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Second phase construction project of Kansai International Airport - Large-scale reclamation works on soft deposits -

Le projet de la deuxième phase du développement de l'aéroport international de Kansaï - La construction d'une nouvelle île et d'une nouvelle piste sur un sol peu solide sous-marin -

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ABSTRACT
Kansai International Airport was constructed as a marine airport 5km offshore in Osaka bay so as not to burden urban dwellers with noise pollution. The second phase construction works are being performed even farther offshore than the first phase. To reclaim land over vast area and complete the island in a short period of time, maximum use is being made of the experience accumulated during the first phase construction works. And by introducing the latest technology and careful planning to procure the large quantity of materials and equipment required, construction works are proceeding in a smooth and efficient manner. This report shows an overview of the construction works of the second phase construction project of Kansai International Airport.

RÉSUMÉ
Construit sur une île artificiellement créée, à la distance de 5km du côte de la baie d'Osaka, l'aéroport international de Kansaï a pour objectif d'atténuer les problèmes sonores des avions utilisant l'aéroport d'Osaka (appelé Itami) situé proche du centre d'Osaka. L'aéroport international de Kansaï mène actuellement sa deuxième phase du développement afin de créer une nouvelle île et une nouvelle piste parallèle. Le projet de la deuxième phase est avancé efficacement et rapidement, grâce aux expériences déjà obtenues durant la phase précédente, à la téchnologie de pointe et à l'achat soigneusement préparé d'une masse de matériels et d'équipements nécessaires. Ce rapport vise à expliquer cette deuxième phase du développement et son état actuel.

1 INTRODUCTION

1.1 *Background of the project*

Kansai International Airport was planned as a fundamental solution to the problem of the aircraft noise pollution surrounding the Osaka International Airport (Itami Airport) and to meet the increasing demand for air transportation. It is the first 24-hour operational airport in Japan and constructed 5km offshore in Osaka bay as a man-made island in order to avoid the impact of aircraft noise on residential areas (Figure 1). Kansai International airport features 24-hour operability, convenience of transfer between international and domestic flights, and diverse accesses by highway, railways and high-speed ferry. It has been playing an important role as an international hub in the global aviation network.

In the Kansai International Airport, the number of aircraft take-offs and landings is already close to its handling capacity (30 per hour) during peak hours. Based on pressure from both home and abroad to further increase its capacity as an international hub airport, the second phase of the construction project was started in 1999. The image of the airport after the completion of the second phase project is shown in Figure 2. In the second phase construction work, land and superstructure is developed by different companies; the land development work of the second airport island by Kansai International Airport Land Development Co., Ltd. (KALD) and airport facilities including new runway by Kansai International Airport Co., Ltd. (KIAC). KALD makes every effort to satisfy necessary conditions as an airport island with more speed, reliability and environmental harmony. The second phase construction is now in progress for opening of the new runway in 2007. This report describes an overview of the second phase construction works of Kansai International Airport.

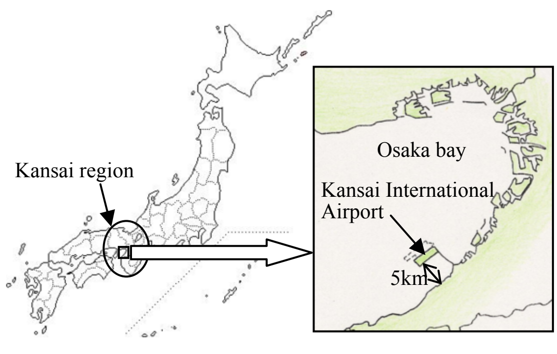


Figure 1. Location of Kansai International Airport

1.2 *Natural condition*

The water depth of the construction site is about 18m to 20m. The Figure 3 shows a general overview below the seabed at the construction site. The layers below the seabed consist of a soft layer of Holocene clay immediately below the seabed surface and alternative layers of Pleistocene clay and sand/gravel. Pleistocene clay deposited from 2 million to 10 thousand years ago during repeated glacial and interglacial periods. The depth and

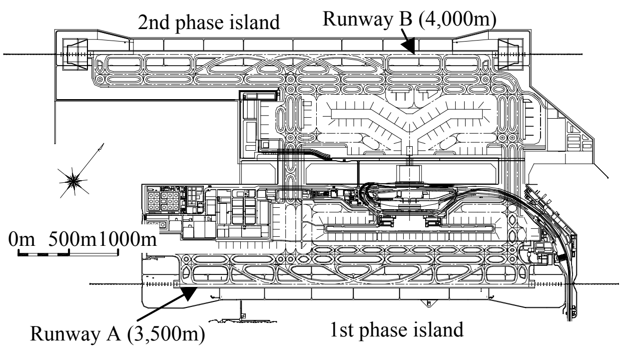


Figure 2. Image of Kansai International Airport after completion of the second phase project)

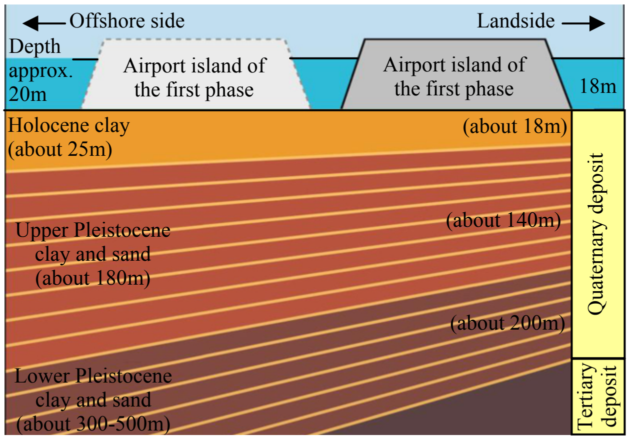


Figure 3. General overview of seabed under airport islands

thickness of each clay layer gently become greater as it goes towards offshore side, as shown in Figure 3 and Table 1.

Large settlement as a result of reclamation work is expected because of these compressible clay layers of great thickness. Holocene clay layer is particularly thick and weak. Therefore, Holocene clay layer should be improved so as to minimize the residual and uneven settlement which will occur after the airport open its operation and to ensure the stability during the construction of the island. The ground improvement is carried out by driving many sand piles into the Holocene clay layer. Sand piles squeeze water from Holocene clay layer, thus promoting settlement by consolidation of the layer. As a result, it is estimated that the settlement of Holocene clay layer will be completed during the construction. On the other hand, it is difficult to improve the Pleistocene clay layers technologically. For this reason, the natural Pleistocene clay layers continue to subside after the airport is opened. Thus, based on the results of large depth borings and laboratory tests, long-term settlement of the Pleistocene clay layer should be predicted and reflected in the design of thickness of reclamation.

2 THE FIRST PHASE OF THE PROJECT

In the first phase project, an airport island of about 510ha was reclaimed, on which one 3,500m runway, takeoff/landing facilities and terminal facilities were built. To swiftly carry out large-scale reclamation works in deep water was an extremely difficult and unprecedented task. Various improvements in operation and technological innovations made it possible.

The first phase of the construction project at Kansai International Airport started in 1987. Holocene clay layer was improved mainly by sand drain method in order to promote settlement and to increase soil strength at an early stage. In the first phase construction, 1 million sand columns were driven. This was followed by construction of an 11km long seawall around the island. Then reclamation inside the seawall was carried out. In the first phase construction, About 180 million m^3 of soil was required for development of the island.

