor Facilities in Japan (OCDI2020)*.

In addition, for water area facilities, their functions may be impaired by floating obstacles or the dumping of sediments and other materials; therefore, attention should also be paid to information provided by facility users and others. For this reason, it is advisable to conduct hearings with facility users as necessary.

3.4 Countermeasures for Concrete Structures

3.4.1 General

In this part, the main repair and strengthening methods for concrete structures, which are also the principal type of structures in the port sector, are presented, together with an outline of these methods and important considerations when applying them to port facilities. When selecting repair and strengthening methods for concrete structures, attention should be paid to the following two points:

(1) For concrete structures, it is necessary to select countermeasures (repair or strengthening) according to the respective deterioration factors.

Concrete structures may develop cracks at an early stage after being put into service, even when not caused by chloride-induced corrosion or alkali-silica reaction (ASR). The main causes of such cracks include loads and plastic shrinkage due to concrete hardening and drying. In addition, concrete structures may contain defects resulting from poor construction, such as cold joints. If cracks or other defects are left untreated, deterioration factors such as chloride ions and water may easily penetrate into the concrete, accelerating deterioration due to chloride-induced corrosion or ASR. Therefore, this chapter also briefly explains preventive measures against defects such as cracks. For detailed guidance on the investigation, repair, and strengthening of cracked concrete structures, reference may be made to the "*Practical Guideline for Investigation, Repair, and Strengthening of Concrete Structures.*"

(2) In many cases, it is difficult to select countermeasures based on quantitative performance evaluation. In such cases, countermeasures must be selected according to the degree of deterioration of the structure. However, it should be noted that in doing so, materials and methods should be selected based on the deterioration mechanisms.

3.4.2 Definition of repair and strengthening

Repair and strengthening can be defined as shown in Table 3.4.1.

In addition, conceptual diagrams of repair and strengthening for concrete structures and concrete members are presented in Figures 3.4.1 and 3.4.2, respectively [2)].

Table 3.4.1 Definitions of Repair and Strengthening

Repair	Actions to restore the mechanical performance, durability, or both of structures or members whose performance has deteriorated due to damage, to a level not exceeding the original state, or to provide durability exceeding the original level. This also includes actions to prevent further deterioration of the existing condition.
Strengthening	Actions to provide mechanical performance that exceeds the level originally possessed by the member.

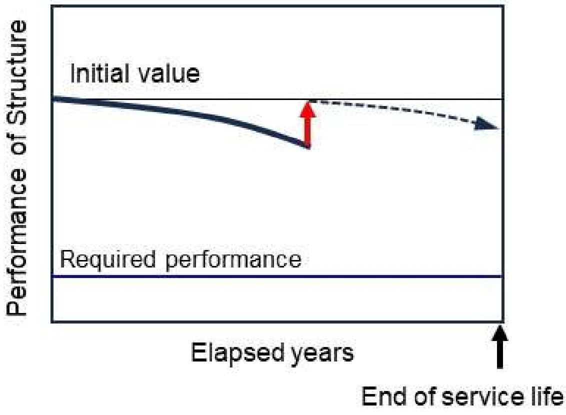


Figure 3.4.1 Concept of repair of concrete structure [3-1)]

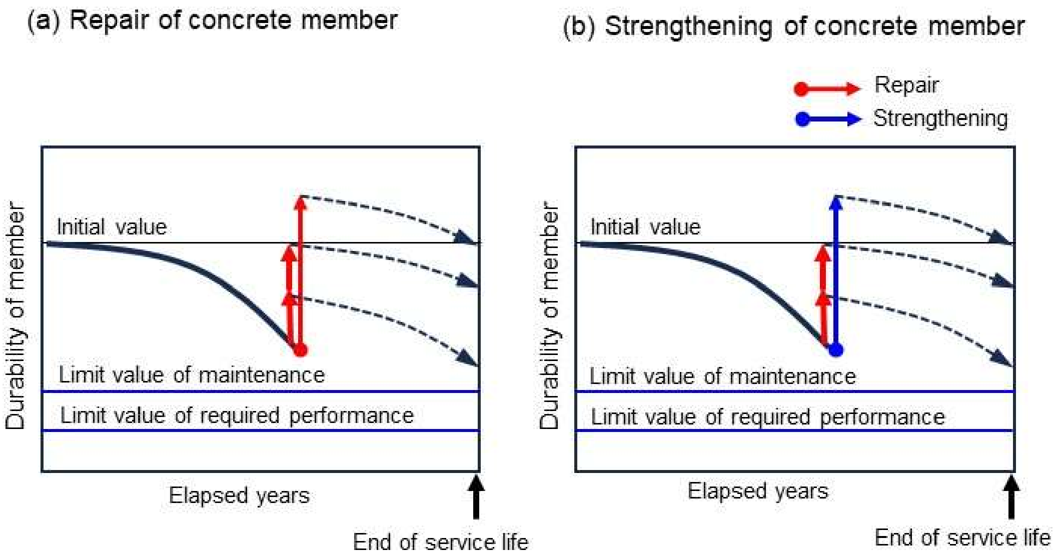


Figure 3.4.2 Concept of repair and strengthening of concrete member [3-1)]

3.4.3 Selection of repair method and strengthening method

For the repair and strengthening of port concrete structures, it is necessary to select appropriate repair and strengthening methods for the constituent concrete members, taking into account the required performance of the structure and the service period expected after the repair or strengthening.
In selecting repair and strengthening methods, attention should be paid to:

① the causes of defects (deterioration mechanisms) and the degree of deterioration of members,
② the natural environmental conditions, and
③ the characteristics of the methods, as well as the differences in structural types between reinforced concrete (RC) and prestressed concrete (PC).

Figure 3.4.3 shows the relationship between the deterioration condition, residual performance, and degree of deterioration of superstructures of piers affected by chloride attack. Since the performance of a structure—such as safety and usability—varies depending on the degree of deterioration, it is necessary to select repair and strengthening methods while considering the performance to be restored and the required level of recovery.

In Figure 3.4.3, a, b, c, and d represent the degrees of deterioration of structures and members, and the criteria for their evaluation are shown in Table 3.4.2.

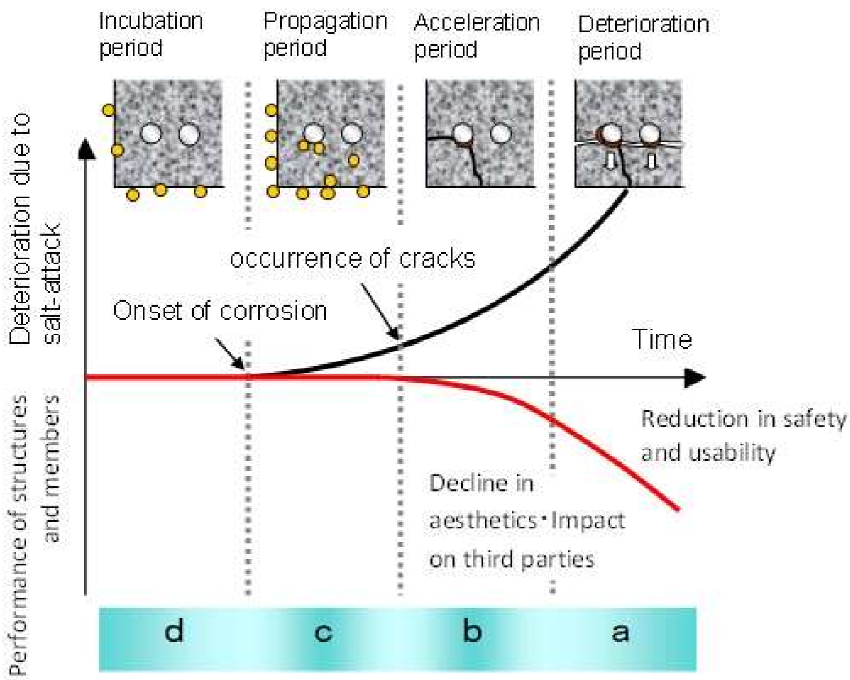


Figure 3.4.3 The relationship between the deterioration level and the remaining performance of the superstructure of a jetty

Table 3.4.2 Descriptions of inspection results

Judgement on the degree of deterioration	Condition of part or component
a	Performance of the component has seriously deteriorated
b	Performance of the component has deteriorated
c	Performance of the component has not deteriorated, but some deformation is occurring
d	No deformation identified

The classification of repair and strengthening methods applied to concrete members of port concrete structures is shown in Figures 3.4.4 and Table 3.4.3. Explanations of representative methods among them are presented in Table 3.4.4.

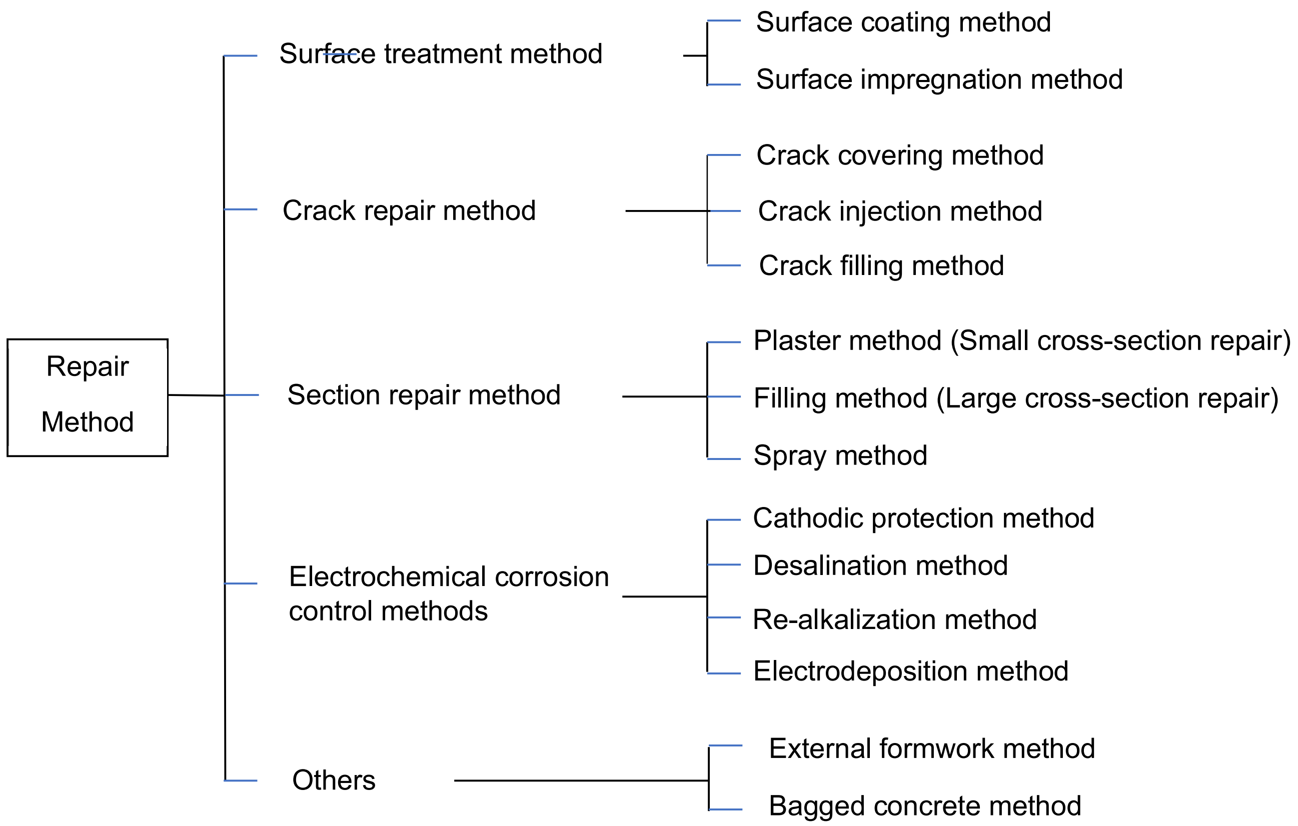


Figure 3.4.4 Classification of Repair Methods for the Durability Performance of Port Concrete Structures

Table 3.4.3 Classification of Strengthening Methods for Concrete Structures

Member replacement	Replacing method
Addition of concrete sections	Surface overlaying method
	Concrete jacketing method
Bonding and jacketing	Steel plate bonding method
	Continuous fiber sheet bonding method
	Steel plate jacketing method
	Continuous fiber sheet jacketing method
Introduction of prestress	External cable method
Addition of members	Member addition method Beam/Girder addition Bridge pier addition

Table 3.4.4 Examples of Repair and Strengthening Methods Applied to Members of Port Concrete Structures

Type	Overview of the repair method
Surface treatment method	By applying a coating material to the concrete surface, the supply of corrosion factors to the internal steel reinforcement is suppressed.
Section repair method	Deteriorated or damaged areas, as well as concrete containing a large amount of corrosion factors for the steel reinforcement, are removed and repaired using materials such as polymer cement mortar. A repair method appropriate to the size of the repair area is applied.
Cathodic protection method	An electrode (anode) is installed either inside or on the surface of the concrete, and electrons are supplied toward the internal steel reinforcement to suppress the corrosion reaction.
Desalination method	An electrode is installed on the concrete surface, and a relatively large current (larger than that used in cathodic protection) is applied to remove chloride ions from the concrete.
Crack repair method	There are methods such as coating, in which resin or other materials are applied to the surface along the crack (coating method); injection, in which resin or other materials are injected into the inside of the crack (injection method); and filling, in which the concrete along the crack is cut into a U-shape and filled with repair materials (filling method).
Replacement method	Deteriorated or damaged parts (members) are removed and newly reconstructed.
External formwork method	Formwork is installed on the outside (seaside) of the perforated area of the caisson's outer wall. Concrete is filled into the perforated area, and the hole is sealed.
Bagged concrete method	The perforated area is covered with bagged concrete from the inside (compartment side) of the caisson to prevent the loss of infill material inside the caisson.
Overlay method	By adding reinforced concrete, the cross-section of the member is increased to restore the reduced strength of the member or prevent further damage.
Steel plate bonding method	A steel plate is attached to the surface of the member to restore the reduced strength of the member.
Continuous fiber bonding Method	Bond continuous fiber reinforcements, such as carbon fibers, to the surface of the member to restore its reduced load-bearing capacity.
External cable method	PC tendons are arranged on the outside of the concrete member, and prestress is introduced to restore the reduced load-bearing capacity of the member.
Grouting solidification method	By solidifying the infill sand in the caisson, the impact resistance of the caisson walls is improved. This method is implemented as a preventive maintenance measure, especially when perforated damage occurs frequently.

