Chapter 2 Surveys and Tests after a Large Earthquake and Tsunami

1 General

1.1 Purpose of this Chapter

This chapter summarizes the surveys and tests that must be implemented after multiple ports are damaged by a large-scale earthquake and resulting tsunami (hereinafter referred to as a "large earthquake and tsunami"), for facilitating the understanding of the overall damage; determining the usability of port facilities, such as mooring facilities; executing emergency measures, such as the elimination of port obstacles; and implementing disaster relief projects based on the measures taken following the 2011 Great East Japan Earthquake.[1)] The contents of this chapter can also be referred to when responding to disasters due to earthquakes without tsunamis, as well as storm surges and high waves.

1.2 Structure of this Chapter

Fig. 1.2.1 shows the structure of this chapter. The contents and purposes of each section are as follows.

①**Section 1:** The purpose and structure of this chapter.

②**Section 2:** The overall procedure for surveys, outlines of the surveys to be implemented at each stage (initial, emergency and full-scale restoration stages), and surveys to determine the usability of ports.

③**Section 3:** The method for resetting Chart Datum Level (C.D.L.) after a large earthquake and tsunami.

④**Section 4:** The viewpoints of the surveys and outlines of the survey methods at each stage, obtainable information, and points to consider with respect to seven major items expected to be surveyed after a large earthquake and tsunami.

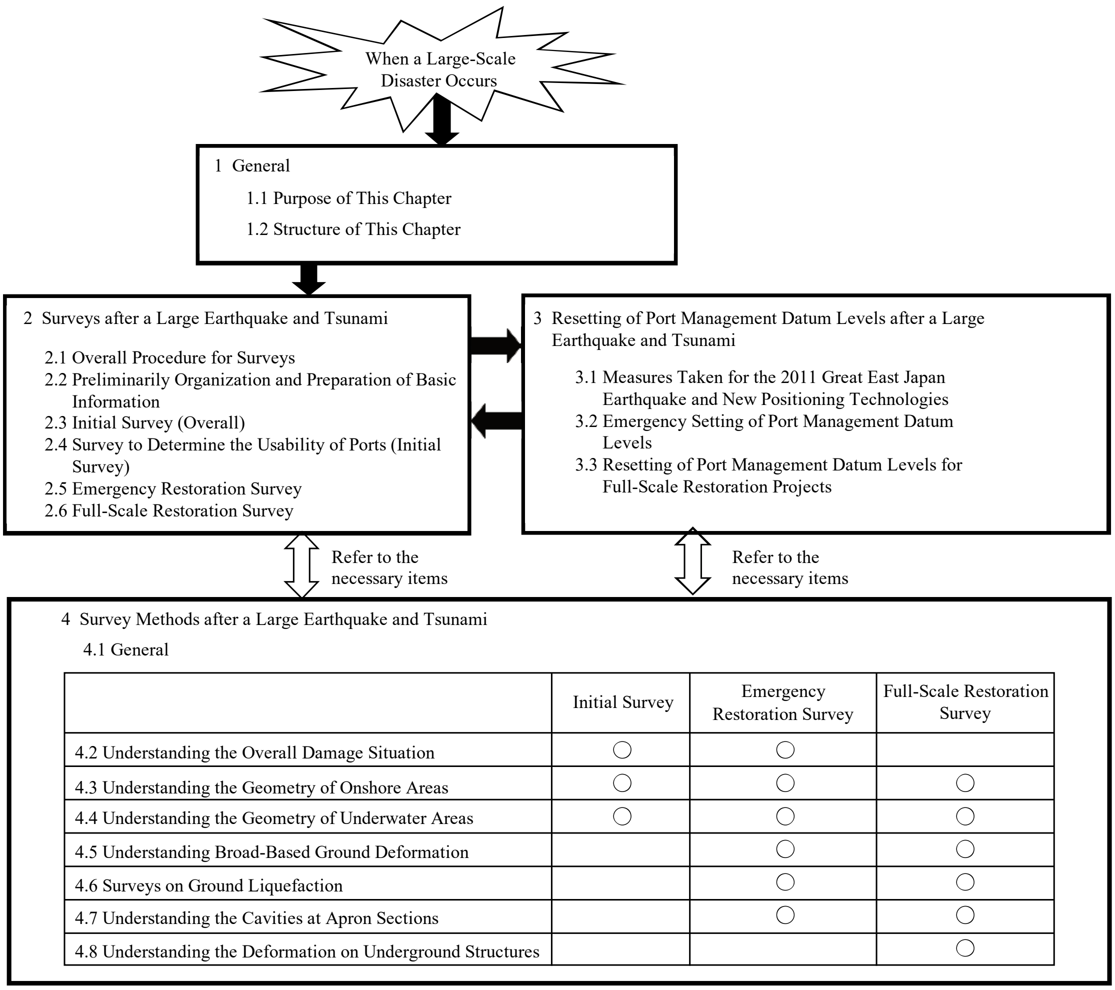


Fig. 1.2.1 Overall Structure of "Surveys and Tests after a Large Earthquake and Tsunami"

[Reference]

1) Sendai Research and Engineering Office for Port and Airport, Tohoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport (Mar.2014): Implementation Guidelines for Investigation after Earthquake and Tsunami Dizaster. (in Japanese)

2 Surveys after a Large Earthquake and Tsunami

2.1 Overall Procedure for Surveys

In order to utilize ports as disaster relief bases after a large earthquake and tsunami, it is necessary to promptly implement several surveys on the damage. **Fig. 2.1.1** shows the overall procedure for surveys after a large earthquake and tsunami based on the measures taken for the 2011 Great East Japan Earthquake.[1)] The outlines of the surveys and points to consider at each stage are described below.

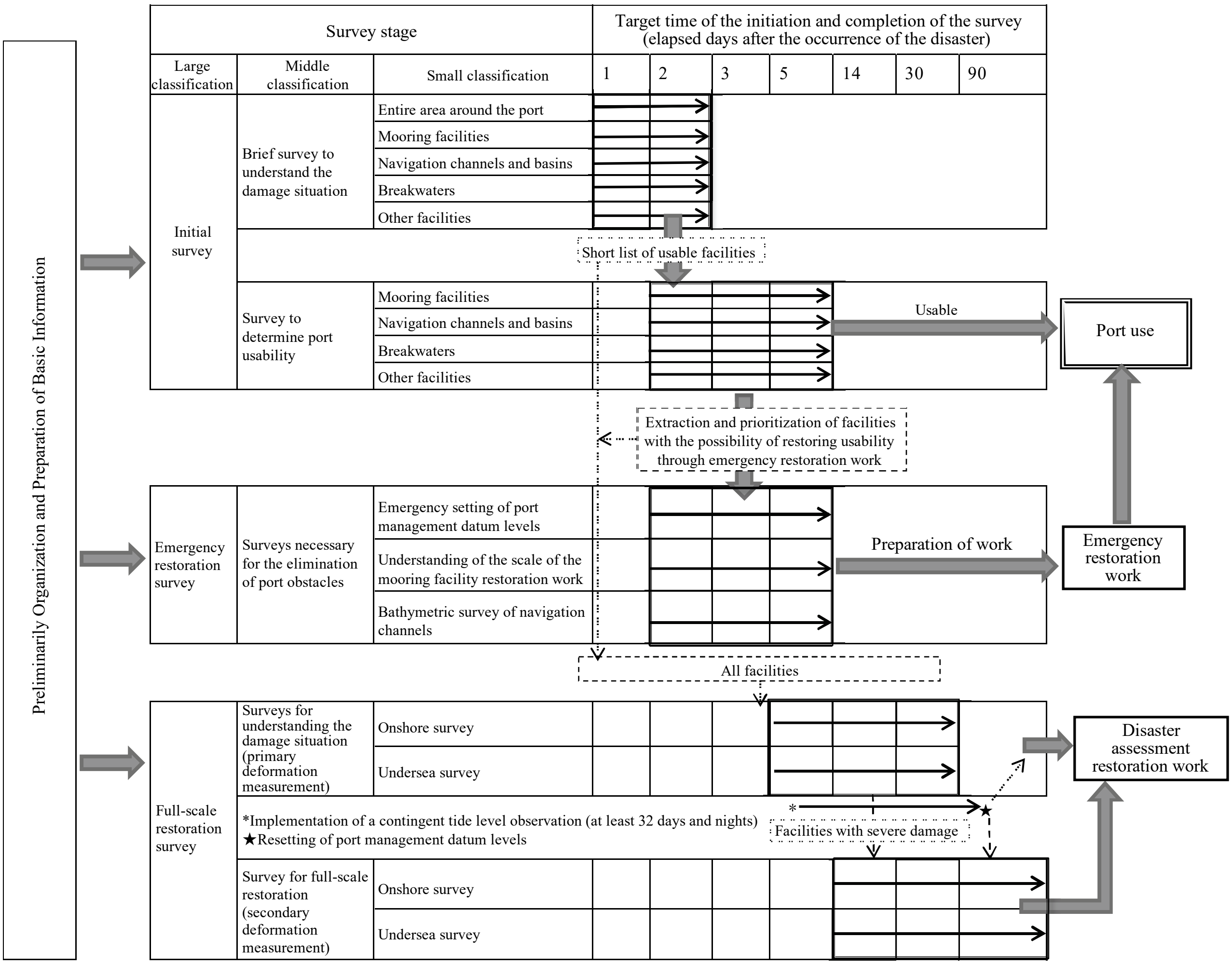


Fig. 2.1.1 Overall Procedure for Surveys on the Damage after a Large-Scale Earthquake and Tsunami

2.2 Preliminarily Organization and Preparation of Basic Information

In preparation for prompt and efficient implementation of post disaster surveys, it is necessary to appropriately organize and manage several pieces of basic information on the facilities that are to be the survey objects and control points so that the information can be readily available. It is also necessary to make the information on the business continuity plans after the occurrence of a disaster readily available for the smooth implementation of surveys in collaboration and coordination with many related organizations. However, there may be cases where the damage to office buildings, including inundation, due to a large earthquake and tsunami causes the information to become inaccessible. Thus, the information necessary for surveys at the initial stage is preferably stored at multiple locations or on several media. The basic information to be organized and prepared in advance is listed below.

- Information on the structural profiles of the object facilities (design conditions, typical cross-sectional drawings, coordinate values, maintenance plans, etc.)
- Information on the control points and chart datum level (refer to **Reference (Part II), Chapter 2, 3 Resetting of Chart Datum Level after a Large Earthquake and Tsunami**)

- Information on port business continuity plans, Technical Emergency Control Forces and disaster-relief cooperation agreements

2.3 Initial Survey (Overall)

(1) General

The initial survey is a type of survey which must be initiated on the day of the occurrence of a disaster, and completed within a few days for the purpose of identifying port facilities (including those which can be reinstated through simple restoration work) that are usable for allowing ships carrying emergency disaster relief supplies to enter and leave the ports, and that allow berthing for loading and unloading the supplies. The initial survey is classified into a "brief survey to understand the damage situation" and a "survey to determine the usability of the facilities." For the details of the initial survey, refer to the **Reference 1)**.

(2) Brief Survey to Understand the Damage Situation

The brief survey to understand the damage situation shall be implemented immediately after the tsunami has struck in a manner that determines the damage situation of the breakwaters, mooring facilities, navigation channels, basins and seawalls through visual confirmation (including observations with binoculars, cameras and video cameras) from safe locations. In this survey, swift information collection is given priority over accurate information, and information collection shall include overall pictures of the disaster situation in the areas surrounding the ports which cover access roads at the back of the port districts by utilizing satellite and aerial photographs and videos (refer to **Reference [Part II], Chapter 2, 4.2 Understanding the Overall Damage Situation**).

Table 2.3.1 shows the methods and standpoints of a brief survey to understand the damage situation. Although the object facilities listed in the table below are limited to mooring facilities, navigation channels, basins, breakwaters and seawalls, other facilities shall also be surveyed as needed.

Table 2.3.1 Methods and Standpoints of a Brief Survey to Understand the Damage Situation

Object	Method	Standpoint
Areas around the port	Satellite imaging (**4.2.2**) Aerial photography using aircraft (**4.2.3**) Aerial photography using UAVs (**4.2.4**) Aerial laser surveys (**4.2.5**) Other (**4.2**)	• Damage situation of several port facilities • Inundation situations of the areas around the port • Situations of wreckage blocking roads • Floating debris blocking navigation channels • Other
Mooring facilities	Visual confirmation, photographs and video recordings	• Abnormalities in the structural bodies (swelling, inclination and settlement) • Caving and level differences on the aprons • Obstacles blocking access roads to the aprons
Navigation channels and basins		• Amounts and types of floating debris in waterways and basins as well as the extent of the impact
Breakwaters		• Abnormalities in the structural bodies (overturning, sliding, inclination and settlement)
Seawalls (revetments, dikes, water gates and land locks)		• Prevention of storm surges from leading to secondary disasters (Current situation of protection line against a high tide)

The results of the brief survey to understand the damage situation are used for identifying those facilities which have a high possibility of being continuously used as is and reinstated through simple restoration work (hereinafter referred to as "emergency restoration work"). When identifying usable mooring facilities and breakwaters, priority shall be given to those that have received only minor damage (e.g., 0 or I) in the classification of physical damage (0 to IV) shown in **Tables 2.3.2** and **2.3.3**. When identifying usable seawalls, priority shall be given to those which shall be reinstated through emergency restoration work from the viewpoint of preventing storm surges from leading to secondary disasters.

Table 2.3.2 Classification of the Levels of Damage to Mooring Facilities[2)]

Damage level	Damage situation
0	No damage
I	No abnormalities in the structural body, except for destruction or deformation of accessories
II	Substantial deformation of the structural body
III	Externally sound but evident internal destruction of the structural body
IV	Total destruction and loss of the original shape

Table 2.3.3 Classification of the Levels of Damage to Breakwaters (Caisson Type)[1)]

Damage level	Damage situation
0	No damage
I	No abnormalities in the caisson body, except for minor deformation, such as the settlement of the levee crown, or deformation or destruction of wave-dissipating work and mounds
II	No abnormalities in the caisson body, except for deformation such as settlement, sliding or inclination, which can be restored without reinstalling the caisson
III	Remarkable settlement, sliding or inclination of the caisson, which can be reinstated through reinstallation of the caisson (including partial repair or reinforcement of the caisson members)
IV	The caisson body has slid out of the mound and has no possibility of being reinstated (including structural destruction and damage preventing the caisson from being refloated)

In addition, a system has been developed that enables damage situations to be understood through strong motion observation records.[3)] This system instantaneously acquires the information on earthquake ground motions observed through strong motion seismometers on the occurrence of an earthquake, and estimates the damage situation of the facilities based on the acquired information. The system is one of the most effective methods for conducting a brief survey to understand the damage situation in cases where field surveys cannot be implemented because a tsunami warning is in effect after a large earthquake, or the disaster occurred at night. Note, however, that this system is considered to be inferior to the in-situ direct measurement of displacement (refer to **Reference (Part II), Chapter 2, 2.4 Survey to Determine the Usability of Ports (Initial Survey)**) in terms of accuracy. The system is divided into a simplified method which uses a relationship between the levels of damage preliminarily obtained through a two-dimensional effective stress analysis (refer to **Reference (Part III), Chapter 1, 2 Basic Items Concerning Seismic Response Analysis**) and the velocity PSI values of the earthquake ground motions,[4)] as well as a detailed method which estimates the levels of damage through an automatic two-dimensional effective stress analysis directly using observed ground motion waveforms. Although the detailed method requires a long calculation time, it is considered to be more accurate than the simplified method. However, the simplified method is advantageous in that it can produce analysis results instantaneously.

(3) Survey to Determine the Usability of the Facilities

The survey to determine the usability of the facilities is a field survey implemented immediately after the **Brief Survey to Understand the Damage Situation Described in Item (2)** above. It shall be initiated about two days after and completed about five days after the occurrence of the disaster for the purpose of ensuring the transportation routes for emergency disaster relief supplies. In the survey, the usability of the port facilities is determined (refer to **Reference (Part II), Chapter 2, 2.4 Survey to Determine the Usability of Ports [Initial Survey]**) for the facilities (such as the mooring facilities, breakwaters, navigation channels and basins) extracted as a result of the brief survey to understand the damage situation as the determination objects. Those facilities determined to be usable as is shall be put back into service as a part of the transportation routes for emergency disaster relief supplies. In addition, the emergency restoration survey (refer to **Reference (Part II), Chapter 2, 2.5 Emergency Restoration Survey**) shall be implemented for the facilities subjected to emergency restoration work.

Table 2.3.4 shows the standpoints for determining the usability of the facilities (such as the mooring facilities, navigation channels, basins and breakwaters). For the details of the survey to determine the usability of the facilities, refer to **Reference (Part II), Chapter 2, 2.4 Survey to Determine the Usability of Ports (Initial Survey)**.

Table 2.3.4 Standpoints in the Determination of the Usability of Facilities (Mooring Facilities, Navigation Channels, and Basins, Breakwaters)

Object	Method	Standpoint (refer to **2.4** for details)
Mooring facilities	(Refer to **2.4**)	• Is the structural stability secured? • Does large-scale scouring occur on the ground in front of the mooring facilities? • Can ships come alongside the mooring facilities? • Can cargo loading and unloading be conducted? • Is road accessibility maintained?
Navigation channels and basins		• Are the required water depths secured? • Is there a large amount of floating debris in the waterways and basins? • Are there obstacles protruding from the sea surface?
Breakwaters		• Can they block waves from the open sea?

2.4 Survey to Determine the Usability of Ports (Initial Survey)

In order to utilize ports as disaster relief bases after a large earthquake and tsunami, it is necessary to promptly implement multiple surveys, put safe and usable facilities back into service early, and take measures to keep people away from those facilities determined to be unsafe. Here, the outlines and points to consider necessary for determining the usability of facilities are described for mooring facilities, navigation channels and basins as the determination objects, based on past experiences with actual disasters involving earthquakes and tsunamis.

The standpoints of the survey vary facility by facility. In the case of mooring facilities, their usability shall be determined according to whether or not the structural stability is secured, whether large-scale scouring occurs on the ground in front of the mooring facilities, whether ships can come alongside them, whether cargo loading and unloading can be conducted, and whether road accessibility is maintained. In the case of navigation channels and basins, their usability shall be determined according to whether or not the required water depths are secured, and whether there is a large amount of floating debris. In any event, advance preparations are important for making an appropriate determination of the usability of facilities after the occurrence of a disaster.

2.4.1 Survey to Determine the Usability of Mooring Facilities

(1) Differences in Survey Contents Depending on Structural Types

It shall be noted that the damage patterns of mooring facilities vary depending on the types of mooring facilities (e.g., gravity-type wharves, sheet pile wharves and piled piers), and, therefore, the information required to determine the usability of mooring facilities largely differs depending on their types.

① **Gravity-type wharves**

The typical type of damage to gravity-type wharves due to earthquakes that has been observed in the past is the seaward displacement of wharf bodies, along with their settlement and inclination, which causes level differences on the ground behind the wharf bodies (refer to **Figs. 2.4.1** and **2.4.2**).[5] Wharf bodies which undergo significant seaward displacement interfere with ship berthing, and large level differences on the ground behind the wharf bodies interfere with vehicle traffic. In contrast, there have been cases where no significant damage to the wharf bodies was reported even after the actions of large external forces, as was the case with Kobe Port, which was hit by the 1995 South Hyogo Prefecture Earthquake. Thus, for gravity-type wharves, it is considered to be sufficient to determine their usability based on whether or not ships can come alongside them and whether road accessibility is maintained. Of course, there may be a risk that the wharf bodies could lose their structural stability when horizontally displaced to a level in which they come very close to the tops of mound slopes. However, the determination criteria for usability are generally much stricter than those for structural stability. Thus, the usability of gravity-type wharves can be visually determined to some extent, and, in that sense, there may be cases where visual surveys using UAVs can be a useful method to determine the usability of gravity-type wharves in the future. When determining the usability of concrete block wharves, which are also classified as gravity-type wharves, it is necessary to confirm that the concrete blocks have maintained their integrity.

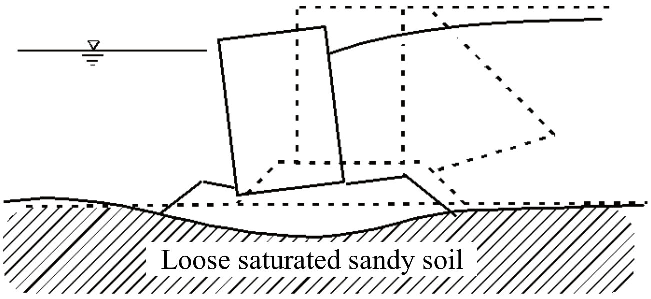


Fig. 2.4.1 Typical Damage Pattern of Gravity-Type Wharves[5)]

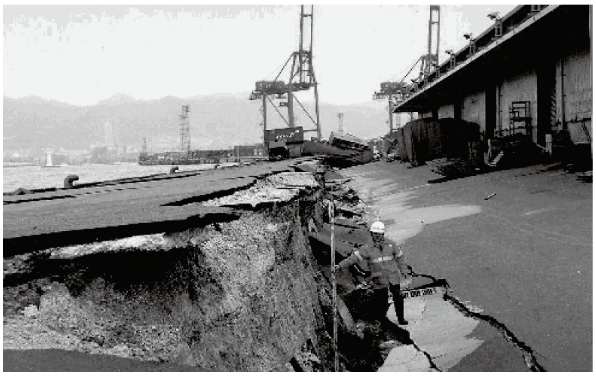


Fig. 2.4.2 Damage to Gravity-Type Wharves Due to the South Hyogo Prefecture Earthquake (The image is reversed)

② **Sheet pile wharves and piled piers**

There have been cases where mooring facilities mainly made of steel members, such as sheet pile wharves and piled piers, have lost structural stability due to damage to these structural members. These cases include, for example, the cracks on the sheet pile wharf in Akita Port due to the 1983 Japan Sea Earthquake (refer to **Fig. 2.4.3**), and the buckling of the steel pipe pile on the piled pier in Kobe Port due to the 1995 South Hyogo Prefecture Earthquake (refer to **Fig. 2.4.4**).[5)] Thus, the determination of the usability of sheet pile wharves and piled piers cannot be sufficiently made based only on the availability of ship berthing and road accessibility, and additionally requires reliable confirmation of the stress state of the structural members. Particular attention shall be given to the fact that the determination of usability may not be possible through visual surveys or submersible surveys by divers in cases where the underground members are damaged, as with previous disasters (refer to **Fig. 2.4.4**).[5)] **Fig. 2.4.4** illustrates a damage pattern of a piled pier. When a sheet pile wharf undergoes a similar deformation mode, as shown in **Fig. 2.4.5**, the bending moment on the structural members is maximized at the underground portions. The following section describes the procedure for determining the usability of mooring facilities mainly made of steel members such as sheet pile wharves and piled piers.

