KGS Fall '92 National Conference/Dredging, Reclamation and Artificial Islands/16-17 October, 1992/Seoul/Korea

ARTIFICIAL ISLANDS RECENTLY CONSTRUCTED IN OSAKA BAY, JAPAN

Toshinobu AKAGI, P. E., Dr. Eng.

Professor of Geotechnical Engineering, Toyo University
Kawagoe City, Saitama 350, Japan

SYNOPSIS An attempt has been made to summarize some of the unique geotechnical problems encountered during construction of a few large man-made islands recently completed off the coast of Osaka Bay, Japan. Large settlements appear to be the most serious problem both during and after construction. Settlements due to consolidation of a thick layer of soft alluvial clay that constitutes seabed seem to virtually cease within a relatively short period of time when vertical drains are installed adequately prior to fill placement. Settlements due to compression of underlying thick diluvial deposits consisting of layers of stiff clays interbedded with coarse-grained soils, however, continue over a prolonged period of time and call for special provisions for structures built on the artificial islands to cope with relatively large future settlements. Although accurate settlement prediction is not possible, it is both technically and economically feasible, nevertheless, to construct large-scale islands. Particularly attractive and promising is creation of sizable new areas for various purposes, immediately adjacent to highly-developed, densely-populated cities situated along the coast such as those around Osaka Bay.

1. INTRODUCTION

1-1 General

While reclamation and construction of artificial islands have been undertaken extensively in various parts of Japan, Osaka Bay has always been one of the centers of such undertakings for the last several decades. Photo 1-1 shows a view of the Osaka Bay area from an artificial satellite revealing extensive reclamation works and man-made islands along the coast of Osaka and Kobe. Table 1-1 summarizes some of the pertinent features of major artificial islands recently constructed in Osaka Bay.

These man-made islands are large in scale, each several hundred hectares (ha), were constructed at great depths of water and on thick deposits of very soft marine clays, and required enormous volumes of fill materials transported mainly by barges over considerable distances.

Artificial islands are built generally for multiple purposes, i. e., to create an offshore land for a harbor, an airport, an industrial area, recreational facilities, oil storage, power plants, sewage treatment plants, waste and garbage disposal, and also for a new city complete with business centers, shopping centers, residential areas and related facilities with an easy access to the major cities located in the vicinity.

This report presents a summary of construction and performance of a few unique artificial islands recently constructed in Osaka Bay; i) Port Island and Rokko Island off Kobe and ii) the Kansai International Airport (KIA) Island south of Osaka.

The following is a summary of information derived from recent publications such as given herein as references and also discussions the writer has had with engineers in charge when he visited the project sites in recent years as well as his own observation.

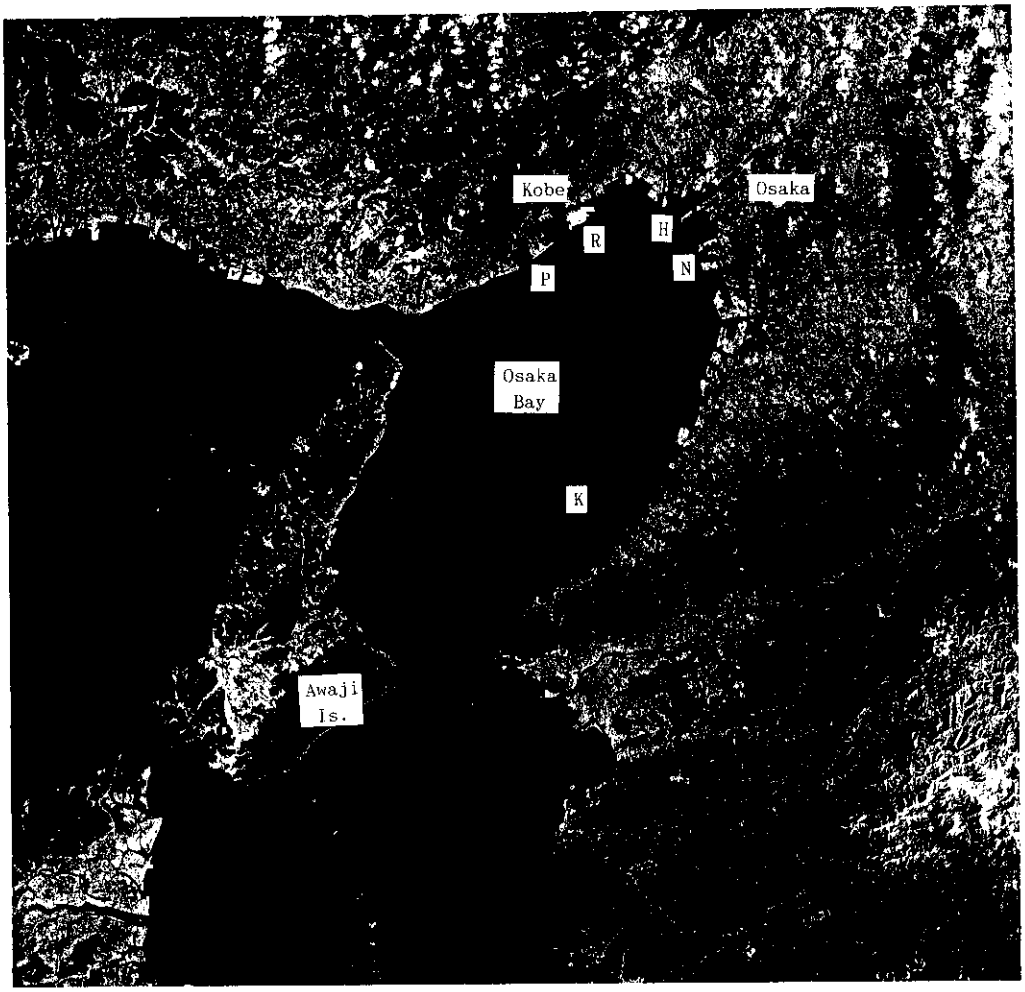
1-2 Subsurface Conditions in Osaka Bay

The subsurface geology in Osaka Bay is relatively uniform and illustrated by Fig. 1-1 (b) and (c) showing a couple of geologic sections the locations of which are indicated on the area map, Fig. 1-1(a), as A-A and B-B crisscrossing Osaka Bay.

The seabed consists of very soft, highly compressible alluvial clay of substantial thicknesses which is essentially normally consolidated having characteristics of being somewhat overconsolidated due to aging. This clay is referred to locally as Ma 13 being the latest marine deposit in this area.

The Ma 13 layer is underlain in general by a deposit of very compact sand and gravel, and clay in alternating layers. The thickness depends upon locality ranging from about 30 to 50 m off Kobe and several m to zero thickness around the site of the KIA island. This deposit is of diluvial origin. The term "diluvial" in Japan refers to compact clay, silt, sand, gravel or their mixtures having a characteristic stiffness with its geologic age being older than what "alluvial" implies.

Beneath the upper diluvial deposit underlies a diluvial layer of medium to stiff, overconsolidated clay which is continuous over the entire basin with varying thicknesses being locally designated as Ma 12. Dotted line contours on the area map, Fig. 1-1(a), represent the bottom elevations of the Ma 12 clay stratum.