The positional zones in which port structures are located can be classified into submerged zone, tidal zone, splash zone, and atmospheric zone above the sea, as shown in Figure 3.4.5. It should be noted that certain repair and strengthening methods or materials may not be applicable depending on the positional zone. As a reference, Table 3.4.5 shows an example of the correspondence between positional zones and applicable repair methods for chloride-induced deterioration.

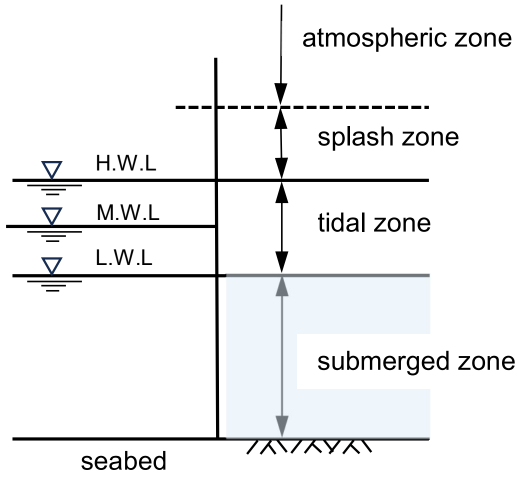


Figure 3.4.5 Location classifications of the marine environment

Table 3.4.5 Examples of Positional Zones and Applicable Repair Methods for Chloride-Induced Deterioration

Repair method / Location	Crack repair※1	Surface treatment	Cross-Section restoration	Cathodic protection ※2
Atmospheric zone	○	○	○	○
Splash zone	△	△	△	○
Tidal zone	△	△	△	△
Submerged zone	△	△	△	△

In the table, ○ indicates that the item is applicable, and △ indicates that sufficient consideration is required before applying the item.

※1：The crack repair method is used as preventive maintenance or as a supplementary method for surface coating methods, cathodic protection methods, and others.

※2：In the case of suspected alkali-silica reaction (ASR), it is necessary to consider the applicability and implementation method of the cathodic protection method.

About the applicability of various repair and strengthening methods to structures (members), Table 3.4.6 serves as a reference. It should be noted, however, that these methods are further subdivided, and there are also methods not described here.

Table 3.4.6 Applicability of Repair and Strengthening Methods to Structures (Structural Members)

Type of Repair Method	Target structure (member)				
	Superstructure of the pier (RC)	Substructure of the pier (PC)	Breakwater Caisson	Coping of the Sheet pile quay wall	Breakwater Superstructure
Surface treatment method	○	○	△	△	×
Cross-Section restoration method	○	○	○	○	○
Cathodic protection method	○	○	△※	△※	×
Desalination method	△	△	×	×	×
Crack repair method	○	○	○	○	○
Replacement method	○	○	△	○	○
External formwork method	×	×	○	×	×
Bagged concrete method	×	×	○	×	×
Overlay method	△	△	×	×	×
Steel plate bonding method	△	△	×	×	×
Continuous fiber bonding method	△	△	×	×	×
External cable method	△	○	×	×	×
Grouting solidification method	×	×	○	×	×

○: Standard method　△: Conditionally applicable　×: Not applicable

※ : Applicable in the case of the galvanic anode system.

3.4.4 Repair method

3.4.4.1 Surface treatment method

The surface coating method involves forming a coating layer on the concrete surface to reduce the penetration of corrosive agents (such as chloride ions, oxygen, and water) into the internal steel materials (reinforcement, etc.), thereby suppressing corrosion of the internal steel or deterioration and erosion of the concrete itself. This method includes the surface coating method, in which the concrete surface is coated with organic or inorganic materials (Photo 3.4.1), and the surface impregnation method, in which colorless and transparent impregnating materials are applied to the concrete surface using a spray, roller, or brush (Photo 3.4.2).

Photo 3.4.1 Application of the surface coating material

Photo 3.4.2 Application of the surface impregnation material and water repellency status

The materials used for the surface coating method include organic and inorganic materials, and the finish may be applied in a single layer or in multiple layers. In the general surface coating method shown in Fig. 3.4.6, the intermediate coating material must not only have the performance to block the ingress of deterioration factors from the external environment but, in the case of RC members, must also have the ability to follow variations in crack width. Therefore, it is applied as a relatively thick film, and in some cases, flexible materials are used. The top coating material must be resistant to deterioration caused by ultraviolet rays and other factors, and coating materials containing resins with excellent weather resistance and coloring pigments are often used. The selection of materials must take into account the factors of deterioration to be addressed, environmental conditions, and the expected effects. For port concrete structures, key points in material selection include excellent resistance to chloride penetration, good crack-following capability, and strong adhesion to existing concrete or section repair materials.

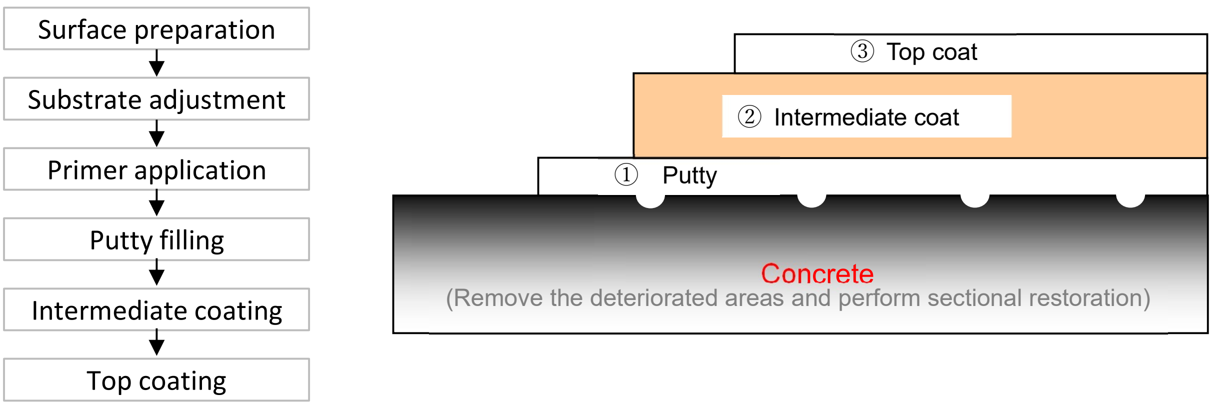


Figure 3.4.6 General construction flow and cross-sectional diagram of the surface coating method

In the surface impregnation method, materials that penetrate into the concrete surface layer to generate calcium silicate and other compounds to densify the microstructure, or materials that impart water-repellent properties to the concrete surface (such as silane-based materials), are generally used. In addition, methods that combine both types of materials have also been developed.
The surface coating method may be used alone when deterioration has not yet progressed; however, when corrosion cracks in the internal reinforcing steel caused by chloride ions have already occurred, it is necessary to use it in combination with the section repair method.
This is because, once chloride ions have penetrated into the concrete to the extent that reinforcement corrosion has already begun, suppressing the ingress of corrosive agents from the concrete surface cannot prevent further corrosion of the reinforcement by the chloride ions that have already penetrated, and may lead to re-deterioration.
Photo 3.4.3 shows a case of re-deterioration in which, despite the application of the surface coating method, corrosion of the reinforcement progressed due to chloride ions that had already penetrated inside, and cracks appeared in the surface coating material as the cracks developed and widened. When applying the surface coating method, careful consideration must be given to the timing of application and the extent of chloride ion penetration.

Photo 3.4.3 Crack occurrence due to re-deterioration after surface coating application

3.4.4.2 Crack repair method

Crack repair methods are used to restore waterproofing and durability for initial cracks such as temperature cracks and drying shrinkage cracks, as well as cracks caused by external forces. As shown in Fig. 3.4.7, crack repair methods include the crack surface coating method, the injection method, and the filling method, which must be selected by considering the extent of crack width variation and crack depth. In the case of cracks caused by corrosion of reinforcing bars due to chloride attack, crack repair methods are generally not applicable because a large amount of chloride ions has already penetrated to the reinforcement level. In addition, when carrying out section repair, sufficient caution is required in determining the repair area and selecting the repair material, since corrosion of the existing reinforcement tends to progress due to macro-cell formation between the existing concrete and the repair concrete.

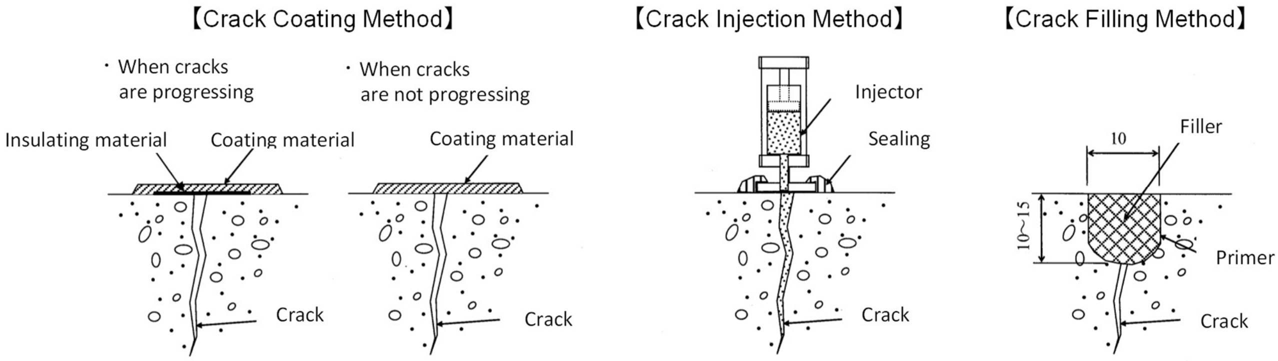


Figure 3.4.7 Types of Crack Repair Methods

An example of the selection of crack repair methods is shown in Fig. 3.4.8. As a general guideline, when the crack width is 0.2 mm or less, the crack surface coating method is often adopted; when the crack width is between 0.2 mm and 1.0 mm, the injection method is often used; and when the crack width exceeds 1.0 mm, the filling method is frequently applied. The materials used for crack repair are generally selected according to the crack width, crack behavior, and the repair method. If the crack width fluctuates due to loads, temperature changes, etc., it is preferable to use materials that can follow the crack behavior.
In the case of port structures, since construction is often carried out underwater or in wet environments and the structures are exposed to such conditions, it is important to select materials that can be applied under these conditions while ensuring the required performance (such as adhesion and workability).

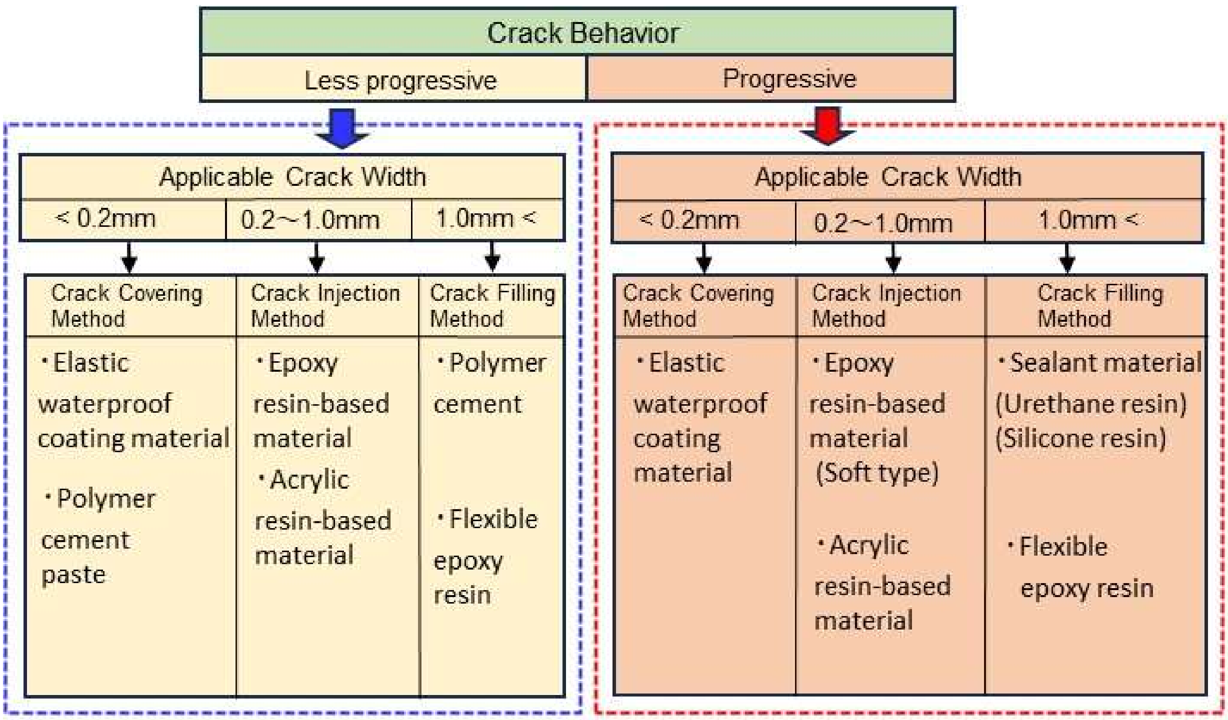


Figure 3.4.8 Example of crack repair method selection [3)]

(1) Crack covering method

The crack covering method involves applying a coating material along the surface of the crack, and it is mainly used when the crack width is small and the crack injection method cannot be applied. As a general guideline, it applies to cracks with a width of 0.2 mm or less. When used along the crack, a drawback is that traces remain visible on the surface, impairing aesthetics. In some cases, such as when the concrete is relatively new or when section repair has been carried out, the material may also be applied over the entire concrete surface to suppress the ingress of deterioration factors. Since the repair material does not fill the interior of the crack, if the crack is progressive or the crack width varies significantly, and the material cannot follow the movement, the repair material may itself crack, making it easier for deterioration factors to penetrate. To prevent such ingress of deterioration factors, it is advisable to further cover the coating material with a protective cover layer.