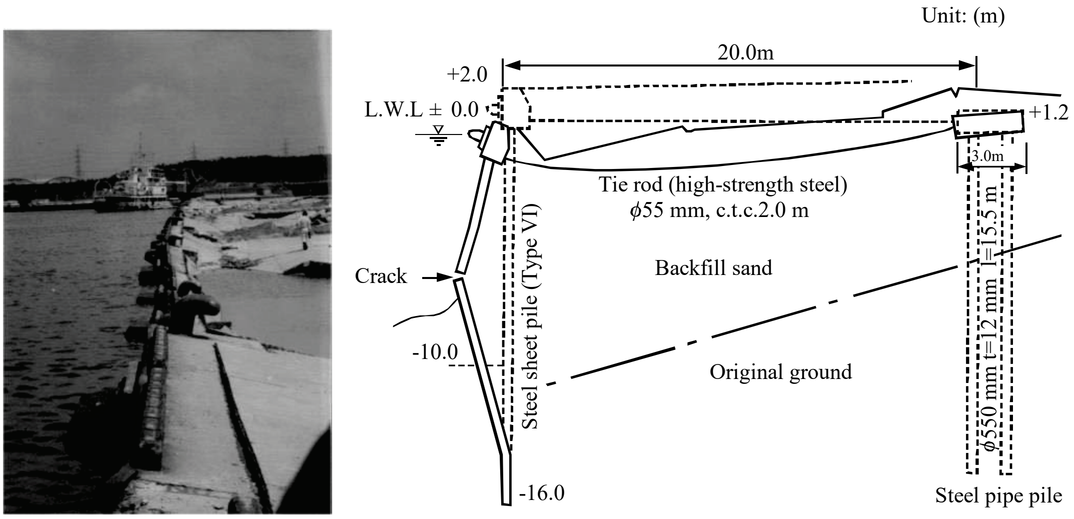


Fig. 2.4.3 Damage to a Sheet Pile Wharf Due to the Japan Sea Earthquake (Cracks on the Sheet Pile)[5)]

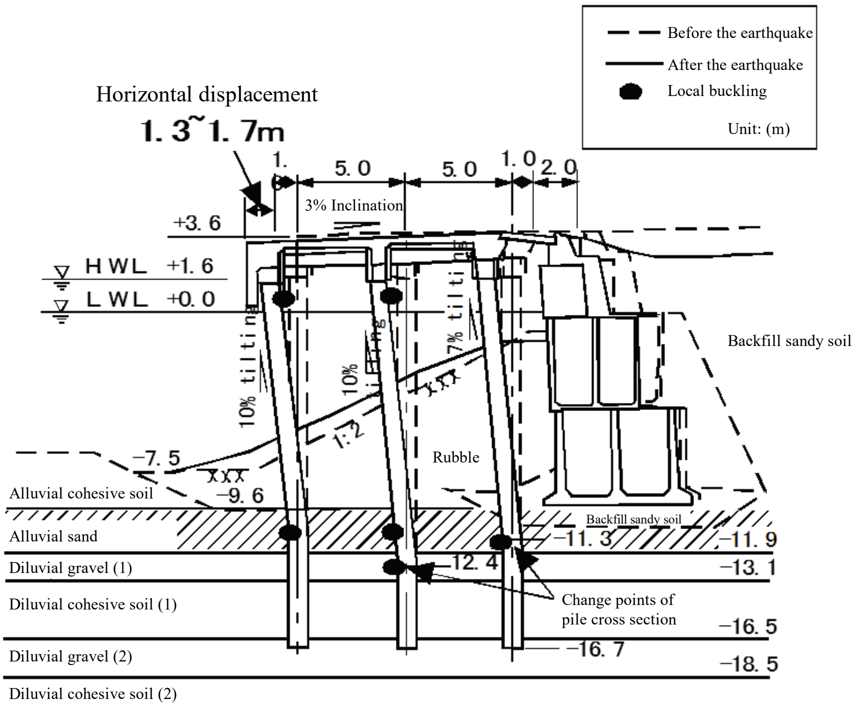


Fig. 2.4.4 Damage to a Piled Pier Due to the South Hyogo Prefecture Earthquake (with Local Buckling on Underground Piles)[5)]

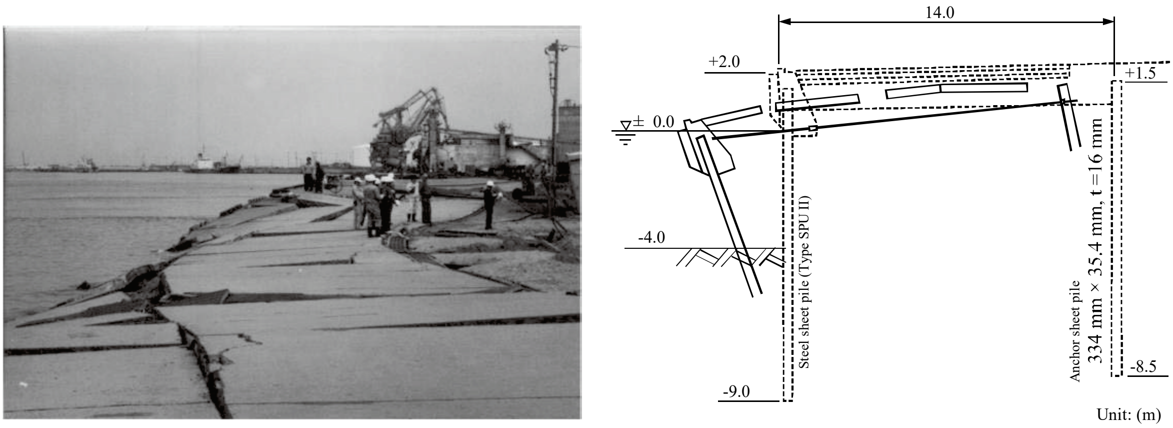


Fig. 2.4.5 Damage to a Sheet Pile Wharf Due to the Japan Sea Earthquake
(Displacement of Anchorage Work)[5)]

(2) Procedure for Determining the Usability of Mooring Facilities Mainly Made of Steel Members Such As Sheet Pile Wharves and Piled Piers

As described in Item **(1)** above, it is necessary to confirm the deformation and stress state of structural members when determining the usability of mooring facilities mainly made of steel members such as sheet pile wharves and piled piers. The deformation and stress state can be confirmed through the following procedure (shown in **Fig. 2.4.6**).

① The residual horizontal displacement of the levee crowns due to the deformation of the mooring facilities shall be acquired through survey results before and after an earthquake.

② The relationships among the residual horizontal displacement of the levee crowns, deformation of the members and stress states shall be preliminarily obtained for the respective facilities. Then, the stress states of the members and the structural stability of the facilities shall be evaluated based on the residual horizontal displacement obtained through ① above.

③ The usability of the mooring facilities shall be finally determined using information on the structural stability together with the determination results based on the availability of ship berthing and road accessibility, as is the case with gravity-type wharves.

In the above procedure, the methods which can be used in ① and ② are the RTK-GNSS (refer to **Reference (Part II), Chapter 2, 4.3.3 Real-Time Kinematic Survey**) and a ground-structure system dynamic analysis, such as the FLIP (refer to **Reference (Part III), Chapter 1, 2 Basic Items concerning Seismic Response Analysis**), respectively. It shall be noted that the determination can be made only when steps ① and ② above are combined. In addition, steps ① and ② respectively require advance preparation, as described below. Furthermore, in the case of remarkable settlement of the ground behind a sheet pile wharf, even though the residual horizontal displacement of the levee crown is small, there may be a risk of damage to the sheet pile body, and, therefore, it is necessary to confirm such damage through a submersible survey.

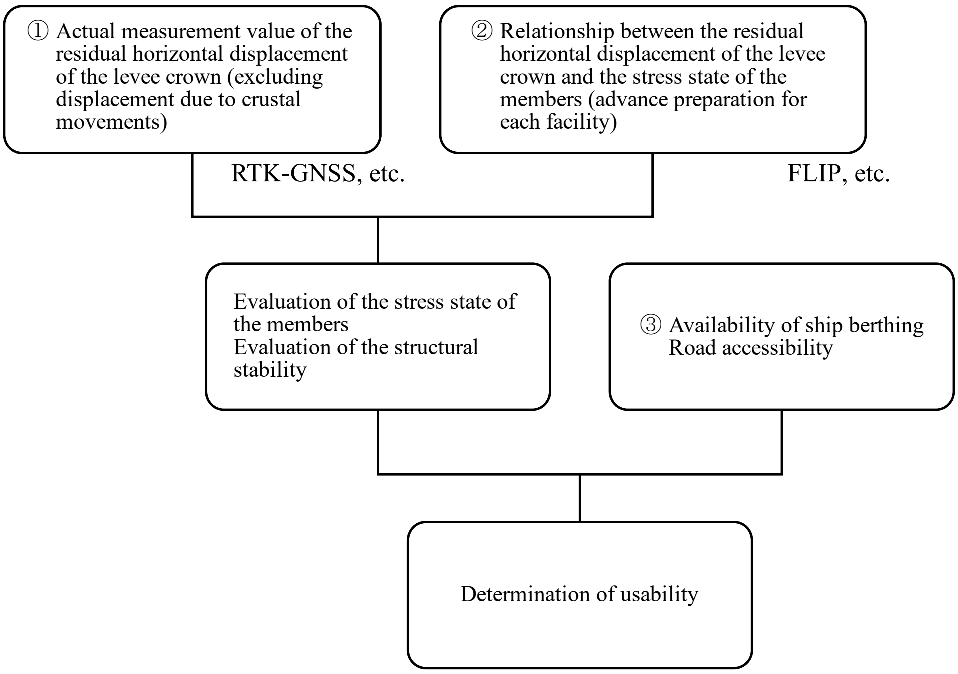


Fig. 2.4.6 Procedure for Determining the Usability of Mooring Facilities Mainly Made of Steel Members such as Sheet Pile Wharves and Piled Piers

(3) Understanding the Residual Horizontal Displacement of Levee Crowns Due to the Deformation of Mooring Facilities

The residual horizontal displacement of levee crowns due to the deformation of mooring facilities shall be acquired through the measurement of the displacement directly related to the stress states of the members with attention paid to the following points based on experiences with past disasters.

First, it is not appropriate to rely on visual confirmation for determining the presence or absence of residual horizontal displacement in consideration of a precedent where a mooring facility, which was hit by the 1995 South Hyogo Prefecture Earthquake, appeared to have almost no displacement, but turned out to have had a displacement of about 50 cm through later aerial photogrammetry[6)] (for an example, refer to **Photo4.2.3.5** of Facility No. ③ at Maya Wharf in the **Reference 7)**). Overlooking a displacement of about 50 cm is a fatal error in the evaluation of the stresses in members. In addition, it is not appropriate to use a tape measure to measure the relative displacement between an object and a facility, which appears to have no displacement to the naked eye. This is because even facilities which appear to have no displacement may have it in reality.

Here, it is necessary to survey the residual horizontal displacement of the levee crowns of mooring facilities; however, it shall be noted that crustal movements (refer to **Reference (Part II), Chapter 6, 2 Crustal Movements**) due to large-scale earthquakes may put the control points of the Geospatial Information Authority of Japan out of commission for some months. Thus, for determining the usability of facilities within five days after the occurrence of a disaster, there is a necessity to establish a survey system without relying on the control points of the Geospatial Information Authority of Japan.

Generally, the displacement of mooring facilities is the sum of the displacement due to crustal movements and the displacement due to the deformation of the mooring facilities (i.e., the displacement due to the local deformation of the ground around the mooring facilities).

(a) Displacement of mooring facility = (b) Displacement due to crustal movements + (c) Displacement due to the deformation of mooring facilities

Because the displacement due to crustal movements has no relationship with the evaluation of the stresses in the members, the differences in the absolute coordinates of the mooring facilities before and after an earthquake include the displacement of (b) and (c) above, and, therefore, they are not appropriate for the evaluation of the stresses in the members.

Then, it is necessary to secure “reference points” behind the mooring facilities, which are not considered to be subjected to the local deformation of the ground around the mooring facilities (although they are subjected to crustal movements), and to measure the relative displacement between the reference points and the displaced mooring facilities (as shown in **Fig. 2.4.7**). Here, the locations of the reference points shall be appropriately selected so as to avoid the influence of the local deformation of the ground around the mooring facilities (or other local ground conditions), with attention paid to the possibility that the influence of the local deformation of the ground around the mooring facilities can be felt at a fairly far distance behind the mooring facilities, as with Maya Wharf in **Fig. 2.4.8**. The information on (c) displacement due to the deformation of the mooring facilities necessary for the evaluation of the stresses in the members can be obtained by comparing the distances between the reference points and mooring facilities before and after an earthquake.

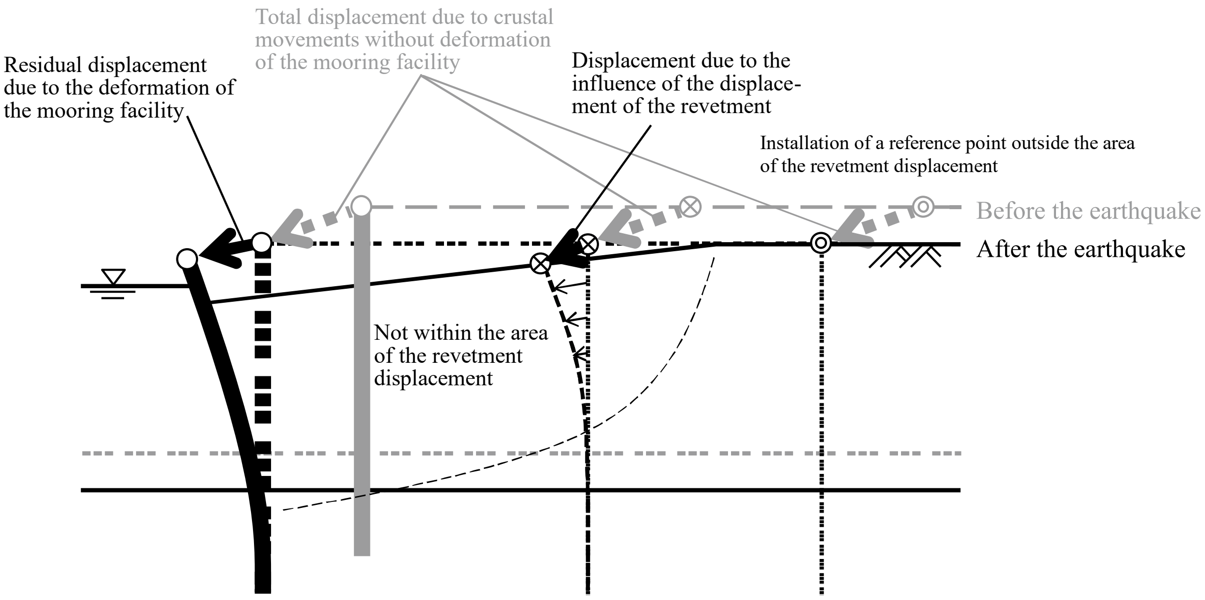
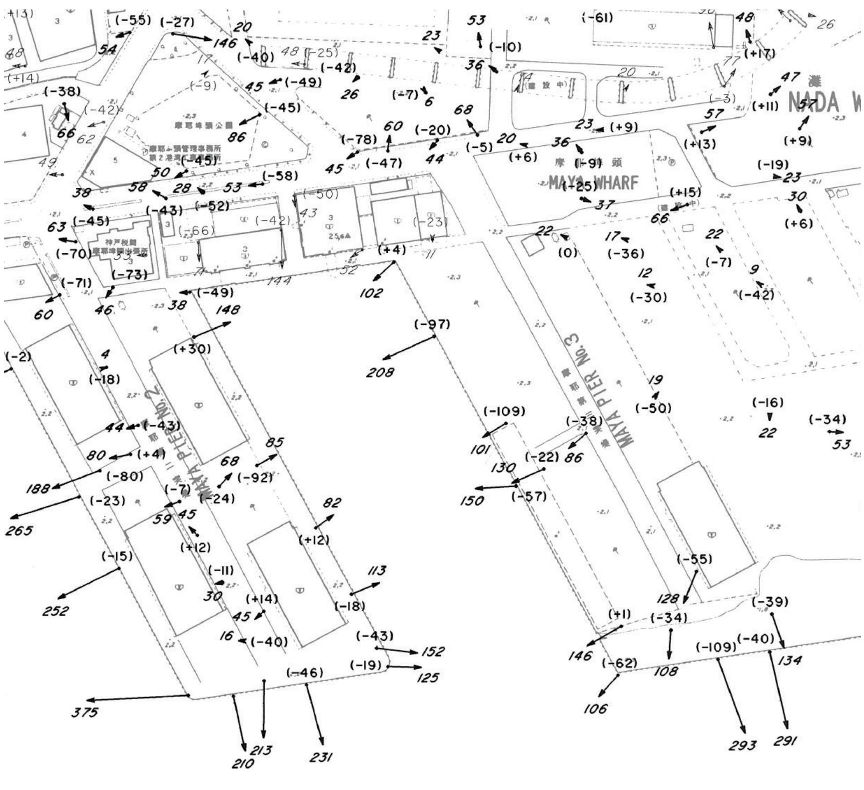


Fig. 2.4.7 Method for Eliminating the Influence of Crustal Movements



(Unit: cm)

Fig. 2.4.8 Distribution of the Displacement at Maya Wharf Due to the 1995 South Hyogo Prefecture Earthquake[6)]

There are several ways of measuring the relative displacement between the reference points and mooring facilities. Among them, the RTK-GNSS[8)] is essentially suitable for the measurement of the relative displacement between two points in that it can cancel out errors associated with the measurement by simultaneously measuring two locations: one on the reference point and the other on the mooring facility. With a measurement accuracy of the relative horizontal displacement between the two locations with a margin of error of about 2 cm, the RTK-GNSS can be sufficiently used for the evaluation of the stresses in the members of mooring facilities.

(4) Preliminary Estimation of the Relationship between the Residual Horizontal Displacement of the Levee Crowns and Stress States

A point of caution in the preliminary estimation of the relationship between the residual horizontal displacement of the levee crowns and stress states of the members is the importance of the individuality of the structures and ground conditions of the respective facilities. For example, the modes of deformation vary depending on the relative relationship between the steel member and the ground stiffness. The deformation modes also vary depending on the relative relationship between the bearing capacity of the members, such as between a sheet pile wall and anchorage work, in the case of a sheet pile wharf. Thus, it is necessary to take into consideration these factors which affect the deformation modes of the mooring facilities when estimating the relationship between the residual horizontal displacement of the levee crowns and stress states. Of course, the deformation of the ground itself needs to be taken into consideration. In the case of a piled pier, if only the superstructure undergoes horizontal displacement without any deformation of the ground, a short pile effect causes the land side piles to become susceptible to severer stress states, but this is not the case when the ground (including rubble) undergoes deformation. In addition, a small difference in ground conditions affect the relationship between the residual horizontal displacement of the levee crowns and stress states. For example, if two types of ground with high stiffness and low stiffness are located next to each other, the ground with low stiffness is subjected to the concentration of strain, thereby affecting the distribution of the stresses in the members.

A ground-structure system dynamic analysis such as the FLIP (refer to **Reference (Part III), Chapter 1, 2 Basic Items concerning Seismic Response Analysis**) can be used as a method for preliminarily estimating the relationship between the residual horizontal displacement of the levee crowns and the stress states of the members while taking into consideration the conditions above. The **References 4)** and **9)** introduce cases of a preliminary estimation of the relationship between the residual horizontal displacement of the levee crowns and stress states of the members conducted through the ground-structure system dynamic analysis with facilities in the jurisdiction of the Chubu Regional Development Bureau as the estimation objects.

2.4.2 Survey to Determine the Usability of Navigation Channels and Basins

In order to enable ports to be utilized as disaster relief bases after a large earthquake and tsunami, it is necessary to be able to not only the mooring facilities but also the navigation channels and basins. For navigation channels and basins, it is necessary to quickly secure temporary water depths (temporary water depths) that allow ships to navigate safely. To that end, it is important to acquire information as early as possible on the extent of the planar distribution of the debris accumulated on the seafloor and the extent of the reduction in water depth due to the accumulation of debris. This information can be effectively acquired with swath sounding machines and side-scan sonars that enable the water depths and obstacles in wide areas to be easily detected, as described in **Reference (Part II), Chapter 2, 4.4 Understanding the Geometry of Underwater Areas**. Furthermore, in order to enhance the accuracy of the water depth measurements, it is necessary to urgently set chart datum level (refer to **Reference (Part II), Chapter 2, 2.5 (3) Emergency Setting of Chart Datum Level in Bathymetric Surveys** and **Reference (Part II), Chapter 2, 3 Resetting of Chart Datum Level after a Large Earthquake and Tsunami**).

2.5 Emergency Restoration Survey

(1) Emergency Restoration Survey

The scope of the emergency restoration survey is the scale of the restoration work (the approximate required quantities of equipment and materials) with respect to the facilities which can be reinstated through emergency restoration work for the early reception of ships transporting emergency disaster relief supplies (the removing port obstacles). For seawalls, the scope of the emergency restoration survey is the scale of restoration work at locations where the temporary restoration of storm surge protection lines through emergency restoration work. The emergency restoration survey needs to be initiated within two days after the occurrence of a disaster and completed within five days, and implemented in parallel with the "survey to determine the usability of facilities." For the details of the emergency restoration survey, refer to the **Reference 1)**.

Table 2.5.1 shows the standpoints of the emergency restoration survey, an outline of the restoration work and methods for obtaining the approximate work quantities.

Table 2.5.1 Standpoints of the Emergency Restoration Survey, an Outline of the Restoration Work and Methods for Obtaining Work Quantities

Object	Standpoint	Outline of restoration work and method for obtaining work quantities
Vicinity of mooring facilities (onshore)	• Restoration of caving and level differences which interfere with vehicle traffic on aprons and roads behind the mooring facilities (with crushed stone, earth fill, steel plates, etc.) • Removal of obstacles that impede vehicle traffic	○ Laying crushed stone and steel plates as well as removing obstacles • Visual survey (visual observations, photographs, etc.) • Simplified measuring (staffs, rods, pinholes, etc.) • Other (refer to **Section 4**)
Navigation channels, basins and mooring facilities (undersea)	• Identification of abnormal objects on the seafloor and deformation of the front sections of the mooring facilities, which interfere with ship navigation, and setting of temporary water depths (changes in seafloor topography and types of debris)	○ Removal of obstacles undersea and on the seafloor with self-propelled grab barges • Bathymetric survey (refer to **4.4**) • Visual survey by divers • Other
Seawalls (mainly onshore)	• Locations requiring emergency protection to prevent the expansion of inundation damage due to storm surges and high waves and to secure the safety of vehicle traffic (with sandbags, concrete blocks, etc.)	○ Laying of sandbags and concrete blocks • Visual survey (visual observations, photographs, etc.) • Simplified measuring (staffs, rods, pin holes, etc.) • Other (refer to **Section 4**)

(2) Points to Consider when Establishing Emergency Restoration Survey Plans

Emergency restoration surveys are implemented for removing port obstacles as early as possible. Thus, emergency restoration surveys shall be flexibly planned in a manner that allows the measuring accuracy to be lowered and the measuring intervals to be decreased.

(3) Emergency Setting of Chart Datum Level in Bathymetric Surveys

Large-scale earthquakes may cause extensive ground deformation. Thus, when implementing bathymetric surveys for navigation channels and basins, as described in Item (1) above, it is necessary to urgently set the temporary chart datum level for the purpose of urgently calculating the water depths. For the methods for urgently setting the temporary chart datum level, refer to **Reference (Part II), Chapter 2, 3 Resetting of Chart Datum Level after a Large Earthquake and Tsunami**.

2.6 Full-Scale Restoration Survey

(1) Outline

In a full-scale restoration survey, the disaster states of the facilities are accurately observed or measured, and two-stage measurements are implemented for the disaster assessments and restoration design of the damaged facilities. In addition, a full-scale restoration survey shall be implemented at the appropriate time or on appropriate schedules in tandem with the preparation and progress of the emergency restoration work. For detailed information on full-scale restoration surveys, refer to the **Reference 1)**.

- Primary deformation measurement: The post-disaster deformation of all damaged facilities shall be measured using measuring equipment. For facilities with minor deformation, the applications for disaster assessments shall be made based on the primary deformation measurement. The primary deformation measurement shall be initiated within 5 days and completed within 30 days after the occurrence of a disaster.

- Secondary deformation measurement: The post-disaster deformation shall be measured in detail for the facilities determined to have major damage in the primary deformation measurement in order to investigate the reasons for the damage, formulating a restoration design policy and reset the design conditions to be a presupposition of the policy. The secondary deformation measurement shall be initiated within 14 days and completed within 90 days after the occurrence of a disaster. For the facilities subjected to the secondary deformation measurement, the applications for disaster assessments shall be made based on the results of the primary and secondary deformation measurements.

(2) Initiation of Emergency Tide Level Observations and Resetting of Chart Datum Level

Resetting the control points and chart datum level is necessary for the execution of full-scale restoration work. It shall be noted that a delay in resetting will cause delays in the full-scale restoration survey and work. Particularly, emergency tide level observations need to be initiated at the earliest possible time because the resetting of chart datum level requires harmonic constants and other parameters, which are based on the tide level observation data from at least 32 days and nights. For the details of the emergency tide level observation method and the resetting of refer to **Reference (Part II), Chapter 2, 3.3 Resetting of Chart Datum Level for Full-Scale Restoration Projects**.

(3) Primary Deformation Measurement

The primary deformation measurement shall be implemented for the main purpose of observing the damage states of all facilities and preparing the materials necessary to apply disaster assessments. Thus, the primary deformation measurement shall be implemented with a focus on obtaining the minimum information (an estimation of the scale of the restoration work in accordance with the damage to the respective facilities) required for the disaster assessments.

Table 2.6.1 shows the work contents, examples of object facilities and points to consider in the primary deformation measurement.