After reclamation work, airport facilities including the runway and the passenger terminal were built, and in September 1994, a little over seven years since the start of the construction, the airport opened its operation.

3 THE SECOND PHASE OF THE PROJECT

In order to meet the growing demand for air transportation, the airport functions should be expanded. Kansai International Airport launched its second phase construction in July of 1999 to complement its current facilities with an additional 4000m runway (Figure 2).

Table 1: Comparison of scale and natural conditions between the first and the second phase construction

	Natural conditions		Scale		
	Water Depth	Thickness of Compressible clay	Reclamation Area	Reclamation Volume	Seawall length
1st phase	18m	150-200m	510ha	180Mm^3	11km
2nd phase	20m	250-300m	545ha	250Mm^3	13km

(M: million)

Table 2: Construction schedule of the second phase airport development

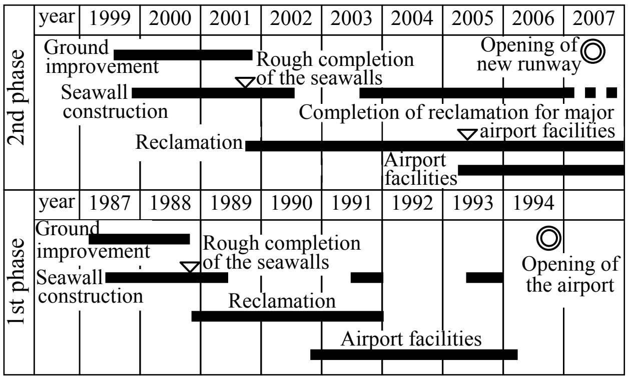


Figure 4. Overview of the first and second airport island of KIA

The second phase of the project involves development of another man-made island of 545ha land 200m off the existing airport island. Thus the natural conditions are more unfavorable than for the first phase construction. The thickness of compressible clay layers and the water depth of the second phase construction site are grater than those of the first phase. The second phase island is expected to settle more than the first phase. In the second phase construction, extraordinary large-scale construction must be conducted in a limited period of time, overcoming these severe conditions. A Comparison of scale and natural conditions between the first and the second phase construction are shown in Table 1. To complete the airport island, the latest technologies are introduced as well as the experience accumulated during the first phase construction.

The construction schedule of the second phase island is shown in Table 2 together with the first phase. The second phase construction works are now proceeding smoothly on schedule despite the severe conditions mentioned above. The overview of the first and second phase island is shown in Figure 4. About 90% of reclamation area of the second phase island has emerged as of January 2005.

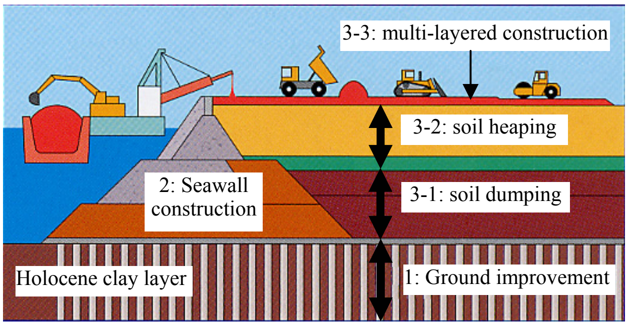
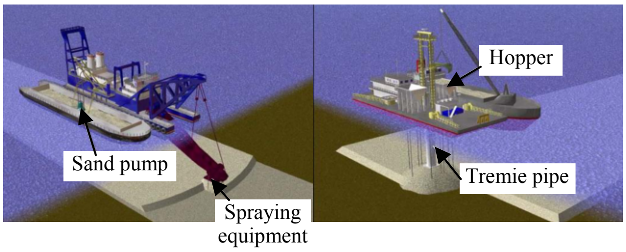


Figure 5. Procedure of second phase construction (Multi-layered construction is in progress.)



(a) Pump method (b) Tremie pipe method

Figure 6. Methods of sand spreading

4 PROCUREMENT OF MATERIALS AND EQUIPMENTS FOR LARGE-SCALE CONSTRUCTION

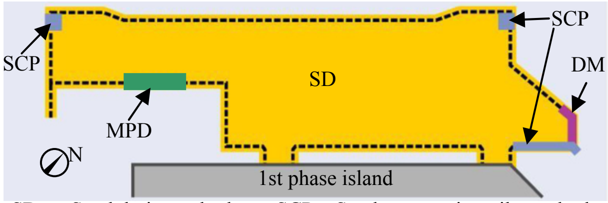
It is important for rapid execution of the large-scale construction to ensure the quick and steady supply of soil required for reclamation.

In the second phase construction, the soil required for seawall construction and reclamation is estimated at 250 million m^3 shown in Table 1. This tremendous amount of soil has mainly been collected from four large-scale supply pits based on the support from local governments around the Osaka bay. Two of these pits were newly developed for the second phase project. The possible impact that development of the supply pits might have on the environment was strictly assessed beforehand. The quick and steady supply of soil is ensured by belt-conveying the collected soil from these pits to their loading points and directly loading them onto barges.

Supply systems have been set up in order to ensure that the necessary reclamation materials are procured, based on capacity of supply pits, transportation capacity and progress of construction. During the peak of reclamation work, total of 100 barges carried 300 thousand m^3 of soil a day into the construction site. The total amount of placed soil in a month reached about 6.5 million m^3. By January 2005, more than 230 million m^3 of soil was placed.

5 CONSTRUCTION WORK

The second phase construction commenced in July 1999. First, ground improvement works for Holocene clay layer mainly using a sand drain method were carried out. After that, the seawall was built all round the second phase island site to start execution of the reclamation. The reclamation work consists of three stages: soil dumping by hopper barges, soil heaping by reclaimer barges and multi-layered construction by bulldozers and rollers. Figure 5 shows procedure of second phase construction. In this section, the outlines of construction works are described.



SD : Sand drain method SCP : Sand compaction pile method
DM : Deep mixing method MPD: Marine plastic drain method

Figure 7. Ground improvement applied in the second phase construction

5.1 *Ground improvement work*

The subsoil immediately below the seabed surface consists of a thick, weak Holocene clay layer, which should be improved so as to minimize the residual or uneven settlement after the airport open its operation and to ensure the stability during the seawall construction and reclamation. The ground improvement work was carried out throughout the entire seawall and reclamation area.

5.1.1 *Spreading of sand blanket*

In the ground improvement work, first, a 1.5m thick layer of sea sand was carefully laid and spread evenly over the seabed as a blanket. The sand blanket allows the water discharged from Holocene clay layer to pass out and disperses the load caused by the seawall construction and reclamation. In the spreading sand blanket, two methods were available, the pump method and the tremie pipe method (Figure 6). The sand blanket was created in 2 or 3 layers by 9 sand spreading barges from July 1999 to July 2000. The volume of the material for sand blanket amounted to 15 million m^3.