(2) Injection method

The mainstream method of crack injection at present is the automatic low-pressure injection method, in which the injection material is injected at low pressure from the surface. However, when the crack depth is large, the high-pressure injection method, which involves drilling holes into the structure and injecting material into the crack from inside, is more suitable. As a guideline, the maximum crack depth suitable for low-pressure injection is approximately 15 to 30 cm, which corresponds to the spacing of the injection holes for the repair material.
The injection materials used in injection methods commonly applied to port concrete structures can be broadly classified into resin-based (organic) and cement-based (inorganic) materials. Among these, epoxy resin, a resin-based material with excellent adhesion and durability, is the most commonly used in underwater and wet environments.
However, when repairing underwater portions of structures such as breakwater caissons, where the automatic low-pressure injection method is difficult to apply, it is common to use either the manual resin injection method or the mechanical resin injection method.
The procedure and conditions of the low-speed, low-pressure injection method, which is the mainstream crack injection method, are shown in Fig. 3.4.10. Furthermore, the spacing of the injection holes should be adjusted according to the crack width, with general guideline values shown in Table 3.4.7.

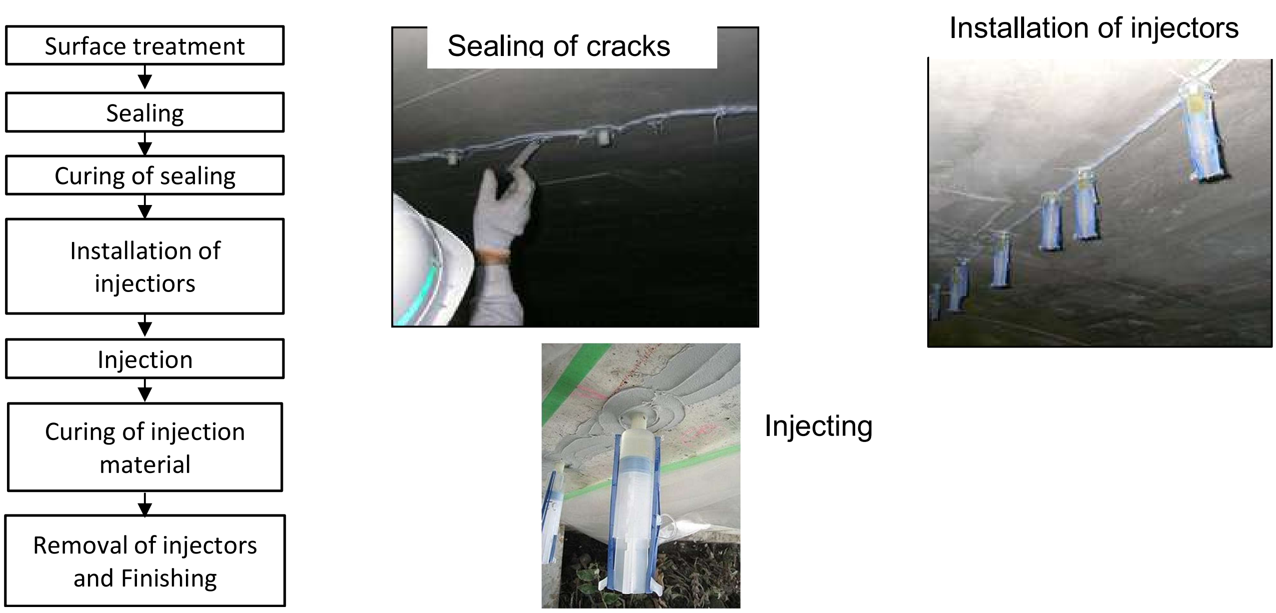


Figure 3.4.10 Construction flow of the crack injection method

Table 3.4.7 Guideline for the Spacing of Injection Holes in the Crack Injection Method

Crack width (mm)	Spacing of Injection Holes (mm)
＜ 0.3	50 ～ 100
0.3 ～ 0.5	100 ～ 200
0.5 ～ 1.0	150 ～ 250
1.0 ＜	200 ～ 300

(3) Filling method

When the crack width exceeds 1.0 mm, the filling method is suitable. In this method, a U-shaped (U-cut) or V-shaped (V-cut) groove is cut along the crack on the concrete surface, and the groove is then filled with filler material and backup material. It should be noted that compared with the V-cut, the U-cut has the advantage of being less likely for the filler material to fall out.

However, although aesthetics may not be a significant issue for ordinary port concrete structures, the filling method leaves repair marks. Therefore, in locations where appearance is important, it may be considered to combine this method with the surface coating method.

3.4.4.3 Section-repair method

The section-repair method is a technique in which deteriorated portions of existing concrete structures, where damage has become apparent or where deterioration factors, such as chloride ions, remain beyond permissible limits, are removed, and the section loss is repaired using section repair materials. Accordingly, by removing and repairing the appropriate areas, improvements in structural performance and durability can be achieved. An outline of section repair construction (cross-sectional view) and the construction flow are shown in Fig. 3.4.11.

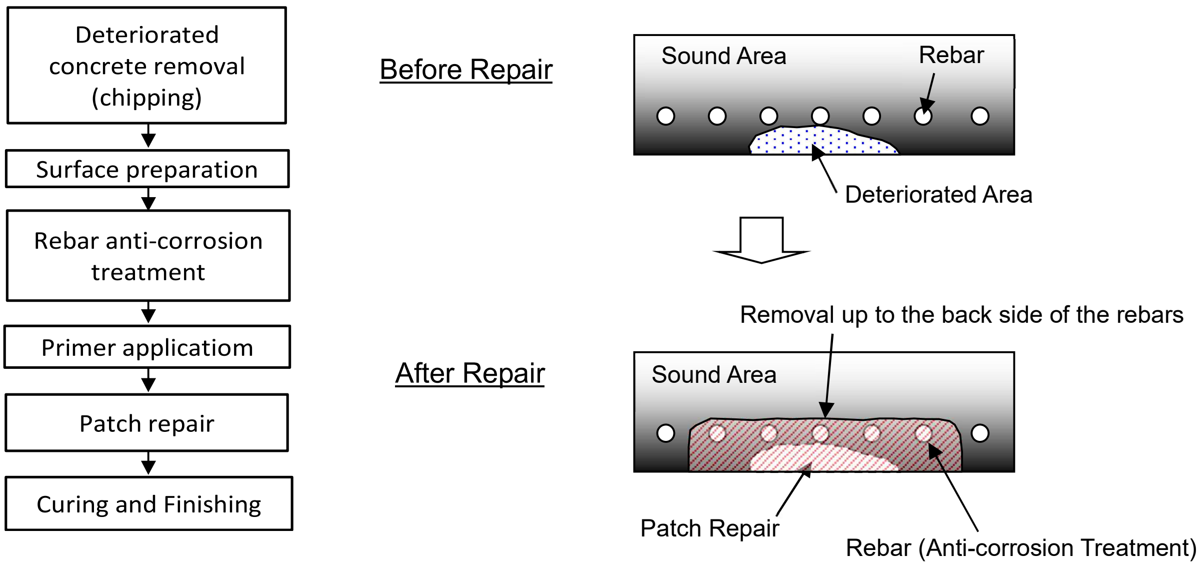


Figure 3.4.11 Construction flow of the section-repair method [2)]

In concrete containing a large amount of chloride ions, if only the visibly deteriorated parts are repaired, a potential difference will occur in the reinforcing steel located near the boundary between the repaired and unrepaired parts. As a result, rapid corrosion of the unrepaired part, known as 'macro-cell corrosion', may occur, which can significantly accelerate the corrosion of the reinforcement in the existing concrete. Therefore, in section repair, it is necessary not only to repair the visibly deteriorated parts but also to remove the concrete behind and around the reinforcement that contains chloride ion concentrations exceeding the corrosion initiation threshold, so that the joint can be made in areas with low chloride ion concentrations.

Section-repair methods can be broadly classified into three types: plaster method, filling method, and spray method (see Photo 3.4.4). Generally, the plaster method is applied when the repair area is relatively small (small-scale repair), while the filling method and spray method are applied when the repair area is large (large-scale repair). When selecting the construction method, it is necessary to consider factors such as the environment and type of the concrete structure to which it is applied, the location and members (including the construction direction, such as upward or downward), and the size of the repair area. The characteristics of the three section-repair methods are shown in Table 3.4.8.

Plaster method

Filling method

Spray method

Photo 3.4.4 Examples of Cross-Section Restoration Methods

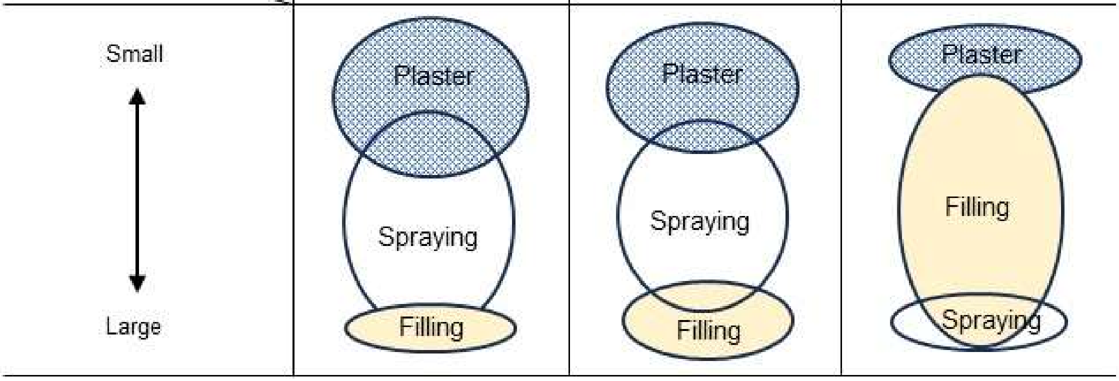
Table 3.4.8 The characteristics of the three section-repair methods

Type	Characteristics
Plaster method	・Generally used for small-scale patch repairs of 100 m² or less. It involves layering and finishing with a trowel. ・It is recommended to apply each layer with a thickness of 10 mm or less. The total thickness applied in one day should not exceed 30 mm.
Filling method	・Generally used for large-scale patch repairs of 100 m² or more. ・The thickness of the patch repair area is typically 30 mm or more. ・Injection is performed from lower to higher positions to prevent air pockets, and air vents should be appropriately placed at higher locations. ・The patch repair material should be injected continuously to avoid construction joints. ・To prevent material segregation, vibration with a vibrator or tapping of the formwork should not be performed during injection.
Spraying method	・Generally used for medium to large-scale patch repairs of 10 to 100 m². 【Wet Spraying Method】 ・The rebound amount and dust generation are minimal. It can also be combined with trowel finishing, providing excellent workability. ・The thickness per application should be 30 mm or less for upward construction and 50 mm or less for horizontal construction. 【Dry Spraying Method】 ・This method has high construction efficiency and rapid mortar strength development, making it advantageous for large construction areas. ・It is possible to spray a thickness of 10 cm or more in a single application.

As an example of the selection of section repair methods, Table 3.4.8 shows the classification of applicable methods according to the location of the target area, the construction direction, and the size of the repair area. In addition, since appropriate repair materials differ depending on factors such as the thickness, area, and repair location, it is necessary to select materials with due consideration of the construction conditions.

Table 3.4.8 Applicable range of section repair methods (schematic diagram) [2)]

Position of repair part	Bottom surface	Side surface	Top surface
Work direction / Repair area	Upward	Horizontal	Downward



Unlike the filling method, the plaster method and the spray method do not require the installation of formwork; however, the quality—such as ensuring adequate filling performance—is greatly influenced by the skill level of the workers (technicians).

Repair materials used in section repair methods must have sufficient strength and density, must not crack due to drying shrinkage or hydration heat, must have excellent adhesion to existing concrete, must possess good workability (flowability and applicability), must provide sufficient durability against seawater, and should have as small a chloride ion diffusion coefficient as possible.

In the filling method, since repair material is injected into a confined space, the material must have sufficient flowability, and attention must be paid to the arrangement of injection points and air vents so that voids are not created by trapped air.

In addition, in the filling method, precast concrete or FRP formwork is sometimes used as permanent formwork, which eliminates the need for dismantling the formwork and also helps prevent the ingress of deterioration factors after section repair, thereby improving durability.

3.4.4.4 Electrochemical Corrosion Control Methods

There are several electrochemical corrosion control methods, including cathodic protection, desalination, re-alkalization, and electrodeposition. These methods prevent corrosion of reinforcing bars inside concrete by utilizing electrochemical reactions. For details of these methods, refer to the Japan Society of Civil Engineers' *Concrete Library 157: Guidelines for Electrochemical Corrosion Control Methods*. Among them, the most commonly used in the port sector is the cathodic protection method, which is outlined below.

In cathodic protection, for cases where the passive film of reinforcing steel in concrete has been destroyed due to chloride ion penetration and the corrosion reaction is progressing, an anode material is installed on the concrete surface, and a direct current protection current is applied toward the reinforcing bars acting as the cathode. The concept of this protection is illustrated in Fig. 3.4.12. When reinforcing steel inside concrete is corroding, differences in potential distribution occur; however, by applying the protection current through the cathodic protection method, the potential difference of the reinforcing bars is eliminated and the corrosion reaction is suppressed. Therefore, cathodic protection is, in principle, the most reliable countermeasure against chloride-induced deterioration.