P : Port Island (I) R : Rokko Island
H : Hokko Island N : Nanko Island K : KIA Island

Photo 1-1 Osaka Bay Area - a View from an Artificial Satellite
(Courtesy of KIA Co., Ltd.)

It has repeatedly been pointed out (e.g., Akai, et. al., 1991) that the Ma 12 clay layer does consolidate and is responsible for significant long-term settlements under stresses induced by large-scale reclamation works in the Osaka Bay area.

The Ma 12 stratum is underlain by alternating strata of compact sand and gravel, and stiff clay to undetermined depths exceeding 1000 m.

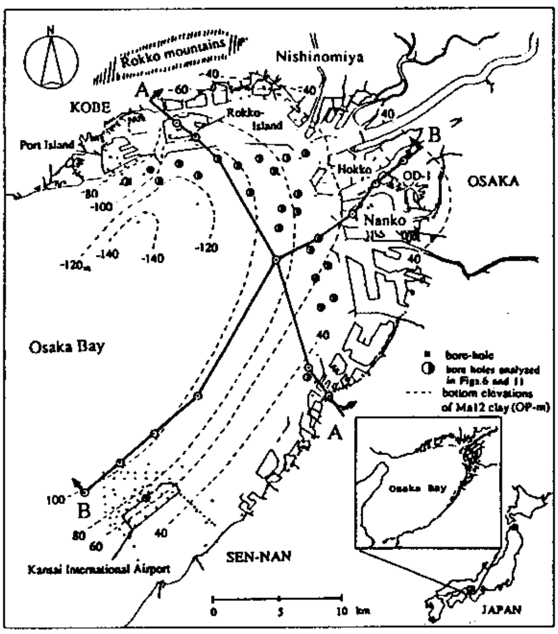
2. PORT ISLAND AND ROKKO ISLAND, KOBE

2-1 General

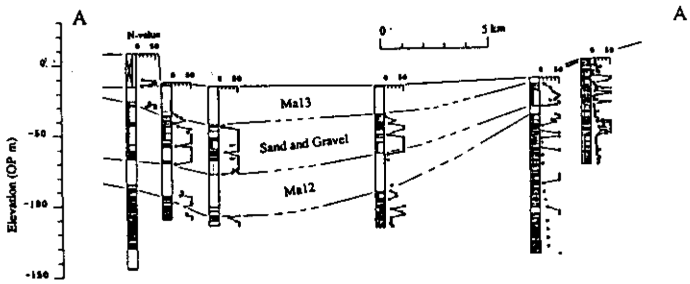
Kobe, being a belt-like city sandwiched by the Rokko mountain range and Osaka Bay, has long been keen on reclaiming its shores by bringing soil and rock from the mountains behind the city, Fig. 2-1. During a period between 1953 and 1970, a total of 543 ha of its offshore areas was reclaimed in the eastern and western parts of the city. For this purpose more than 62 million cubic meters of fill was hauled, which virtually leveled a few mountains behind the Suma area.

Table I-1: Major Artificial Islands in Osaka Bay

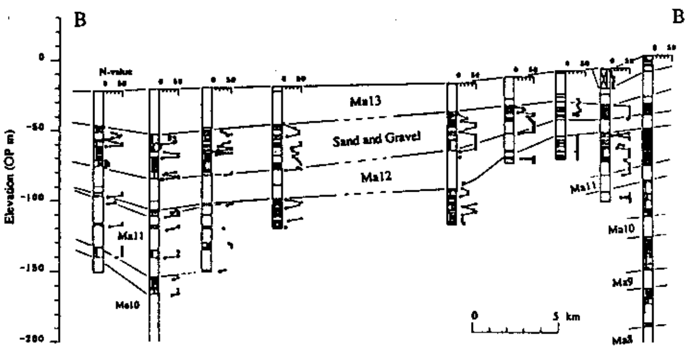
	Nanko Island Osaka	Hokko Island Osaka	Port Island Stage I, Kobe	Port Island Stage II, Kobe	Rokko Island Kobe	Kansai Int'l Airport Island
Area of Island (ha)	937	615	436	390	580	511
Volume of Fill (million cu. m)	103	-	80	92	120	183
Seawall length (km)	26.7	-	13.7	8.3	12.5	11.2
Average Water Depth (m)	5.5	10	12	13	12	18
Distance from Shoreline (km)	0	0.5	0.2	0.2	0.4	5.0
Construction Period	1958-1980	1972-1993	1966-1980	1986-1996	1972-1991	1986-1994



(a) Area Map, Osaka Bay



(b) Geologic Section A-A



(c) Geologic Section B-B

Fig. 1-1 Area Map and Geologic Stratigraphy, Osaka Bay (Akai, et al, 1991)

In order to provide the rapidly growing city with new port facilities and create a multi-functional urban area, it was decided to construct an artificial island near the central district of the city. Thus the 436 ha Port Island was built during the 1966-1980 period. Having already been built up almost completely with preplanned infrastructures, this island is being expanded to the south to add another 390 ha of reclaimed land. This extension is called the Port Island Stage II Project, the earth work of which is roughly 50% complete as of the summer, 1992.

Almost in parallel with the progress of the Port Island Stage I project, another man-made island named Rokko Island was implemented, being situated just east of Port Island, during a period between 1972 and 1991. Photo 2-1 shows an aerial view of Port Island (I) and Rokko Island.

2-2 Subsurface Conditions
The subsurface conditions at the sites of Port Island and Rokko Island may be illustrated by geologic sections in Fig. 2-2. At an average water depth of 12 to 13 m the seabed consists of very soft alluvial clay (Ma 13), 10 to 20 m thick, underlain by alternating layers of compact sand and gravel with some clay, all of diluvial origin, ranging from 30 to 50 m in thickness.

Beneath these upper diluvial strata underlies a layer of stiff diluvial clay (Ma 12), 15 to 25 m thick, then underlain by the lower diluvial strata to undetermined great depths. All the strata tend to dip and thicken as the distance increases away from the shoreline.

The Ma 13 and Ma 12 clays are both highly plastic and compressible essentially, although the latter clay being of diluvial origin is overconsolidated and very stiff.

2-3 Reclamation
Fill materials were excavated from mountains situated north-west of Kobe. The borrow areas were simultaneously developed into residential, industrial, recreational and other areas. There are several more large borrow areas outside the map, Fig. 2-1. Excavated materials were brought down to Suma Beach by means of an underground belt-conveyor system, 14.6 km in total length, to be loaded onto barges from the terminal jetty, Fig. 2-1.

Then fill material was transported by sea to the site by bottom-dump barges equipped with openable bottoms, each carrying fill ranging from 1000 to 6000 cu. m and being pushed by a pusher boat. At the site barges are positioned precisely at a predetermined place and dumped fill material by opening bottoms with careful control over the depths so as to minimize disturbance and lateral flow of the underlying soft mud.