Because of depletion of sea sand in the Seto Inland Sea, which is a source of sea sand close to the construction site, substitutes were used in some part of sand blanket. One of the substitutes was graded aggregate of nonstandard crushed stone. Because the grain size of graded aggregate is larger than that of other materials, it was used for upper part of sand blanket as a cushion to reclamation. Another substitute was imported sand from China and Korea. The imported sand was directly carried into the construction site by large vessels after checking the influence on the natural environment since it was the first case in Japan.

To secure the high quality material for permeable layer, grain size distribution of sand was checked at each source in advance. Furthermore, the fine fraction content of materials was also checked to be less than 10% by simple method with coagulant on all barges.

In order to create the uniform permeable layer, the thickness of the sand blanket was carefully controlled by latest technologies linked with RTK-GPS, such as accurate positioning of barges, real-time sounding and two dimensional bathymetric survey (see Subsection 6.3).

5.1.2 *Ground improvement*

The ground improvement was carried out, following the spreading sand blanket. In the second phase construction site, the sand drain method (SD), the sand compaction pile method (SCP), the deep mixing method (DM) and the marine plastic drain method (MPD) was adopted. Figure 7 shows the location of each method of ground improvement. The second phase island has settled as it was predicted, as mentioned in the following section. This implies that the improved ground have no defect such as discontinuity of the sand pile. Ground improvement was carried out night and day to double the pace of execution, resulting in the completion of the work two or three months ahead of the initial schedule. The outlines of the ground improvement methods are described below.

Figure 8. Sand-piling barge

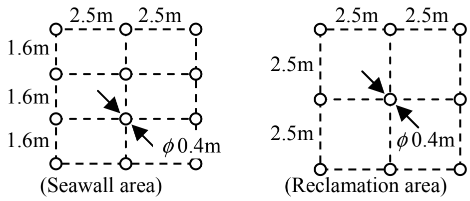


Figure 9. Spacing of sand drain piles

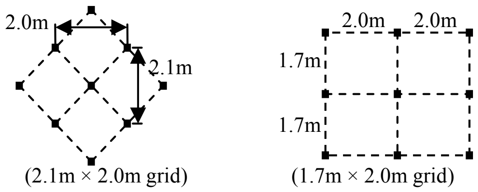


Figure 10. Spacing of plastic drain

(1) Sand drain method

In the second phase construction as well as in the first phase, a sand drain method was applied to most parts of the seawall construction area and all of the reclamation area. Sand piles of 40cm diameter were driven into Holocene clay with average thickness of 25m by sand piling barges (Figure 8). The domestic sea sand was used for sand piles and its quality was checked in the same manner as sand blanket.

Spacing of the sand piles was set at 2.5m × 2.5m square grid, excluding the area beneath the seawall with spacing of 1.6m × 2.5m rectangular grid (Figure 9). The two spacing distances were determined by consolidation analysis solution by Baron. The narrower spacing for the seawall area was set in order to achieve early strengthening of Holocene clay with a more accelerated degree of consolidation, because seawall construction preceded reclamation. According to a finite element consolidation analysis, the spacing of 1.6m × 2.5m is equivalent to a spacing of 2.0m × 2.0m in terms of degree of consolidation (Kobayashi, 1976). The spacing of 1.6m × 2.5m was set for efficient construction, since intervals of pile drivers of sand piling barges were 2.5m. Furthermore, for continuous and seamless placing of sand piles between reclamation area and seawall area, the rectangular spacing is applied for the seawall area (Maeda, 1989).

Because thickness of Holocene clay layer becomes greater towards offshore side, the sand piles in the second construction site were longer than those in the first. Furthermore, it was apprehended that large settlement of Holocene clay layer might induce discontinuity or large deformation of the sand piles. Therefore, in order to ensure the effect of promoting consolidation, the sand piles were driven to the sand layer beneath Holocene clay layer so that the water could be squeezed through the sand layer as well as the sand blanket. The pile drivers were confirmed to reach the sand layer, based on penetration resistance evaluated by rate or load of penetration. The criterion of the penetration resistance of each sand piling barge was determined by penetration test carried out at the site where the thickness of Holocene clay layer was obtained by boring.

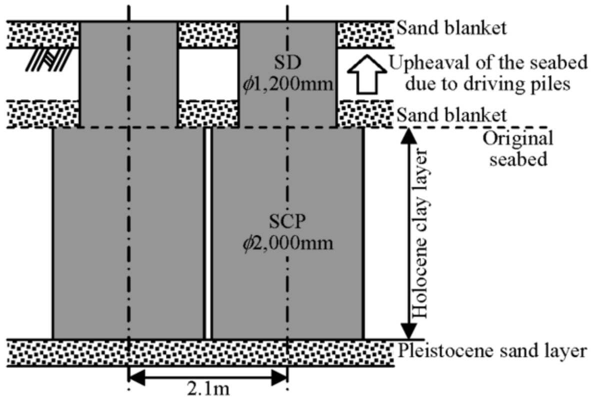


Figure 11. Sand compaction pile method

The sand piles were driven into the prescribed points precisely by positioning control system of sand piling barge linked with RTK-GPS. The sand piles were simultaneously driven in the area of 30m width because the sand piling barges were equipped with 12 pile drivers with interval of 2.5m. The sand piling barges carried out driving sand piles by unit area of 100m × 90m (30m × 3) where the sand piling barges could drive sand piles without weighing anchors by controlling length of four anchoring cables.

About 1.2 million sand piles were driven in 16 months from August 1999 by 8 sand piling barges.

(2) Marine plastic drain method

The marine plastic drain method was employed to shorten the work period and to reduce of sea sand for the ground improvement. The plastic board was driven to sand layer beneath Holocene clay layer and about 24m in average length by a MPD barge. The position of the MPD barge was also controlled by RTK-GPS for precise driving.

The spacing of plastic drain was set so that the same effect of promoting consolidation as sand drain method could be obtained. The interval of mandrel of MPD barge, which is 2.0m, was also considered in the determination of the spacing distance for efficient construction. The two spacing of 2.1m × 2.0m rhombic grid and 1.7m × 2.0m rectangular grid were adopted, which were equivalent to spacing of 1.6m × 2.5m and 2.5m × 2.5m of sand drain method respectively (Figure 10). The equivalent rectangular grid of plastic drain to the spacing of 1.6m × 2.5m in sand drain method is 1.05m × 2.0m. It was, however, apprehended that sufficient effect of promoting the consolidation could not be obtained by rectangular grid with the ratio of short side to long side less than 0.6. Accordingly, the rhombic grid of 2.1m × 2.0m was adopted.

About 82 thousand plastic drains were driven by a MPD barge in 9 months from October 1999.

(3) Sand compaction pile method

The sand compaction pile method was adopted in the area of embedded-type steel cellular-bulkhead seawall. The sand compaction piles were 2m in diameter, and spacing of sand compaction piles was 2.1m square grid. The piles were driven to sand layer beneath Holocene clay layer by a sand compaction piling barge and were about 23m in average length. In driving the sand compaction pile, RTK-GPS was used for positioning of sand compaction barge.

The upheaval of the seabed due to driving piles was about 6m in average and improved by the sand drain method of 1.2m diameter at the same grid as the sand compaction piles (Figure 11).