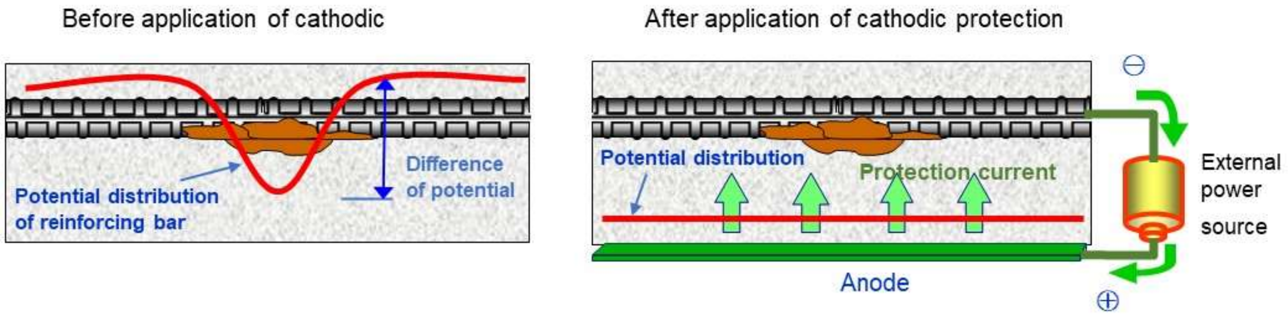
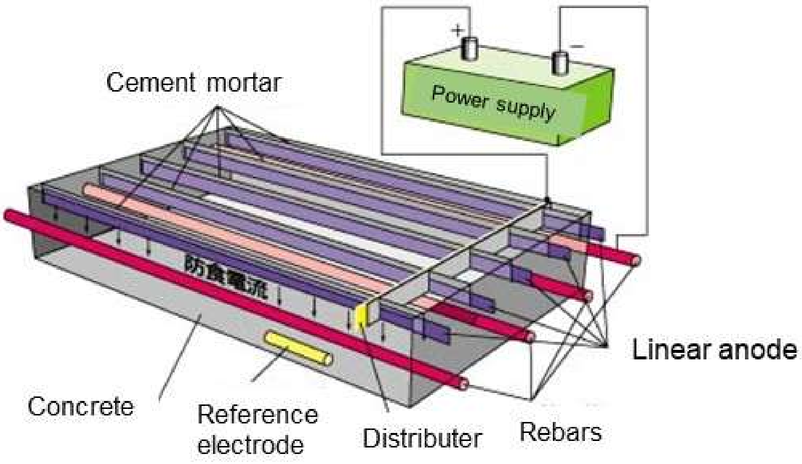


Figure 3.4.12 Conceptual Diagram of Corrosion Protection by Cathodic Protection Method

The advantages of the cathodic protection method include: its applicability even to concrete containing a large amount of chloride ions; the fact that during surface preparation for sectional repair, only deteriorated areas that hinder current flow, such as delaminated or loose parts, need to be removed—removal of the concrete behind the reinforcing bars is unnecessary; no need for anti-corrosion treatment of the reinforcing bars; and the ability to quantitatively verify the corrosion protection effect through monitoring of the steel bar potential.

As for methods of supplying the protective current, there are two types:

1. Impressed Current Method
 ・A direct current (DC) power supply device is installed externally.
 ・Anode materials (e.g., titanium mesh with mixed metal oxide coating) are placed on the concrete surface or embedded in mortar.
 ・A continuous DC current is supplied (current density: 1–30 mA/m², applied voltage: 1–5 V).
 ・The protective effect is confirmed by measuring the potential of the reinforcing bars or monitoring the potential change caused by the applied current.
 ・Advantage: Current can be controlled and adjusted precisely.
 ・Typical Application: Long-term protection in severe chloride-contaminated marine environments.
2. Galvanic Anode Method (Sacrificial Anode Method)
 ・Anode materials with a greater tendency to ionize than iron (e.g., zinc, aluminum, magnesium alloys) are directly connected to the reinforcing bars.
 ・The anode itself corrodes (sacrifices) and supplies the protective current.
 ・Advantage: Simple system with no need for an external power source.
 ・Limitation: Current output is relatively small and depends on the environment.
 ・Typical Application: Localized repair works or areas with moderate chloride contamination.



External power supply unit

Figure 3.4.13　Cathodic Protection Method by Impressed Current System

In the impressed current system, anode materials made of titanium as the base material are used. Depending on their shape, these are classified into panel-type anodes, linear-type anodes (Photo 3.3.5), and point anodes. In the galvanic anode system, panel-type anodes (Photo 3.3.6) are generally used.

(Panel-type anodes)　　(Linear-type anodes)

Photo 3.4.5　Installation Conditions of panel-type anodes, linear-type anodes

Photo 3.4.6　Anode Installation Conditions in the Galvanic Anode System

3.4.4.5 External Formwork Repair Method

In breakwater caissons and similar structures, wave-dissipating blocks installed in front of the caisson may repeatedly collide with it due to wave action, which can sometimes cause perforation damage on the side walls. Once such perforation damage occurs, the filling material may leak out, leading to a decrease in the stability of the caisson. Therefore, repairs are carried out using the external formwork method, with the objective of preventing the outflow of filling material.

The external formwork method involves setting formwork on the outside of the caisson side wall, drilling from the superstructure into the interior chambers where perforations have occurred, and placing concrete into the cavities to close the holes and secure the overall mass of the caisson.

However, in cases where the repair area is located at a considerable depth, it is advisable to adopt other methods in consideration of workability and safety. This method is better suited for situations where the damaged area is relatively shallow.

When placing concrete into cavities, as seawater remains inside the chamber, the concrete has to be placed underwater. For this reason, underwater concrete or anti-washout underwater concrete with sufficient strength must be used. The mix design and other properties of the concrete should ensure strength characteristics equal to or greater than those of the parent concrete.

The construction flow and overview of the external formwork method, as shown in the *Manual for Repair of Port Concrete Structures*, are presented in Fig. 3.4.14. An example of formwork installed on the caisson side wall is shown in Photo 3.4.7.

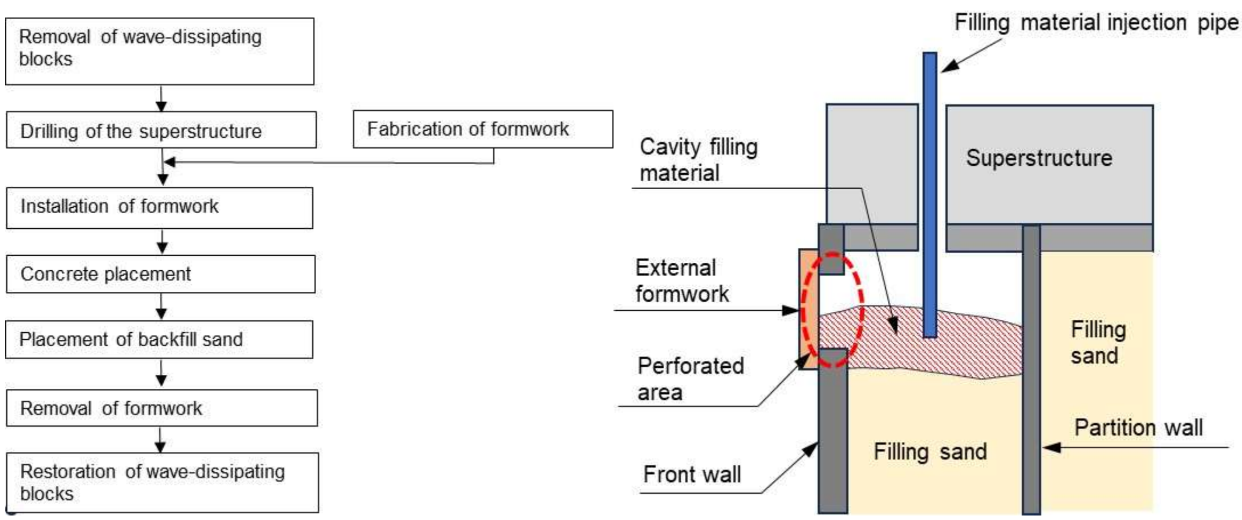


Figure 3.4.14 Construction Procedure and Schematic Diagram of the External Formwork Method [2)]

Photo 3.4.7 Example of External Formwork Installation [2)]

Similar to the external formwork method, there is also the bagged concrete method, which aims to prevent the outflow of filling material from the caisson side walls.
The bagged concrete method involves sealing perforated sections inside the chamber—where the filling material has leaked—by placing concrete bags. A major advantage of this method is that it generally does not require the removal of the wave-dissipating blocks in front of the caisson.

3.4.5 Strengthening method

The general relationship between major strengthening methods for concrete structures and the structural members to which they can be applied is shown in Table 3.4.9. Among these methods, some require special attention when applied to port structures.

Table 3.4.9 Examples of major strengthening methods and applicable members

Target of Countermeasure	Type of Countermeasure	Examples of Strengthening Methods	Applicable Members			
			Beam	Column	Slab	Wall
Concrete Member	Bonding of Reinforcing Materials	Bonding method	◎	○	◎	○
	Introduction of prestress	External Prestressing Method	◎	○	○	
	Section Thickening	Concrete jacketing method	○	○	◎	○
	Member Replacement	Replacement Method	○	○	◎	◎
Structure	Addition of Beams (Girders)	Additional Construction Method	◎		◎	
	Addition of Walls	Additional Construction Method				◎
	Addition of Supports	Additional Construction Method	◎		◎	

(Notice) ◎ : Methods with a relatively large number of practical applications,
○ : Methods considered applicable

3.4.5.1 Concrete jacketing method

The concrete jacketing method is intended to restore load-bearing performance by placing reinforcing materials such as reinforcing bars on the upper or lower surface of existing concrete members, casting concrete or mortar, and integrating the thickened section with the existing concrete.
When the purpose is to reinforce slab concrete, there are two variations: the top-surface jacketing method, in which the thickening is applied to the upper side, and the bottom-surface jacketing method, in which it is applied to the underside. In either case, it is essential to ensure that the thickened section is integrated with the existing concrete. Therefore, careful attention must be given to the concrete or mortar used in the

thickened section, particularly with respect to the following points:

・Good bond with the existing concrete

・Minimal shrinkage deformation

It should also be noted that the concrete jacketing method involves an increase in the self-weight of the superstructure, which requires attention to its effects on the substructure.

(1) Top-surface jacketing method

The top-surface jacketing method includes two approaches: one in which steel fiber reinforced concrete is placed on the upper surface of existing concrete and integrated with the old concrete, and another in which reinforcing bars are arranged within the thickened concrete section. Steel fiber reinforced concrete is used for the top-surface jacketing because the addition of steel fibers improves fatigue resistance. Standard examples of construction cross-sections are shown in Fig. 3.4.15.

The top-surface jacketing method is expected to enhance load-bearing capacity against punching shear. In addition, thickening shifts the neutral axis of the cross-section upward, thereby improving bending strength, while also increasing the overall stiffness of the structure, which contributes to reducing beam deflection.

The thickened concrete used in the top-surface jacketing method is generally produced at large on-site plants, due to requirements such as: (i) using ultra-rapid hardening cement, (ii) mixing steel fibers, and (iii) reducing drying shrinkage by using concrete with a slump of around 5 cm.

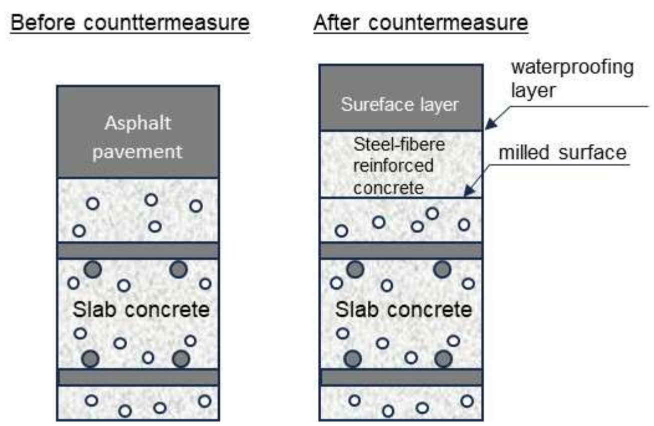


Figure 3.4.15 Example of Cross-Section of Top-Surface Jacketing Method

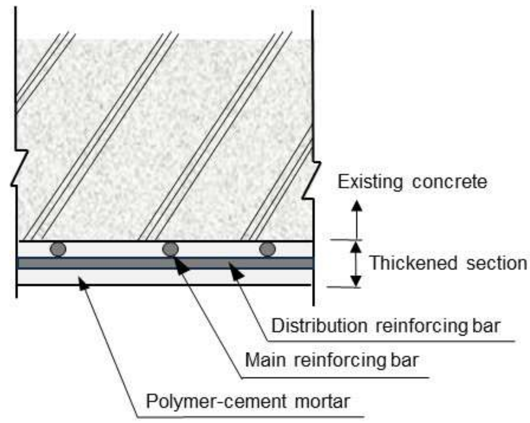


Figure 3.4.16 Example of Cross-Section of Bottom-Surface Jacketing Method

(1) Bottom-surface jacketing method

The bottom-surface jacketing method is a reinforcement technique in which reinforcing materials, such as reinforcing bars, are arranged on the underside of an existing concrete slab, and the section is thickened with high-bond mortar to integrate it with the existing concrete. By achieving this integration, bending strength is improved, while the deflection of the existing slab, reinforcement stress, and crack width are reduced, thereby enhancing fatigue resistance. A standard example of a cross-section of the bottom-surface jacketing method is shown in Fig. 3.4.16.

3.4.5.2 Bonding method

The bonding method is a reinforcement technique in which panel- or sheet-shaped reinforcement materials are bonded to existing concrete members to integrate them with the existing concrete.

Depending on the type of reinforcement material used, there are two variations of the bonding method: the continuous fiber (FRP) sheet bonding method and the steel plate bonding method. In either case, if the existing concrete has deteriorated or if cracks have progressed, the integration between the reinforcement

material and the existing concrete will be insufficient, and the intended reinforcement effect cannot be achieved. Therefore, appropriate preliminary repairs must be carried out.
Additionally, since polymer materials, such as adhesives, may not perform optimally under certain environmental conditions during construction—such as temperature and humidity—strict quality control is necessary. For example, epoxy resin may fail to cure properly under low temperatures or when moisture is present. Therefore, construction is generally recommended under conditions of an ambient temperature of 5 °C or higher, humidity of 85% or lower, and a concrete surface moisture content of 10% or less.

(1) Continuous fiber (FRP) sheet bonding method

The continuous fiber sheet bonding method is a reinforcement technique in which continuous fiber sheets are laminated onto the surface of existing concrete members while impregnating and curing the adhesive, thereby integrating them with the existing members. A standard example of a construction cross-section is shown in Fig. 3.4.17.