Fill was dumped in this manner up to a depth of 2 m below sea level. Filling above that level to final grade was accomplished by a combined use of barges capable of unloading fill scooped automatically by a bucket wheel and a highly automated shiftable belt conveyor system with a special spreader at its terminus. A typical construction procedure is illustrated by Fig. 2-3(a) and (b).

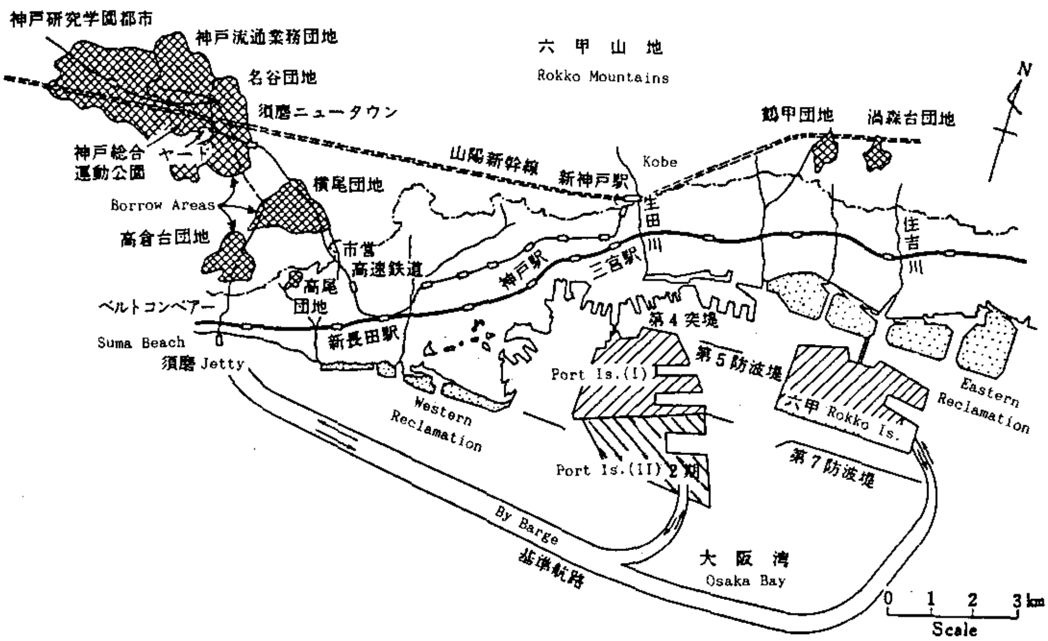


Fig. 2-1 Man-made Islands, Kobe (Kanazawa, et al, 1989)

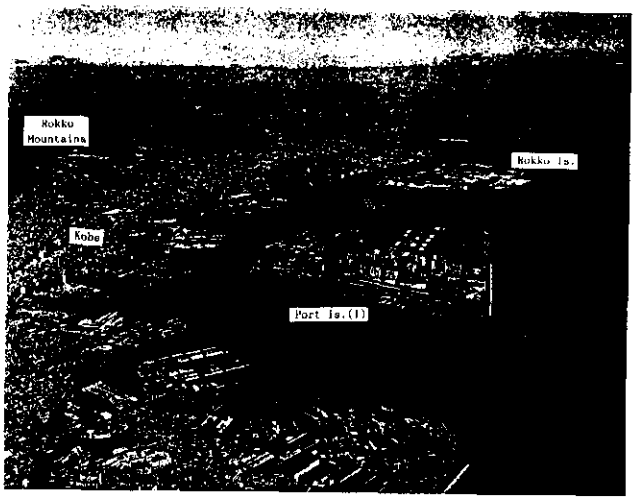


Photo 2-1 Aerial View of Port Island (I) and Rokko Island (Courtesy of the City of Kobe)

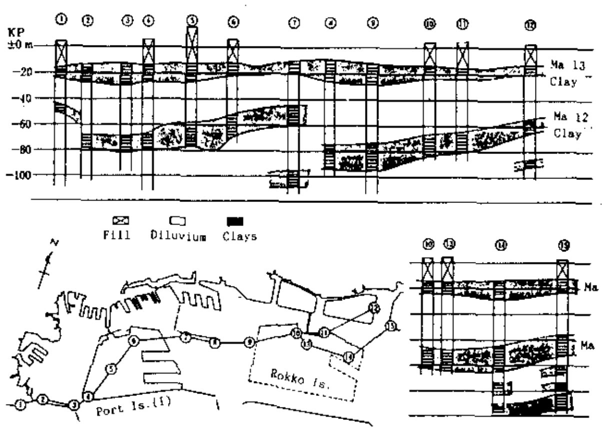
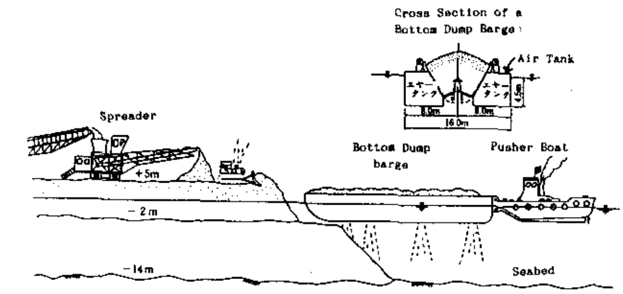


Fig. 2-2 Subsurface Stratigraphy, Port Island and Rokko Island (Kobe, 1981)

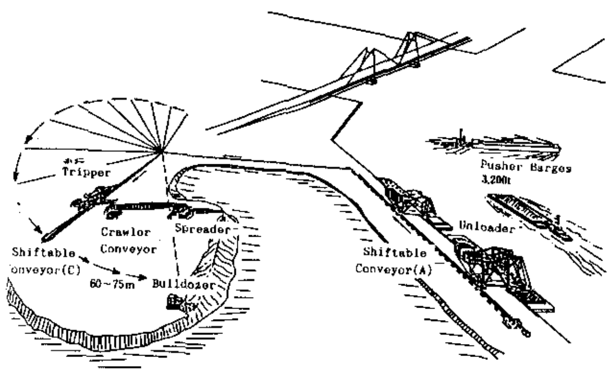
2-4 Settlement of Reclaimed Land

Relatively large settlements were expected to develop during and after construction due in large part to consolidation of the very soft alluvial clay (Ma 13) layer. Fig. 2-4(a) shows a typical time versus measured settlements of a settlement plate installed at the top of the seabed (solid curve) before the start of fill placement and also of that installed at the surface of the fill (dotted curve) after it was brought up to Elevation +6.5 in Rokko Island.

These curves indicate that settlements are accelerated when the fill is brought up above sea level and continue over a long period of time at a considerable rate. At this location the Ma 13 clay was about 12 m thick and settlement exceeding 3 m was recorded during a period between 1976 and 1988.