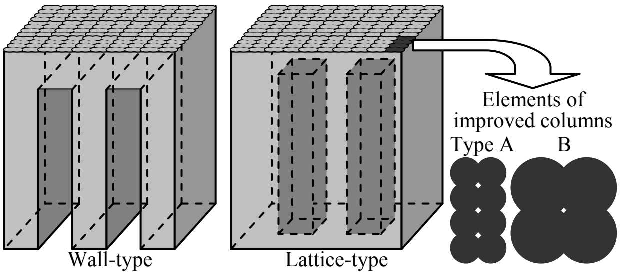


Figure 12. Image of improvement patterns in the deep mixing method

1750 piles were driven by a sand compaction piling barge in 2.5 month from September 1999.

(4) Deep mixing method

The deep mixing method was applied in the area where stability of foundation ground was required. In the deep mixing method, the columns of Holocene clay mixed with cement milk were created by deep mixing barges. Four or eight improved columns were created at the same time. The improved columns were connected with each other and formed a sort of underground structure, which was wall-type or lattice-type. About 330 thousand m^3 of soil were improved by two deep mixing barges in 7 months from August 1999.

5.2 *Seawall construction work*

The Seawall forms the perimeter of the airport island of 13km long, which is embankment of about 30m height and about 250-300m base width. The seawalls were constructed before reclamation so as to protect a reclaimed land from waves and to prevent turbidity caused by reclamation from spreading. The seawall construction was started in December 1999 in the area where ground improvement was completed, and was completed in August 2002 except for three navigation passages for barge operations on the south and the north side of the airport island.

Figure 13 shows a layout of the seawalls. The each seawall has different functions in accordance with its orientation, land use and construction schedule. Functional requirements for each seawall section are summarized in Table 3 in terms of (a) need for reducing disturbance due to reflective waves in the nearby sea area, (b) need for the quay to function both as a sea access wharf and landing place for construction equipments and materials, and (c) the need for short-term construction in accordance with the construction plan. Various types of seawall structures satisfying functional requirements were compared and selected in terms of economic feasibility, ease of construction, stability against settlement and the impact on the surrounding environment. In the second phase project, rubble mound type seawall was adopted in the part more than 90% of the total. Other portions are built as upright wave-dissipating caisson type seawall or embedded-type steel cellular-bulkhead seawall.

5.2.1 *Rubble mound type seawall*

Figure 14 shows a typical cross section of the rubble mound type seawall. As in the first phase construction, seawalls were

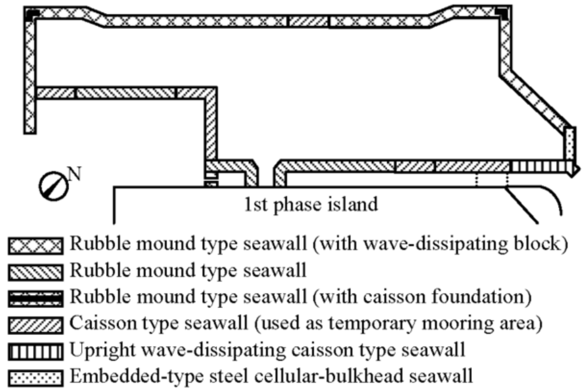


Figure 13. Layout of seawall

Table 3: Functional requirements for seawall

Requirement / Type	Reducing of reflective wave	Quay function	Required for rapid construction
Rubble mound	Required		
Caisson		Required during work period	
Wave-dissipating Caisson	Required	Required	
Steel cellular			Particular Requirements

predominantly (more than 90% of the total) constructed as a rubble mound type seawall with gentle slope because of its structural flexibility to uneven settlement of the seabed, relatively low-cost advantage, and environmental friendliness to surrounding marine habitats. This type is constructed by placing sand and stones layer upon layer to form a structural embankment with gently sloping surface. In the area where intensive wave action was expected, wave-dissipating blocks were placed in front of the seawall to minimize wave overtopping onto land as well as the effect of reflective waves on small boats navigating nearby waters. The corners on offshore side of the second phase island should be built for high rigidity since they are battered by waves from many directions. The seabed at the corners was improved by the deep mixing method and caisson placement. After that, corners were built as a rubble mound type seawall. Some parts of the rubble mound type seawall are being used as temporary mooring area for delivering supplies and machinery during the second phase construction work period. However, they shall be recovered to the standard condition of the rubble mound type seawall.

Figure 15 shows a flowchart of the construction of the rubble mound type seawall. The schematic land development workflow is as follows:

(a) Sand fill: As the first step of seawall construction, sand fill with a layer thickness of about 16m was constructed by direct dumping by hopper barge on the sand blanket.

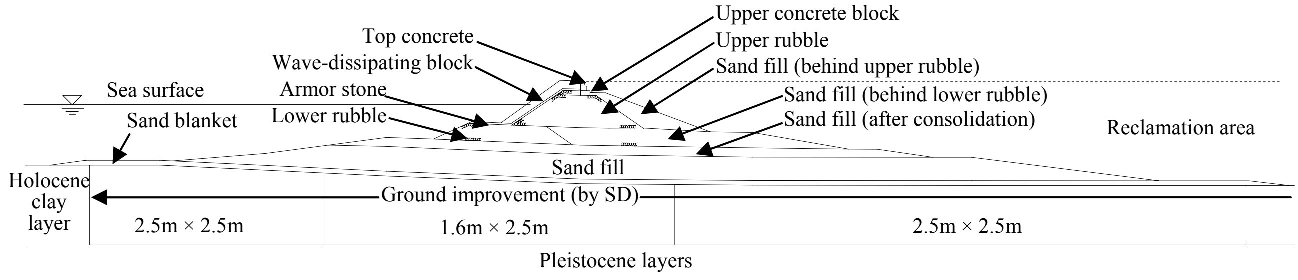


Figure 14. Typical cross section of the rubble mound type seawall (with wave-dissipating block)

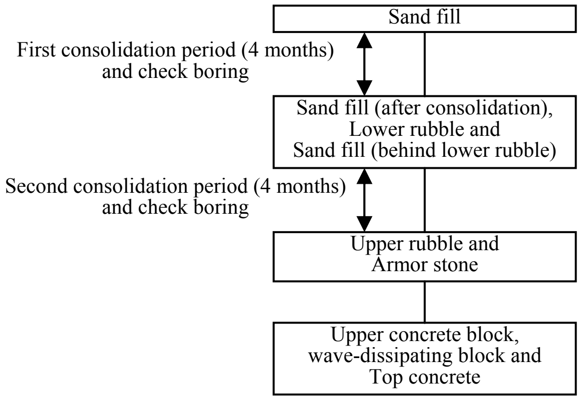


Figure 15. Flowchart of construction of rubble mound type seawall

(b) Rubble dumping: Rubble, which is dumped by sand carrier with grab bucket, serves as a foundation for upper concrete blocks.
(c) Armor stone: Weight of an armor stone which was placed outside of the upper rubble mound was about 1t and it fortifies the rubble against waves. The armor stone was leveled by backhoe above water or manpower of a diver below.
(d) Upper concrete block: Upper concrete blocks were placed to form an earth retaining wall on the rubble mound. The concrete blocks, which were produced on land, transported and placed by crane barge.
(e) Wave-dissipating block: Wave-dissipating blocks were placed in front of the seawall subjected to strong and high waves. In the second phase construction, about 100 thousand blocks were placed.
(f) Top concrete: Top concrete blocks were placed one at a time by concrete mixer barge.