Table 2.6.1 Work Contents, Examples of Object Facilities and Points to Consider in the Primary Deformation Measurement

Work content	Classification	Example of object facilities and points to consider
Control point survey	Initiation of emergency tide level observations Resetting of chart datum level	• Resetting of chart datum level using the results of emergency tide level observations (from 32 days and nights) (refer to **3.3**)
Onshore measurement	Measurement of deformation on breakwaters, quaywalls and seawalls above sea levels	• Measurement of the misalignment of normal lines, inclination and settlement of facilities • In the case of caisson type breakwaters, identification of the turnover, sliding and settlement of each caisson by measuring the positions and heights of at least four locations on each caisson • In the case of mooring facilities, identification of the misalignment of normal lines and unevenness by measuring at least four locations in each span
	Measurement of cavities in aprons	• Necessity of drilling for the final confirmation of cavities in aprons
Undersea measurement	Measurement of deformation on breakwaters, quaywalls and seawalls in the sea	• Necessity of confirming whether or not work quantities can be easily calculated from survey results in the case of using swath sounding machines (including the narrow multi-beam method; refer to **4.4**) because of the necessity of indicating work quantities in the application for disaster assessments • Necessity of confirmation by divers
	Measurement of scouring and siltation of navigation channels and basins	

(4) Secondary Deformation Measurement

Because the secondary deformation measurement is implemented for the main purpose of investigating the reasons for such damage, formulating a restoration design policy and resetting the design conditions to be a presupposition of the policy, the methods for the secondary deformation measurement differ depending on the locations and the levels of damage. **Table 2.6.2** shows the purposes, items and outlines of the secondary deformation measurement.

Table 2.6.2 Purposes, Items and Outlines of the Secondary Deformation Measurement

Large classification	Measurement purpose and item	Outline of measurement
Onshore measurement	○ Observation of accurate disaster states • Plane survey	• Plane survey of facilities with total stations
	○ Approximate evaluation of the residual bearing capacity of the sheet pile quaywalls • Measurement of the deformation tie rods on sheet pile quaywall	• Survey of horizontal and vertical displacement, looseness and corrosion states of tie rods
	○ Confirmation of the deformation of steel pipe piles and sheet piles • Measurement of the deformation of steel pipe piles and sheet piles	• Steel pipe piles: Survey of verticality and deformation through borehole radar and elastic wave measurements as well as video recordings in the pipe • Sheet piles: Survey of deformation using clinometers
	○ Confirmation of the residual bearing capacity of sheet pile quaywalls and pile piers • Measurement of the wall thicknesses of steel pipe piles and sheet piles	• Wall thicknesses: Using ultrasonic thickness indicators
	○ Evaluation of the residual bearing capacity of sheet pile quaywalls and piled piers • Residual bearing capacity survey (sheet pile quaywalls and piled piers)	• Steel pipe piles and sheet piles: Measurement of wall thicknesses • Tie rods: Lift-off test • Bearing piles: Dynamic bearing capacity test and static bearing capacity test
	○ Confirmation of the soundness of concrete structures • Crack survey	• Survey of cracks, peeling, falling, swelling and joint openings • Hammering test (as needed)
	○ Confirmation of the soundness of concrete structures • Concrete degradation survey	• Observation of the quality of existing concrete structures (compression strength, chlorine contents and neutralization)
	○ Prediction and determination of liquefaction • Soil survey	• Stratum structure, in-situ tests and laboratory soil tests

Large classification	Measurement purpose and item	Outline of measurement
Undersea measurement	○ Disaster states of seafloor topography • Bottom sediment survey	• Superficial bottom sediment: Side-scan sonars and lead line • Types of sediment: Sampling of bottom sediment
	○ Confirmation of the deformation of gravity-type and sheet pile quaywalls • Confirmation of the structural soundness in front of quaywalls	• Front sections of quaywalls: Survey of inclination, joint openings, damage and scouring (by divers, clinometers, underwater cameras, acoustic video cameras and underwater 3D scanners)
	○ Confirmation of the deformation of piled piers • Confirmation of the structural soundness at the bottom sections of the piled piers	• Cracks, peeling, falling and swelling of the lower faces of superstructures (beams and floor slabs) • Presence or absence of pile deformation (irregular geometry, buckling, etc.) (by divers, clinometers, underwater cameras, acoustic video cameras and underwater 3D scanners)
	○ Confirmation of the deformation of caisson type breakwaters • Confirmation of the damage situations of areas around the caissons	• Caissons exposed above sea levels: Survey of joint openings, sliding states, damaged states due to impacts, scattering of mound protection blocks and armor blocks, scouring immediately below the caissons, and cavities • Submerged caissons: Survey to determine the reusability of submerged caissons • Breakwater mounds: Continuous survey of mound damage states

(5) Surveys and Analyses for Formulating a Restoration Work Policy

In addition to the primary and secondary deformation measurements, the following surveys and analyses need to be implemented for formulating the main restoration work policies, including the priorities and orders of the respective facilities in the restoration work, and the resetting of the restoration designs based on the tsunami alleviation effects of breakwaters. It is necessary to initiate the following surveys and analyses at the early stages of the full-scale restoration survey because they require a significant amount of time for preparation and implementation.

• **Harbor calmness analysis:**

Overall port restoration procedures shall be determined based on the evaluation results of the states of reduction in the cargo handling operation rates at the respective mooring facilities in ports due to the damage to the breakwaters and the levels of the restoration of the cargo handling operation rates for the respective restoration cases (with different orders of breakwater restoration). The cargo handling operation rates can be evaluated as harbor calmness (ratios of waves having wave heights measured at the front of quaywalls that do not exceed the critical wave height for cargo handling to all waves) calculated based on the conditions for setting the deepwater wave heights, the results of the wave transformation calculation (using the energy balance equation) up to the port entrances, and the wave height ratios (ratios of wave heights at the fronts of quaywalls to the deepwater wave heights) at the respective mooring facilities in the ports.

The Takayama method[10)] has been mainly used for calculating the wave height ratios. However, recently, in order to cope with a problem with reductions in harbor calmness due to long-period waves, another method using the Boussinesq equation, which is capable of simultaneously calculating the wave transformation and wave height distribution inside ports, has come into use.

• **Tsunami trace survey:**

In the tsunami trace survey, the extent of inundation due to a tsunami in terms of the areas and depths is measured through the traces from the tsunami at major facilities which show the highest elevations that the tsunami reached (through indirect leveling from known elevations).

• **Inundation damage prediction analysis in the case of the collapse of breakwaters:**

In the inundation damage prediction, the extent of inundation due to tsunamis and the associated damage are evaluated in a manner that conducts inundation simulations with conditions set by combining several states of the breakwaters, such as before, during and after construction, as well as when damaged by disasters and restored after disasters, with several tsunami heights, such as the design heights for restoration work and heights exceeding the design heights. Then, the evaluation results are used in the formulation of the restoration work policies. Specifically, the evaluation results are used for setting the design tsunami heights for the restoration of damaged breakwaters, the examination conditions to improve the durability of the breakwaters, and the new crown heights of the seawalls at the back of the breakwaters.

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3 Resetting of Chart Datum Level after a Large Earthquake and Tsunami

3.1 Measures Taken for the 2011 Great East Japan Earthquake and New Positioning Technologies

3.1.1 Damage Situations

The crustal movements due to the Great East Japan Earthquake (on March 11, 2011) put the existing control points, including local electronic control points and benchmarks, out of commission as known coordinates. In addition, all the tidal observatories (refer to **Fig. 3.1.1**) in the Tohoku region were completely disabled, including the tide level observation benchmarks (the level indicators that show level differences from the lowest levels [D.L.: Datum Line] at the tidal observatories). Under these circumstances, the Hydrographic and Oceanographic Department of the Japan Coast Guard deleted the reference tables of the mean, highest and lowest water levels at

almost all the ports located along the Pacific coast of east Japan from Hachinohe Port to Choshi Fishery Port, which were published on the Internet, on March 31, 2011.

Fig. 3.1.1 Example of a Damaged Tidal Observatory (Left: Before the Disaster, Right: After the Disaster)

3.1.2 Issues with Emergency Restorations

As mentioned above, the Great East Japan Earthquake put the existing control points and GNSS (GPS at that time) out of commission. Thus, the surveys of port facilities were implemented in a manner that set the temporary control points and proceeded with the survey work using temporary local coordinates. The bathymetric surveys immediately after the earthquake were implemented in a manner that established temporary benchmarks as references to calculate the water depths, set temporary chart datum level (temporary lowest levels) based on the estimated tide levels and measurements using auxiliary gauges (refer to **Reference [Part II], Chapter 2, 3.2 Emergency Setting of Chart Datum Level**), and temporarily used the relationships of the elevations between the temporary benchmarks and temporary chart datum level.

Because the bathymetric survey data is of particular importance for setting temporary water depths on which the elimination of obstacles from navigation channels is based, it is necessary to estimate the temporary chart datum level (reference levels that take into consideration the influences of the settlement or uplift of the ground due to crustal movements with a certain level of accuracy) as soon as possible after an earthquake. However, at the time of the Great East Japan Earthquake, there were cases where it took a long time before the temporary chart datum level were set because the method for estimating the levels in a short period of time after crustal movements (refer to **Reference [Part II], Chapter 2, 3.2 Emergency Setting of Chart Datum Level**) was not fully understood. Furthermore, there were cases of obstacles preventing the restoration work due to a lack of knowledge on the basic requirements of the tide level observation for 32 days and nights before resetting the chart datum level.

In addition, after waiting for the redistribution of renewed electronic control points by the Geographic Survey Institute after two and a half months had passed since the earthquake, the positional information on the temporary control points needed to be immediately converted to the Japanese Geodetic Datum (JGD) through control point surveys. At the same time, the vertical coordinates and the water depth values based on the temporary chart datum level (lowest levels), which were set using temporary tide level observations, also needed to be converted to the JGD in accordance with the survey results using the renewed electronic control points.

3.1.3 New GNSS Positioning Technology (PPP-AR System) and Its Utilization after Earthquakes

The advancements in positioning technology since the Great East Japan Earthquake make the GNSS survey capable of precise point positioning with ambiguity resolution (hereinafter referred to as "PPP-AR") available with an accuracy of about ±5 cm, both in vertical and horizontal directions within a wide area of about 1,000 km from the control point network (worldwide control point network) when the conditions of the satellite positions at the time of the surveys and the visibility of the sky above the survey points are favorable (refer to **Reference [Part II], Chapter 2, 4.3.2 Precise Point Positioning with Ambiguity Resolution [PPP-AR]**). Thus, even in cases where all the existing control points and benchmarks fail over a wide range (all over the country), PPP-AR enables the temporary control points to be newly set immediately after an earthquake.

In addition, with the required information on the existing control points, such as Port B.M. and tidal observation B.M., preliminarily stored before the occurrence of an earthquake, PPP-AR enables the temporary chart datum level described in **Reference [Part II], Chapter 2, 3.1.2 Issues with Emergency Restorations** to be promptly set after an earthquake through the calculation (subtraction) of the differences between the coordinate values. The details of the setting of chart datum level with PPP-AR is described in **Reference [Part II], Chapter 2, 3.2 Emergency Setting of Chart Datum Level** below.

3.2 Emergency Setting of Chart Datum Level

3.2.1 Basic Procedures

This section describes the procedures to promptly set the temporary chart datum level required for the initial and emergency restoration surveys. It shall be noted that these procedures are based on the assumption that the GNSS PPP-AR survey is available after an earthquake.

The temporary chart datum level can be set through either **Procedure i** or **Procedure ii**, with the former being able to be implemented at an earlier stage in the restoration than the latter. **Fig. 3.2.1** illustrates the concepts of several types of values used in the detailed descriptions of the procedures below.

[Procedure i]

① Preliminarily acquisition of the following information on the existing control points (Point II in the figure) before the earthquake

- The ellipsoidal height of control point II (A in the figure) through a GNSS survey[1)]
- The level difference between control point II and the chart datum level (B in the figure) (refer to **Reference [Part II], Chapter 1, 2.3.5 Organization and Coordination of Tide Level Observation Data**)
- The ellipsoidal height of the chart datum level (C in the figure) based on the above height and difference

② Acquisition of the following information on the existing control point (II in the figure) after the earthquake

- The ellipsoidal height of control point II, identical to the above (A' in the figure), through a GNSS (PPP-AR) survey after the earthquake

③ Setting of a temporary chart datum level

- Acquisition of the relationship in the heights between control point II and the chart datum level after the earthquake (B' in the figure) (B' = A' − C)

[Procedure ii]

(*When a GNSS survey has not been implemented before the earthquake, or when setting a new control point after the earthquake)

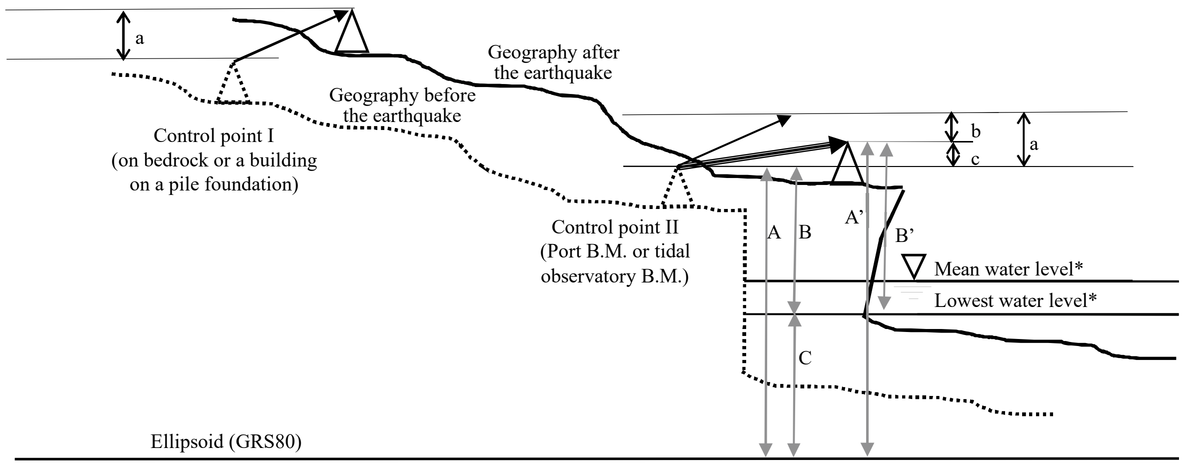
① Acquisition of the following information on the existing or new control point (II in the figure) after the earthquake

- Acquisition of the ellipsoidal height of control point II (A' in the figure) through a GNSS (PPP-AR) survey

② Visual observation of tide levels using a staff-gauge (hereinafter referred to as "staff-gauge observation") after the earthquake (refer to **Reference [Part II], Chapter 2, 3.2.2 Staff-Gauge Observation and Method for Setting Temporary Chart Datum Level Using a Staff-Gauge**)

③ Setting of the temporary chart datum level (refer to **Reference [Part II], Chapter 2, 3.2.2 Staff-Gauge Observation and Method for Setting Temporary Chart Datum Level Using a Staff-Gauge**)

- Acquisition of the relationship in the heights between control point II and the chart datum level (B’ in the figure) after the earthquake using the staff-gauge observation results and the estimated tide levels at identical times (astronomical tides)



*Mean water level and lowest water level: No change in ellipsoidal heights before and after the earthquake

(Legend)

A: Ellipsoidal height before the earthquake through a GNSS survey (control point II)
B: Height from the lowest water level to control point II
C: Ellipsoidal height of the lowest water level (control point II)
a: Vertical displacement before and after the earthquake due to crustal movements (control points I and II)
b: Vertical displacement before and after the earthquake due to local ground deformation at control point II
c: Vertical displacement before and after the earthquake of control point II (sum of the vertical displacement due to crustal movements and local ground deformation)
→ : Displacement before and after the earthquake due to crustal movements (control points I and II)
➡ : Displacement before and after the earthquake at control point II (sum of the displacement due to crustal movements and local ground deformation)

Fig. 3.2.1 Illustration of Setting the Temporary Chart Datum Level Using a GNSS PPP-AR Survey

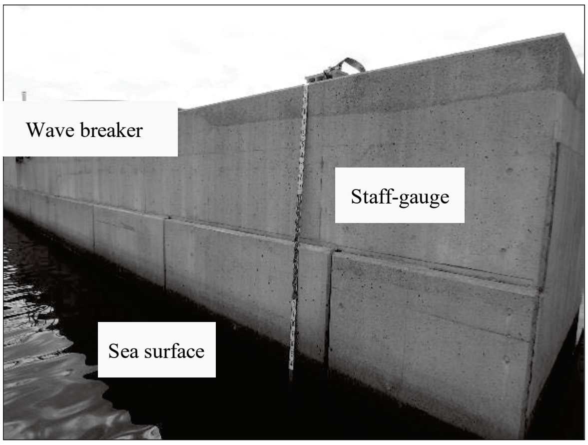
3.2.2 Staff-Gauge Observation and Method for Setting Temporary Chart datum level Using a Staff-Gauge

(1) Outline

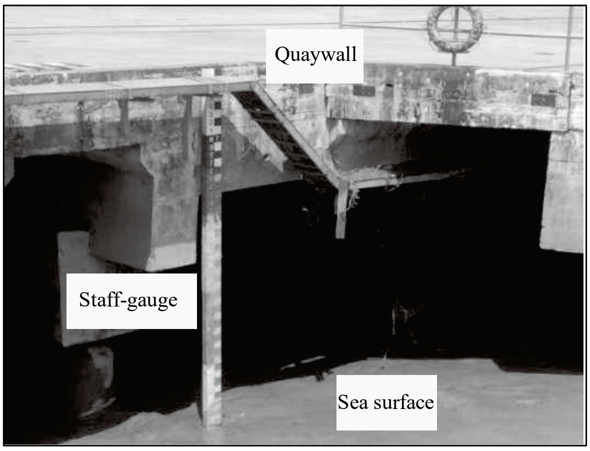
This section describes a specific method for calculating the relationship in the heights between control point II and chart datum level (B’ in the figure) after an earthquake, as required in **Procedure ii** in **3.2.1 Basic Procedures** above. This method is used to estimate the temporary chart datum level using the information on two types of tide levels: the visual tide level observation results using a staff-gauge, as described in Item (2) below, and the estimated tide levels (tide levels estimated from astronomical tides), as described in Item (3) below.

(2) Visual Tide Level Observation Using a Staff-Gauge (Staff-Gauge Observation)

Staff-gauges are staffs[2), 3)] with scales installed on quaywalls to observe the tide levels (refer to **Fig. 3.2.2**). Those installed near tide gauges for comparative observations are sometimes called “auxiliary gauges.” Observations of tide levels using staff-gauges are basically implemented through visual observations at time zones with calm hydrographic conditions. In the case of emergency situations, visual tide level observations shall be implemented for acquiring two or more sets of data, with the respective sets acquired in a manner that measures the tide levels for 30 minutes at 5-minute intervals before and after the highest and lowest water levels on different days. It shall be noted that observers need to reliably observe the tide levels at identical locations and eye heights.



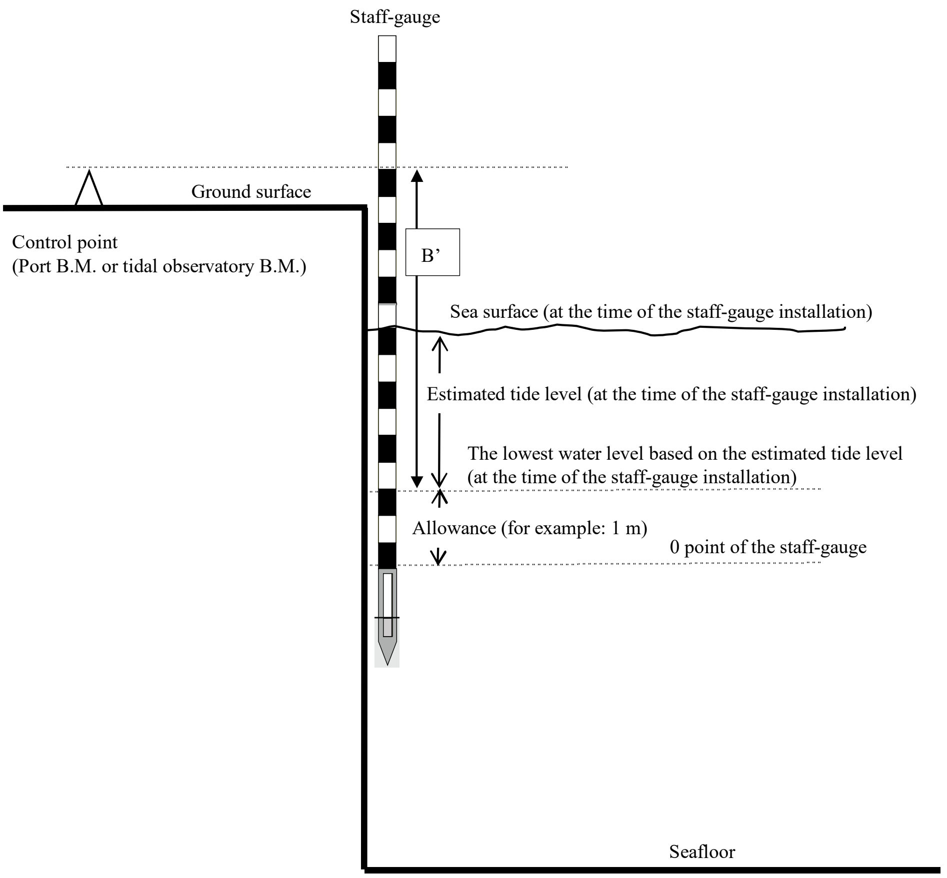
(a) Example of a Tide Level Observation on a Wave Breaker[2)]



(b) Example of a Tide Level Observation on a Quaywall[3)]

Fig. 3.2.2 Example of a Tide Level Observation Using a Staff-Gauge

When installing staff-gauges after an earthquake, it is necessary to measure the level differences between the staff-gauges and the onshore fixed points (e.g., control points including port B.M.) through direct leveling. In addition, the staff-gauges shall be installed with their 0 points positioned sufficiently low enough to enable the lowest water levels to be reliably measured. Specifically, staff-gauges can be installed with their 0 points set at the levels determined in a manner that first lowers the sea surfaces by heights corresponding to the estimated tide levels (with reference to the lowest water levels at the time the staff-gauges are installed) at the time they are installed, and then further lowers the levels by about 1 m as an allowance (refer to Fig. **3.2.3**).



B': Height between control point II and the port management datum level after the earthquake (Fig. 3.2.1)

Fig. 3.2.3 Schematic Drawing of a Visual Tide Level Observation Using a Staff-Gauge

(3) Estimated Tide Levels

The estimated tide levels mean the astronomical tides calculated based on the harmonic constants obtained for 60 tidal constituents using tide level observation data for at least one year. For the definition of the estimated tide levels, refer to **Reference [Part II], Chapter 1, 2.3.1 (4) Explanations of the Terms Related to Tide Level Observations**.

For the astronomical tides, the Japan Coast Guard has published hourly “sea level heights” in the form of a “tide table.” The sea level heights mean the heights from the lowest water levels. When using the estimated tide levels after an earthquake disaster, it is necessary to acquire the times and sea level heights of the low and high tides from the tide table and interpolate the sea level heights between the low and high tides at 10-minute intervals.

In addition, when actually using the estimated tide levels, it is necessary to take into consideration the differences between the estimated tide levels and the actual tide levels. These differences are called “sea-level deviation.” The magnitudes of the sea-level departures vary depending on the ocean areas, seasons, time zones and the presence or absence of disturbances due to typhoons; however, under normal meteorological and hydrographic conditions (that allow bathymetric surveys to be implemented), the sea-level departures are around ±20 cm or less, and within ±30 cm in most cases, except under abnormal meteorological conditions. The sea-level departures of the estimated tide levels also need to be considered when setting the temporary chart datum level. Considering that the sea-level departures are mainly affected by atmospheric pressure variations, the errors in the measurements of the sea-level departures can be reduced by averaging three pieces of data obtained on different days.

(4) Setting of Temporary Chart Datum Level

The temporary chart datum level can be set by comparing the results of Items (2) and (3) above, specifically by visualizing the results of both the staff-gauge observation through the method described in Item (2) and the estimated tide levels at the time of the staff-gauge observation through the method described in Item (3). After confirming that there are no major differences in the values and fluctuation patterns between the tide levels obtained through the staff-gauge observation and estimated tide levels, the lowest water levels based on the estimated tide levels are set as the temporary chart datum level.