This method has the following characteristics: since continuous fiber sheets are lightweight, they can be cut into any shape, and can be easily formed on site; work can be carried out even in spaces with severe constraints. In most cases, high-strength and high-modulus carbon fibers are used as the fiber sheets for this method.

When the deterioration of the epoxy resin used as the impregnating adhesive due to ultraviolet radiation is a concern, a highly weather-resistant coating material should be selected as the finishing layer applied on the surface.

In the case of the underside of pier superstructures, humidity is generally very high due to the influence of waves, and the concrete surface tends to be wet with a high moisture content. If bonding is performed under such conditions, peeling between the existing concrete and the sheet may occur easily due to expansion pressure from saturated vapor. Therefore, when applying the sheet bonding method to the underside of piers in such humid environments, it is necessary not only to sufficiently dry the substrate concrete beforehand, but also to prevent moisture from penetrating through cracks and other defects from the upper surface of the superstructure concrete.

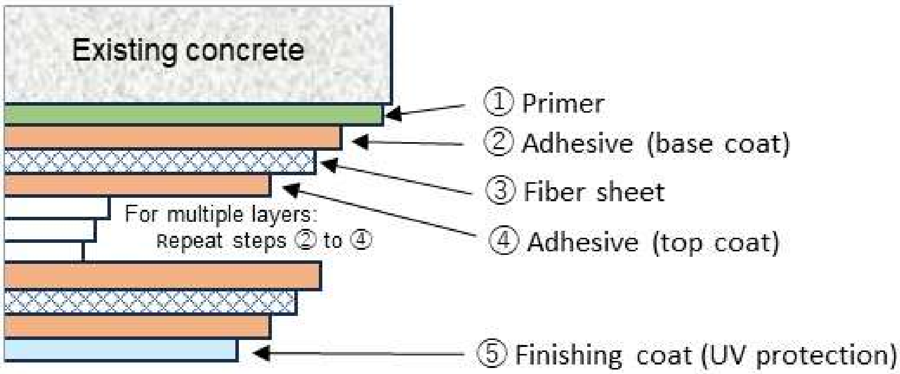


Figure 3.4.17 Example of Cross-Section of Continuous Fiber Sheet Bonding Method [2)]

(2) Steel plate bonding method

The steel plate bonding method is a reinforcement technique in which steel plates are integrated with existing concrete members by either applying adhesive to the surface of the existing concrete and bonding the steel plate or by injecting adhesive into the gap between the steel plate and the concrete.
The thickness of the steel plate is determined through design calculations; however, in practice, plates of 4.5 mm or more are generally used. This is because thinner plates are prone to uneven bonding when

pressed in place, and excessive deflection may occur under pressure when adhesive is injected. For workability reasons, the maximum plate thickness is generally about 12 mm. As for the adhesive, epoxy resin-based materials are typically used.
Steel plates are generally flat plates; however, due to their heavy weight, application on the underside of pier superstructures presents difficulties in transportation and installation, and also requires attention to safety. Furthermore, since port concrete structures are exposed to severe chloride environments, bonded steel plates and anchor bolts are prone to corrosion. Even if a protective coating is applied to the steel plates, the coating itself is susceptible to deterioration, requiring frequent maintenance. Therefore, special caution is necessary when applying this method to port structures.

3.4.5.3 External cable method

The external cable method is a reinforcement technique in which prestressing tendons are arranged outside an existing concrete member, tensioned, and anchored to introduce prestress into the member, thereby providing flexural and shear reinforcement. This method has been widely applied for strengthening against increased live loads and for the deterioration of prestressing steel due to chloride-induced corrosion.

In the external cable method, the cables must be arranged so as to resist external forces such as live loads and self-weight. The concept of this method is shown in Fig. 3.4.18, and an example of reinforcement is shown in Photo 3.4.8. The external cable method has the following characteristics:

- The reinforcement effect is mechanically clear.
- Maintenance after reinforcement is relatively easy.
- The stiffness of the member is not improved.

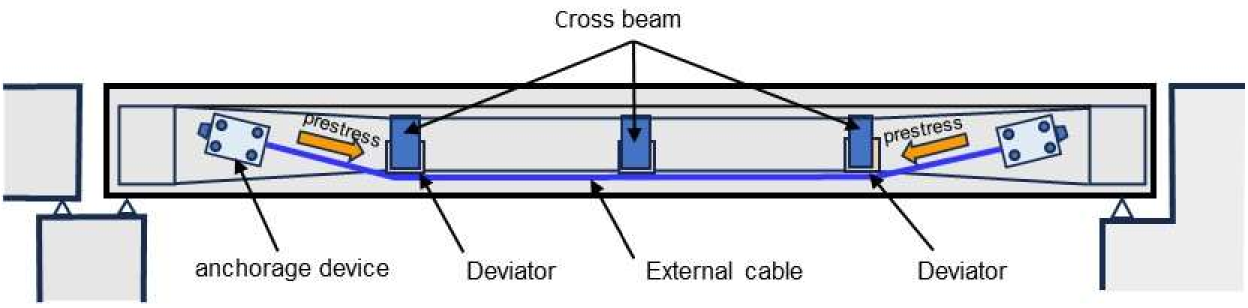


Figure 3.4.18　Conceptual Diagram of the External Cable Method

Photo 3.4.8　Example of Reinforcement by the External Cable Method

3.5 Countermeasures for steel structures

3.5.1 General

Since the port steel structures are exposed to severe marine environments, corrosion of steel caused particularly by chloride ions becomes a major problem. Chapter 2 describes in detail the items and methods of corrosion investigation, such as measurement of steel potential and measurement of remaining thickness; in this section, corrosion protection measures, repair methods, and reinforcement methods for steel materials are discussed.

It should be noted that the various countermeasures described here are based on extensive knowledge obtained in Japan. However, in Vietnam, in addition to the external forces acting on port structures, factors such as soil conditions and the properties of seawater in contact with the structures differ from those in Japan, and these may have different impacts on the structures. Therefore, when using this manual, it is essential to properly understand the various factors affecting structures in Vietnam.

In the past, when designing steel materials for use in marine environments, the thickness of steel members was intentionally increased at the new construction stage so that even if the cross-sectional area decreased due to corrosion, the load-bearing capacity would not be reduced. In Japan, steel structures designed and constructed under this concept are still in service today.

The vertical distribution of corrosion rates in steel structures located in marine environments is shown in Fig. 3.5.1. As illustrated, severe macro-cell corrosion occurs just below the mean low water level, and this phenomenon is referred to as localized corrosion. Photo 3.5.1 shows examples of perforations that developed in steel sheet piles and steel pipe piles as a result of such localized corrosion. This type of corrosion can lead to cave-ins of quay aprons and even the collapse of superstructures (Photo 3.5.2).

To prevent such localized corrosion and protect steel materials in general, cathodic protection is typically applied to underwater portions, while protective coatings are applied from the submerged zone up to the atmospheric zone. The cathodic protection method electrochemically prevents corrosion of steel, whereas the coating method prevents corrosion by applying a protective layer on the steel surface to block the ingress of corrosive agents. A combined system of cathodic protection and coating protection, as shown in Fig. 3.5.2, is often adopted; in most cases, coating protection is applied from approximately 1 m below the low tide level upward.

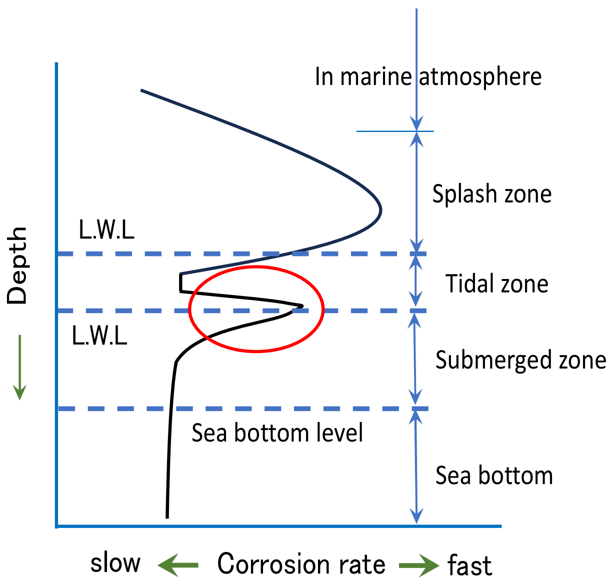
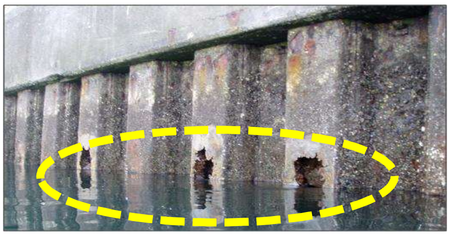


Figure 3.5.1 Depth Distribution of Corrosion Rate [5)]



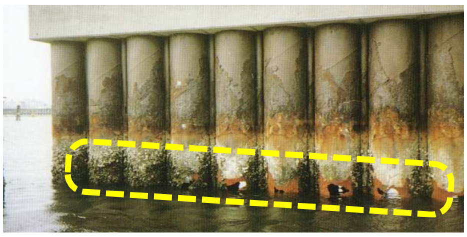


Photo 3.5.1 Example of Perforation of Steel due to Localized Corrosion [5)]

Photo 3.5.2 Collapse of superstructures

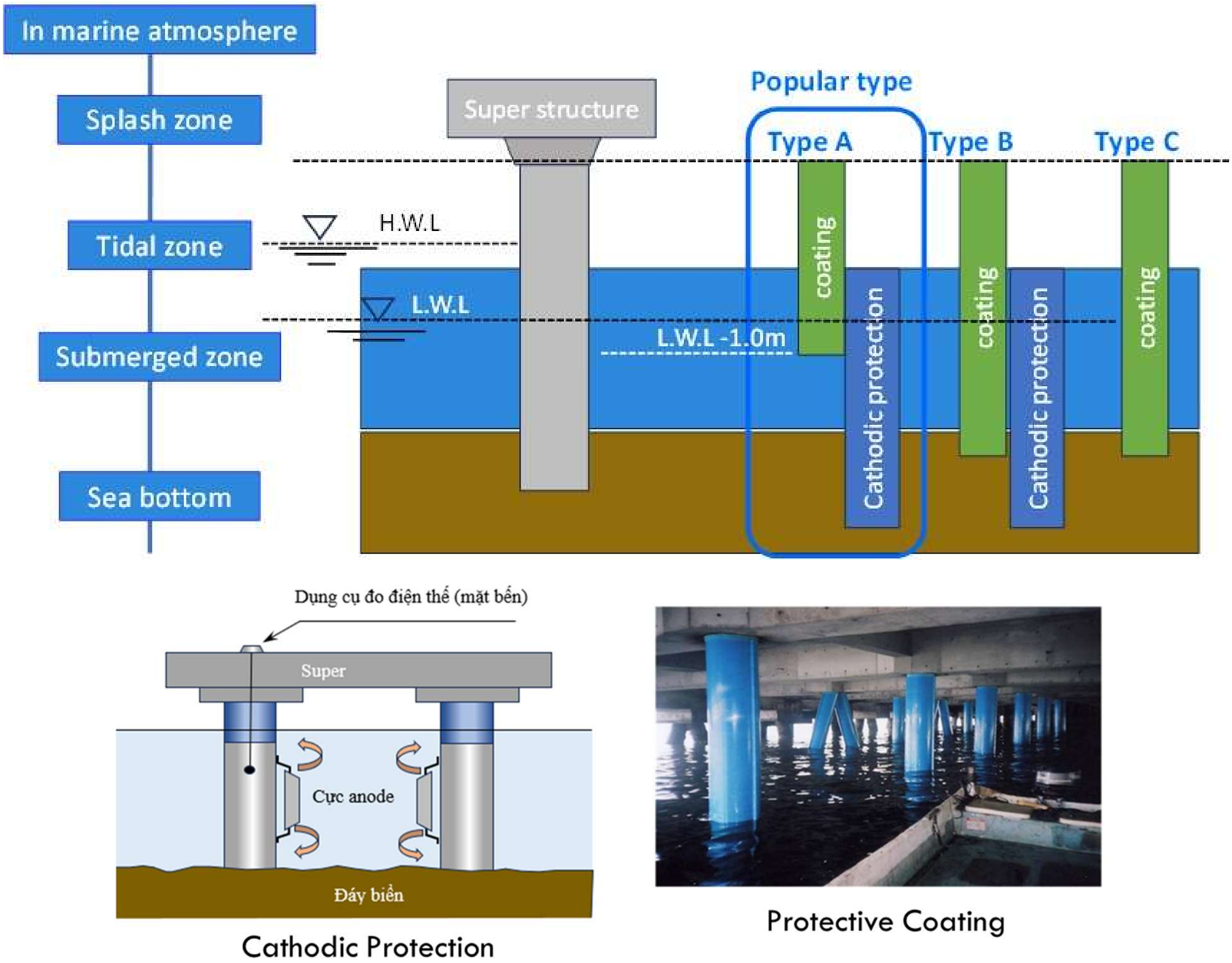


Figure 3.5.2 Combination Method of Cathodic Protection and Coating Protection

In general, for steel structures, if corrosion protection measures such as cathodic protection or coating protection are properly functioning, it is considered that the performance of the structure will not deteriorate due to corrosion. Among these measures, cathodic protection allows for relatively easy quantitative evaluation of performance, making it comparatively simple to determine whether countermeasures (such as anode replacement) are necessary and to set the timing for such measures.

On the other hand, for coating protection, it is often difficult to select countermeasures and determine their timing based on quantitative evaluation. In such cases, the selection of countermeasures and the determination of timing can be made based on the degree of deterioration of the structure.
If no corrosion protection has been implemented, it is necessary not only to select appropriate protective measures considering the corrosion environment classification and the current corrosion status, but also to examine reinforcement measures to address the insufficient thickness of the steel members.

3.5.2 Diagnosis and Repair of Cathodic Protection

There are two types of cathodic protection, the galvanic anode system and the impressed current system, as shown in Fig. 3.5.3. For details of inspection and investigation methods, refer to Chapter 2 of this manual.