(a) Bottom Dump Barge and Spreader



(b) Shiftable Belt Conveyor System

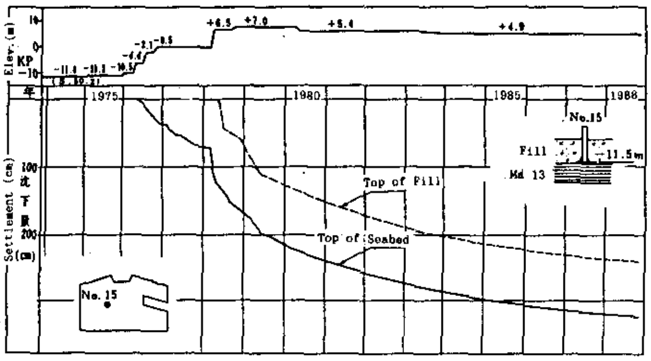
Fig. 2-3 Construction Procedure for Reclamation (JSCE, 1991)

Fig. 2-4(b) shows settlements measured at different subsurface levels as shown by a profile diagram; the curves a, b, c and d indicate settlements, respectively, at the top of the seabed (top of the Ma 13 alluvial clay layer), the top of the upper diluvium, at the top of the Ma 12 clay stratum and at the top of the lower diluvium. These curves clearly indicate that the settlement due to consolidation of the Ma 13 layer is predominant and still continuing, but significant compressions are also in progress in the underlying diluvial strata.

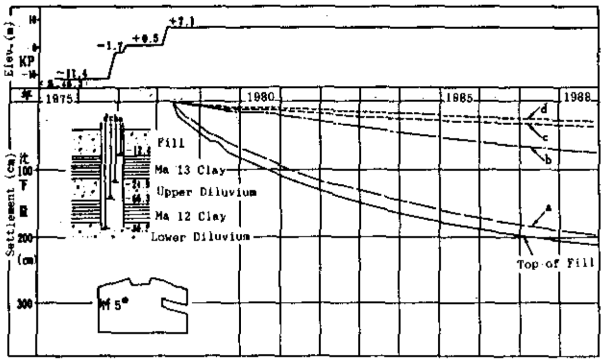
2-5 Sea Walls and Wharves

Reclamation of an area was preceded by construction of sea walls and wharves which defined the periphery of an island to be created. Generally the soft alluvial clay was excavated by a barge-mounted grab dredger having a capacity of up to 8 cu. m to the the top of the upper diluvial layer and replaced it with dumped sand. Granular fill was placed over the sand and then precast caissons were brought in and placed in position.

Figs. 2-5 and 2-6 show a couple of typical cross-sections each, respectively, of the container berths which constitute part of the outer boundaries of Port Island and Rokko Island. Soft clay was dredged out to a depth of 24~28.5 m and 32 to 36 m below sea level, respectively.

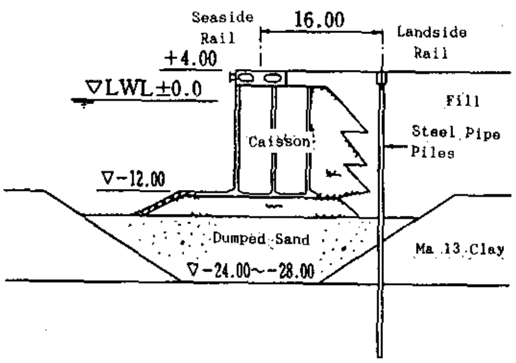


(a) Settlements of Top of Seabed and Top of Fill

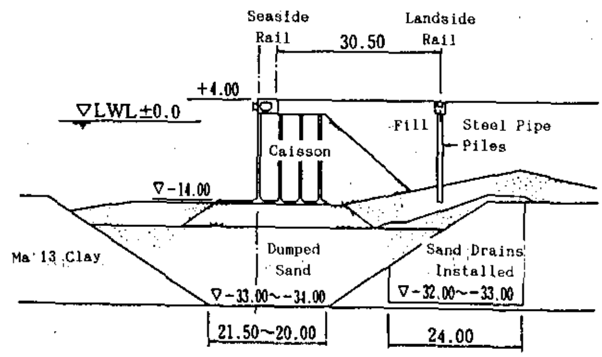


(b) Settlements at Different Levels

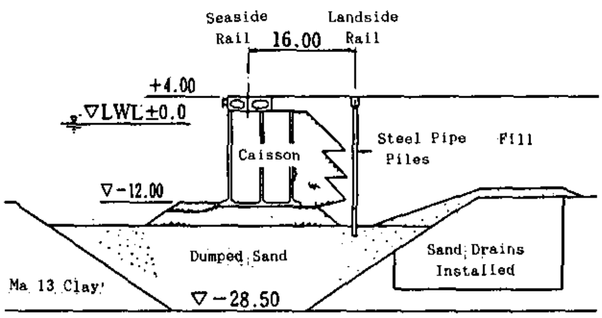
Fig. 2-4 Measured Settlements, Rokko Island (Kanazawa, e a, 1989)



(a) Standard Cross Section

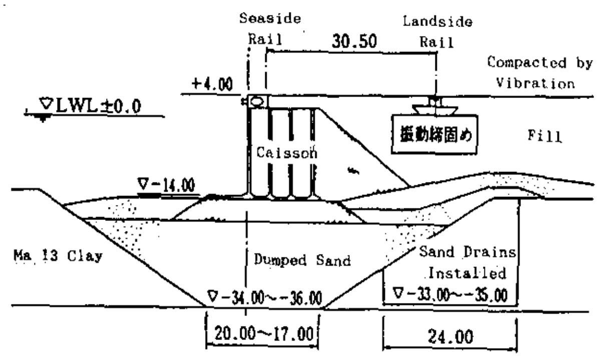


(a) Cross Section for Berth C-3



(b) Cross Section for Berths #10 and #11

Fig. 2-5 Container Berths, Port Island
(Fujishima, et al, 1992)



(b) Cross Section for Berths C-4 and C-5

Fig. 2-6 Container Berths, Rokko Island
(Fujishima, et al, 1992)

While seaside rails for container cranes were to be placed on caissons with no apparent problems, it was evident that the landside rails required special attention. In the beginning the landside rails were supported by end-bearing piles as shown in Fig 2-5(a) in Port Island. This soon resulted in objectionable vertical gaps between landside rails and subsiding ground surface and also significant widening of the distance between rails.

In the subsequent construction, therefore, a landside portion of the soft clay was stabilized by sand drains before filling and shorter friction piles were driven to support the rails as shown in Fig. 2-5(b), resulting generally in satisfactory performance.

Although the distance between crane rails was almost twice as large and the soft clay was approximately 6 m thicker in Rokko Island, the experience in Port Island was fully utilized; the landside rails were supported by footings placed in fill compacted by vibration, Fig. 2-6(a) or on short friction piles consisting of steel pipe piles, 80 cm in diameter, Fig. 2-6(b) over the alluvial clay stabilized by sand drains, so that the rails could settle with the subsiding fill.

Fig. 2-7 shows, with elapse of time, typical horizontal movement of crane rail or increase in the rail span, and settlement of the landside rail at Berth C-1 in Rokko Island. During a 6 year period in service, about 35 cm of lateral movement and about 60 cm of settlement were recorded. With the container crane and the rail foundation both designed to be adjustable, adjustments were made relatively easily to insure safe and smooth operation of the gigantic crane on the berth.