3.3 Resetting of Chart Datum Level for Full-Scale Restoration Projects

3.3.1 Simplified Methods for Emergency Tide Level Observations

(1) Outline

After setting the temporary chart datum level as a provisional measure in the emergency restoration survey, the chart datum level shall be subjected to resetting for the implementation of full-scale restoration work. For resetting the chart datum level, continuous tide records shall be obtained with simplified observation equipment that is additionally installed. The chart datum level are normally set based on tidal data observed for one year or longer. In contrast, in the case of emergency tide level observations, the chart datum level are set based on tidal data observed for 32 days and nights.

The following two types of observation methods, (1) the ultrasonic method and (2) the hydraulic method, are introduced as typical methods for simplified tide level observations.

(2) Simplified Tide Level Observations through the Ultrasonic Method

The equipment for the ultrasonic method measures the water levels (tide levels) on a principle that takes the time required for the ultrasonic waves emitted from a detector installed on a quaywall, revetment or inner breakwater to reflect off the sea surface and return to the detector and converts it into distance (refer to **Fig 3.3.1**). The equipment can be mounted on a temporary trestle fixed to a revetment or other structure with anchor bolts, thereby enabling speedy installation of the equipment and early implementation of the tide level observations. The ultrasonic method has the advantage that the equipment can be easily maintained because it can measure the distance to the sea surface without touching the sea surface.[2] There are also cases of combining the ultrasonic method with visual observations using an auxiliary gauge to directly confirm the actual tidal variability.

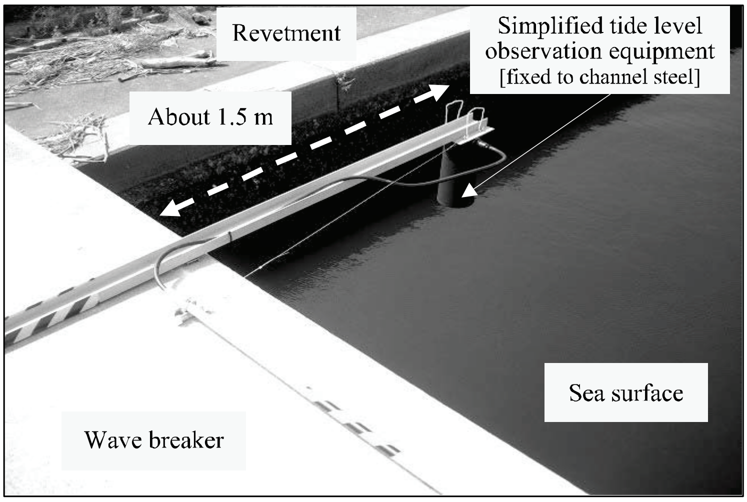


Fig. 3.3.1 Example of an Installation of Simplified Tide Level Observation Equipment (Ultrasonic Method)

(3) Simplified Tide Level Observations through the Hydraulic Method

The equipment for the hydraulic method uses a principle that takes the water pressure detected through pressure sensors preliminarily inserted into single pipes, which are attached to the side faces of the quaywalls, revetments or inner breakwaters, or fixed to the seafloor if possible, and converts it into water levels (refer to **Fig. 3.3.2**). Due to having an advantage in enabling speedy installation of the equipment and early implementation of the tide level observations, the hydraulic method was used in the tide level observations after the 2011 Great East Japan Earthquake. In the hydraulic method, it is necessary to calculate tide level data through reduction rate correction (a comparison between the values of the water pressure sensors and readings of the auxiliary gauges) based on the results of a continuous auxiliary gauge observation for 8 hours or longer at spring tides.

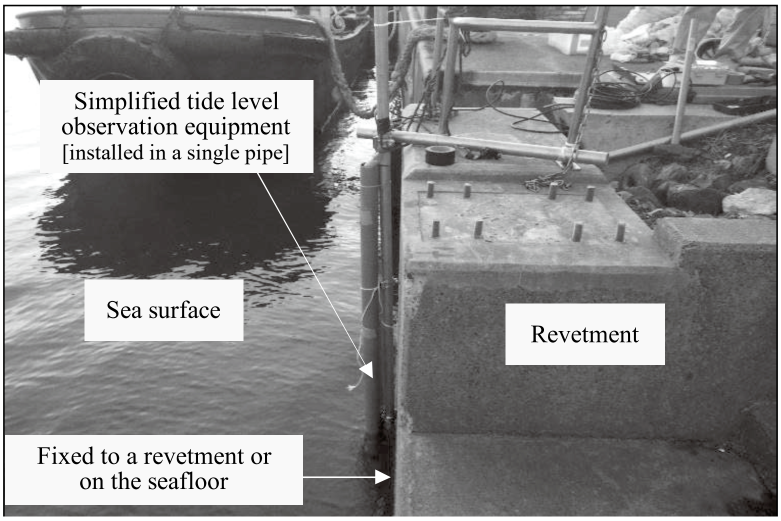


Fig. 3.3.2 Example of an Installation of Simplified Tide Level Observation Equipment (Hydraulic Method)

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4 Survey Methods after a Large Earthquake and Tsunami

4.1 General

Depending on the stages of the survey after a large earthquake and tsunami, there may be cases where identical survey methods are used for different purposes and scopes, which require different degrees of accuracy. **Table 4.1.1** summarizes the survey purposes at each stage from the initial stages to full-scale restoration stages with respect to seven survey objects throughout the three stages.

Table 4.1.1 Survey Objects and Survey Purposes at Each Stage

Object	Purpose		
	Initial stage	Emergency restoration stage	Full-scale restoration stage
Understanding the Overall Damage Situation (**4.2**)	General understanding of the overall damage situations of onshore facilities and offshore facilities above sea surfaces in ports	Understanding of the distribution of floating objects for the determination of the soundness of ports and the elimination of port obstacles	
Understanding the Geometry of Onshore Areas (**4.3**)	Understanding of the damage situations and determination of the usability of each port facility	Understanding of the scale of the emergency restoration work for quaywalls and cargo handling equipment	Acquisition of basic information for the restoration design of each facility Determination of the reasons for the damage
Understanding the Geometry of Underwater Areas (**4.4**)	Understanding of the distribution of debris on the seafloors of navigation channels and basins as well as in front of quaywalls Determination of available water depths for the temporary use of these facilities	Confirmation of the safety of waterways and basins, including navigation channels Understanding of the scale of emergency restoration work for mooring facilities, including piled piers	Acquisition of basic information for the restoration design of each facility Determination of the reasons for the damage
Understanding Broad-Based Ground Deformation (**4.5**)		Understanding of the tendencies of ground deformation in wide areas, including ports	Understanding of the tendencies and terminations of crustal movements in wide areas Understanding of fault structures
Surveys on Ground Liquefaction (**4.6**)		Confirmation of the safety of quaywalls, including aprons and yards Understanding of the scale of emergency restoration work for these facilities	Determination of the reasons for the damage Acquisition of basic information for the restoration design of each facility
Understanding the Cavities at Apron Sections (**4.7**)		Confirmation of the safety of quaywalls, including aprons and yards Understanding of the scale of emergency restoration work for these facilities	Determination of the reasons for the damage Acquisition of basic information for the restoration design of each facility
Understanding the Deformation on Underground Structures (**4.8**)			Determination of the reasons for the damage to underground structures, such as the steel piles of piled piers Acquisition of basis information for the restoration design of each facility

4.2 Understanding the Overall Damage Situation

4.2.1 General

When disaster occurs due to large earthquakes and tsunamis, it is necessary to promptly establish initial reaction systems. In order to understand the overall damage situation due to a large-scale disaster. At ports, it is necessary to have a general understanding of the overall damage situation of the onshore and offshore facilities above sea surfaces at the initial survey stage. Furthermore, at the emergency restoration survey stage, it is necessary to understand the usability of ports and distributions of floating objects to determine navigation routes.

Table 4.2.1 shows main survey methods for understanding the overall damage situation and its characteristics. Immediately after a disaster, visual observations such as note taking and sketching, and taking photos using cameras are major survey methods to assess the damages. Although these methods are simple, they are not suitable for observing damage situations in wide areas and are not available for observing damage situations at inaccessible locations. In contrast, aerial photography using UAVs (Unmanned Aerial Vehicles) or radio control balloons can be employed for understanding the damage situations at inaccessible locations. Similarly, satellites imagery and aerial photography can be employed for understanding the damage situations in wide areas.

The following sections describe the **utilization of satellite imagery (4.2.2)**, **aerial photography using aircraft (4.2.3)**, **aerial photography using UAVs (4.2.4)**, and **aerial laser surveys (4.2.5)**.

Table 4.2.1 Main Survey Methods for Understanding the Overall Damage Situation and the Characteristics of the Methods

Main survey method	Initial stage	Emergency restoration stage	Characteristic
Visual observation, note taking and sketching	○		Simple method available on site Not suitable for wide-area observations
Cameras and video cameras	○	○	Simple method available on site Not suitable for wide-area observations
Satellite imaging (**4.2.2**)	○	○	Implementation when disaster charter is activated Availability of a variety of information obtained through a variety of sensors
Aerial photography using aircraft (**4.2.3**)	○	○	Implementation when disaster charter is activated Availability of detailed and extensive information
Aerial photography using UAVs (**4.2.4**)	○	○	Availability of detailed information Suitable for the observation of narrow areas
Aerial photography using radio control balloons	○		Availability of detailed information Suitable for the observing small areas Longer airborne duration than UAVs
Aerial laser surveys (**4.2.5**)	○	○	Suitable for the observation of wide areas Availability of the detection of geography below trees

4.2.2 Utilization of Satellite Imagery

(1) Outline

Considering the difficulty in accessing damaged areas immediately after a large-scale disaster, satellite imagery can be used effectively to understand the damage situations in wide areas, such as entire port and its surrounding water areas. By comparing pre- and post- disaster satellite imagery, satellite imagery provides variety of useful information for understanding damage situations in wide areas shown in Item (3).

In the case of the 2011 Great East Japan Earthquake, imagery captured by X-band synthetic aperture radar satellite (TerraSAR-X) and numerous optical satellites were used for analyzing (estimating) inundated areas and monitoring submerged areas due to the tsunami.[1]

Currently, more than 20 satellite types are available in Japan, and satellite ground stations (antennas) have been in operation to quickly provide post-disaster information. Also, satellites have been used for surveying and remote sensing application services such as disaster prevention, agriculture, forestry and environment. These services have been developed by analyzing and processing satellite imagery.[2].

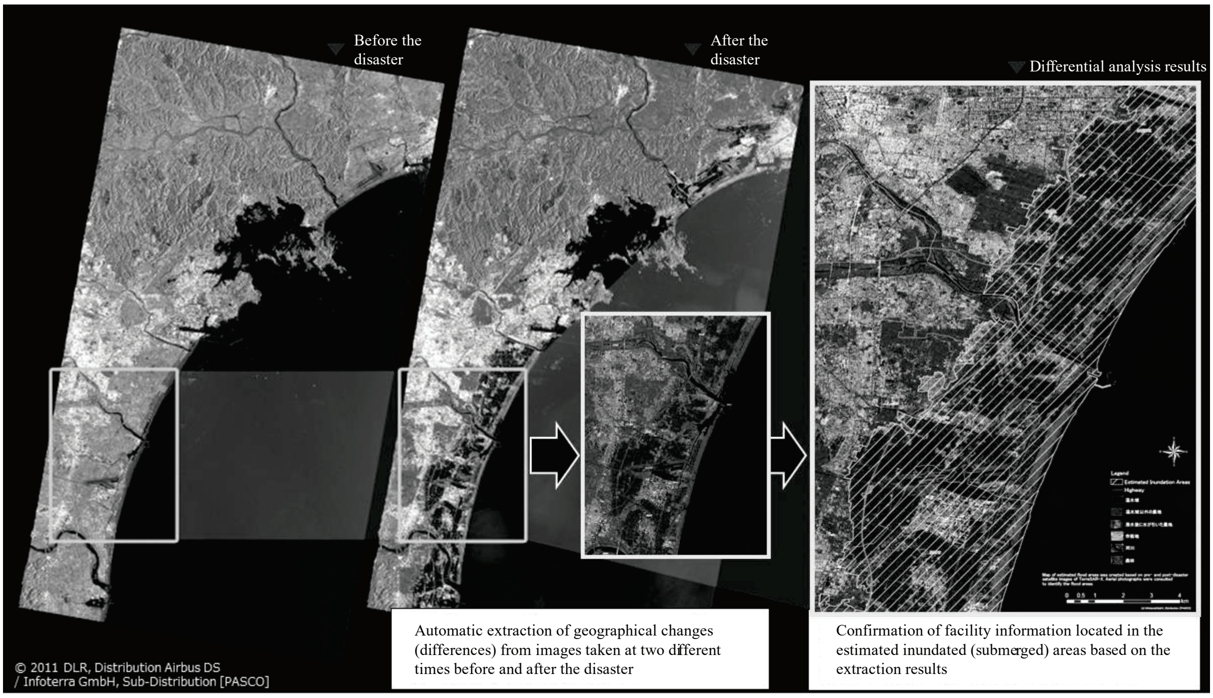


Fig. 4.2.1 Estimation of the Areas with Inundation Damage (at the Time of the Great East Japan Earthquake in March 2011)[1]

(2) Types and Characteristics of Observation Satellites

Earth observation satellites are classified into two types: (a) optical satellites and (b) SAR satellites. **Table 4.2.2** shows the usability and quick response capability of satellite images, and **Table 4.2.3** shows the characteristics of each type of satellite.

Table 4.2.2 Usability and Quick Response Capability of Satellite Images[3]

Wide areas	Instantaneously capturing imagery of wide areas	Effective means to acquire ground surface information of relatively wide areas without time lag
Reliablility	Capable of capturing images in bad weather	Increasing use of SAR satellites, which can capture images without being affected by weather conditions
Quickness	Quickly conduct change detection	By using pre-disaster archive imagery, changes can be quickly extracted by comparing imagery from two different acquisition date.

Table 4.2.3 Characteristics of Optical and SAR Satellites

Optical satellite	SAR satellite
○ Maximum resolution: 50 cm ○ Availability of color images × Cannot capture imagery under cloudy conditions and at night ○ Normally imagery is captured once a day ◎ Familiar imagery (can be understood by looking at them)	○ Resolution: 1 m, 0.25 m at most ○ Monochrome images only ◎ Capture imagery under rainy or cloudy conditions and at night ◎ Imagery is captured twice a day (morning and evening) ◎ Quickly conduct quantitative change extraction by semiautomatic analysis of two imagery taken at two different times pre- and post- disaster

*SAR: Synthetic Aperture Radar

(a) Optical Satellites

Currently, almost all commercially available digital map data has been created through image data obtained by aerial photography. Since it takes roughly 10 years to collect aerial photography for an entire area of Japan, it is nearly impossible to acquire or update the map data in within a certain time period.. In contrast, optical satellites can conduct data acquisition for an entire area of Japan within a month, thus ground surface change information can be extracted in a short period of time, resulting in fundamental changes in a way digital map is updated and maintained. In order to move towards an establishment of advanced digital map society, optical satellite has been used to create and update high resolution and updated digital map data..4)

(b) Synthetic Aperture Radar (SAR) Satellites

SAR satellites can be useful for quickly understanding the extensive damage of tsunamis and typhoons. In the cases of the Sumatra Earthquake and the Niigata Chuetsu Earthquake, it took a long time to assess damage situations in a secluded coastal and intermountain regions, therefore resulting in long delay in emergency response in those regions. SAR satellites are capable of measuring changes in ground surfaces during the day and night, and are not affected by weather conditions which makes it suitable for capturing damage situations and determine proper emergency measures. SAR satellites can also be used for monitoring crustal movements, ground subsidence and active faults for predicting volcanic activities and earthquakes.5)

(3) Obtainable Information and Methods for Utilization

By using satellite imagery, topics ① through ⑤ provides variety of information to assess the damaged situation for wide areas (mainly ports and the surrounding water areas).

① Understanding present damage situation of port facilities (mainly by using optical and SAR satellites)

- Assessing damage situation of port facilities and surrounding areas from wide swath imagery
- Assessing damage situation of facilities such as breakwaters and quaywalls, through wide swath imagery
- Assessing present obstructive situation of navigation channels due to the accumulation of debris and floating objects
- Assessing situation of the settlement of quaywalls and wharf areas

② Estimating damaged and inundated areas (mainly by using optical and SAR satellites)

- Automatic extraction of geographical changes (differences) from two imagery taken at two different times pre- and post-disaster to estimate the damaged areas
- Understanding the estimated inundated (submerged) areas through images regularly taken after the disaster

③ Estimating the amount of debris and floating objects (mainly by using optical satellites)

- Understanding the amount of debris based on the damaged areas extracted and estimated through images regularly taken after the disaster

④ Comparing port facilities pre- and post-disaster (mainly by using optical satellites)

- Detailed extraction of the misalignment of the normal lines of facilities from two imagery taken at two different times pre- and post- disaster to estimate the damaged areas to determine the usability of these facilities

⑤ Assisting in field surveys (mainly by using optical and SAR satellites)

- Assistance in the determination of the prioritized locations for the field surveys until the tsunami warnings and advisories are lifted

Differences in use of data obtained through optical and SAR satellites are as follows. Imagery obtained by optical satellites can be used to assess the extent of the damages from the disaster. Although the resolution of a SAR imagery is inferior to that of optical satellites, SAR satellites can be used even in a bad weather. It can be used to understand changes in land coverage and ground deformation by analyzing two imagery taken at two different times pre- and post- disaster.

4.2.3 Aerial Photography Using Aircraft

(1) Outline

Considering the difficulty in accessing damaged areas immediately after the occurrence of a large-scale disaster, aerial photography using aircraft can be effectively utilized for understanding the damage situations in wide areas (entire ports and the surrounding water areas) immediately after the occurrence of a disaster. Basically, images shall be taken by oblique and vertical shooting using digital cameras. Digital surface models (DSM) and digital elevation models (DEM) obtainable through concurrent implementation of the aerial laser measurement (surveying) to be described in **Reference [Part II], Chapter 2, 4.2.5** with aerial photography enable the amount of debris to be estimated.

With aerial photography using aircraft, the types of cameras generally used are handheld cameras for oblique shooting and dedicated aerial cameras (vertical cameras and oblique cameras). The oblique cameras can perform vertical and oblique shooting concurrently.

(2) Obtainable Information

The results of the aerial photography, or the results of the aerial laser measurements implemented concurrently with the aerial photography, can be used for obtaining the same information as that obtainable through optical satellite photography among a variety of information for understanding the damage situations (**Reference [Part II], Chapter 2, 4.2.2 Utilization of Satellite Photography (3**) in wide areas (entire ports and the surrounding water areas) immediately after a disaster. However, these results cannot be used for the automatic extraction of inundated areas through multi-spectrum analyses, unlike in the case of optical satellite photography.

The following section describes the types of images and an outline of the information specific to aerial photography using aircraft.

① **Vertical images**

Aerial images are generally vertical images taken using dedicated cameras. These vertical images are texture images of vertical planes, which are generally roads and the roofs of buildings. The vertical images taken in the course of a survey after a large earthquake and tsunami can be used for understanding the outline of the damage situations of the entire port (collapse and inundation situations and positional relationships).

② **Oblique images**

Oblique images are taken in oblique directions from aircraft using handheld cameras or dedicated cameras (oblique cameras). These oblique images are bird's-eye images, which are advantageous in making positional relationships of the subjects with the surrounding objects, and the sizes as well as three-dimensional shapes of subjects easily understood. As with Item ① above, the oblique images can be used for understanding the outline of the damage situations of the entire port (collapse and inundation situations and positional relationships).

Fig. 4.2.2 Example of a Vertical Image (the Ofunato area at the time of the Chilean Earthquake in 1960)[6)]

Fig 4.2.3 Example of an Oblique Image (Kesennuma City, Miyagi Prefecture, at the time of the Great East Japan Earthquake)[7)]

③ Orthophotos and three-dimensional models

Orthophotos are composite images created by connecting vertical images with identical scales so as to cover wide areas and using elevation data when vertical images are taken with the positions of the respective vertical images adjusted through aerial triangulation. In many emergency cases, the processing time to generate orthophotos is shortened by using the data of GNSS/IMUs (the measuring positions of aircraft) and elevation data.

Orthophotos can be used for directly generating three-dimensional point groups, which can be output as three-dimensional models. Then, using the three-dimensional models as the latest elevation data, updated orthophotos can be generated. In addition, the three-dimensional models can be used for three-dimensional measurements (of the amounts of debris, etc.) in damaged areas.

Fig. 4.2.4 Example of an Orthophoto (Ishinomaki City, Modification of Reference 8))

4.2.4 Aerial Photography Using UAVs (Unmanned Aerial Vehicles)

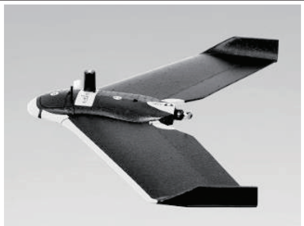
(1) Outline

Considering the difficulty in accessing damaged areas immediately after the occurrence of a large-scale disaster, aerial photography using UAVs (also called drones or UASs [Unmanned Aerial Systems]) is effective in understanding the damage situation in relatively small areas (a few ha to a few km^2).

Recently, aerial photography using UAVs has been used for researching and surveying object areas smaller than those of aerial photography using aircraft. There have also been cases of coastal surveying through aerial photography using UAVs.[9)] Aerial photography using UAVs is particularly effective in observing those places in ports which need to be surveyed urgently, cannot be observed directly (due to obstacles blocking access), and are difficult to access (such as offshore breakwaters).

Table 4.2.4 shows the types of UAVs and their outlines.

Table 4.2.4 Outlines of Several Types of UAVs

Type	Rotating wing		Fixed wing
	Single rotor	Multiple rotor	
Photograph			
Power source	Gasoline	Motor	Gasoline or motor
Flight performance	• Limitation in flight altitudes • Longer flight time and larger payload (can carry a large amount of weight) compared to the battery type	• High flight stability • Can be used at high flight altitudes (1000 m or higher) • Requires an onboard battery, which is susceptible to cold temperatures and reduces flight times	• Longer flight time and distances compared to rotating wing types • Requires a large area for taking off and landing

(2) Obtainable Information

Aerial photography using UAVs can be used for obtaining the same information as that obtainable through optical satellite photography among the variety of information for understanding the damage situations (**Reference [Part II], Chapter 2, 4.2.2 Utilization of Satellite Photography (3**) in relatively small areas (a few ha to a few km^2) immediately after a disaster. However, aerial photography using UAVs cannot be used for the automatic extraction of inundated areas through multi-spectrum analyses, unlike in the case of optical satellite photography.

The types of information specific to aerial photography using UAVs are as follows.

① **Aerial photographs and videos**

In addition to aerial photographs, aerial videos become available by changing the types of cameras mounted on the UAVs. Although the image quality is not favorable due to band limitations, real-time videos can be observed on the ground by communicating with the UAVs.

② **Three-dimensional models and orthophotos**

The photographs taken with UAVs can be used for generating three-dimensional models and creating orthophotos through photographic surveying. Owing to the popularization of software using SfM (Structure from Motion), aerial photographs can be easily processed into three-dimensional point group data and three-dimensional models with texture images.[10)] UAVs enable the three-dimensional models of locations under overhangs to be generated, as shown in the right side of **Fig. 4.2.5**, by photographing these locations sideways. Orthophotos can also be used for photomaps of damaged areas. In addition, the three-dimensional models generated from orthophotos can be used for measuring the damage situations (e.g., the inclinations of buildings).

Fig. 4.2.5 Example of a Three-Dimensional Model of a Coastal Cliff[11)]

4.2.5 Aerial Laser Surveys

(1) Outline

Considering the difficulty in accessing damaged areas immediately after the occurrence of a large-scale disaster, laser surveys using aircraft (aerial laser surveys) are effective for understanding the damage situations in wide areas (entire ports and the surrounding water areas) immediately after a disaster.

In aerial laser surveys, the sensor units (laser scanners, GPS/IMUs and digital cameras) mounted on board aircraft are used for acquiring laser point group data (elevation data) of wide areas by combining three-dimensional data (DSM/DEM) with two-dimensional digital images taken with digital cameras. The laser point group data can be processed into microtopography three-dimensional maps and sedimentation variation distribution maps. Furthermore, in surveys after a large earthquake and tsunami, comparing the laser point group data before and after the disaster enables the amounts of debris to be estimated and ground subsidence to be confirmed.