The rubble mound type seawall structure was built up from the seabed improved by the sand drain method. To achieve stability of the seawall during the construction stage, and to prevent uneven settlement, it was necessary to check how the strength of the seabed was increasing with the progress of construction works. In the seawall construction, a consolidation period of 4 months was allowed each time between sand fill and sand fill (after consolidation) placement, and also between lower rubble and upper rubble placement (see Figure 14). The check borings were performed in the end of each consolidation period, and the next stage was commenced after it has been verified that the strength of Holocene clay layer has sufficiently increased for the next stage. The check borings were carried out at 19 sections of the seawalls.

The seawall was required to have uniform thickness in order to avoid the uneven settlement. For the seawall to gain uniform thickness, precise site management was carried out, considering the settlement during construction, as shown in subsection 6.2.

5.2.2 *Upright wave-dissipating caisson type seawall*

A caisson used for this type of seawall is composed of front wall with slits, a water chamber and an impermeable rear wall, and reduces reflective waves. Upright wave-dissipating caisson type seawall was adopted for the seawall joined to quay wall of the port, which is eastern corner of the second phase island, to enhance calmness in enclosed sea area. In order to ensure the bearing capacity of foundation ground, the seabed was improved by the deep mixing method, because the upheaval of the seabed due to ground improvement is small. A typical cross section of the upright wave-dissipating caisson type seawall is shown in Figure 16.

5.2.3 *Embedded-type steel cellular-bulkhead seawall*

The area of the embedded-type steel cellular-bulkhead seawall, which is a part of the northeastern area of the second phase island, was established as a navigation passages for barge operations. The passage shall be closed urgently just before the completion of reclamation work. The embedded type steel cellular-bulkhead seawall shall be adopted as the most suitable structure to meet the requirement of rapid construction. A typical cross section of the upright wave-dissipating caisson type seawall is shown in Figure 17.

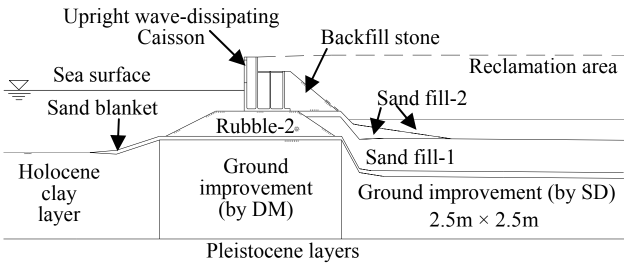


Figure 16. Typical cross section of the upright wave-dissipating caisson type seawall

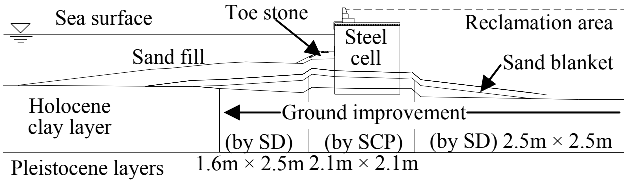


Figure 17. Typical cross section of the embedded-type steel cellular-bulkhead seawall

In the area of embedded type steel cellular-bulkhead seawall, the construction has been suspended after the ground improvement, because the water depth of 6m is needed to ensure draft of the barges in the passage area. The passage shall be closed with cylindrical steel cells driven to the prescribed depth by a floating crane mounted with a vibration hammers. After the dumping of filling material, sand fill and toe stones shall be placed in front of the steel cells.

5.3 *Reclamation work*

Because of the great amount of reclamation soil, settlement of the seabed was expected to be large and to occur in both Holocene and Pleistocene layers. While the settlement of Holocene clay layer will be completed during the reclamation work by ground improvement, Pleistocene clay layers continue to subside after the airport is opened. This large and long-term settlement was reflected in setting of thickness of reclamation land. Furthermore, to minimize the uneven settlement, which will occur after the completion of the airport island and may cause damage to airport facilities, reclamation work was conducted as evenly and uniformly as possible.

The reclamation work consists of three stages: soil dumping, soil heaping and multi-layered construction, as mentioned above. The reclamation work was started in May 2001 following the ground improvement work and the seawall construction. About 90% of reclamation area of the second phase island has emerged as of January 2005. And the multi-layered construction, which is the last step of the reclamation work, is now in progress. In this section, the outlines of each stage of reclamation are described.

5.3.1 *Soil dumping*

After the seawall broke the water surface except for navigation passages for barge operations, soil dumping was started. In the soil dumping work, uniform thin layers of mountain soil were created by directly dumping from hopper barges on the sand blanket to minimize the uneven settlement (Figure 18). These thin layers had the total thickness of 14-15m and formed depth

Figure 18. Soil dumping by hopper barge

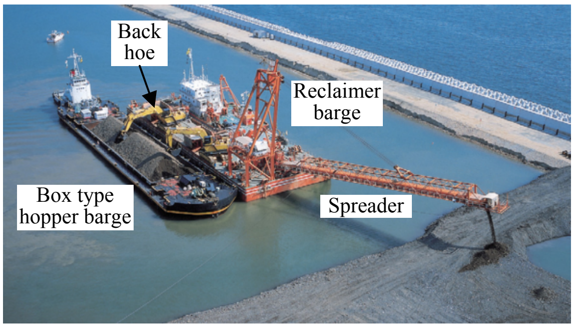


Figure 19. Reclaimer barge

of 6m below sea level. The 6m depth limit was established to allow for draft of hopper barges. The soil dumping was carried out by 8 layers, and lower layers were designed to be thinner than upper layers so as not to disturb the improved ground.

The entire reclaimed area was divided into blocks of 200m × 200m and site management was strictly carried out on each block to achieve the uniform layers. Furthermore, the soil dumping was conducted so that the difference of the loading history among blocks adjacent to each other might be minimized as much as possible to minimize uneven settlement. The layers reclaimed in soil dumping work serve as a load to promote the consolidation and increase the strength of the improved seabed before soil heaping. Thus, precise settlement measurement and bathymetric surveys mentioned later were carried out to confirm that the effect of ground improvement was obtained as designed.

The soil dumping was conducted by 48 hopper barges, loading volume of which is 2,000-4,500m^3, from May 2001 to June 2002, and 62 million m^3 of mountain soil was used.

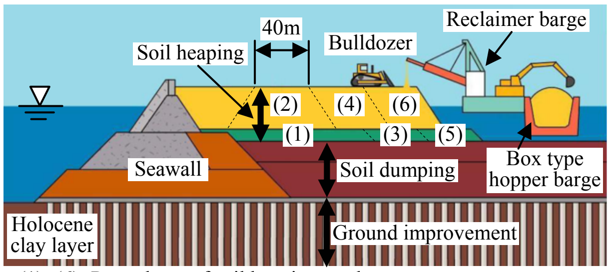
5.3.2 *Soil heaping*

Soil heaping work consists of dumping soil by hopper barge and unloading soil by reclaimer barge, which are called as dumping-2 and reclamation-1 respectively. The dumping-2 is carried out by directly dumping soil from small bottom open type hopper barges to a depth of 3m, which is the depth limit for draft of reclaimer barge. Then, the reclamation-1 is carried out on the ground reclaimed in the dumping-2. Mountain soil is carried into the site by box type sand carrier, transshipped into a reclaimer barge which carries spreader mounted conveyors, and unloaded in a prescribed area (Figure 19). Figure 20 shows a cross section of the reclamation work normal to the direction of reclamation progress. The dumping-2 and the reclamation-1 are conducted alternately for a 40m wide row as a work unit, which is a working limit of the reclaimer barges. The site management blocks of 200m × 200m were further divided into smaller management blocks of 40m × 40m.