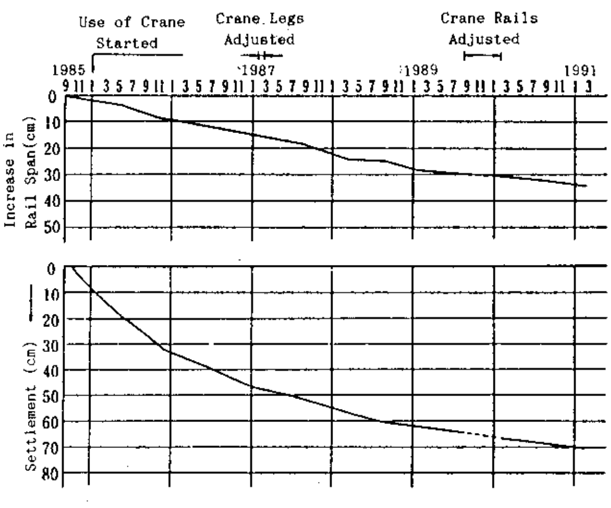


Fig. 2-7 Horizontal and Vertical Movements of Landside Crane Rail at Berth C-1 (Fujishima, et al, 1992)

2-6 Disposal of Excavated Clay

While dredging and replacing soft sea mud with imported sand is a reliable construction method to provide good foundation for wharves, breakwaters, etc., it brings up a problem of disposing excavated mud without contaminating sea water. Soft clay dredged from the Port Island Stage I project site was transported and discarded at a specified area in the sea some 10 km south of the site, while soft clays from Rokko Island and Port Island Stage II were used as clay fill as part of the material for reclamation. During consolidation of the latter project, the area of excavation and subsequent filling was surrounded by silt protection fence consisting of woven textile being suspended by floats to minimize mud flowing out of the construction site.

2-7 Foundations for Structures

In Port Island and Rokko Island numerous tall buildings stand with no serious signs of distress. Many building sites were sand-drained and/or preloaded at an early stage. Most of high-rise buildings were built on pile foundations. Where end-bearing piles were employed, efforts were made to minimize negative skin friction by applying a highly viscous coating on pile skin. Lighter structures were supported by friction piles or sand compaction piles. Piers for large bridges were supported by pneumatic caissons.

3. KANSAI INTERNATIONAL AIRPORT (KIA) ISLAND

3-1 General

Another huge man-made island was created for an airport, at an average water depth of 18 m, 5 km offshore, founded on a thick soft marine clay deposit in Osaka Bay. The following is an expanded and updated version of the report prepared by the writer about a year ago (Akagi, 1991). Photo 3-1 shows an aerial view of the KIA island as of the end of June 1992.

The project site is situated approximately 35 km southwest of downtown Osaka. In January 1987, construction of the airport island commenced with building 11.2 km long sea-walls encircling the area to be filled. The earth work for reclamation was completed in late December, 1991. In order to link the airport island with the Main Island, a 3.8 km viaduct has been constructed with 6 lanes on the upper deck and two railway tracks on the lower deck.

The project is unique in the following points:
A) Great depth of water; the site is located 5 km offshore where the average depth of water is 18 m. Seabed contours are indicated in the plan of the project area, Fig. 3-1, showing also locations of deep exploratory borings.

B) Poor foundation condition with extraordinarily large settlements; the seabed consists of a 16 to 20 m thick deposit of highly compressible, very soft alluvial clay (Ma 13), underlain by diluvial deposits consisting of relatively stiff but still compressible clays (Ma 12, etc.) interbedded with layers of sand and/or gravelly soils and extending down to a depth of the order of 400 m. Fig. 3-2 illustrates a geologic section along the northern edge of the KIA Island. Extremely large settlements exceeding 10 m were expected to occur during and after

Photo 3-1 Aerial View of the KIA Island, June 1992
(Courtesy of KIA Co., Ltd.)

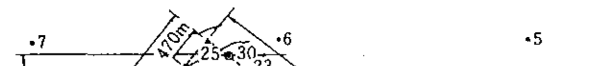


Fig. 3-1 Project Site; Seabed Contours, Boring Locations and Future Expansion Plans (Kanda, et al, 1991)

construction particularly with sizable post-construction settlements continuing over a long period of time.

C) A large-scale project to be completed in a limited time; the man-made island, 511 hectares (4370 m x 1250 m), requiring a total of 183 million cubic meters of fill material, had to be constructed in 5 years with the schedule to complete the whole airport project in 7.5 years.

3-2 Geotechnical Problems
Difficult problems related to geotechnical engineering included the following: 1) deep exploratory borings with satisfactory sampling and in-situ testing to be conducted in deep waters, 2) prediction of large settlements, particularly consolidation settlements of diluvial strata at great depths, 3) selection of methods to improve soft marine clay through deep water, 4) development of a system to control settlements and stability of reclamation fill, 5) development of methods to measure reliably settlements during filling operations, 6) installation of devices for long-term observation of compressions taking place in the deep diluvial formations, 7) selection of foundations for structures to be built on the island to minimize differential settlements.

As has frequently been reported, some of the foregoing problems have been solved or passed the critical stage quite successfully so far. It appears that the large settlement (the foregoing items 2, 4 and 7) remains to be the most serious problem at the present time and for many years to come. In fact, due largely to this cause, the estimated volume of the fill had to be increased from an initial value of 150 million cu. m to 183 million cu. m resulting in a delay of

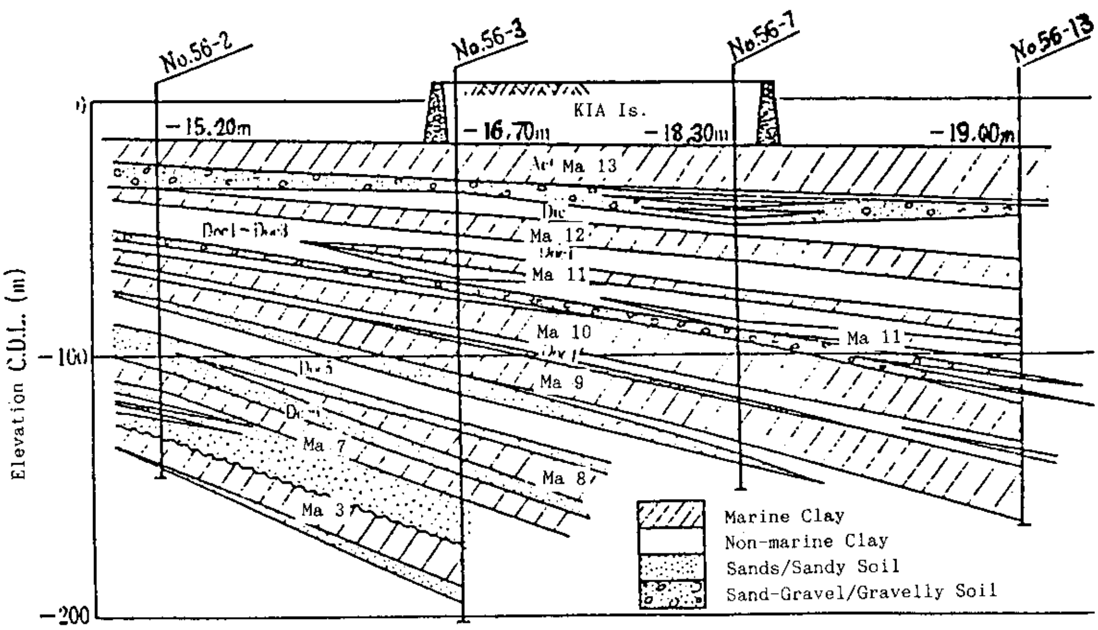


Fig. 3-2 Geologic Section Along the Northern Edge of the KIA Island (Komatsu, et al, 1991)

the construction schedule as much as about a year and a half.