In addition, there are cases where the damage situations of shallow water areas around port facilities become obtainable by combining general aerial lasers with ALB (Airborne LiDAR Bathymetry).

(2) Obtainable Information

① Three-dimensional terrestrial topographic information

Aerial laser surveys are capable of acquiring three-dimensional topographic information of the ground surfaces even when the ground surfaces are covered with vegetation such as trees. **Fig. 4.2.6** shows an example of a digital surface model (DSM) representing the ground surface information, including trees, and a digital elevation model (DEM) representing topographic information. DSMs and DEMs are generally used as two-dimensional images represented by gradient tint maps, shaded-relief maps and red-relief maps.

In the case of the surveys after a large earthquake and tsunami in ports, DSMs can be directly used for understanding the damage situations of buildings and distribution patterns of debris. **Fig. 4.2.7** shows an example of the measurement of the damage situation (washing out and inundation) in Ishinomaki Port after the Great East Japan Earthquake.

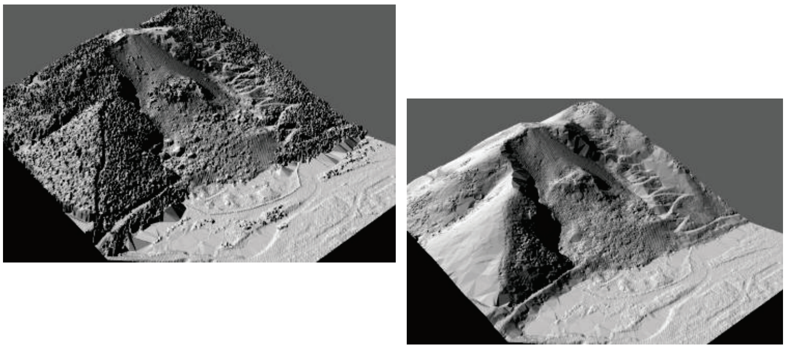


Fig. 4.2.6 DSM (Left) and DEM (Right)[12)]

Fig. 4.2.7 Example of an Aerial Laser Survey in a Port (Vicinity of Ishinomaki Port, Modification of the Port in Reference 8))

② **Sounding information in shallow water areas through ALB**

Seafloor topography and obstacles to ship navigation in shallow water areas can be measured by irradiating the seafloor with both normal near-infrared pulses used in laser measurements and green pulses, which transmit through seawater. In addition, water depths can be calculated as the differences between the elevations measured through the pulses reflected on sea surfaces and those reflected on the seafloor. Although there may be cases where ALB cannot be used in the water areas around port facilities immediately after a disaster, because measurements with ALB are subjected to the wave conditions, ALB is generally capable of measuring water depths 1.5 times the underwater visibility. ALB is also capable of measuring seafloor topography of extremely shallow water areas (-3 m or less) where measurements with narrow multi-beam echo sounders are not available or are inefficient (**Fig. 4.2.8**).

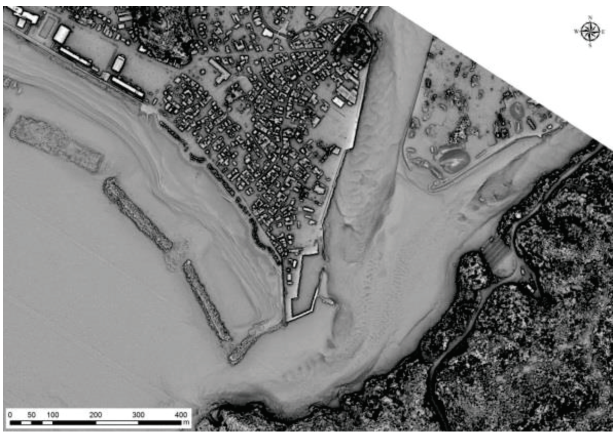


Fig. 4.2.8 Example of a Measurement with ALB
(at the Mouth of the Hioki River, Shirahama Town, Wakayama Prefecture)[13)]

4.3 Understanding the Geometry of Onshore Areas

4.3.1 General

In order to utilize ports as disaster relief bases after a large earthquake and tsunami, it is first necessary to understand the damage situation of the onshore facilities in the ports. For the requirements of the three survey stages, a general understanding of the damage situation of the port facilities, a determination of the usability of the quaywalls and cargo handling equipment, and the acquisition of basic information for the restoration design and investigation of the reasons for the damage are required in the initial, emergency restoration and full-scale restoration stages, respectively.

Table 4.3.1 shows the main survey methods for understanding the damage situation of the structures above ground, the geography and the geometry of the structures. In the initial stage, an understanding of the damage situations is made mainly through visual confirmation, cameras and video recordings, as well as by shooting images with UAVs. In the emergency restoration stage, measurements using staffs and rods are additionally used for understanding the damage situations. In the full-scale restoration stage, a topographic survey is additionally implemented to understand the geometry of the structures above ground. The deliverables of the topographic survey in this stage need to be as accurate as those of a general topographic survey when the situation is normal.

It is expected that extensive crustal movements cause the existing control points to be put out of commission when topographic surveys are to be implemented after a large earthquake and tsunami. Thus, in the following section, based on the assumption that new control points are set through satellite positioning for a topographic survey in the full-scale restoration stage after an earthquake, outlines of the satellite positioning methods and utilization methods of the respective satellite positioning methods after an earthquake are described in the order of: **4.3.2 Precise Point Positioning with Ambiguity Resolution (PPP-AR)**; **4.3.3 Real-Time Kinematic Survey**; and **4.3.4 Network-Type VRS-RTK-GNSS**.

Table 4.3.1 Survey Methods for Understanding the Geometry of Structures above Ground

<table>
<tr><th>Initial stage</th><th>Emergency restoration stage</th><th colspan="3">Full-scale restoration stage</th></tr>
<tr><td rowspan="5">Visual confirmation, note-taking, cameras, video recordings and imaging with UAVs</td><td rowspan="5">Visual confirmation, note-taking, cameras, video recordings, imaging with UAVs, and measurements with staffs, rods, pin holes and levels</td><td rowspan="5">Topographic survey</td><td>Control point survey</td><td>PPP-AR</td></tr>
<tr><td>Plane survey</td><td>Total station (TS), RTK method, UAV, VRS-RTK method*</td></tr>
<tr><td>Cross-section survey</td><td>TS, leveling instruments (auto levels, etc.)</td></tr>
<tr><td>Settlement survey</td><td>Leveling instruments (auto levels, etc.)</td></tr>
<tr><td>Displacement survey</td><td>TS, laser surveys</td></tr>
</table>

*: Not available in the event of the occurrence of crustal movements

4.3.2 Precise Point Positioning with Ambiguity Resolution (PPP-AR)

(1) Outline

The PPP-AR is a positioning method capable of point positioning by receiving precise orbit information and clock information from GNSS satellites as correction data in real time, and measurements with an accuracy of ±5 cm in vertical and horizontal directions under favorable conditions (**Fig. 4.3.1**).

The correction data enables highly precise positioning data to be obtained in an area with a 1000-km radius with a local control point not affected by crustal movements as its center. The time required for measuring a position is 30 minutes for the initial setting and another 20 minutes for satellite observation.

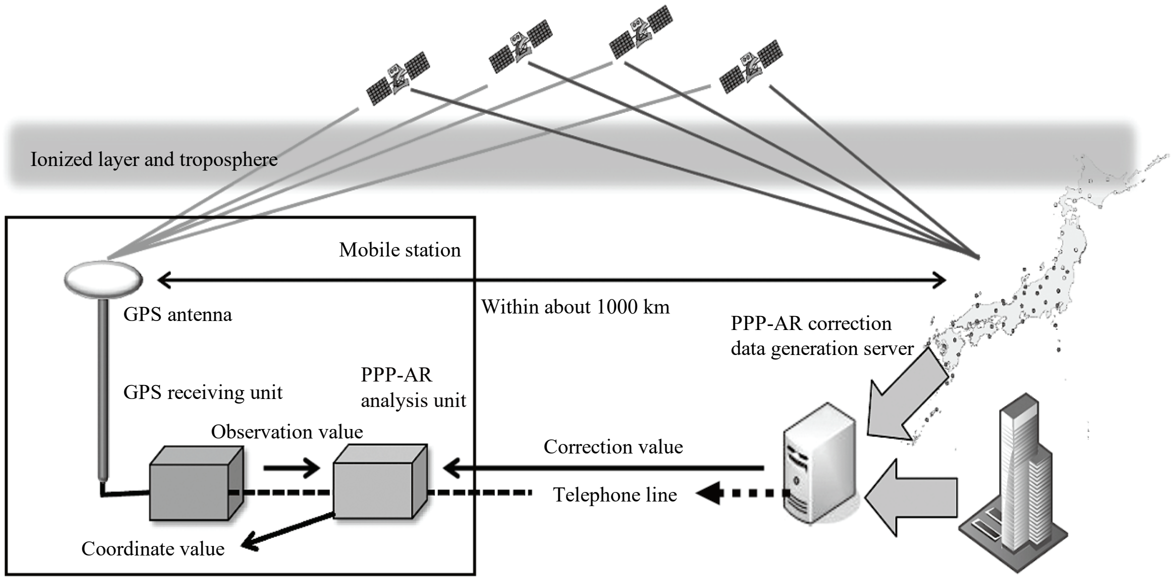


Fig. 4.3.1 Outline of Precise Point Positioning with Ambiguity Resolution (PPP-AR)

(2) Use of the PPP-AR after a Large Earthquake and Tsunami

① The positioning results of the PPP-AR can be used for setting temporary control points immediately after an earthquake even when the existing control points, including electric control points and benchmarks, are out of commission due to crustal movements (refer to **Reference [Part II], Chapter 2, 4.3.3 Real-Time Kinematic Survey**).

② The PPP-AR enables the coordinates (JGD) and elevations (CDL) of the main control points to be easily established even on facilities isolated from land, such as breakwaters.

③ The PPP-AR enables the elevation observation of B.M. installed near temporary tidal observatories.

④ The equipment of the PPP-AR has not been used in general surveys because there have been no provisions pertaining to the PPP-AR in the public survey work rules. In order to use the PPP-AR method in emergency cases, it is necessary to prepare the facilities and receive training.

4.3.3 Real-Time Kinematic (RTK) Survey

(1) Outline

As shown in **Fig. 4.3.2**, the RTK survey obtains a baseline vector between a known point (control point: base station) and a new point (mobile station) based on corrected observation data wirelessly transmitted from the known point and the GNSS radio waves acquired at the new point, instantaneously calculates the coordinates of the new point, and displays the observed data on a GNSS controller mounted on the mobile station. The observation accuracy of the RTK survey is ±2 to 5 cm and ±5 to 7 cm in horizontal and vertical directions, respectively.

Because the RTK survey requires the wireless transmission of data from the base stations, the availability of high accuracy measurements is limited to a relatively small range (with a radius of about 500 m) from the base stations. The time required for measurements through the RTK survey is 1 minute for the initial setting and another 10 seconds for satellite observations. Thus, the RTK enables observations to be performed in real time.

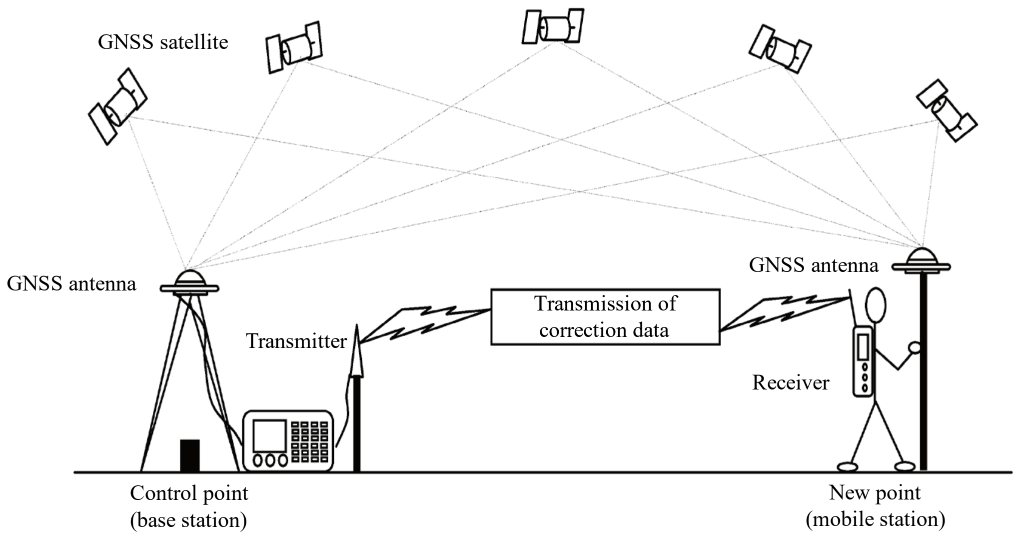


Fig. 4.3.2 Schematic Drawing of an RTK Survey[14)]

(2) Utilization of the RTK Survey after a Large Earthquake and Tsunami

① The RTK survey cannot be used when the control points near the damaged areas are out of commission due to crustal movements or damage caused by the earthquake, as was the case with the Great East Japan Earthquake. However, the RTK survey becomes available by using temporary control points installed through the PPP-AR as base stations, as described in **Reference [Part II], Chapter 2, 4.3.2 Precise Point Positioning with Ambiguity Resolution (PPP-AR)**.

② The RTK survey system under development by the Port and Airport Research Institute will enable the relative positional relationships between the control points and port facilities to be measured regardless of the presence or absence of ground deformation, thereby allowing for displacement to be measured for determining the usability of the quaywalls, even immediately after the earthquake.[15)]

4.3.4 Network-Type VRS-RTK-GNSS (Virtual Reference Station-Real-Time Kinematic-Global Navigation Satellite System) Survey

(1) Outline

In a network-type VRS-RTK-GNSS survey, the virtual control points around the mobile stations are established (in software) from the data on the electronic control point networks if no control points exist within 20 km of the mobile stations. The network-type VRS-RTK-GNSS survey can calculate the positions of new points in real time in a manner that transmits the approximate positions of the new points to a distributor through a mobile telephone circuit, receives the observation data and correction information for the virtual control points, and performs base line analyses using the virtual control points and new points (**Fig. 4.3.3**). The observation accuracy of the network-type VRS-RTK-GNSS survey is about ±3 to 5 cm in a horizontal direction and about ±5 to 10 cm in a vertical direction under favorable conditions.

With the virtual control points automatically set around the mobile stations, the network-type VRS-RTK-GNSS survey enables wide-area positioning to be performed.

The time required for a measurement through the network-type VRS-RTK-GNSS survey is about 1 minute for the initial setting and another 10 seconds for satellite observations. Thus, the RTK enables observations to be performed in real time.

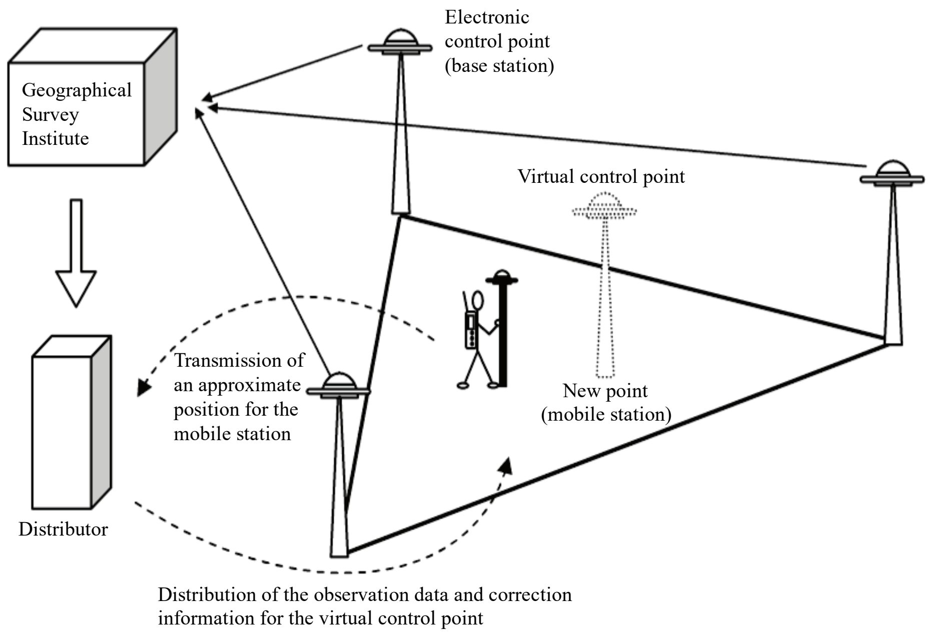


Fig. 4.3.3 Schematic Drawing of a Network-Type VRS-RTK-GNSS Survey[14)]

(2) Utilization of the Network-Type VRS-RTK-GNSS Survey after a Large Earthquake and Tsunami

① The network-type VRS-RTK-GNSS survey cannot be used when the electronic control points near the damaged areas are out of commission due to crustal movements or damage caused by earthquakes, as was the case with the Great East Japan Earthquake (because the Geographical Survey Institute stopped data distribution).

② In the case of the Great East Japan Earthquake, the Geographical Survey Institute resumed the distribution of data on new electronic control points two and a half months after the earthquake.

4.4 Understanding the Geometry of Underwater Areas

4.4.1 General

In order to utilize ports as disaster relief bases after a large earthquake and tsunami, it is first necessary to determine the damage situation and debris accumulated on the seafloor of the navigation channels, basins and underwater sections of the breakwaters and mooring facilities. In the initial and emergency restoration stages, surveys are required for confirming the safety of waterways and basins, including navigation channels, and determining the usability of mooring facilities, such as piled piers and sheet pile quaywalls. In the full-scale restoration stage, surveys are required for the acquisition of basic information for the restoration design and investigation of the reasons for the damage.

The methods to understand the underwater conditions and water depths are based in optical devices (e.g. still and video cameras) that collect images, and swath sounding devices (e.g. narrow multibeam swath sounders) that measure water depths, in addition to the visual confirmations by divers and lead sounding.

Table 4.4.1 shows the main survey methods for understanding the conditions of the underwater sections and water depths. In the initial and emergency restoration stages, because of the urgent need to quickly measure the water depths and understand the debris accumulated on the seafloor in large areas, including navigation channels, basins and the water areas in front of mooring facilities, it is effective to implement swath sounding (refer to **Reference [Part II], Chapter 1, 2.6 Bathymetric Survey** and **Reference [Part II], Chapter 1, 2.7 Swath Sounding**) using survey boats (with capacities of about 70 PS). In the full-scale restoration stage, because of the need to determine and acquire detailed information on the deformation of the facilities, it is effective to implement acoustic sounding using acoustic cameras and underwater three-dimensional cameras in addition to the above sounding.

The following section describes several types of acoustic equipment used to measure underwater features, focusing on their use in areas affected by a large earthquake and tsunami: **4.4.2 Swath Sounders**, **4.4.3 Side Scan Sonars** and **4.4.4 Acoustic Video Cameras and Underwater Three-Dimensional Scanners**. In the full-scale restoration stage, it is also necessary to detect the deformation of the vertical plane of the structures above sea level, in addition to the deformation of the underwater sections of breakwaters and mooring facilities. In such cases, to detect the deformation of the vertical plane of the structures above the sea level can be surveyed by mounting laser scanners, widely used in onshore topographic surveys, on the survey boats. To that end, **4.4.5 Laser Scanners Mounted on Survey Boats** is described at the end of this section.

Table 4.4.1 Methods for Understanding the Geometry of Underwater Areas

	Initial and emergency restoration stages	Full-scale restoration stage
Navigation channels and basins (waterways and basins)	(Confirmation of safety) ① Water areas where survey boats with a capacity of about 70 PS are navigable ● Narrow multibeam swath sounding machines ● Interferometry swath sounding machines ● Side scan sonars, etc. ② Water areas where boats with outboard engines are navigable ● Single beam echo sounders ● Lead sounding ● Underwater three-dimensional scanners, etc.	(Sounding) ① Understanding of water depths for disaster assessments Restoration design (dredging design, etc.) ● Narrow multibeam swath sounding machines ● Single beam sounders
Structures such as breakwater and mooring facilities and water areas in front of these structures	(Confirmation of safety) ① Water areas where survey boats with a capacity of about 70 PS are navigable ● Narrow multibeam swath sounding machines ● Side scan sonars, etc. ② Water areas where survey boats are not navigable due to floating debris ● Visual confirmation by divers ● Underwater cameras, underwater video cameras, etc.	(Survey for restoration design) ① Detailed measurements of facility deformation [Underwater section] ● Narrow multibeam swath sounding machines ● Side scan sonars ● Acoustic video cameras ● Underwater three-dimensional scanners ● Underwater cameras, underwater video cameras, etc. [Vertical plane of the structures above sea surfaces] ● Laser scanners mounted on board survey boats

4.4.2 Swath Sounders

(1) Outline

Swath sounding is a method for batch measurements of water depths at multiple measuring points during the navigation of survey boats in a manner that emits acoustic beams with sharp directivity toward the seafloor in a port-starboard direction. In swath sounding, the measured raw data is subjected to several types of processing (noise reduction, oscillation correction such as pitch and roll of the survey boats, tidal correction etc.) and is finally converted into planar bathymetric data (seafloor topographic data). Depending on the sounding principles, swath sounding is classified into a multibeam system (alternatively called a “narrow multibeam system”) and an interferometry system.

The interferometry system has a wide swath angle, allowing it to collect depth soundings in large areas on a single operation. However, since the interferometry system requires a lot of effort during the noise reduction processing, it takes a relatively long time to produce deliverables. In addition, it shall be noted that the interferometry system is likely to have larger measurement errors in shallow water areas, and the areas immediately beneath the transducers have a distribution of measuring points that is less dense than the other areas, which might create the possibility of overlooking anomalies on the seafloor. Thus, careful consideration shall be given to the survey line intervals. When measuring the anomalies (deformations) of structures using swath sounders, there may be cases where the collected data of acoustic reflections do not correspond to the actual structures, caused by defused reflections of the acoustic waves. In contrast, the narrow multibeam systems can be used for both the sounding and detection of obstacles with highly reliable sounding data.

For the details of swath sounding, refer to **Reference [Part II], Chapter 1, 2.6 Bathymetric Survey** and **Reference [Part II], Chapter 1, 2.7 Swath Sounding**.

(2) Obtainable Information and Points to Consider

① **Initial and emergency restoration stages**

(Obtainable information)

Swath sounding can be used to confirm the water depths of navigation channels and basins and the water areas in front of mooring facilities after an earthquake, and the distribution states of debris floating into the sea, which has accumulated on the seafloor as a result of the disaster, can be obtained. Thus, swath sounding can be used for acquiring information (to confirm safe navigation areas, positions of the obstacles and the areas that need dredging etc.) necessary for the elimination of port obstacles.

(Points to consider)

i) Simplification of patch tests

For swath sounding implemented for the elimination of port obstacles, by taking into consideration the emergency situation, a simplified patch test can be used in place of the test specified in **Reference [Part II] , Chapter 1, 2.7 Swath Sounding** (an offset correction of each sensor in the sounding system, a correction of the deflection of the installation angles of the transducers [bias] and a correction of the recording delays for each device). An ordinary patch test is implemented daily with respect to the parallel and round-trip survey lines, and if necessary, cross survey lines, if necessary, in addition to the actual measurement. In the simplified version, a patch test can be implemented with respect to the actual survey line data.

ii) Conversion to water depths using temporary chart datum level

In the emergency restoration stage, the chart datum level affected by crustal movements cannot be used as they are. Thus, in the emergency restoration stage, the swath sounding data can be converted to water depths by using the temporary chart datum level set in accordance with **Reference [Part II], Chapter 2, 3.2 Emergency Setting of Chart Datum Level**. In the implementation of the elimination of port obstacles, abnormal objects on the seafloor need to be treated as abnormalies points instead of noise.

iii) Selection of equiangular mode

The narrow multibeam system requires a large number of survey lines in shallow water areas so as not to leave any unmeasured water areas. Considering the improved availability of the types of swath sounding machines capable of changing beam forming systems in recent years, it is preferable to implement highly accurate measurements by adopting an equiangular mode when exploring abnormal objects on the seafloor of shallow water areas.

② **Full-scale restoration stage**

(Obtainable information)

Swath sounding can clarify the clarify the states of displaced or scattered armor and wave-dissipating blocks for breakwater mounds, and the scope as well as quantities of the restoration work for displaced or scattered blocks, thereby contributing to the restoration design of the facilities.