Because hopper barges can not navigate and conduct soil dumping evenly in the area shallower than 6m, the reclaimer barge heaps up the soil to predetermined height at a time. The reclaimed land breaks the water surface by the reclamation-1. Therefore, an increment of the load caused by reclamation-1 is larger than that of previous work. The uniform thickness of soil heaping was established on each 200m × 200m blocks in order to avoid the uneven settlement within the 200m square block caused by the difference of the load of reclamation. The thickness of soil heaping was from about 17 to 19m. To gain the uniform thickness of the soil heaping, heaping height is set for 40m square block, taking into consideration the settlement until the reclamation-1 as well as the ability of reclaimer barge and stability the ground. The difference of loading history in reclamation-1 was expected to cause the uneven settlement because of its large load. Thus, the reclamation-1 was started from the areas of important facilities such as runway, access taxiway and apron, and was conducted intensively by 11 reclaimer barges in these areas, in order to minimize the difference of the loading history among blocks adjacent to each other.

For conducting of the reclamation-1, it is imperative for the reclamation-1 to ensure the stability of the ground. The dumping-2 is carried out for one block ahead of the reclamation-1 as shown in Figure 20, and plays a role of counterweight to the reclamation-1. The check borings were carried out before the soil heaping work at points of settlement plates, mentioned in section 6.1, in order to confirm the soil strength. Stability analyses based on modified Fellenius method and Bishop method are also conducted on each 40m × 40m blocks.

The mountain soil used in soil heaping (the dumping-2 and the reclamation-1) reached 96 million m3 as of January 2005. About 90% of reclamation area of the second phase island has consequently emerged.



(1)~(6): Procedures of soil heaping work
(1), (3), (5): Dumping-2
(2), (4), (6): Reclamation-1

Figure 20. Cross section of the Soil heaping work normal to the direction of progress of reclamation-1

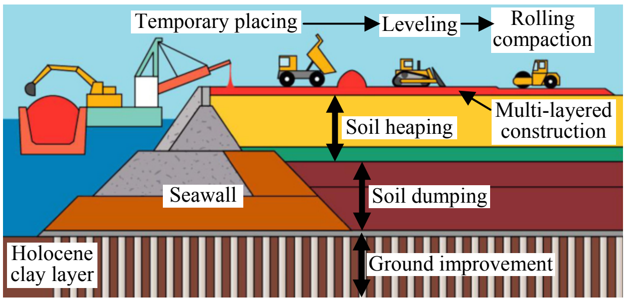
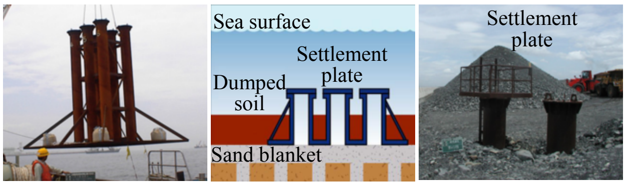


Figure 21. Progress of multi-layered construction

5.3.3 *Multi-layered construction*

The reclaimed area by soil heaping is further covered by multi-layered construction called reclamation-2. The Reclamation-2 work has been started as the final work of land development of the second phase construction in the areas of runway and access taxiway, which will be opened in 2007.

The reclamation-2 work is carried out by placing and compacting mountain soils layer upon layer. The thickness of each compacted soil layer was designed to be 60cm in terms of effective compaction. The compacted layers are required to be uniform and to satisfy designed thickness and stiffness as a foundation for airport facilities. The reclamation-2 must be carried out by layering to provide uniform quality of the ground. In order to precisely develop multi-layered ground, a rolling compaction method using heavy vibration rollers was adopted. Mountain



(a) Settlement plate (b) During dumping work (c) After heaping work

Figure 22. Hydraulic pressure gauge with a magnetic transmitter

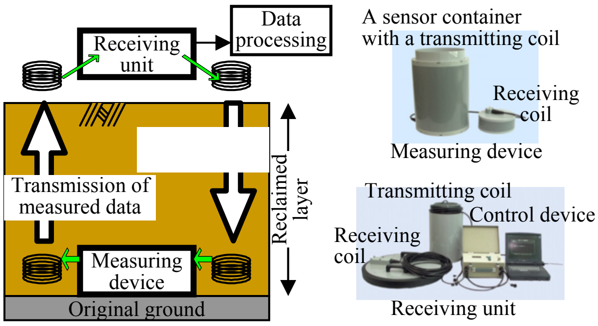


Figure 23. Hydraulic pressure gauge with a magnetic transmitter

soil is put in a temporary placing by the reclaimer barge and is transferred to prescribed area by heavy dump trucks for leveling by bulldozers. And then, rolling compaction was carried out by heavy vibration rollers to form a uniform and stiff layer of 60cm thickness. (Figure 21)

Rolling compaction tests were conducted prior to the reclamation-2. The tests used an automated scanning type radio isotope method, the in-situ soil density measurement method using water replacement, and plate loading tests, by which ground density, water contents, subgrade reaction modulus, and elastic modulus were obtained, thus confirming effects of rolling compaction. Based on the tests results, thickness of a layer, types of heavy equipment, the number of rolling operations, and a site management method for quality control were determined.

In order to develop a stiff and uniform quality ground, site management is carried out as follows.

(a) Water content: Water content is measured and controlled to be optimum for compaction before construction for effective compaction.

(b) Height of the reclaimed land: In order to provide the layers of designed thickness, leveling is carried out with measuring position and height by GPS attached on bulldozers.

(c) Degree of compaction: In order to construct uniform and stiff ground, rolling compaction is carried out with measuring position by GPS attached to vibration rollers, so that number of rolling operation can be controlled. Accelerometers are also attached to vibration rollers for detection of the part of low stiffness.

(d) Thickness and density: After compaction of each layer the height and density of the ground are measured for inspection of thickness and quality of the layer. The height of the ground is measured by working car with GPS. The density of the ground is obtained by radio isotope method.

The multi-layered construction in the area of facilities which will be opened in 2007 is scheduled to be finished in the summer of 2005. In the other area, the multi-layered construction is started following the soil heaping.

6 SITE MANAGEMENT

6.1 *Settlement measurement*

It is essential for the large-scale, rapid reclamation works on the soft grounds to precisely monitor settlement of the seabed during construction. In order to efficiently measure the settlement, two types of settlement measuring device were placed in the second phase construction site: a settlement plate and a hydraulic pressure gauge with a magnetic transmitter.