Prior to filling the area, sea walls were first constructed along the periphery of the island. In general, sand drains were driven into the soft alluvial clay and granular fill was placed before being topped by precast concrete structures or steel cellular bulkheads as illustrated in Fig. 3-3. In some places, sand compaction piles, as well as the deep mixing technique, were employed instead of sand drains to stabilize the sea wall foundation.

After placement of a 1.5 m thick sand mat on seabed, a total of approximately one million sand drains, 40 cm in diameter, were installed generally on 2.5 m spacings, penetrating the soft alluvial clay layer, 16 to 20 m thick, over the entire area to be reclaimed. Barge-mounted sand drain drivers, with each barge capable of installing 12 to 14 sand drains simultaneously, were employed with a high degree of precision and efficiency.

In the south-east corner of the man-made island, some 6500 prefabricated vertical drains (Geodrains) were installed, roughly between depths 17 and 32 m below sea level on 1.3 m spacings in square patterns on an experimental basis to stabilize the soft clay foundation. It was reported that performance of these vertical drains was quite satisfactory (Oikawa, et. al., 1989).

In the early stage of construction, the entire site was surrounded by double rows of silt protection sheets to keep turbid water from flowing out of the site. Fig. 3-4(a) shows the layout and Fig. 3-4(b) illustrates a cross section of such installation consisting of 2 types protectors; one hanging down in water from floats and the other standing up from seabed with floats in water with the lower end fixed at the seabed. Additionally, meticulous surveillance was maintained to monitor the quality of sea water and turbidity around the construction site as part of the environmental control program.

3-3 Pilot Area

A 6 hectare pilot area (341 m x 173 m), Fig. 3-5, was provided near the north-west corner of the island and filled first to obtain much-needed data about the settlement and stability behaviors of the thick fill to be placed on the soft clay. Granular fill was brought from land quarries 10 to 30 km away and dumped by bottom hopper barges equipped with openable bottoms up to 3 m below sea level, above which level soil unloader barges were employed to dump the fill, Fig.3-6. Generally the fill amounted to 33 m in thickness exerting an effective pressure increase on the order of 450 kPa in the underlying alluvial and diluvial clays.

The pilot area was extensively instrumented with conventional and newly developed devices and frequent measurements were taken at various depths of settlements, horizontal displacements, porewater pressures and increases in strength of soft clays (by check borings).

3-4 Settlement of the Alluvium

Fig. 3-7 shows the time-settlement data of the Ma 13 alluvial layer observed in the central part of the pilot area (Point K) for the first 1200 days, together with the design settlement curve shown by dotted line which was constructed on the basis of Barron's theory using the design parameters indicated in the diagram. The

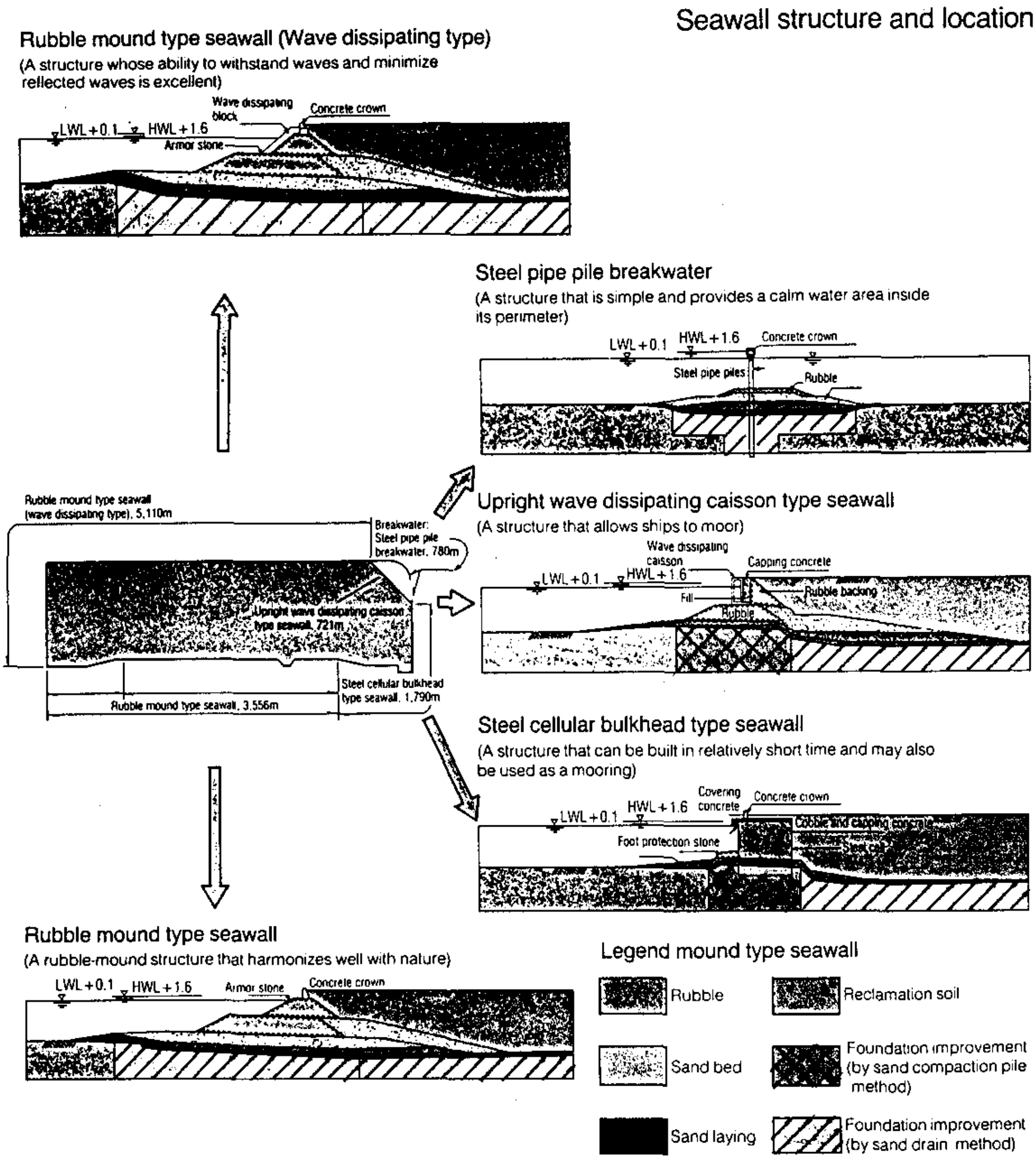
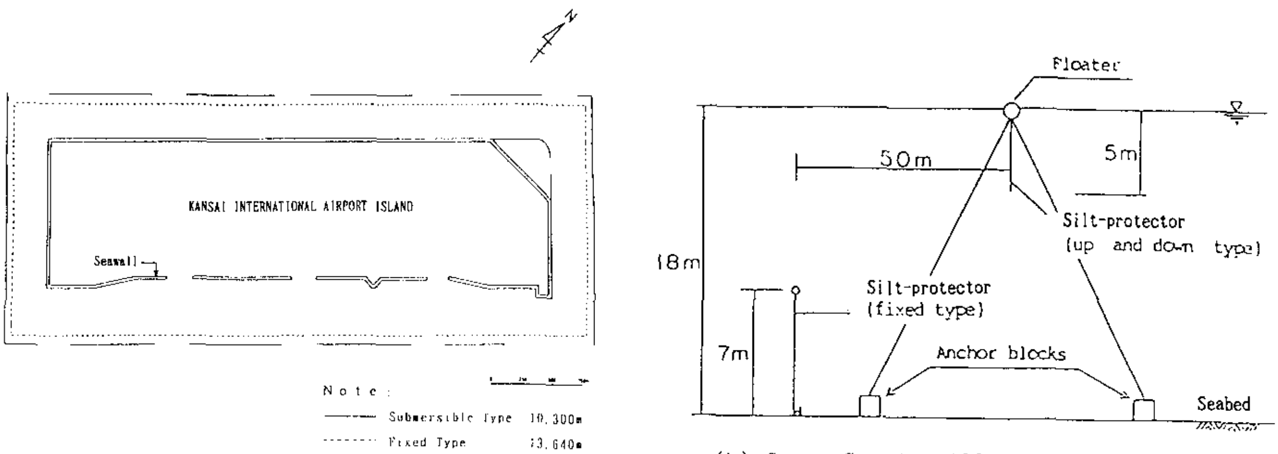