Swath sounding is effective in obtaining information for formulating the design and construction plans pertaining to the overall restoration work, such as the states of scouring and debris accumulation in front of the revetments and quaywalls, as well as the deformation of the revetments and quaywalls, necessary for formulating the design and construction plans pertaining to the overall restoration work.

4.4.3 Side Scan Sonars

(1) Outline

Side scan sonars are capable of obtaining planar acoustic image records of a certain width in a manner that laterally emits ultrasonic waves in a fan-like formation toward the seafloor from a device (side scan sonar) towed by a survey boat, and receives the ultrasonic waves reflected off the seafloor or underwater structures (refer to **Fig. 4.4.1**). Sounding conducted by a side scan sonar can classify the seafloor materials (mud, sand and gravel) relatively, and detect the states of the displaced or scattered blocks through planar imaging, as it generates images of the reflected wave intensity (refer to **Fig. 4.4.2**). Side scan sonars are highly convenient, because they are compact and user friendly, they can be used in narrow and shallow water areas, and they come in a wider variety of popular models than narrow multibeam echo sounders.

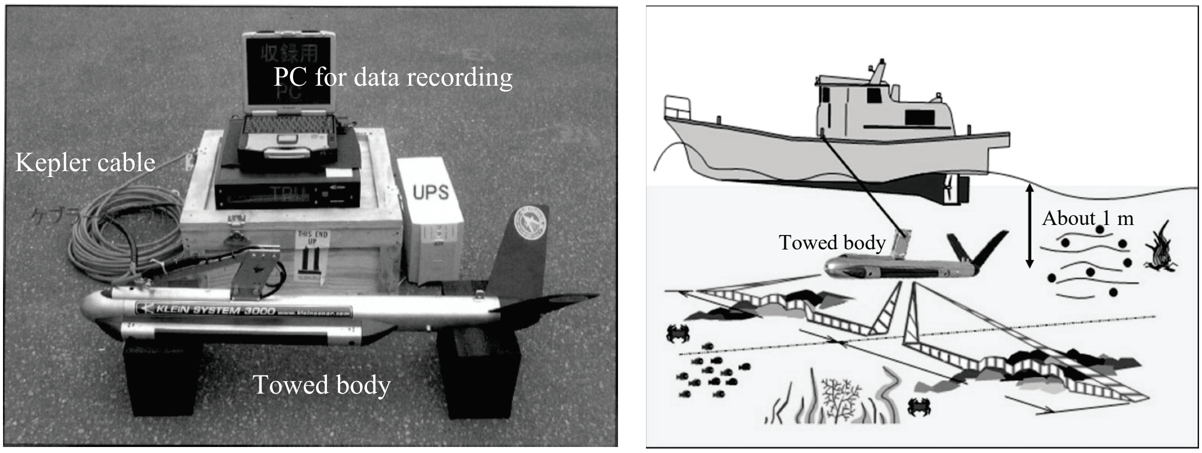


Fig. 4.4.1 Side-Scan Sonar and Schematic Drawing of a Side-Scan Sonar Towed for Sounding

Fig. 4.4.2 Image Obtained Using a Side-Scan Sonar
(State of Displaced and Scattered Foot Protection Blocks of a Damaged Breakwater)

(2) Obtainable Information and Points to Consider

① **Initial and emergency restoration stages**

(Obtainable information)

Side scan sonars can detect the distribution states (planar positions) of debris (including containers and vehicles) accumulated on the seafloor in navigation channels, basins and water areas in front of mooring facilities after the disaster, contributing in determining safe water areas for navigation and detecting the presence of unsafe obstacles for navigation.

(Differences between swath sounding machines and side scan sonars)

In the initial and emergency restoration stages, the scattering intensity data obtained by swath sounders (refer to **Reference [Part II], Chapter 1, 2.7 Swath Sounding** and **Reference [Part II], Chapter 2, 4.4.2 Swath Sounders**) may be used for detecting submerged debris, but swath soundings require too much time for a data analysis to produce quick estimations at the sites. In contrast, side scan sonars can detect debris of certain sizes on the monitor screens onboard survey boats during sounding.

Furthermore, there may be cases where inundation due to tsunamis temporarily generates suspended mud above the seafloor of shallow waters. In such cases, acoustic waves with frequencies of 200 to 400 kHz normally used in swath sounders cannot reach objects below the upper surfaces of the suspended mud. In contrast, acoustic waves with frequencies of about 100 kHz used by side scan sonars can penetrate suspended mud, and therefore have a high possibility of detecting debris in the suspended mud (it is also difficult for divers to visually identify debris in suspended mud).

(Points to consider)

During soundings by side scan sonars, the debris scattered on the seafloor can be identified as objects of particularly strong reflections on a monitor screen on board the survey boat. The positions of the objects of particularly strong reflections are then recorded in a computer and analyzed on shore later for final confirmation of whether or not these objects represent debris or not. **Fig. 4.4.3** shows a typical example of an image on a monitor screen of a side scan sonar that has been determined to be debris.

In the case of the elimination of port obstacles requiring an urgent determination of debris, the data of the estimated types and positions of the objects can be used as the information for the port obstacle removal work. In such cases, it is preferable to obtain the information on the approximate water depths of these objects.

Generally, after measuring with a side scan sonar, the records of the survey lines are compiled on a single mosaic seafloor topographic map to enable the overall distribution of the debris to be understood. It is also preferable to organize the data on the positions (latitudes and longitudes and national coordinates), lengths and widths of the objects determined to be debris in entirely explored water areas to enable the data to be effectively used in the obstacle removal work.

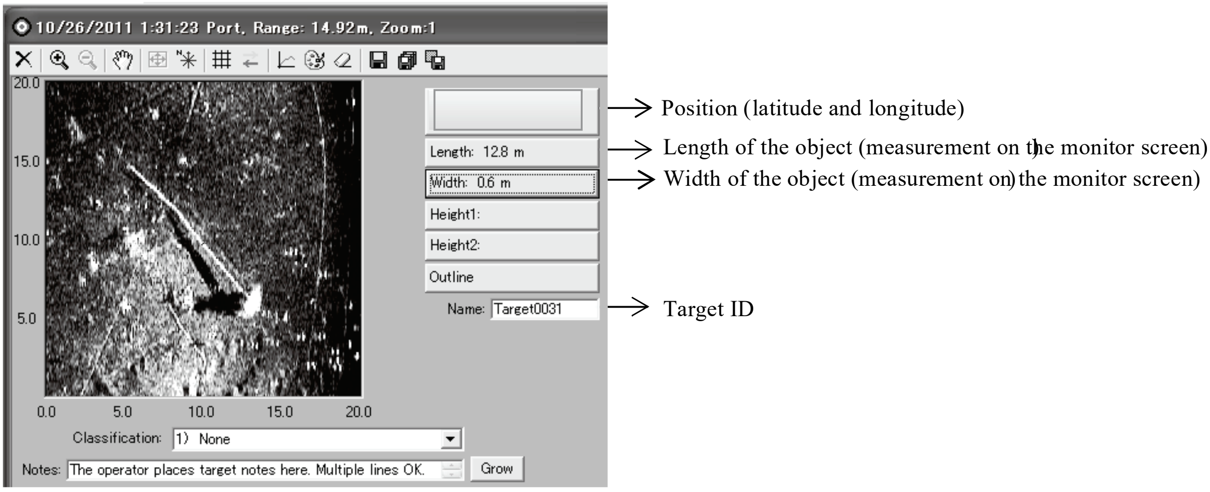


Fig. 4.4.3 Example of a Recording from a Side-Scan Sonar (Japanese Cedar Driftwood)

② **Full-scale restoration stage**

(Obtainable information)

In the full-scale restoration stage, side scan sonars can be used to obtain information on the states of the displaced and scattered armor and wave-dissipating blocks of sloping breakwaters in shallow water. This information can be used for determining the scopes and quantities of the block restoration work and in the restoration design of the facilities.

4.4.4 Acoustic Video Cameras and Underwater Three-Dimensional Scanners

(1) General

The information required in the full-scale restoration stage are the detailed deformation states of the underwater sections of facilities in relatively wide areas, which can be effectively obtained through acoustic imaging sonars. These sonars visualize underwater spaces or measure coordinates using acoustic waves. Although acoustic imaging sonars can be used in turbid waters with low visibility, or in nighttime measurements with low illuminance using the physical properties of the sound waves, they may have fuzzy images or incorrect coordinate data due to unnecessary responses generated by multipath or residual images in narrow indented water areas.

Acoustic imaging sonars can be selected from a variety of models for different types of transmission and reception as well as image provision systems. Thus, it is important to select models suitable for the use purposes. Among the various types, a device capable of displaying real-time acoustic images (acoustic video cameras) and a device capable of conducting surveys using acoustic data (underwater three-dimensional scanners) are described below.

(2) Acoustic Video Cameras

① Outline

Acoustic video cameras (refer to **Fig. 4.4.4**) are acoustic imaging sonars capable of sequential updates of high-resolution acoustic images of two-dimensional underwater spaces. Although acoustic video cameras are not suitable for surveying comparatively large water areas because of their narrow angle of view, they can be used for detailed (close range) investigations of comparatively narrow water areas, and, therefore, are suitable for detailed visual surveys of deformed sections identified through wide range explorations. Outputting measured data is not available with general models because the measured data are two-dimensional video images. In contrast, the acoustic video cameras developed by the Port and Airport Research Institute (refer to Item ③ below) are capable of outputting such data.

In addition to the method for visualizing underwater spaces with acoustic video cameras attached to survey boats, they can be carried by divers or mounted on ROVs or AUVs, taking advantage of their reduced size and weight and energy-saving performance.

Fig. 4.4.5 shows the comparison of an image of an underwater section of a steel sheet pile taken by an acoustic video camera on the left side, with an image of an above-water section of a steel sheet pile taken by an optical camera on the right side.

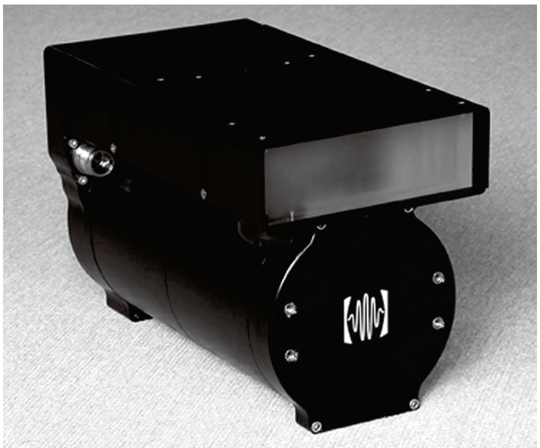


Fig. 4.4.4 Acoustic Video Camera[16)]

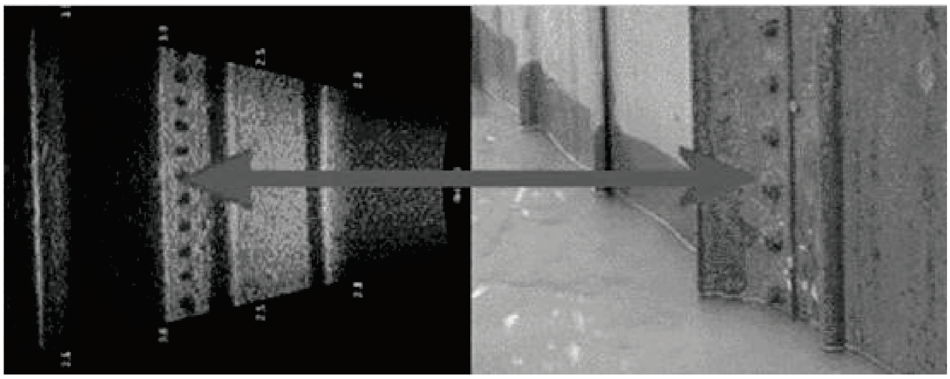


Fig. 4.4.5 Underwater Section of a Steel Sheet Pile Taken by an Acoustic Video Camera (Left) and Above-Water Section of a Steel Sheet Pile taken by an Optical Camera (Right) (provided by the manufacturer)

② **Obtainable information and points to consider**

(Obtainable information)

In the full-scale restoration stage, acoustic video cameras can be used effectively for detailed investigations of deformed sections identified through wide area explorations. For example, acoustic video cameras are suitable for detailed (close range) visual investigations of comparatively narrow areas, such as underwater sections with suspected damage on the mooring facility or revetment.

In addition, by taking advantage of their high update rates, acoustic video cameras can be used for visualizing the movements of objects in real time (e.g., the monitoring of oil leaks from underwater pipelines, or the safety monitoring of underwater work by divers).

(Points to consider)

Acoustic video cameras are:

- not suitable for wide-area explorations because of their narrow angle of view;
- not suitable for coordinated measurements because of the two-dimensional display of the azimuth direction and range;
- not physically capable of observations of small cracks and corrosion because of the limitations in the acoustic wavelengths expressed by wavelength (m) = acoustic velocity 1500 (m/s)/frequency (Hz);
- slower in the visualization of close-range images than information collection through visual observations by divers when underwater visibility is high.

③ **Other**

Unlike the acoustic video camera shown in **Fig. 4.4.4**, the camera developed by the Port and Airport Research Institute is capable of sequentially updating high-resolution acoustic images of wide three-dimensional underwater space in real time and providing acoustic images close to the visual perception of human beings. Thus, the acoustic video camera developed by the Port and Airport Research Institute is expected to improve the performance of detailed visual confirmations of damage situations. Furthermore, because of its capability of measuring three-dimensional coordinates while conducting real-time monitoring, it can be applied to the direct visual supervision of underwater work.

(3) Underwater Three-Dimensional Scanners

① **Outline**

Underwater three-dimensional scanners are acoustic imaging sonars capable of acoustic scanning linear (one-dimensional) spaces widely in a vertical direction and extremely narrow in a horizontal direction. By mechanically rotating the sonar head (**Fig. 4.4.6**) installed on a tripod or ROV, underwater three-dimensional scanners enable three-dimensional coordinate measurements to be easily implemented.

For coordinate measurements where a sonar head fixed on a tripod is rotated, since a single probe requires 1 second, it takes about 6 minutes to acquire coordinate data by rotating the sonar head 360 degrees horizontally. The coordinate data is 360-degree, three-dimensional point group data with the sonar head as the center and converted into three-dimensional data of the structures after being subjected to post-processing, such as tide level and acoustic velocity correction.

Fig. 4.4.7 shows an example of a three-dimensional coordinate measurement of underwater structures and seafloor topography implemented as a verification test[17)] of the seafloor state observation technology for the elimination of port obstacles.

In addition to the method for visualizing underwater spaces with sonar heads attached alongside survey boats, there are cases of using underwater three-dimensional scanners in a manner that attaches sonar heads to fixtures extended from quaywalls for simple measurements and mounts sonar heads on ROVs, taking advantage of their reduced size and weight and energy-saving performance.

Fig. 4.4.6 Underwater Three-Dimensional Scanner[17)]

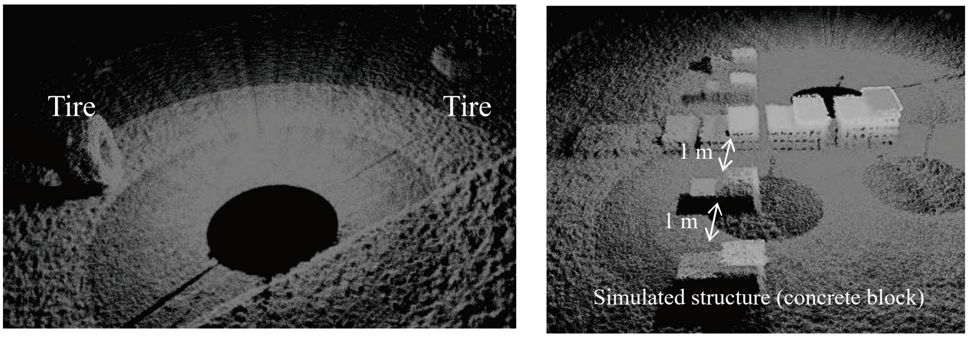


Fig. 4.4.7 Result of a Verification Test of Seafloor State Observation Technology for the Elimination of Port Obstacles[17)]
(Three-dimensional coordinate measurement with an underwater three-dimensional scanner installed on the seafloor)

② **Obtainable information and points to consider**

(Obtainable information)

In the full-scale restoration stage, underwater three-dimensional scanners are used for acquiring three-dimensional coordinate data by mechanically rotating a sonar head attached to a tripod, and converting the three-dimensional coordinate data into three-dimensional point group data through post processing with the sonar head as the center.

Thus, underwater three-dimensional scanners enable to determine the damage states of underwater structures, the amounts of scouring on the seafloor around the structures, and the quantities of debris removal work.

(Points to consider)

- Underwater three-dimensional scanners are generally used with sonar heads installed on tripods set on the seafloor by divers.

- In the case of environments that do not allow divers to access the seafloor, underwater three-dimensional scanners can still be used in a manner that suspends sonar heads in the seawater from fixtures set above the sea levels.
- The point group data obtained through the underwater three-dimensional scanners can be analyzed concurrently with other point group data obtained through onshore laser scanners or narrow multibeam swath sounders.
- As underwater three-dimensional scanner is small and light, it can be used as a mobile three-dimensional measurement device by fitting out on small, light-weight boats with outboard engines with an oscillation correction device. It is effective to use underwater three-dimensional scanner even in water areas where survey boats with a capacity of 70 PS cannot approach due to the floating objects and debris.

4.4.5 Laser Scanners Mounted on Board Survey Boats

(1) Outline

Laser scanners mounted on survey boats are scanners widely used for onshore topographic surveys, with oscillation and heading correction devices fitted out on the survey boats. The laser scanners mounted onboard can measure the three-dimensional point group data on the vertical plane of the port structures above sea levels with a high accuracy and density to be acquired while navigating the survey boats alongside the structures (**Fig. 4.4.8**). In particular, laser scanners mounted onboard are effective to measure the vertical plane of treacherous port structures, such as wave-dissipating blocks positioned in front of breakwaters and revetments, safely with a high density and accuracy.

(2) Seamless Three-Dimensional Data from Underwater Sections to above Sea Levels

Seamless three-dimensional point group data on the vertical plane of the port structures from the underwater sections to above sea levels can be obtained by combining the three-dimensional point group data on the structures above sea levels obtained using laser scanners mounted on survey boats with the three-dimensional point group data shown below.

(Example of point group data)

- Three-dimensional point group data on the port structures above sea levels measured with a UAV (e.g., breakwater superstructures and wave-dissipating blocks)
- Three-dimensional point group data on the port structures below sea levels measured with narrow multibeam swath sounders or underwater three-dimensional scanners.

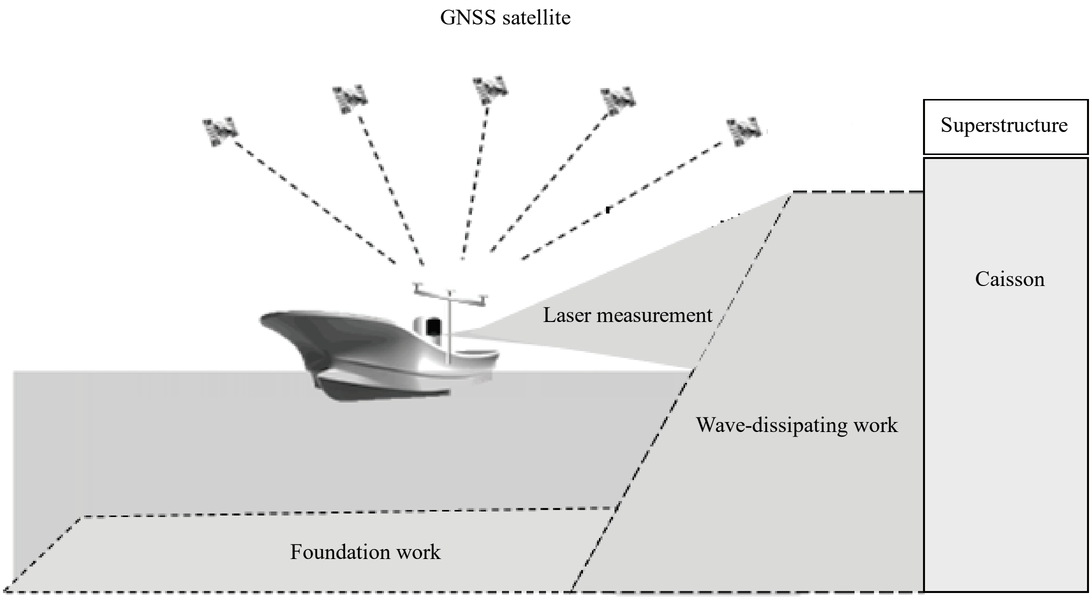


Fig. 4.4.8 Schematic Drawing of a Survey with a Laser Scanner Mounted on Board a Survey Boat

4.5 Understanding Broad-Based Ground Deformation

4.5.1 General

In the case of extensive ground deformation due to a large-scale earthquake, it is necessary to understand the trends of ground deformation in broad areas, including entire ports, determine the presence or absence of faults, and implement long-term observation of the trends. The survey methods for understanding broad-based ground deformation are twofold, as shown in **Table 4.5.1**. The following section describes these two methods (**4.5.2 Broad-Based Ground Deformation Analysis Using Satellite Images** and **4.5.3 Broad-Based Ground Deformation Analysis Using Aerial Laser Data**). A variety of methods have been developed for broad-based ground deformation analysis using satellite images. The description in the following section focuses on the PSInSAR method, which is suitable for coastal areas with a heavy concentration of artificial structures, such as port areas.

Table 4.5.1 Method for Understanding Broad-Based Ground Deformation

	Emergency restoration stage	Full-scale restoration stage
Main survey method	• Broad-based ground deformation analysis using satellite images • Broad-based ground deformation analysis using aerial laser data	Same as described in the column to the left

4.5.2 Broad-Based Ground Deformation Analysis Using Satellite Images (PSInSAR)

(1) Outline

PSInSAR is an abbreviation for “Persistent Scatterer Interferometric Synthetic Aperture Radar,” which is a technology applicable to analyzing ground deformation in millimeters using SAR images taken by satellites.

PSInSAR is capable of measuring ground deformation in millimeters using the phase differences of reflected microwaves emitted toward the ground from satellites. The broad-based ground deformation analysis using satellite images is conducted with respect to the reflected microwaves from specific reflectors, such as artificial structures, by selecting only the points (persistent scatterers) that can ensure a certain level of coherence (the phase function accuracy of the sine waves). The deformation amounts of the persistent scatterers are calculated in a manner that superimposes multiple images taken at different times and reduces noise by correcting orbit errors, distortions due to unevenness in the ground surfaces, and the influences of the atmosphere included in the reflected waves.

PSInSAR can analyze the deformation of a wide area at one time. For example, in urban areas, PSInSAR can perform a broad-based ground deformation analysis at around 200 points per km^2 (1 point in a 50- to 100-meter square) to 600,000 points per km^2 (60 points in a 10-meter square), depending on the observation modes. PSInSAR conducts measurements using reflections from the roofs of existing buildings without requiring measuring equipment or special devices to be brought in and set up at the measuring points. The satellite image data available for broad-based ground deformation analysis is limited to that obtained after 1992. In addition, PALSAR-2, which is a domestic SAR on board the Japanese satellite “Daichi No. 2,” has been observing the whole of Japan since 2014.

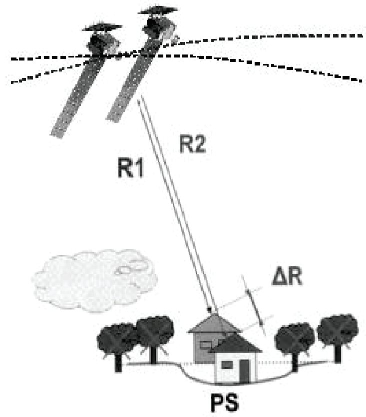


Fig. 4.5.1 Schematic Drawing of the Measurement Principle of PSInSAR

(2) Obtainable Information and Points to Consider

(Obtainable information)

The broad-based ground deformation analysis using satellite images enables the amounts of ground deformation and the chronological changes in the deformation after a disaster to be monitored using the SAR(Synthetic Aperture Radar) images before and after the disaster.[18)] In the case of the Great East Japan Earthquake, extensive ground deformation due to the earthquake included the ground subsidence along coastal areas, which increased the risk of secondary disasters due to inundation and storm surges. The broad-based deformation analysis using satellite images is effective in understanding the damage situations of extensive areas, as is the case with the extraction of the areas affected by ground deformation or liquefaction[19)] as a result of a large-scale earthquake (**Fig. 4.5.2**).