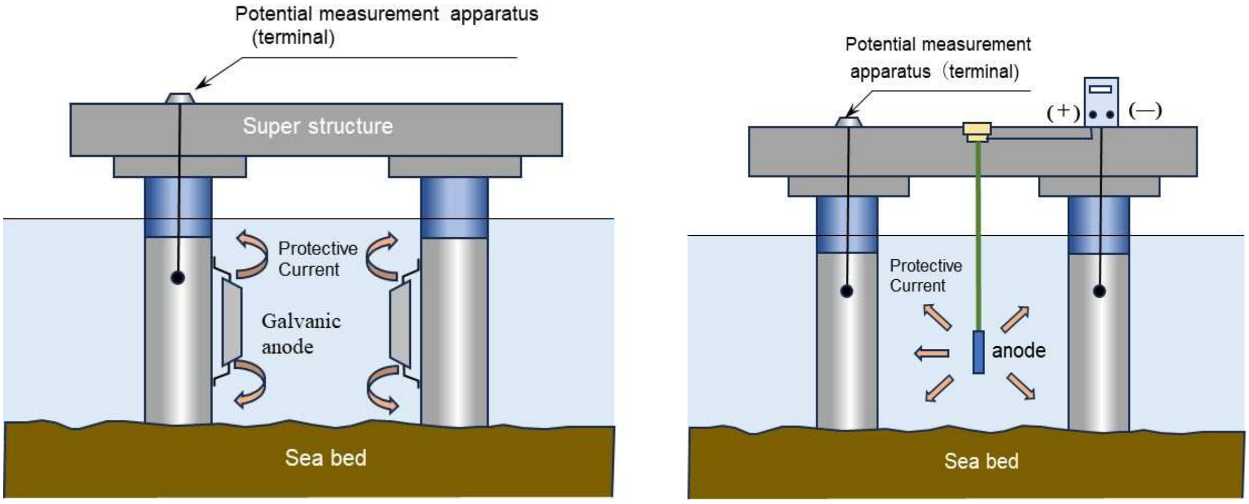


Figure 3.5.3 Galvanic Anode System and Impressed Current System

There is no direct relationship between the degree of mechanical performance degradation of steel structures and the potential of the steel material. However, if the cathodic protection applied to the steel structure is effective, corrosion of the steel will be suppressed, and thus the mechanical performance of the steel will not deteriorate. Therefore, potential monitoring serves as an indirect means of confirming that the load-bearing performance of the steel is maintained, provided that the potential of the steel under cathodic protection satisfies the specified values.

In the galvanic anode system, inspection and investigation of anodes are generally carried out by potential measurements, and Table 3.5.1 shows the criteria for evaluating the degree of deterioration based on potential measurement results. In addition, when necessary, diver inspections may be conducted as detailed investigations to confirm the installation condition of anodes after storms, to examine their consumption status, and to estimate their remaining service life (see Chapter 2).

Table 3.5.1 Criteria for Evaluating Degree of Deterioration Based on Potential Measurement Results[1)]

Inspection method	Deterioration judgment criteria	
Measurement of electrical potential	a	□The corrosion control potential (-800mV vs Ag/AgCl [sw]) is not maintained
	b	---------------------
	c	---------------------
	d	□The corrosion control potential (-800mV vs Ag/AgCl[sw]) is maintained

※ Ag/AgCl[sw] : Seawater silver chloride

If the results of anode inspection show deterioration level a, it is necessary to carry out partial or full repair to restore the performance of cathodic protection, even if the protection potential (−800 mV vs Ag/AgCl [sw]) is being maintained. If, due to anode consumption or other reasons, the protective condition has not been properly maintained for a long period of time, the remaining thickness of the steel should first be measured to confirm whether the steel still retains the required performance. Once it is confirmed that the required performance is retained, new anodes should be promptly installed. In cases where anodes are consumed earlier than their design service life, the cause should be investigated and countermeasures taken, such as adjusting the design protective current density.

If anode replacement is carried out after the anodes are completely consumed, electrocoating (electrodeposited film) will have disappeared, and thus additional protective current is required for the re-formation of electrocoating. Furthermore, if the unprotected period continues for a long time (2–3 years), part of the protective current will be consumed as a reduction current of rust formed on the steel surface. Therefore, it is necessary to assume an initial protective current density 1.1 to 1.2 times higher, taking into account the ratio of required protective current to reduction current and the service life of the anodes.

On the other hand, if anode replacement is carried out before the anodes are completely consumed, the electrocoating formed on the steel surface will remain, and the protective current consumed at the time of anode replacement can be reduced. Therefore, it is preferable to replace the anodes before they are completely consumed.

For the impressed current system as well, if any performance degradation is observed, appropriate measures must be taken. Table 3.5.2 shows typical operational failures of DC power supply equipment, possible causes, investigation methods, and guidelines for countermeasures.

Table 3.5.2 Diagnosis, Investigation, and Countermeasures for DC Power Supply Abnormalities [5)]

Abnormal Condition	Probable Cause	Investigation Method	Suggested Countermeasures
・No current is flowing to any circuit from the power supply. ・Frequent malfunctions occur	Transformer insulation failure	Damage to rectifier elements is suspected, so inspection of the transformer and rectifier elements should be carried out	In many cases, replacement of parts or partial repair is not sufficient, and full-scale repair such as replacement of the power panel is required
・The instrument readings are not displayed ・The output values and indicated readings from the electrodes fluctuate significantly	・Malfunction of measuring instruments ・Wiring defects in the output circuit	Damage to the energized electrodes is suspected, so divers should inspect the electrodes and measure the insulation resistance of the wiring	Replace parts such as instruments and electrodes
Operation lamps may burn out, and fuses may blow	・Expired lamp bulb ・Fuse blown due to overcurrent	If fuses blow repeatedly, measure the insulation resistance of the circuit	Replace parts such as lamps and fuses

3.5.3 Diagnosis and Repair of Coating Protection

As described in Chapter 2 of this manual, there are many types of coating protection methods. Among them, those considered applicable in Vietnam are shown in Table 3.5.3. Methods include applying coating to steel pipe piles and steel sheet piles immediately after they are manufactured at the factory, as well as applying coating to steel pipe piles and steel sheet piles after they are installed on site. Various materials are also used for the coating.

When repairing degraded or damaged coatings, it is necessary to carefully consider not only the coating fabrication method and the properties of the materials used, but also the construction conditions at the time of repair.

Table 3.5.3 Protective coating methods applicable in Vietnam

Type of Corrosion Protection		Method type and name		
Cathodic Protection Method		Galvanic Anode Method		
		Impressed Current Method		
Corrosion Protection Coating Method	Factory coating	Painting		Marine thick epoxy resin film
		Organic coating	Heavy-duty anticorrosion coating	Polyethylene coating
				Urethane elastomer coating
	On-site coating	Organic coating	Underwater coating	Painting
				Putty-type coating
				Wetting area-type coating
		Petrolatum coating		Resin protective cover
				Corrosion-resistant metal protective coating
		Inorganic coating	Mortar coating	Resin protective cover
				Corrosion-resistant metal protective coating
			Reinforced concrete coating	Removing form type
				Stay-in-place form type

In repairs of coating protection, the repair method should be determined by considering conditions such as the deterioration status of the area to be repaired and the compatibility of overcoating with the existing coating material. Table 3.5.4 shows basic examples of countermeasures for each level of deterioration in coating protection.

For partial repairs, it is generally common to use the same type of method as the existing coating protection. However, depending on the type of coating protection, the deterioration condition, the degree of surface preparation, and the environmental conditions, it may be difficult or inappropriate to perform repairs with the same materials or methods. In particular, in the case of painting or organic coatings, it is necessary to determine the repair method with due consideration of factors such as the repair area, deterioration condition, degree of surface preparation, and overcoating compatibility.

For full-scale repairs (re-application of coating protection), it is necessary to determine the repair method by examining factors such as the service history, site conditions, durability of the coating material (expected service life), and the anticipated remaining service life of the structure.

Table 3.5.4 Examples of Basic Countermeasures for Each Level of Deterioration in Coating Protection [5)]

Degree of Deterioration	Examples of Countermeasures
a	Full-scale repair of the coating protection work is required.
b	Repair the deteriorated areas, and consider measures such as advancing the timing of subsequent periodic inspections and diagnoses.

c	No special repair is necessary, but since some deterioration has begun, it is desirable, depending on the type of coating protection, to consider advancing the timing of subsequent periodic inspections and diagnoses.
d	Continue periodic inspections and diagnoses as usual.

3.5.3.1 Painting method

An example of deterioration assessment of painting work based on inspection is shown in Table 3.5.5. Countermeasures such as repair must be implemented according to the degree of deterioration.

Table 3.5.5 Example of deterioration assessment of painting method [5)]

Judgment on the degree of deterioration	Inspection Results
a	・Extensive rusting and blistering are observed. ・Peeling and cracking accompanied by rust are occurring over a wide area. ・The rust area ratio is 10% or more.
b	・Significant rusting and blistering are present. ・Peeling accompanied by rust is occurring over a large area. ・The rust area ratio is between 0.3% and less than 10%.
c	・Rust and blistering are scattered. ・Peeling and cracking of the coating film are scattered. ・The rust area ratio is between 0.03% and less than 0.3%.
d	・There is little to no change from the initial state, and the condition is sound. ・The rust area ratio is less than 0.03%.

As indicators of the degree of rusting, blistering, cracking, and peeling, there are methods such as assigning ratings using standard photographs that classify the size and occurrence density into several levels, or quantifying them by the percentage of affected area. Fig. 3.5.4 shows the reference values of defect area percentage in ASTM D 610.

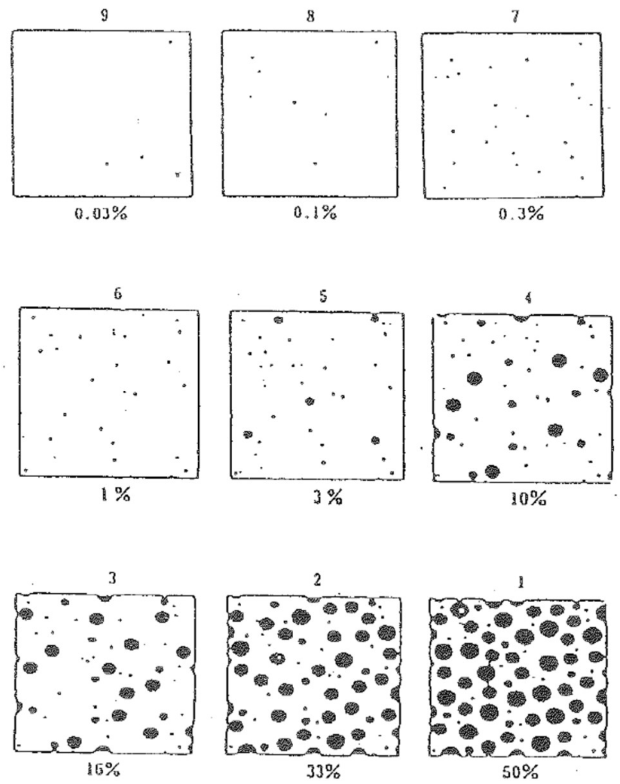


Figure 3.5.4 Rust Area Ratio according to ASTM D 610

For partial repair of coatings in the atmospheric zone above the sea, it is common to apply painting methods. In such cases, if there are no problems with overcoating compatibility, the repair can be limited to removing the deteriorated or damaged paint, performing appropriate surface preparation, and applying the same paint as that already used in the existing coating.
For partial repair of coatings in the splash zone, tidal zone, and underwater areas, the application of painting methods is generally difficult; therefore, underwater-curing coating methods are usually applied.
In the case of full-scale repair (re-application of coating protection), it is necessary to determine the repair method by considering the service history, site conditions, durability of the coating material, service life of the structure, and repair costs. For full repair of coatings, painting methods are applied in the atmospheric zone above the sea, while underwater-curing coating methods, petrolatum coating methods, or mortar coating methods are applied in the splash zone, tidal zone, and underwater areas. Examples of repair classifications and methods for coatings are shown in Table 3.5.6.

Table 3.5.6 Examples of Repair Classifications and Methods for Coatings [5)]

Repair type / position	Partial Repair	Full-scale Repair
marine atmosphere zone	・Painting method ・Underwater Curing Coating Method	・Painting method ・Underwater Curing Coating Method
splash zone tidal zone submerged zone	・Underwater Curing Coating Method	・Underwater Curing Coating Method ・Petrolatum Coating Method ・Mortar Coating Method

3.5.3.2 Organic coating

An example of deterioration assessment of organic coating (heavy-duty protective coating) based on inspection is shown in Table 3.5.7. Repairs or other countermeasures must be carried out according to the degree of deterioration.

Table 3.5.7 Example of deterioration assessment of organic coating (heavy-duty protective coating) [5)]

Judgment on the degree of deterioration	Results of inspection
a	The coating is severely damaged, and the steel is corroded
b	Damage to the coating extends to the steel in some areas, and corrosion of the steel is observed
c	Many instances of damage to the coating are present, but they do not reach the steel
d	The condition remains almost unchanged from the initial state and is considered sound

Examples of repair classifications and methods for polyethylene coatings and urethane elastomer coatings are shown in Table 3.5.8 and Table 3.5.9, respectively.
For partial repairs in the atmospheric zone above the sea, the stick method and patch method are commonly used for polyethylene coatings, while repairs using polyurethane repair materials are generally applied for urethane elastomer coatings.
It should be noted that when using underwater-curing coating methods to repair polyethylene coatings, the adhesion between the two is not very strong; therefore, measures such as increasing the frequency of post-repair inspections are necessary.

Table 3.5.8 Examples of repair classifications and methods for heavy-duty protective coatings [5)] (polyethylene coating)

Position \ Type	Partial Repair	Full-scale Repair
marine atmosphere zone	・Stick Method ・Patch Method ・Petrolatum Coating Method ・Underwater Curing Coating Method	・Petrolatum Coating Method ・Underwater Curing Coating Method
splash zone tidal zone submerged zone	・Petrolatum Coating Method ・Underwater Curing Coating Method	

Table 3.5.9 Examples of repair classifications and methods for heavy-duty protective coatings [5)] (Urethane elastomer coating)

Position \ Type	Partial Repair	Full-scale Repair
marine atmosphere zone	・Method Using Repair Polyurethane ・Petrolatum Coating Method ・Underwater Curing Coating Method	・Method Using Repair Polyurethane ・Petrolatum Coating Method ・Underwater Curing Coating Method
splash zone tidal zone submerged zone	・Petrolatum Coating Method ・Underwater Curing Coating Method	・Petrolatum Coating Method ・Underwater Curing Coating Method

An example of deterioration assessment of underwater-curing coating methods is shown in Table 3.5.10. Repairs or other countermeasures must be carried out according to the degree of deterioration.