Fig. 3-3 Cross Sections of Sea Walls (KIA Co., Ltd.)



(a) Layout of the Silt Protectors

(b) Cross Section Illustrating Silt Protectors Installed around the Site

Fig. 3-4 Silt Protectors Installed around the KIA Island(JSCE, 1992)

modified curve which best fits the observed data is also shown by solid line, together with the values of parameters required for such good fitting.

Fig. 3-7 also shows the excess porewater pressures in the sand mat and at two levels in the Ma 13 clay layer. The way the porewater pressures dissipated in the clay, as well as the way the settlements proceeded, was reported to be indicative of the effectiveness of sand drains (Arai, et al, 1991) and also of virtual completion of the consolidation settlement of the alluvium.

Fig. 3-8 indicates the relationship between the measured settlements and the calculated ones showing good agreement for the values of settlements smaller than about 4 m. The observed settlements were measured at 5 locations in the general reclaimed area, while the calculated settlements were computed based on the soil conditions at each location which had been modified on the basis of the empirical relationship obtained earlier in the test area.

It was pointed out by Arai, et al.(1991), that a considerable deviation for the values greater than 4 m settlements was due to compressions of the diluvial strata at great depths which became significant when the total settlement reached that value and the fill was brought up to Elevation +8.5 by means of soil unloading barges, see Fig. 3-6. The "calculated settlement" at that time did not include compressions in the diluvial strata.

Compressions in the deep strata which had been observed were incorporated in the subsequent modified estimates of settlement by manipurating consolidation parameters and drainage conditions. The "calculated" total settlements then showed good agreement with the observed as may be seen in Fig. 3-9 (JSCE, 1992).

3-5 Settlement of the Diluvium

The settlement of the diluvial strata has been measured by means of a double tube subsidence meter with the tip of the inner tube placed in the top portion of the diluvium. Figs. 3-10 and 3-11 show the measured settlement of the

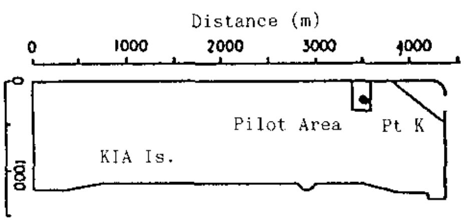


Fig. 3-5 Location of Pilot Area (KIA Co., Ltd.)

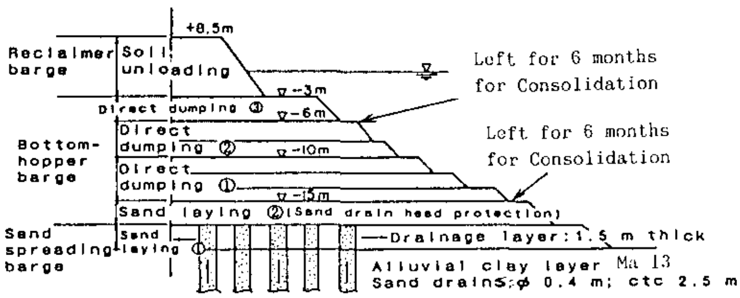


Fig. 3-6 Reclamation Process (KIA Co., Ltd.)

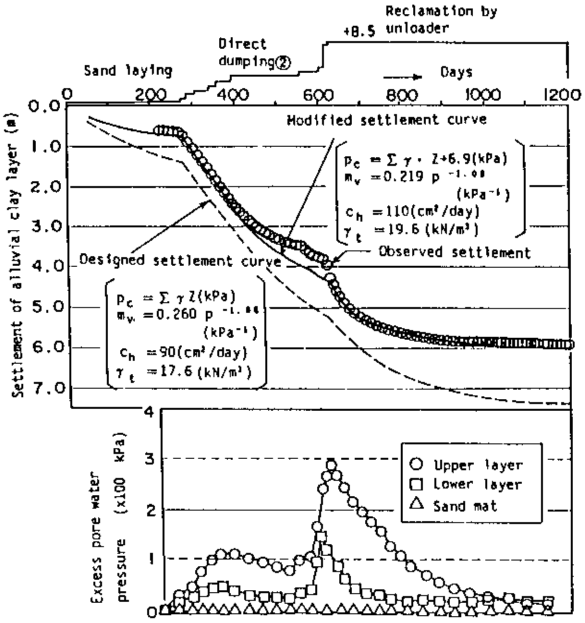


Fig. 3-7 Settlement of the Alluvium and Excess Porewater Pressures Observed at Point K in the Pilot Area (Arai, et al, 1991)

diluvial layer as well as the measured total settlement in the pilot area, together with the "calculated" estimates. Note that the time axis represents the proportionate scale in Fig. 3-10 and the logarithmic scale in Fig. 3-11. The data recorded up to May, 1992 are plotted in these diagrams, indicating a total settlement of approximately 10 m consisting of settlements on the order of 6 m and 4 m in the alluvial and the diluvial strata, respectively.