When surveying the areas and magnitudes of onshore ground deformation in the emergency restoration stage, the ground deformation can be analyzed in centimeters, both in horizontal and vertical directions, by combining the measurements through a simplified interferometer SAR with data correction with reference to the GNSS values.[20)]

In the full-scale restoration stage, the amounts of ground deformation can be analyzed in millimeters by obtaining multiple satellite images after the disaster over time, thereby enabling the restoration plans to be formulated in consideration of the distribution of the damage quantities caused by extensive ground deformation with temporal changes.

(Points to consider)

The Great East Japan Earthquake caused extensive ground uplift and subsidence, with the amounts of ground subsidence exceeding 1 m in some locations. After the earthquake, the uplifted or subsided ground deformed back to the original elevations (after the effect deformation); this deformation still continues with a gradual attenuation of resilience. After a large-scale earthquake, it is important to understand the presence or absence of broad-based ground deformation and local changes in the ground elevations due to local damage, such as liquefaction, and reflect on the influences of these different types of ground deformation when deliberating on countermeasures. Furthermore, when analyzing the trend of ground deformation, it is necessary to fully consider the situation in the survey area because ground deformation such as land subsidence may occur due to nearby construction.

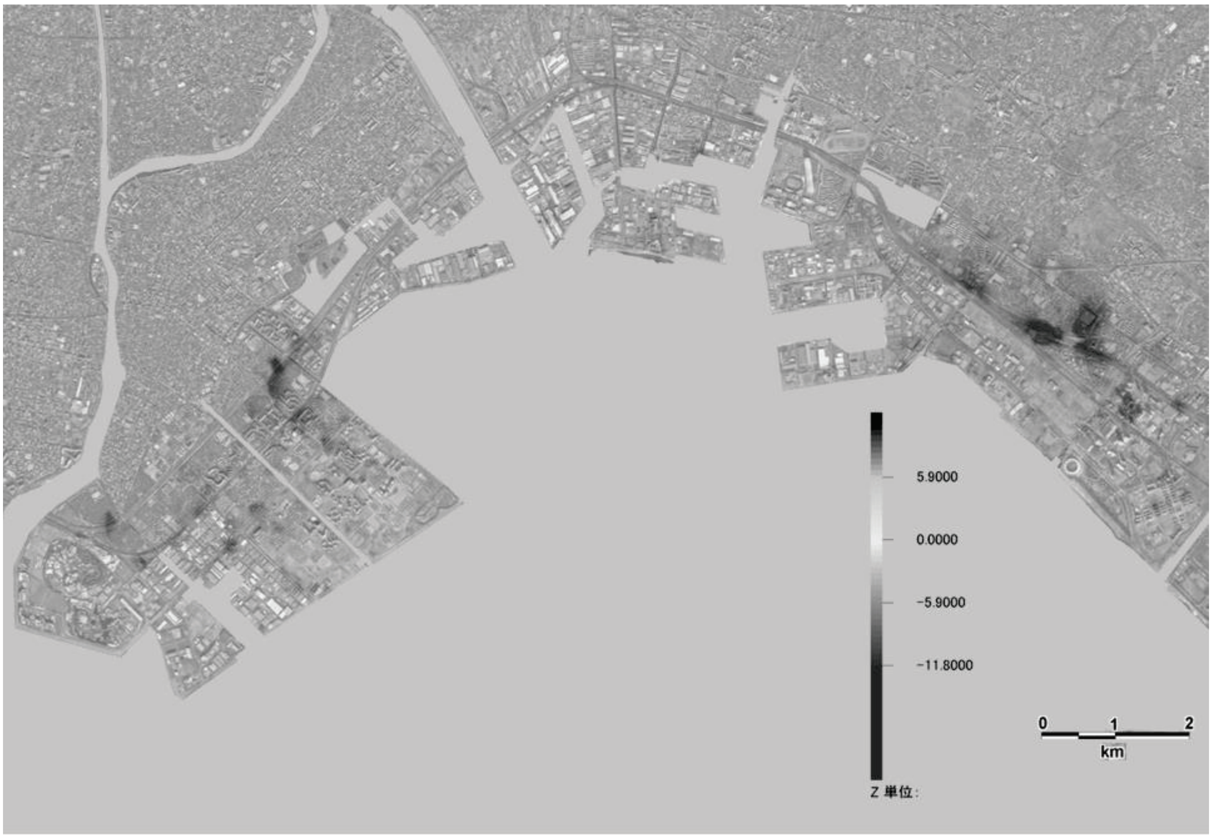


Fig. 4.5.2 Example of an Analysis of the Subsidence Amount Using PSInSAR in the Tokyo Bay Area, Which Underwent Liquefaction Due to the Great East Japan Earthquake (Modification of Reference 19))

4.5.3 Broad-Based Ground Deformation Analysis Using Aerial Laser Data

(1) Outline

There are cases where broad-based ground deformation can be analyzed by comparing the data obtained through aerial laser surveys (refer to **Reference [Part II], Chapter 2, 4.2.5 Aerial Laser Surveys**) before and after an earthquake. For the execution of accurate analyses, it is preferable to compare the data obtained on dates close to each other before and after the earthquake.

(2) Obtainable information and points to consider

(Obtainable information)

Faults can be identified as level differences in the images showing the differences in the DSMs (Digital Surface Models) before and after an earthquake. In addition, horizontal displacement before and after an earthquake can be identified from the differences in DSMs, and additional image processing or point group processing can enable the horizontal displacement amounts to be automatically estimated.

Fig. 4.5.3 shows a default location map (upper diagram) and a displacement vector analysis diagram (lower diagram) created from the differences in the aerial laser data obtained before and after the Kumamoto Earthquake (on April 16, 2016).[21)] The displacement vector analysis was executed through a method called ICP (Interactive Closest Point) used for aligning three-dimensional point groups.

(Points to Consider)

The same points to consider as described in **Reference [Part II], Chapter 2, 4.5.2 Broad-Based Ground Deformation Analysis Using Satellite Images (PSInSAR)** apply to the use methods of the broad-based ground deformation analysis using aerial laser data.

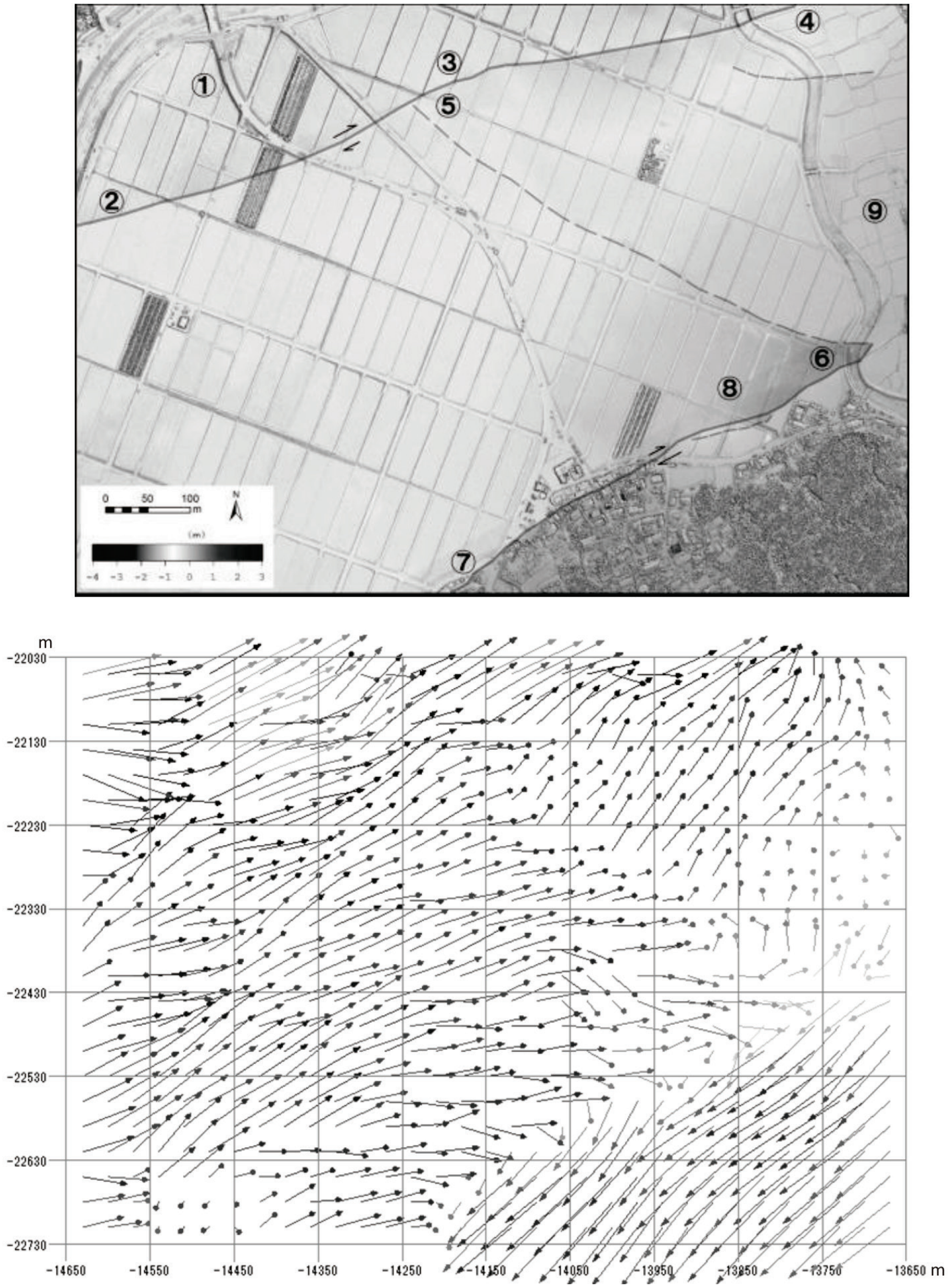


Fig. 4.5.3 Extraction of a Fault through the Differences in Aerial Laser Data[21)]

4.6 Surveys on Ground Liquefaction

4.6.1 General

The occurrence of ground liquefaction during an earthquake intensifies the damage to port structures such as mooring facilities and revetments. Liquefaction can cause an increased seaward displacement of mooring facilities and cavities beneath aprons, and it is important to understand whether or not liquefaction has occurred as basic information to determine the safety of using the mooring facilities immediately after an earthquake. It is also effective to acquire information on whether or not liquefaction has occurred for the restoration design and investigation of the reasons for the damage in the full-scale restoration stage. **Table 4.6.1** shows the methods for understanding whether or not liquefaction has occurred and survey methods which can be used for predicting and determining the possibility of liquefaction in the design stage.

In the emergency restoration stage, whether or not liquefaction has occurred at the quaywalls and aprons can be confirmed through visually identifying, sketching or taking photographs of any evidence of sand boiling. The evidence of sand boiling will remain on the ground surfaces when no tsunamis run up to the sites after an earthquake, but it can be easily erased by rainfall or storm surges. Thus, in cases where the determination of whether or not liquefaction has occurred is considered to largely affect the determination of the reasons for the damage, it is necessary to identify early the occurrence of liquefaction after the earthquake.

In the full-scale restoration stage, for the purpose of determining restoration design and identifying the reasons for the damage, there may be cases of predicting and determining the occurrence of liquefaction and the presence or absence of cavities in the surrounding ground when subjected to design earthquake motions or reproduced earthquake motions as needed. In addition to normal boring surveys, the methods listed in **Table 4.6.1** can be used for the above purpose. Among these methods, the outlines of **two-dimensional surface wave exploration** and the **Piezo Drive Cone (PDC)** are described in **4.6.2** and **4.6.3**, respectively.

Table 4.6.1 Liquefaction Determination Survey Methods

	Emergency restoration stage	Full-scale restoration stage
Main survey method	(Confirmation of whether or not liquefaction has occurred) Visual confirmation, sketching, photographs and video recordings	(Prediction and determination of liquefaction) Boring, two-dimensional surface wave exploration and the Piezo Drive Cone (PDC)

4.6.2 Two-Dimensional Surface Wave Exploration

(1) Outline

Two-dimensional surface wave exploration is a survey method for obtaining the S-wave velocity distribution in the ground by measuring the surface waves (Rayleigh waves) in surface layers with thicknesses of about 20 m (**Fig. 4.6.1**).[22] In two-dimensional surface wave exploration, a cable with geophysical exploration seismometers attached alongside it with intervals of 1 m is laid on a survey line and ground motions are artificially applied to the surface layer by hitting it with a wooden maul (**Fig. 4.6.2**). Then, the measurements of the surface waves propagating through the shallow ground with multichannel seismometers (12 to 48 channels) are processed into an S wave velocity structure profile of the ground along the survey line.

Because S wave velocities correlate with the stiffness of the ground, they can be used for understanding the ground's geophysical properties. When combined with an analysis of the *N* values obtained through the standard penetration test, the surface wave exploration enables a two-dimensional *N*-value profile to be estimated. The two-dimensional *N*-value profile can be used for predicting and determining the liquefaction of the ground and identifying large cavities.

Fig. 4.6.3 shows a contour figure of the S wave velocity distribution in the ground of S Airport. The two-dimensional surface wave exploration was implemented in the course of the supervision of the liquefaction countermeasure work for the runways and taxiways. The runways and taxiways for which the liquefaction countermeasure work was implemented did not undergo liquefaction during the Great East Japan Earthquake.

Two-dimensional surface wave exploration has also been used to understand the stratum structure of very soft ground such as tidal flats.

As is the case with the study on the sedimentary structure of the soil under the tidal flat in the Buzen Sea shown in **Fig. 4.6.4**, the two-dimensional surface wave exploration that enables the shear wave velocity distribution, which represents the hardness or softness of the ground, to be quantitatively understood is proven to be an effective means to efficiently evaluate the stratum structures of the ground of tidal flats.[23]

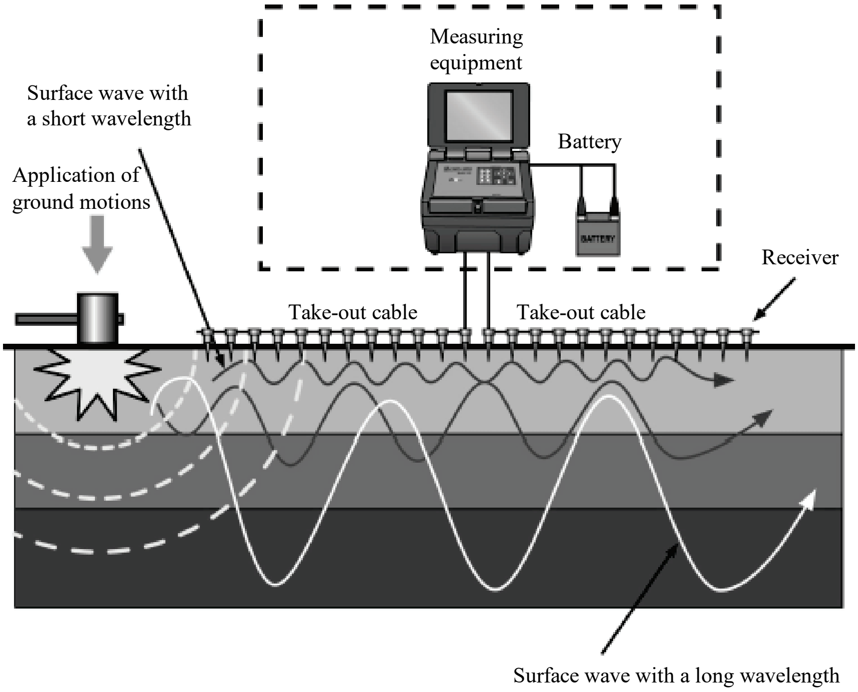


Fig. 4.6.1 Schematic Drawing of Two-Dimensional Surface Wave Exploration[22)]

Fig. 4.6.2 Geophysical Seismometer (Left) and Application of Ground Motions (Right)

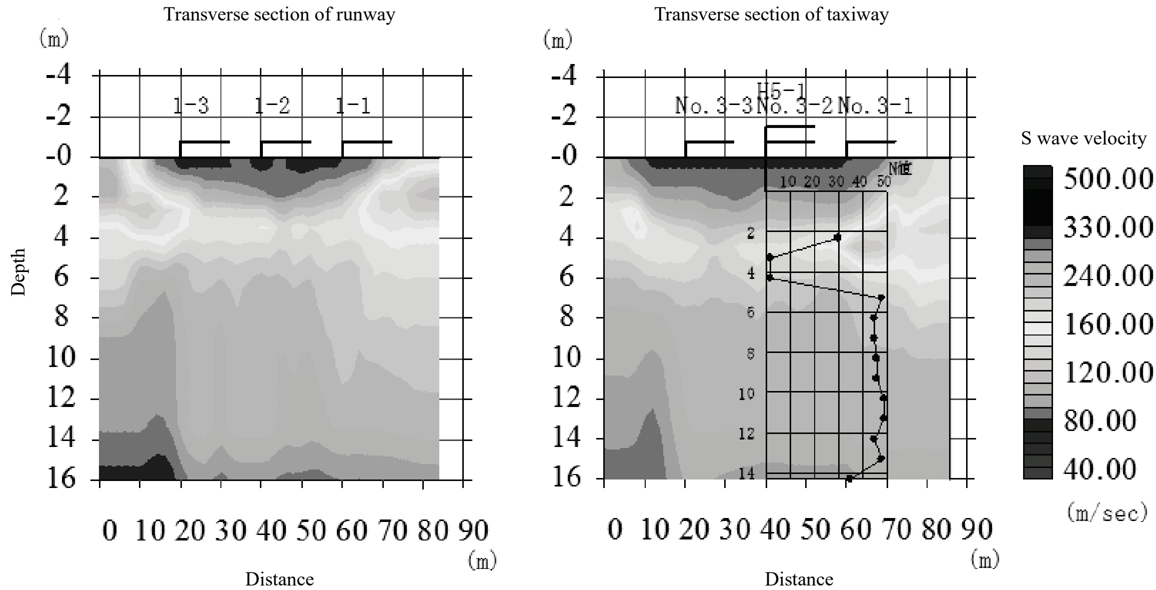


Fig. 4.6.3 Example of Two-Dimensional Surface Wave Exploration Results
(After the Liquefaction Countermeasure Work at S Airport)

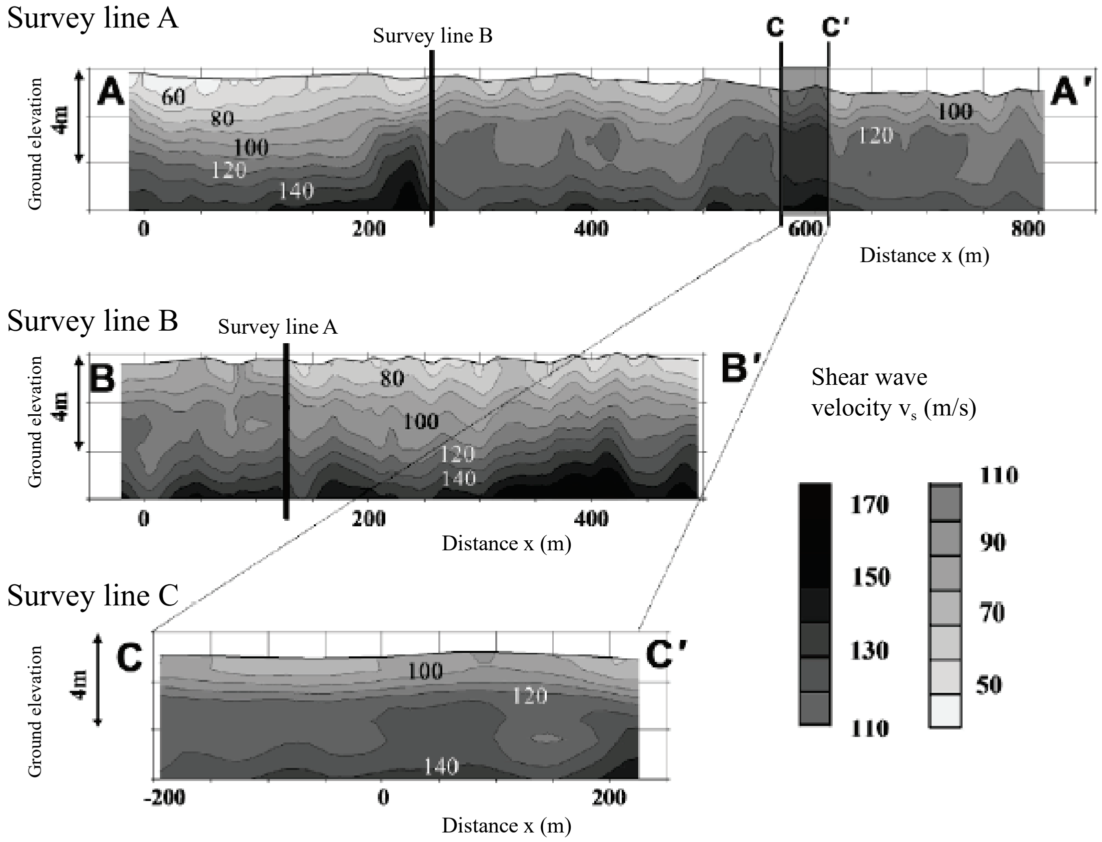


Fig. 4.6.4 Example of Two-Dimensional Surface Wave Exploration Results
(Sedimentary Structure of the Soil under the Tidal Flat in the Buzen Sea)[23)]

(2) Obtainable Information

In the full-scale restoration stage, the combination of the two-dimensional surface wave exploration results with the boring or sounding survey results enables the two-dimensional stratum structure in a vertical direction to be understood and facilitates the selection and examination of the types and scopes of liquefaction countermeasure work.

(3) Points to consider

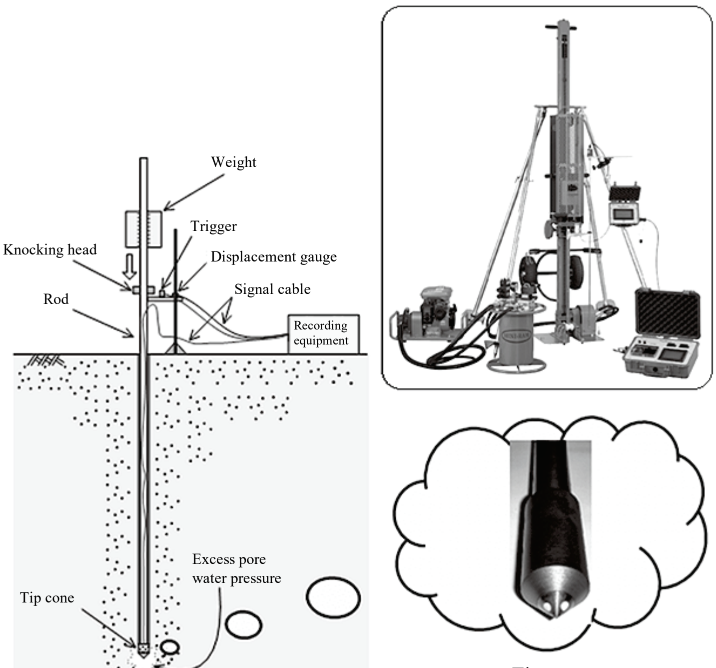
Because the surface wave exploration analyzes the surface waves that propagate through horizontally stratified ground, there may be cases where the exploration results are affected by structures when the survey line is set parallel to a structure, such as a quaywall or revetment. Thus, it is preferable to consult with a specialist about the appropriateness of setting the survey lines close to the structures when planning the surface wave exploration.

4.6.3 Piezo Drive Cone (PDC)

(1) Outline

The PDC is capable of surveying the in-situ liquefaction strength of the ground in a manner that measures the ground resistance against percussive penetration and pore water pressure generated in the ground at the tip of the cone when the cone is percussively penetrated into the ground, evaluates the *N* values representing the penetration resistance of the ground, and estimates the ground water level and the soil properties (fine contents [F_C]) by depth (**Fig. 4.6.5**).

Because the PDC enables measurements to be easily conducted in a short period of time, it can be used for planar and dense surveys, even when the object ground is extensive and inhomogeneous. In addition, the PDC can shorten the survey periods and reduce survey costs because the measurements of the PDC can be used directly without requiring additional laboratory soil tests, such as grain size tests, and the penetration of the PDC into the ground can be executed easily with a compact dynamic penetration machine.