Table 3.5.10 Example of Deterioration Assessment of Underwater-Curing Coating Method [5)]

Judgment on the degree of deterioration	Results of Inspection
a	The coating is severely damaged, and the steel is corroded
b	Damage to the coating extends to the steel in some areas, and corrosion of the steel is observed
c	Many instances of damage to the coating are present, but they do not reach the steel
d	The condition remains almost unchanged from the initial state and is considered sound

Examples of repair classifications and methods for underwater-curing coatings are shown in Table 3.5.11. Partial repairs of underwater-curing coatings in the atmospheric zone above the sea, splash zone, tidal zone, and underwater areas are carried out using underwater-curing coatings.

Table 3.5.11 Examples of Repair Methods for Underwater-Curing Coatings [5)]

Position \ Type	Partial Repair	Full-scale Repair
marine atmosphere zone splash zone tidal zone submerged zone	Underwater-curing coating method	・Underwater-curing coating method ・Petrolatum coating method ・Mortar coating method

3.5.3.3 Petrolatum coating

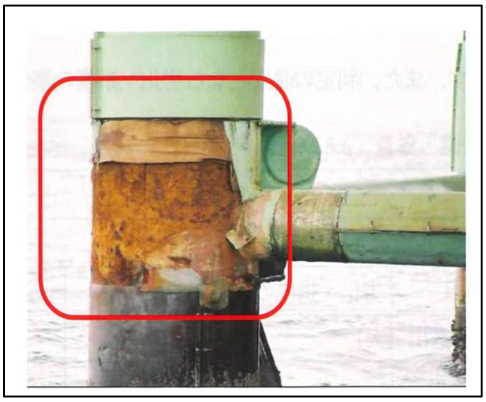
An example of deterioration assessment of the petrolatum coating method based on inspection is shown in Table 3.5.12. Repairs or other countermeasures must be carried out according to the degree of deterioration.

Table 3.5.12 Example of Deterioration Assessment for the Petrolatum Coating Method [5)]

Judgment on the degree of deterioration	Countermeasures
a	・Due to the detachment of the protective cover, the petrolatum-based anticorrosive material is exposed or has fallen off, and rust is observed on the steel surface
b	・Cracks or damage are observed on the protective cover or backing plate. ・Displacement of the protective cover is observed. ・Severe corrosion or damage is observed on bolts, nuts, and similar components. ・Cracks or partial detachment of the end seal are present, and rust stains are observed
c	・The protective cover is discolored or shows signs of chalking. ・Fine cracks or peeling are observed on the surface of the protective cover. ・Loosening is observed in bolts, nuts, band materials, etc. ・Minor corrosion is observed on bolts, nuts, and similar components. ・Partial peeling of the end seal is observed.
d	・The condition remains almost unchanged from the initial state and is considered sound

In the case of the petrolatum coating method, repairs should, in principle, be carried out using the same petrolatum coating method. This is because petrolatum-based corrosion protection materials adhere firmly to the steel surface, making surface preparation cumbersome if other methods are applied.

In the petrolatum coating method, inorganic coating method, and similar methods, protective covers are generally installed to protect the coating material. These protective covers are prone to deterioration and damage. An example of the deterioration of a protective cover is shown in Photo 3.5.1.



・Detachment of protective cover due to collision with drifting objects
(degree of deterioration: a)

・Damage to protective cover due to collision with drifting objects
(degree of deterioration: a)

・Displacement of protective cover
(degree of deterioration: b)

・Loss of protective cover
(degree of deterioration: b)

Photo 3.5.1 Example of Deterioration and Damage of Protective Covers in the Petrolatum Coating Method

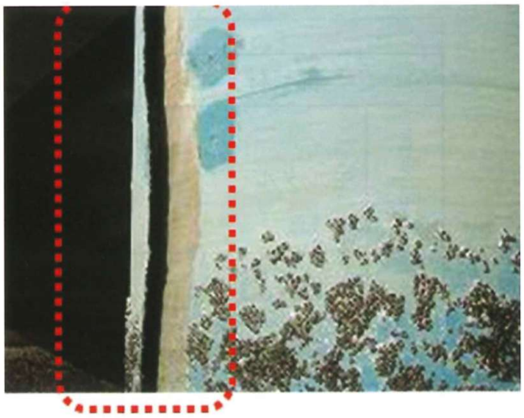
3.5.3.4 Inorganic coating (Mortar coating)

The example of deterioration degree assessment for mortar coating is shown in Table 3.5.13. The degree of deterioration is determined based on the inspection and investigation results of the mortar coating, and repairs are carried out accordingly.

Table 3.5.13 Example of deterioration assessment for mortar coating [5)]

Judgment on the degree of deterioration	Countermeasures
a	・The protective cover has detached over a wide area ・Rust stains are visible on the surface of the mortar ・The mortar has peeled off, and rust has formed on the surface of the steel ・(After removing the cover material and mortar layer,) a reduction in the steel thickness is observed
b	・Cracks are observed in the protective cover and mounting materials, and partial detachment of the protective cover is evident ・Minor rust staining is visible, but no significant rust runoff is present ・(After removing the cover material,) numerous cracks are observed in the mortar, along with rust staining
c	・Discoloration and chalking are observed on the protective cover ・Cracks are visible on the surface, but they cover less than 1% of the area ・Loosening is observed in the protective cover fasteners, such as bolts, nuts, and bands
d	・It remains unchanged from its initial state and is in good condition

・Damage to protective cover
(degree of deterioration: a)



・Cracks and peeling of protective cover
(degree of deterioration: a)

・Damage to protective cover and spalling of mortar
(degree of deterioration: a)

・Damage to protective cover and spalling of mortar
(degree of deterioration: a)

Photo 3.5.2　Examples of deterioration and damage of protective covers in the mortar coating method

Examples of deterioration and damage of protective covers in the mortar coating method are shown in Photo 3.5.2.
The deterioration of mortar coating generally progresses in several stages: cases where only the cover material has deteriorated; cases where not only the cover material but also the mortar layer has deteriorated; and cases where the corrosion of steel members has advanced due to the loss of corrosion protection performance of the mortar layer. In mortar coatings of many structures built in the past, it is considered that deterioration of the mortar layer has sometimes led to corrosion of steel materials.
In deterioration level c, where only the cover material is deteriorated and the deterioration is assumed not to extend to the mortar layer, no repair is particularly necessary. However, if the timing of deterioration is earlier than expected, it may be necessary to advance the timing of subsequent periodic inspections and diagnoses. Nevertheless, in cases where Hume pipes (reinforced concrete pipes) are used as cover material, or where precautionary reinforcement bars are placed inside the mortar coating, it is desirable to consider repair from the perspective of preventive maintenance.
In deterioration levels a and b, the repair method differs greatly depending on the results of a detailed investigation. If a detailed investigation determines that there is little deterioration of the mortar layer,

repairing only the cover material is sufficient. However, if deterioration of the mortar layer is confirmed, the countermeasure varies depending on the remaining service life and the extent of deterioration.

[Partial repair: when the remaining service life is short, or the deterioration range is limited]
In the atmospheric zone, the deteriorated part of the mortar layer is removed, the steel surface is cleaned, then section restoration is carried out with non-shrink mortar or similar materials, and the surface protective cover material is reinstated. If the protective cover material is a precast concrete product such as a hume pipe, section restoration is carried out, including the cover material.

[Full repair: when the remaining service life is long, or the deterioration range is wide]
If long-term corrosion protection performance cannot be expected even with the above partial repair of the deteriorated mortar layer, the entire mortar coating layer is removed, and a new coating protection is applied. In this case, although it is possible to remove the existing mortar coating and renew it with mortar coating, it is also advisable to consider the application of different coating protection methods, such as underwater hardening coating methods or petrolatum coating methods, taking into account workability and other factors.

For mortar coatings below M.S.L., if the mortar adheres closely to the steel surface, steel corrosion can be considered to have hardly progressed. This is because the mortar layer prevents seawater on the surface from moving, thereby suppressing the supply of oxygen necessary for corrosion, which in turn drastically reduces the corrosion rate of steel. Therefore, when slight deterioration is confirmed in mortar coatings below M.S.L., repair to ensure durability—such as attaching cover materials to stop seawater movement in that area—can also be considered.

Examples of repair classifications and methods for partial and full repair of mortar coating are shown in Table 3.5.14.

Table 3.5.14 Examples of Repair Methods for Mortar Coatings [5)]

Position \ Type	Partial Repair	Full-scale Repair
marine atmosphere zone	・Mortar Coating Method （Remove the protective cover, repair the deteriorated mortar, and then restore the removed protective cover.） ・Underwater-curing coating method （Repair of deteriorated sections of the cover）	・Mortar Coating Method （Including the cover） ・Underwater-curing coating method ・Petrolatum coating method （After removal of the deteriorated mortar coating）
splash zone		
tidal zone		
submerged zone		

3.5.4 Repair of Corroded Steel Members

In the case where no protective coating or corrosion protection is applied to the steel (unprotected condition), localized corrosion (pitting) tends to occur in the tidal zone, as shown in Photo 3.5.6. When such pitting causes sectional loss or reduction of plate thickness in the steel, the initial load-carrying capacity cannot be maintained. Therefore, depending on the importance of the facility, the remaining service life, and the utilization status of the facility, reinforcement is generally implemented to improve the load-carrying capacity.

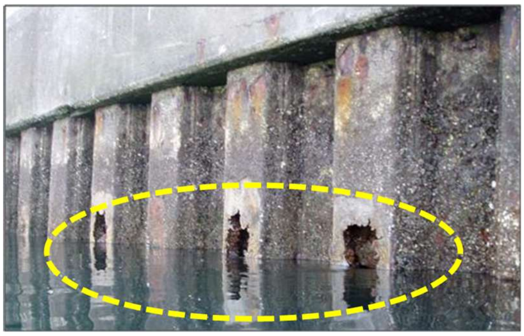


Photo 3.5.6 Pitting due to localized corrosion in unprotected steel structures [5)]

To determine the extent of strength recovery (degree of repair/reinforcement), it is necessary to conduct a corrosion survey (such as plate thickness measurement by ultrasonic testing) to assess the amount of thickness reduction, and then decide on repair/reinforcement measures based on structural calculations. The flow of repair and reinforcement measures for unprotected steel structures is shown in Fig. 3.5.5.

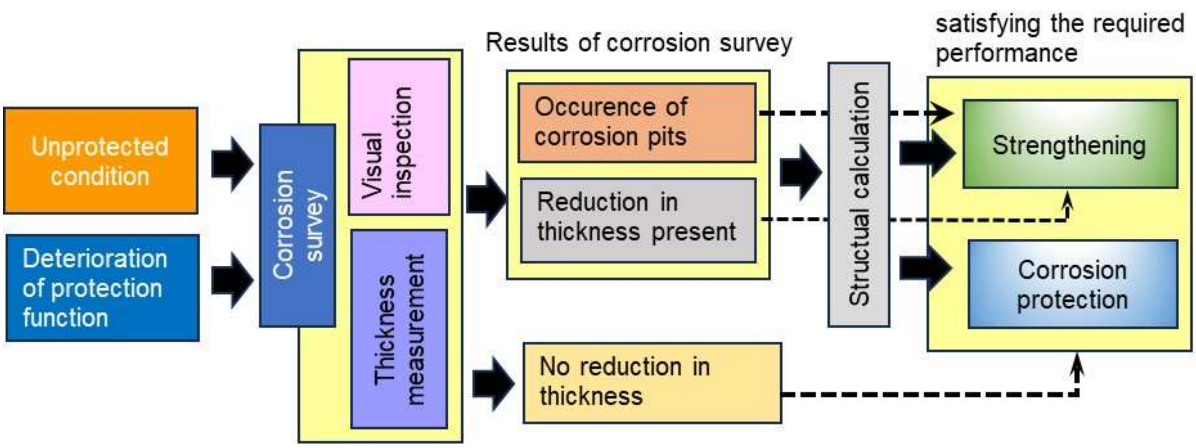
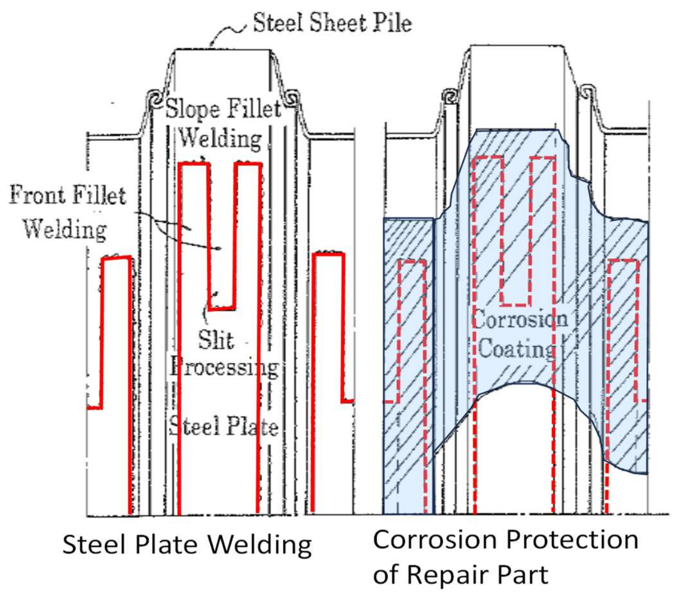


Figure 3.5.5 Flow of repair and reinforcement measures for unprotected steel structures

When holes occur in steel sheet piles or steel pipe piles, the load-bearing capacity decreases, resulting in reduced safety. As an example of repair/reinforcement in this case, a method is to seal the perforated section and attach a steel plate to the section-loss area to restore the load-carrying capacity. Examples of repair and reinforcement for steel sheet piles and steel pipe piles are shown in Fig. 3.5.6.