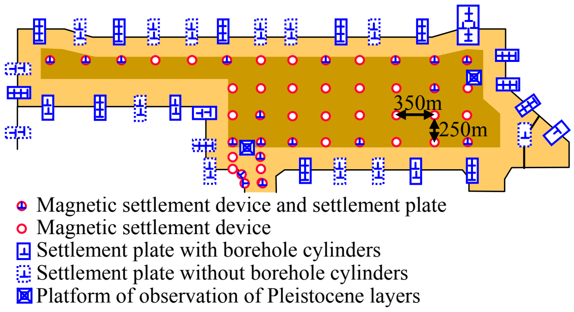


Figure 24. Arrangement plan of settlement measuring devices

Settlement plate is one of the most basic settlement measuring devices. A typical settlement plate is shown in Figure 22. It consists of a bottom plate and several upright cylinders. A settlement plates were placed on the surface of sand blanket right after the ground improvement. The settlement of the seabed is obtained by gauging water depth or height of the top of the cylinder. This method has many previous experiences, but has some disadvantages: A bad weather sometimes prevents weekly measurement of settlement because the settlement measuring was carried out by a diver putting down a handy water pressure gauge on the top of the cylinder before reclaimed land emerged. Also the settlement plate may become an obstacle against navigation of work vessels such as a hopper barge.

The other type of settlement measuring device is a hydraulic pressure gauge with a magnetic transmitter (hereinafter referred to as magnetic settlement device), which was placed on the seabed mainly in the reclamation area. This settlement monitoring method is also based on measuring the increase of water pressure due to the settlement of the seabed. This device detects water pressure every two hours automatically. Then the device transmits data via a magnetic transmitter to a receiving unit as shown in Figure 23. Significant merits of this method are: the device can be placed anywhere; it is not an obstacle to work vessels; and it makes possible continuous, unhindered settlement measurement.

The seawall construction area was divided into 34 site management blocks, and each block has 2 or 3 settlement plates in the representative cross section. Settlement plates equipped with borehole-cylinders were installed at 19 blocks, and used as a guide during check boring as well as settlement measurement. Settlement plates without a borehole-cylinder were installed at another 15 blocks. In the reclamation area there are 37 magnetic settlement devices and 17 settlement plates. Magnetic settlement devices are placed at a rectangular grid of 350m × 250m (Figure 24).

6.2 *Controlling the thickness of the reclaimed layer and settlement*

In order to develop the seawalls and reclaimed land of uniform thickness, the thickness of reclaimed layer needs to be precisely controlled. The thickness of the reclaimed layer is estimated from settlement of the seabed during reclamation work in addition to difference of heights of the reclaimed land between before and after the work. The settlement during reclamation is obtained by settlement measuring devices. On the other hand, the settlement at the point where the devices were not installed needs to be predicted. Because the predicted settlement does not always fit in with the observed settlement, it is corrected by "settlement ratio". The settlement ratio is defined on each settlement measuring device as the ratio of the observed settlement to the predicted settlement in a specific time period, and is used for correction of the predicted settlement around the device.

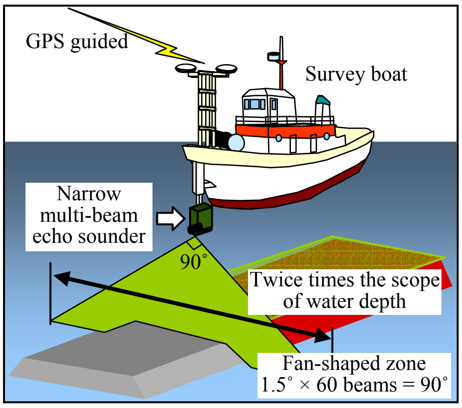


Figure 25. Conceptual scheme of bathymetric survey

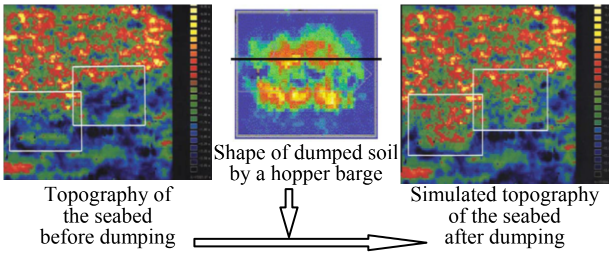


Figure 26. preliminary dumping simulation

Settlement prediction of the seabed is based on two methods: One is "m_v method" for site management purpose, and the other is elasto-viscoplastic analysis by a finite element method. In this section, m_v method is to be explained, and the finite element analysis will be mentioned later. m_v method was adopted mainly for site management purpose because it is relatively easy to use and it is built into a set of computational programs, "Settlement-stability analysis system", developed by KIAC for consultants and contractors to utilize. In m_v method, S_t; settlement at time t, is calculated by the following formula:

$$S_t = m_v\, p\, H\, U_t, \tag{1}$$

where, m_v is a coefficient of volume compressibility, p is a consolidation pressure, H is thickness of clay layer, and U_t is a degree of consolidation at time t, which is calculated by Barron's formula, using c_v, a coefficient of consolidation determined by consolidation tests. It is practically assumed that c_v (vertical coefficient) of the Holocene clay at the construction site is equal to c_h (horizontal coefficient) (Maeda, 1989). m_v is also determined by consolidation tests.

When noticeable discrepancies appear between observed and predicted settlement, we may slightly modify the m_v and c_v so that the predicted settlement curve can better fit in with the observed settlement curve for site management. In most cases, the observed settlement data are plotted within a range of the predicted settlement because of high accuracy of prediction supported by precise site management, to be described in the next section. In some cases, though, calculation results do not seem to fit in well with observed data. Therefore, it is important that settlement management should be carried out with careful consideration to varied conditions and circumstances of soil properties, loading steps, etc.

6.3 *Site management*

One of the technical challenges for the second phase construction is to conduct the land reclamation as evenly and uniformly as possible, taking spatial distribution of the weight of the dumped soil on the seabed into consideration, and thereby minimizing the uneven settlement that will occur with the completed airport island. In order to achieve the evenness and uniformity of the land reclamation, the latest technologies advanced after the first phase construction, such as GPS, were introduced in the second phase construction.

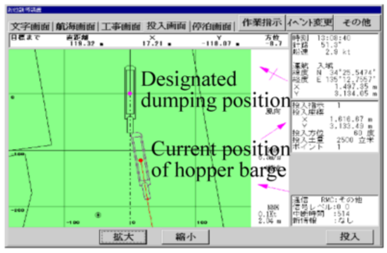


Figure 27. Navigation management support system

Acquiring data continually on settlement tendency and exact location and volume of soil dumping and heaping should be very important for the site management. Digitized data from various technologically advanced systems were combined with those obtained from bathymetric survey, and were unitarily managed so that required data for site management can be accessed quickly. Newly developed "VS10" system is installed on all hopper barges for land reclamation operation in the second phase construction. The VS10 system manages all data including each barge's name, soil dumping position, soil dumping volume and soil source data, in a single database.

An accurate monitoring of gradual buildup of dumped soil was carried out by a narrow multi-beam echo sounder before and after dumping. This sounder emits 60 beams of ultrasonic waves with an acute directive angle of 1.5˚ at one time to a fan-shaped zone at 90˚ and conducts the bathymetric survey in two dimensions as shown in Figure 25 (in the past, only a linear survey was performed). A position survey was performed using GPS and the effect of ship motions such as pitching and rolling is compensated for with correcting instruments.