Tip cone
(white spots correspond to porous stones)

Fig. 4.6.5 Conceptual Drawing of the Piezo Drive Cone (Modification of Reference 24))

Fig. 4.6.6 shows an example of a liquefaction strength evaluation using measurements done with the PDC.[25)] The N_d values measured with the PDC are almost equivalent to the *N* values of the standard penetration test, and can express the changes in soil properties in the depth direction with a higher resolution than the *N* values in that the N_d values can be obtained continuously in the depth direction, while the *N* values are available every 1 m. Thus, compared to the conventional liquefaction strength R_L obtained from the *N* values of the standard penetration test and F_C (fine contents), the PDC enables the continuous distribution of the liquefaction strength in the depth direction to be evaluated. Furthermore, the liquefaction strength obtained through measurements using the PDC is proven to correspond well to the conventional liquefaction strength. It is also confirmed that the PDC enables the settlement amounts to be predicted with a high accuracy through comparisons between the predicted values of settlement due to the dissipation of excess pore water pressure after liquefaction and the actual measurements.

Currently, the exploratory committee for ground improvement work through the chemical grouting method in reclaimed areas (under the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transportation and Tourism) has been studying the applicability of the PDC to the evaluation of ground improvement effects.[26)]

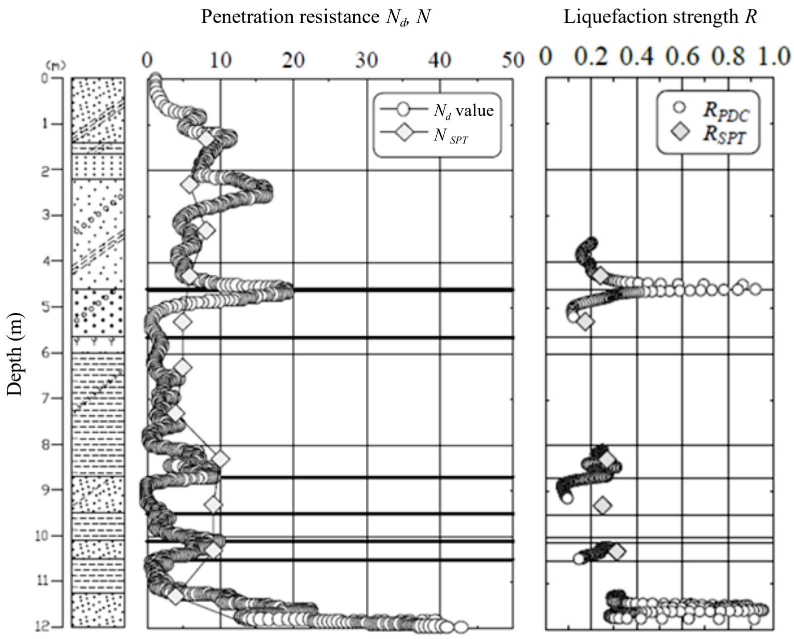


Fig. 4.6.6 Example of Measurement Results (Modification of Reference 25))

(2) Obtainable Information

The estimation results using the PDC can be combined with the boring survey results (as needed) for obtaining the three-dimensional stratum structure, which can be used for selecting and examining the types and scopes of liquefaction countermeasure work.

(3) Point of Caution

When using the PDC, an appropriate penetration machine shall be selected in accordance with the hardness or softness of the ground and depths to be surveyed.

4.7 Understanding the Cavities at Apron Sections

4.7.1 General

It is important to determine the presence or absence and the extent of cavities in the ground immediately below aprons (concrete pavement) and yards (asphalt and concrete pavements) as basic information to determine the usability of mooring facilities immediately after an earthquake. In addition, such information can be effectively used for the restoration design and the investigation of the reasons for the damage in the full-scale restoration stage. **Table 4.7.1** summarizes the methods which can be used for determining the presence or absence of cavities in aprons and yards.

In the emergency restoration stage, the presence or absence of cavities is estimated based on the states of subsidence and deformation of pavement surfaces identifiable through visual confirmation, sketches or photographs.

In the full-restoration stage, the areas of aprons and yards suspected to have cavities below them are estimated through nondestructive exploration, such as underground radar exploration, on-vehicle subsurface exploration and two-dimensional surface wave exploration (refer to **Reference [Part II], Chapter 2, 4.6.2 Two-Dimensional Surface Wave Exploration**) for determining the restoration design and investigating the reasons for the damage. There may also be cases where the pavement in areas suspected to have cavities needs to be drilled so as to enable the cavities to be visually identified with endoscopic cameras. This section describes **underground radar explorations** and **on-vehicle subsurface explorations** in **4.7.2** and **4.7.3**, respectively.

Table 4.7.1 Survey Methods for Exploring Cavities below Aprons and Yards

	Emergency restoration stage	Full-scale restoration stage
Main survey methods	(Estimation of the presence or absence of cavities) Visual confirmation, sketches, photographs and video recordings	(Estimation of the presence or absence of cavities through nondestructive exploration) Underground radar exploration, on-vehicle subsurface exploration and two-dimensional surface wave exploration (Direct confirmation of the presence or absence and the extent of cavities) Drilling and excavation surveys

4.7.2 Underground Radar Exploration

(1) Outline

The underground radar exploration is a method for surveying objects in the ground by emitting electromagnetic waves into the ground and receiving them reflected from boundaries that have different electric properties (**Fig. 4.7.1**).[27] The boundaries with different electric properties correspond to, for example, cavities, buried pipes, buried objects, stratum boundaries, cracks, crushed zones, the upper surface of structures and waste. The exploration depths of the underground radar exploration are 2 to 3 m in the ground of general soil. Electromagnetic waves with longer periods can explore deeper ground but produce shape information at lower resolutions. Mobile underground radar exploration can be implemented by mounting the equipment on a dedicated cart. Furthermore, underground radar explorations enable the planar exploration of underground objects to be easily implemented by simultaneously obtaining their positional information through RTK-GNSS satellite positioning (**Fig. 4.7.2**).

Fig. 4.7.3 shows an example of the identification of an area suspected to have a cavity through underground radar exploration and confirmation of the cavity through an excavation survey.

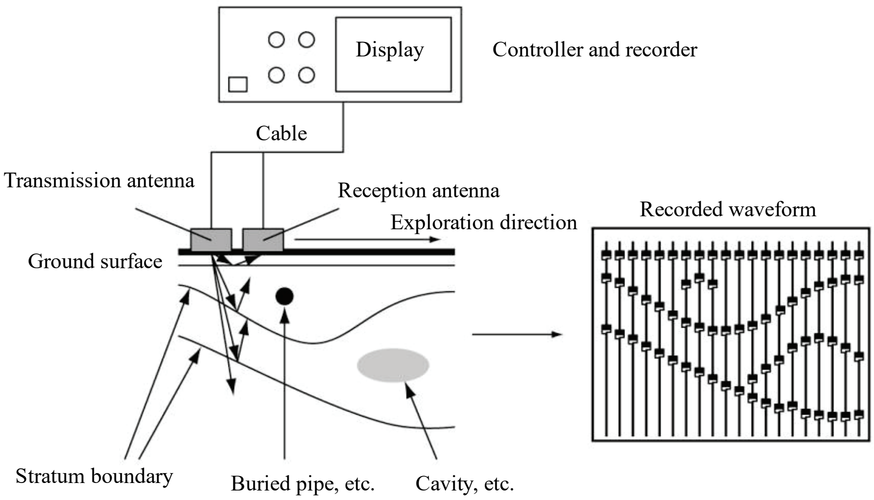


Fig. 4.7.1 Schematic Drawing of Underground Radar Exploration[27]

Fig. 4.7.2 Underground Radar Exploration

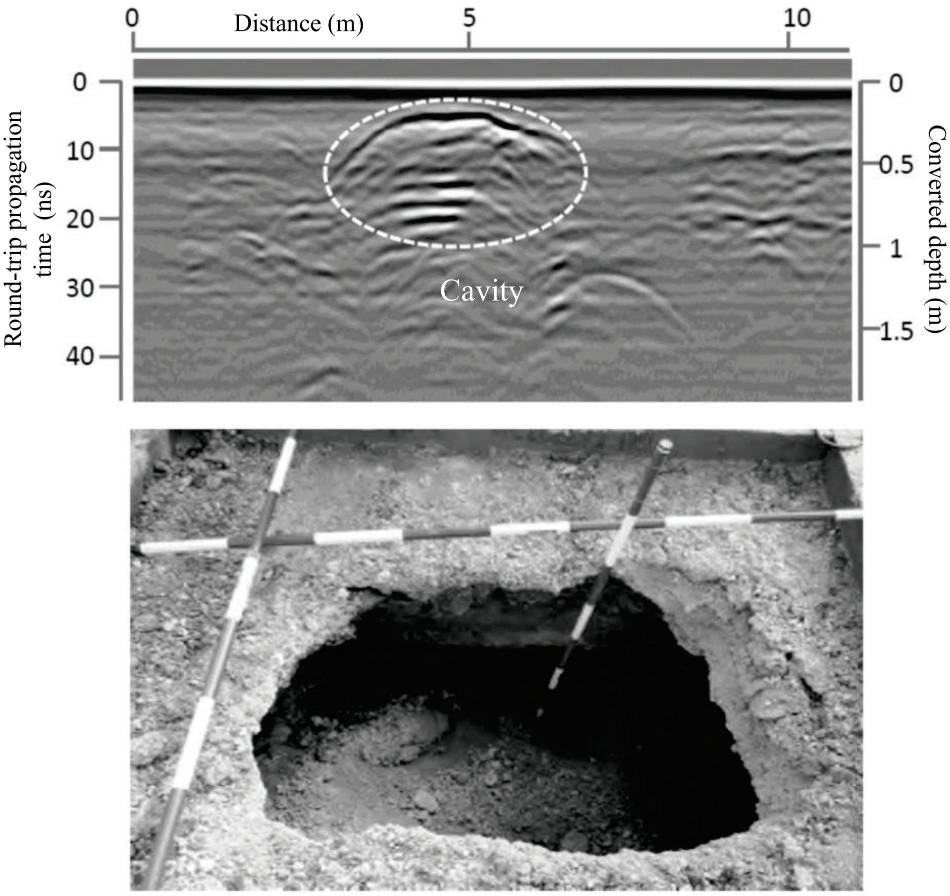


Fig. 4.7.3 Example of a Cavity Identified through an Underground Radar Exploration
(Upper image: record showing a cavity; lower image: photograph of an uncovered cavity)

(2) Obtainable Information

The results of the underground radar exploration can be used for estimating the presence or absence and extent of the cavities in the ground, which cannot be confirmed from the surfaces of the aprons and yards. The information on the cavities in turn can be used for determining the running safety of the construction vehicles, heavy machines and cargo handling equipment (prevention of secondary disasters such as cave-in). In the full-scale restoration stage, the information on the cavities can be used for estimating the work quantities for repairing the concrete pavement in the aprons and filling the cavities, as well as positioning the buried objects that require restoration. It shall be noted that there may be cases where the underground radar exploration cannot produce correct information (e.g., shallower depths than the actual depths when affected by an abnormal specific resistance of ground, as is the case with ground subsidence bringing ground surfaces very close to the residual groundwater accumulated below them).

4.7.3 On-Vehicle Subsurface Exploration

(1) Outline

The on-vehicle subsurface exploration is a method for surveying the presence or absence of cavities below road surfaces with underground radar exploration equipment (refer to **Reference [Part II], Chapter 2, 4.7.2 Underground Radar Exploration**) mounted on a vehicle traveling on the road (**Fig. 4.7.4**). The on-vehicle subsurface exploration enables the presence or absence of cavities and looseness in the ground below road surfaces to be efficiently and speedily surveyed by simultaneously exploring the subsurface conditions in the transverse direction of the roads using multiple radar antennas. The exploration depth of the on-vehicle underground radar exploration is about 2 m.

Fig. 4.7.5 shows an example of a cavity identified through an on-vehicle subsurface exploration.

Fig. 4.7.4 Image of an On-Vehicle Subsurface Exploration[28)]

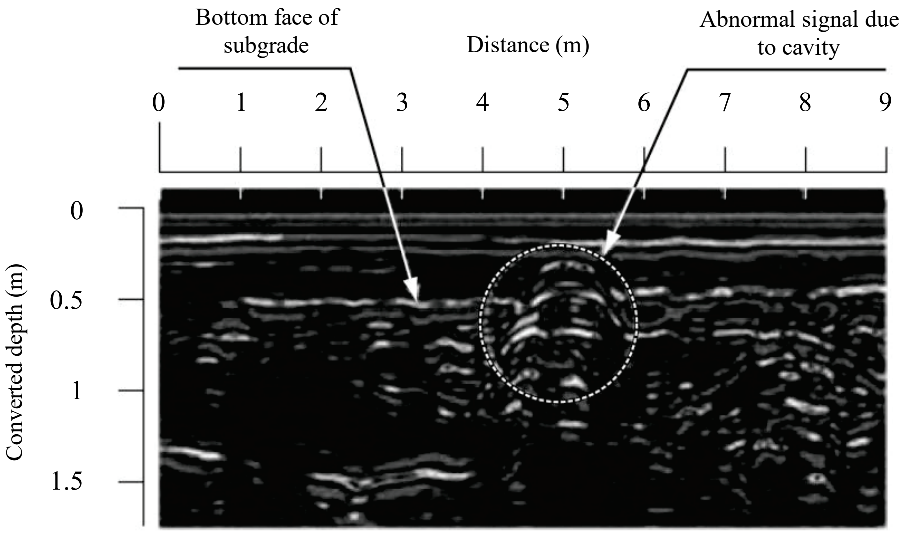


Fig. 4.7.5 Example of a Cavity Identified through On-Vehicle Subsurface Exploration (Vertical Section)

(2) Obtainable Information

The information obtainable through an on-vehicle subsurface exploration is the same as that described in **Reference [Part II], Chapter 2, 4.7.2 Underground Radar Exploration**.

4.8 Understanding the Deformation on Underground Structures

4.8.1 General

The deformation on underground structures driven into the ground, such as the steel pipe piles of piled piers, steel sheet piles of sheet pile quaywalls and foundation piles of cargo handling cranes, needs to be surveyed for obtaining the basic information to investigate the mechanisms of the damage when these structures are subjected to earthquakes and tsunamis, and to facilitate the restoration design of the damaged facilities.

The methods for surveying the deformation of steel pipe piles include verticality measurements with ultrasonic measuring equipment inserted into the steel pipe pile after the soil inside the pile has been removed with a submerged sand pump, and visual identification of the deformed locations by taking video images inside the pile using monitoring equipment, such as a borehole camera inserted into the steel pile after the soil inside the pile has been removed. In addition, impact elastic wave exploration can be used for measuring the lengths of the piles and identifying the locations of breakage on the piles, including concrete piles.

Table 4.8.1 lists the survey methods useful for understanding the deformation on underground structures. From this list, the **impact elastic wave exploration** and the **borehole radar exploration** are described in **4.8.2** and **4.8.3**, respectively.

Table 4.8.1 Main Survey Methods for Understanding the Deformation on Underground Structures

	Full-scale restoration stage
Main survey method	Ultrasonic measuring equipment, video recording inside piles, impact elastic wave exploration and borehole radar exploration

4.8.2 Impact Elastic Wave Exploration

(1) Outline

The impact elastic wave exploration is a survey method for understanding the damage states of concrete piles, steel pipe piles and steel sheet piles driven into the ground. The impact elastic wave exploration, alternatively called the “integrity test,” can be used for evaluating the soundness of concrete, measuring the embedment lengths of the piles and the locations of the cracks and breakage by measuring the time required for elastic waves to generate when impacts are applied to an object structure with a hammer to reflect off the tip of the pile or cracks along the way and return to the signal reception sensor.

The signal reception sensor is attached to the upper edge of the object structure, and an impact is applied using a hammer to a point on the structure close to the sensor.

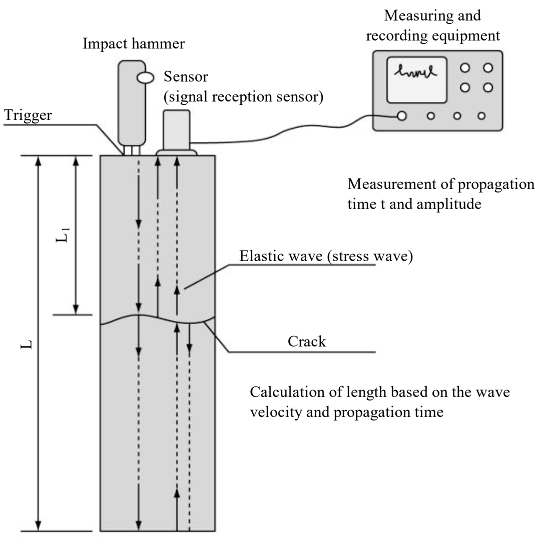


Fig. 4.8.1 Schematic Drawing of an Impact Elastic Wave Exploration[29)]

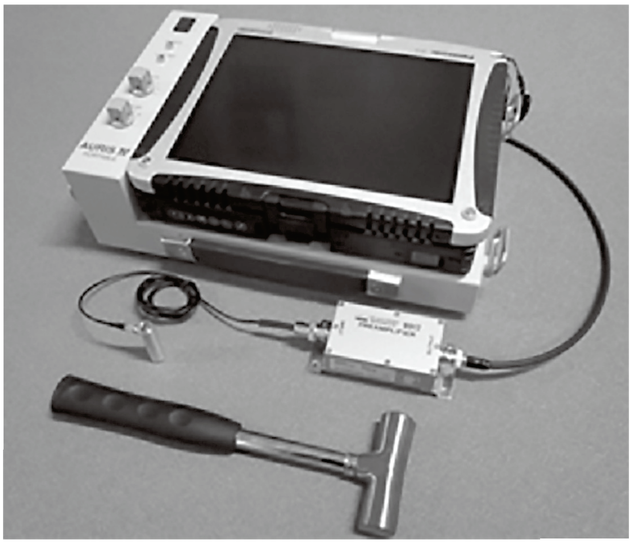


Fig. 4.8.2 Example of Measuring Equipment[29)]

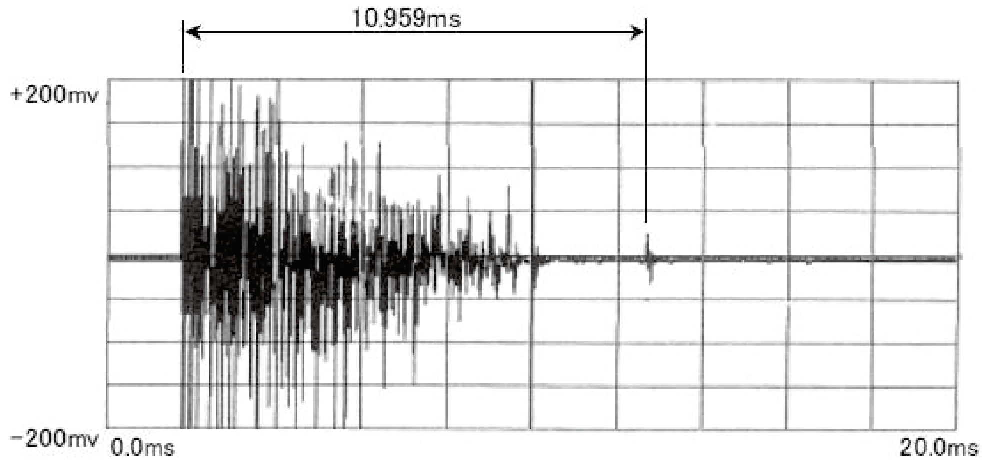


Fig. 4.8.3 Example of the Waveform of an Elastic Wave Propagated in a Steel Pipe Pile in an Impact Elastic Wave Exploration[30)]

Fig. 4.8.3 shows an example recording of the impact elastic wave exploration used for an experimental measurement of the length of a foundation pile from the upper surface of the apron concrete to the superstructure of a piled pier. The waveform of the elastic waves was recorded with a signal reception sensor installed on the upper face of the apron concrete above the center of the pile head when the elastic waves, generated by an impact applied to a point close to the sensor, reflected off the pile tip and returned to the sensor. Based on the propagation time obtained through in-situ exploration and the propagation velocity preliminarily obtained with a test pile, the length of the steel pipe pile on the piled pier was estimated. In the experiment, the effectiveness of the impact elastic wave exploration was reportedly verified with a certain level of allowance.[30)]

(2) Degrees of Damage to Foundation Structures

Ahead of the full-scale restoration of damaged facilities, the impact elastic wave exploration is used for the purpose of understanding the deformation of underground structures, such as the foundations. The impact elastic wave exploration is also one of the most effective methods for confirming whether or not the foundation structures are damaged when the fluidization of the ground, such as liquefaction, has caused the superstructures to have significant displacement.

(3) Points to consider

It is preferable to use the impact elastic wave exploration with due consideration to its applicability to the types and situations of foundation structures that are to be the exploration objects. Because the impact elastic wave exploration requires measurement spaces at the edges of the exploration object structures, it is necessary to coordinate the procedures for the restoration work and exploration work. In the case of foundation piles, it is considered to be practical to start the impact elastic wave exploration with the piles around the structures.

4.8.3 Borehole Radar Exploration

(1) Outline

The borehole radar exploration is a type of underground radar exploration that uses special types of equipment that are usable inside boreholes. The borehole radar exploration can also be used for surveys on geological structures, such as the depths of the boundaries between the soil and bedrock, as well as the locations of the cracks in the bedrock, and for confirming the states of the existing underground structures, such as the embedment lengths of the existing piles.[31)]

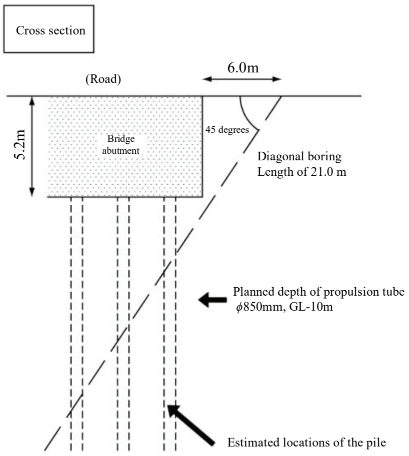


Fig. 4.8.4 Example of a Borehole Radar Exploration Used for Confirming the Existing Piles[31)]

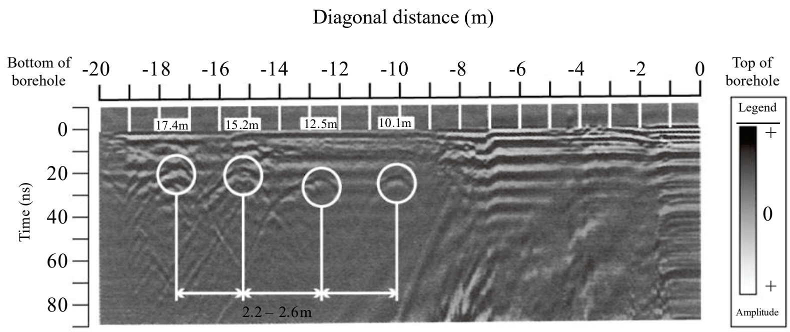


Fig. 4.8.5 Example of a Measurement Record in the Left Example (Fig. 4.8.4)[31)]

Fig. 4.8.5 shows an example of a borehole radar exploration used for understanding the positions of foundation piles of the bridge abutment constructed with positional relationships, as shown in **Fig. 4.8.4**. The positions of the foundation piles were explored in a manner that drilled a diagonal borehole toward the lower section of the bridge abutment, inserted borehole radar equipment into the borehole and explored the existing piles positioned adjacent to the diagonal borehole. The positions of the foundation piles beneath the bridge abutment were calculated based on the measured diagonal distances.

(2) Understanding the Embedment Depths

The borehole radar exploration can be used for compensating for the lack of information on the foundation of the damaged facilities in designing the full-scale restoration work. For example, in the case of a lack of information on the presence or absence, positions and embedment depths of existing foundation piles, a borehole can be drilled as close to these foundation piles as possible, and the measurements of the reflection waves from these piles can be converted into information on the positions and embedment depths of the piles.

(3) Points to Consider

The borehole needs to be positioned close to the exploration object structures (e.g., within 1 m). Furthermore, there may be cases where the borehole needs to be drilled diagonally. Thus, it is necessary to prevent the existing structures from being damaged when drilling the borehole or from being adversely affected by its proximity, as well as confirming its straightness.

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