【Steel sheet pile】



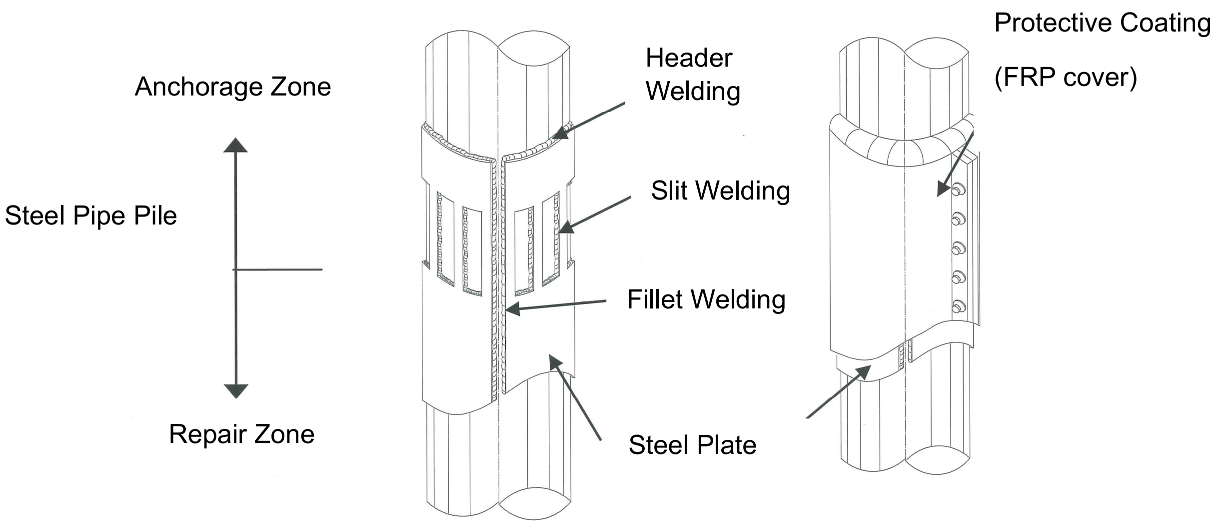


Figure 3.5.6 Example of repair and strengthening methods for steel sheet piles and steel pipe piles using steel plates

For steel sheet pile structures that have suffered insufficient load-bearing capacity due to localized corrosion and other damage under unprotected conditions, countermeasures are sometimes implemented not only to restore load-carrying capacity but also to ensure durability. For this purpose, Fig. 3.5.7 shows a case where repair and reinforcement were carried out by thickening with reinforced concrete, serving also as corrosion protection. In this case, reinforcing bars and formwork were installed in front of the steel sheet piles, and underwater (anti-washout) concrete was cast in place within the formwork. After the concrete hardened, the formwork was dismantled.

In contrast, in the example shown in Fig. 3.5.8, durable pre-cast concrete (PCa) panels were used as permanent formwork, which also simplified the conventional process of installing and dismantling formwork.

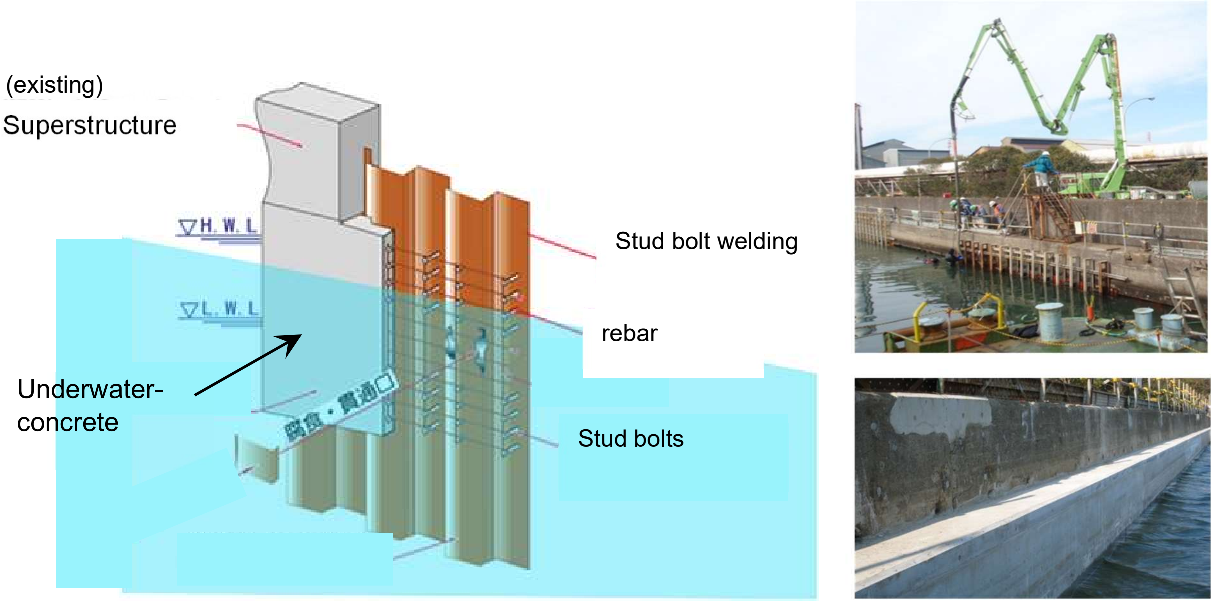


Figure 3.5.7　Example of repair and reinforcement of steel sheet piles by thickening with reinforced concrete

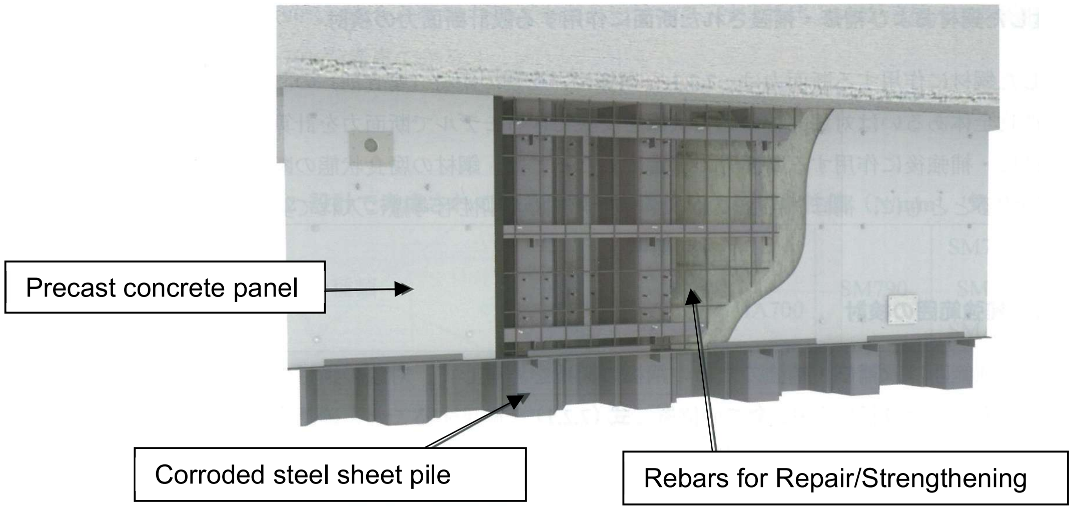


Figure 3.5.8　Example of repair and reinforcement of steel sheet piles using PCa panels as permanent formwork

An example of reinforcing corroded steel pipe piles by jacketing with reinforced concrete is shown in Fig. 3.4.10. In this case, stud dowels were installed on the existing steel pipe piles to ensure the integrity between the jacketed concrete and the existing steel pipe piles, using a method that allows the installation of stud dowels underwater.

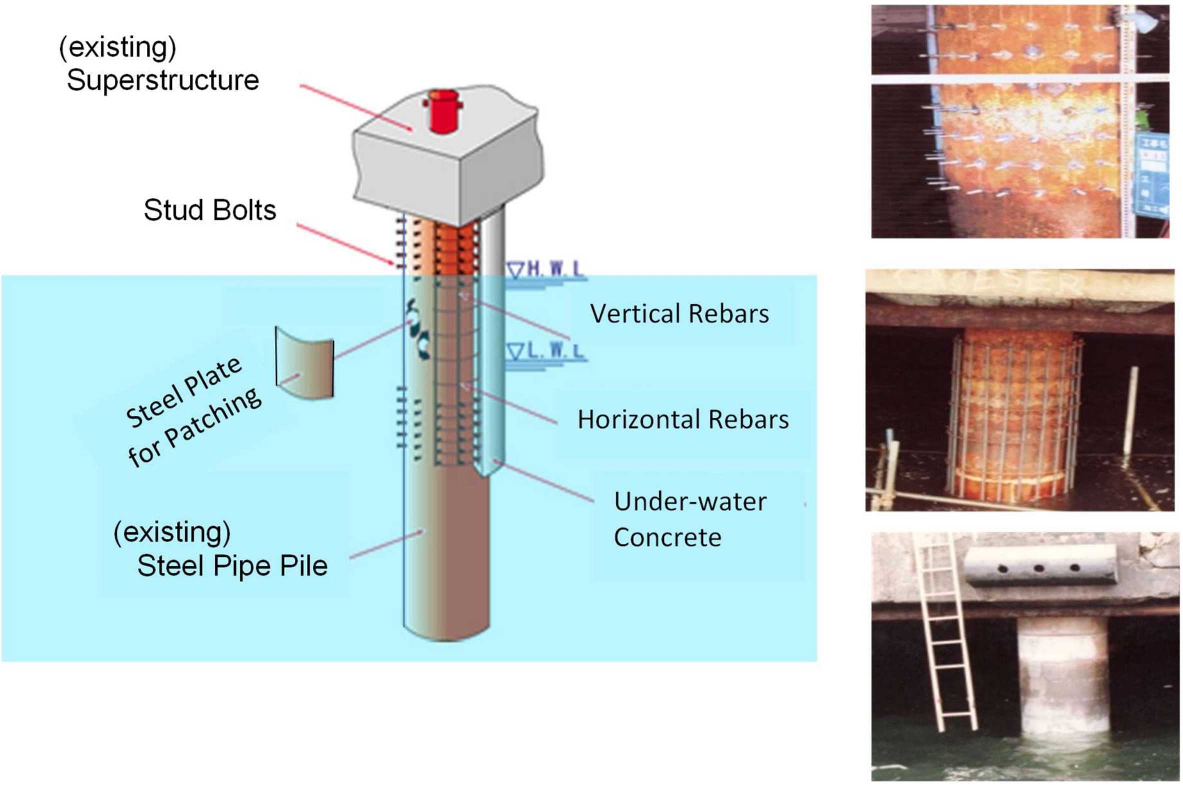


Figure 3.5.9 Example of repair and strengthening of steel pipe piles by jacketing with reinforced concrete

3.6 Repair of voids beneath the apron caused by corrosion of steel sheet piles

3.6.1 General

In steel sheet pile quay walls, when openings occur in the sheet piles due to corrosion, the backfill soil behind the wall flows out into the seawater in front through the openings. As a result, voids are formed beneath the apron, which can easily lead to accidents such as apron collapse, as shown in Photo 3.6.1. The mechanism of apron collapse is illustrated in Fig. 3.6.1. Its cause lies in the occurrence of holes in the steel sheet piles due to corrosion, through which the backfill soil flows out. To prevent this, it is necessary to protect the steel sheet piles from corrosion and thereby prevent the formation of holes.

Photo 3.6.1 Example of apron collapse

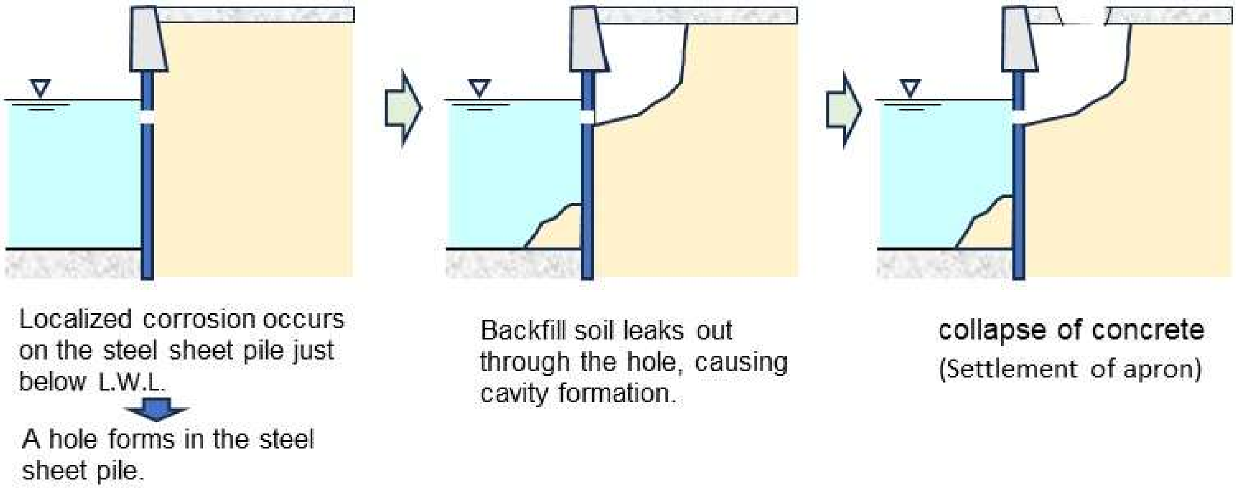


Figure 3.6.1 Mechanism of apron collapse caused by corrosion of steel sheet piles

3.6.2 Repair of Voids

The investigation methods for voids formed beneath the apron are described in Chapter 2. When voids are discovered beneath the apron during inspection, it is necessary to implement safe countermeasures, such as imposing partial or extensive usage restrictions or promptly conducting repairs (filling the voids). Several methods have been proposed for filling voids with filling materials. As filling materials, concrete, mortar, or fluidized soil can be used. Photo 3.6.2 shows the situation of filling voids.

(a) Filling using a concrete pump truck (b) Direct filling from an agitator truck

Photo 3.6.2 Void filling condition using fluidized soil（https://www.tokura.co.jp/）