In the information database, shapes of the soil dumped from each hopper barges on the seabed of various depths were stored as well as results of pre-dumping bathymetric survey. The database made it possible to estimate how the buildup of reclaimed land will take shape through preliminary dumping simulations (Figure 26). This had an effect on uniformity of dumped soil to be confirmed in advance and allowed adjustments in soil dumping position.

The suitable dumping location, the depth of water, the direction of the bow etc. were determined based on the preliminary dumping simulations. The hopper barge was led to designated dumping position by the navigation management support system called as VS10 as mentioned above (Figure 27).

7 SETTLEMENT ANALYSIS OF PLEISTOCENE CLAY

Large settlement as a result of land development was expected because of thick compressible clay layers below the seabed. The soft Holocene clay layer just beneath the seabed was improved by sand drain method in order to promote the consolidation of the layer. On the other hand, the settlement of Pleistocene clay layers was expected to continue to subside after the airport is opened, since it is difficult to improve these layers in terms of technology. In order to sustain the functions of airport facilities, it is important to predict the long-term settlement of Pleistocene clay layers and to reflect the predicted settlement in the design of land development. In this section, measuring and predicting settlement of Pleistocene clay layers is described.

7.1 *Settlement measurement*

It is important to monitor settlement of Pleistocene clay layers and pore water pressures of Pleistocene sand and clay layers in order to predict the long-term settlement as accurately as possible. Two “offshore oil-rig” type platforms are placed in the second phase construction site in order to install various measurement devices into Pleistocene layers deep down to 350m (Figure 24). The devices installed include: an anchor-rod type settlement gauge, a differential settlement gauge, and a pore water pressure gauge.

An anchor-rod type settlement gauge made of long steel pipe was installed in upper and lower stratums of deepest compressible clay layers. Settlement is obtained by monitoring height of the upper end of the steel pipe. An inclinometer is used to compensate for inclination of the pipe.

A differential settlement gauge was installed in every clay layers from the nethermost compressible Pleistocene clay layer to the uppermost. In the thicker clay stratums there are two or more gauges at the different level of the same stratum. By measuring the level of magnetized elements installed in each stratum, changes in thickness of each layer are obtained. Data obtained from this device is cross checked with data obtained by the anchor rod type settlement gauge.

A pore water pressure gauge is installed in every clay and sand layers. This gauge measures a pore water pressure by finding the pressure value of the gas in a measuring instrument that is balanced with the pore water pressure around the measuring instrument.

7.2 *Settlement prediction*

In order to identify the properties of the Pleistocene clay and the layer configuration, prior to commencing the first phase construction, a total of 65 boring explorations were conducted. Two boring were 400m class, and the others were 100m and 200m class. In addition, four 400m class boring explorations were conducted before the second phase construction. The system of wire line drilling developed by the Port and Harbour Research Institute was used to ensure high quality and efficiency during the work. In this soil exploration program, a series of laboratory tests and geologic tests was carried out on all of the soil samples obtained. The database of the soil profile of the construction site and soil properties for settlement prediction was built based on the results of boring and geological studies, such as emergence pattern of the nannofossil and existence of the volcano glass.

Prediction of the long-term settlement of clay layers of both Pleistocene and Holocene at the second phase construction site is based on “FCAP” program. FCAP (Finite-element Consolidation Analysis Program) conducts a one-dimensional finite element consolidation analysis with the boundary conditions of pore water pressures of each Pleistocene sand layers, which are calculated by a separate two-dimensional seepage analysis. The constitutive model developed based on the results of various types of laboratory tests and behaviour of the ground observed at the first phase island, such as settlement and pore water pressure. In this method, the bi-linear elasto-plastic constitutive model is used. Pleistocene clays were considered as normally consolidated aged clay since they exhibit the apparent overconsolidation without definite mechanical overconsolidation history (Shinohara, 2003). Based on some settlement observed in lower Pleistocene clay layers, elasto-viscoelastic model using secondary consolidation coefficient is assumed only in the settlement prediction of the layers for safety.

The validity of this prediction method was confirmed by applying this method on the settlement observed during more than 10 years at the first phase island. The prediction method and conditions has been revised and refined with academic cooperation from distinguished scholars of an investigation committee for settlement prediction of the second phase island.

Furthermore, in order to verify the validity of this settlement prediction method, a new program called KCAP is now being developed by KALD and Kobayashi (Kobayashi, 1982). KCAP is a one-dimensional finite element soil-water coupled analysis program. The constitutive model in KCAP is developed considering the complex characteristics of Pleistocene clay, such as

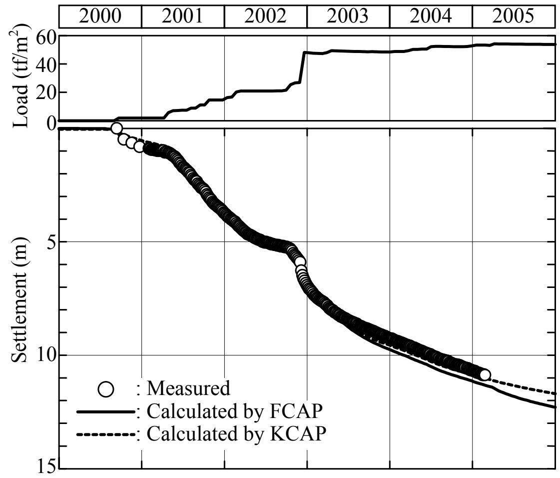


Figure 29. Observed vs. calculated settlement

high compressibility around a consolidation yield stress and the behavior dependent on strain rate.

FCAP predicts about 8m settlement for Holocene clay and about 10m for Pleistocene clay layers on average for the second phase island from commencement of construction to 50 years after opening the new runway. It can be considered that this prediction has been attained by using the latest technology. Figure 28 shows an example of comparison among settlements observed by a magnetic settlement device and predicted by FCAP and KCAP. It is found that the predicted settlements are in good agreement with observed one. This implies the validity of this prediction method for the present time.

8 POSTSCRIPT

In the land development of the second phase island, reclaimed land of uniform thickness were developed through precise site management. At each step of the second phase construction project, such as planning, design and execution, measures against the settlement were taken to maintain and to sustain the airport facilities. As a result, the uneven settlement after opening the new runway is expected to be minimized. The function of airport facilities will be able to be sustained through careful management. For example, a jack-up system will be incorporated into the building pillars to meet the uneven settlement.

It is already five years since the second phase construction started, and about 500ha of reclaimed space, accounting for some 90% of the whole island, has emerged. The second phase construction project is now in progress for opening of the new runway in 2007.

REFERENCES

Kobayashi, M. 1976. Analysis of consolidation problem by a finite-element method. *Technical note of Port and Harbour Research Institute*, No. 247. (in Japanese)

Kobayashi, M. 1982. Numerical analysis of one-dimensional consolidation problems. *Report of Port and Harbour Research Institute*, Vol. 21, No. 1. (in Japanese)

Maeda, S. 1989. Research on settlement and stability management system of soft grounds improved by sand drain for large-scale offshore artificial island. *Thesis of Dr. Eng.* (in Japanese)

Shinohara, M. 2003. Settlement analysis and intelligent site management of the second-phase land reclamation works for Kansai International Airport. *Soft Ground Engineering in Coastal Areas* (*Proceedings of the Nakase Memorial Symposium*), Pp. 159-167.