Calculated settlements of the diluvial layers are basically based on Biot's 1-D consolidation theory using representative laboratory data with an assumed multi-layer drainage condition which best fits the observed data. It is reported by Endo, et al.(1991) that the calculated settlement curve thus determined would be refined further as more observed data are obtained and reviewed to predict more reliable future settlements in the general reclaimed area.

It is interesting to note that an additional 3 m fill was placed in the Point K area in April 1991, approximately 1300 days after soil improvement, and that consequently settlement was accelerated. The rate of settlement increased to more than 10 cm a month for a while, but soon subsided to a previous rate of approximately 6 cm a month, Fig. 3-11.

Practically all the settlement that will occur henceforth is considered due principally to compressions in the upper strata of the diluvial deposit where the effective overburden pressure plus the stress increase due to the fill weight exceeds the preconsolidation pressure of the clay, i. e., shallower than a depth of approximately 190 m below sea level. At the present time it is estimated that settlement will practically cease 30 years after the opening of the airport in the summer of 1994 with a total settlement amounting to 11 to 13 m.

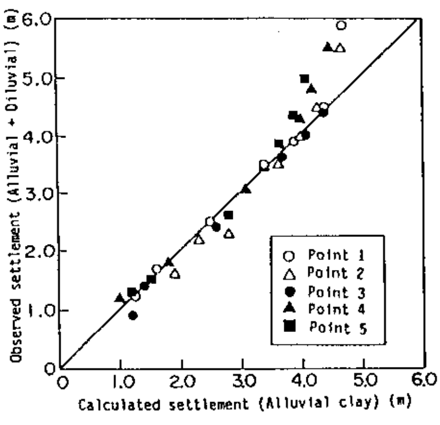


Fig. 3-8 Comparison between Calculated and Observed Settlements in the General Reclaimed Area (Arai, et al, 1991)

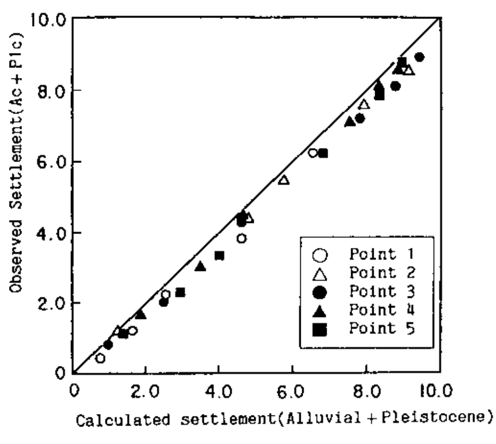


Fig. 3-9 Comparison between Calculated and Observed Settlements in the General Reclaimed Area after Recent Modification of Calculation (JSCE, 1992)

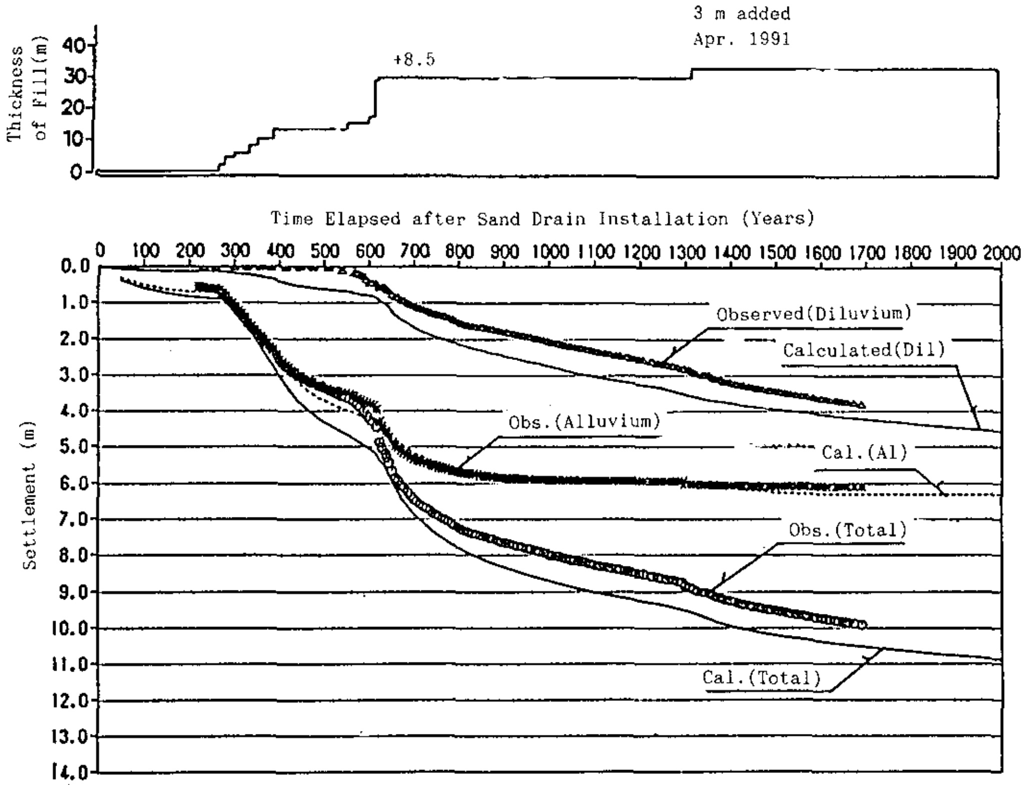


Fig. 3-10 Total Settlement and Settlement of the Diluvium Observed at Point K in the Pilot Area; the Time Axis in Arithmetic Scale. (KIA Co, Ltd.)

3-6 Settlement of Structures

It is generally recommended that various structures to be built on the airport island be designed so as to settle together with the thick fill and to minimize unequal settlements incorporating the following procedures; i) Compact fill beneath the proposed structure to a substantial depth. ii) Preload the site by placing a surcharge having an effect comparable to the stresses to be applied by the proposed structure. In case of a structure having a basement, excavate to a depth where the overburden pressure is roughly equal to the stress increase due to the weight of the structure. iii) Design the foundations to be basically a floating type equipped with a jacking system so that any objectionable differential settlements may readily be corrected.

Continuing settlement will be the most crucial problem for the future of the airport island. Settlement control by maintaining the field observation network and critical review of the collected data, as well as preparedness for correction of differential settlements, will be essential for successful operation of the airport.

4. CONCLUDING REMARKS

When a large artificial island is to be constructed at an offshore site consisting of a thick deposit of alternating layers of clays and sands extending down to a great depth, the greatest difficulty lies in large settlements that continue over a prolonged period of time resulting from consolidation of not only soft alluvial clay at a shallow depth but also stiff diluvial clays at great depths. Stability of reclamation fill and seawalls is no doubt also a serious problem particularly during the initial stage of reclamation.

At the present state of the art it is still extremely difficult to determine with reasonable accuracy the stratigraphy, the consolidation characteristics and the drainage condition of diluvial clay strata at great depths. As compared with this difficulty, it is not too difficult to evaluate those of a soft alluvial clay stratum constituting seabed. It is not an easy task, therefore, to correctly forecast settlements of diluvial clay strata. Experience indicates that it is not impossible to predict

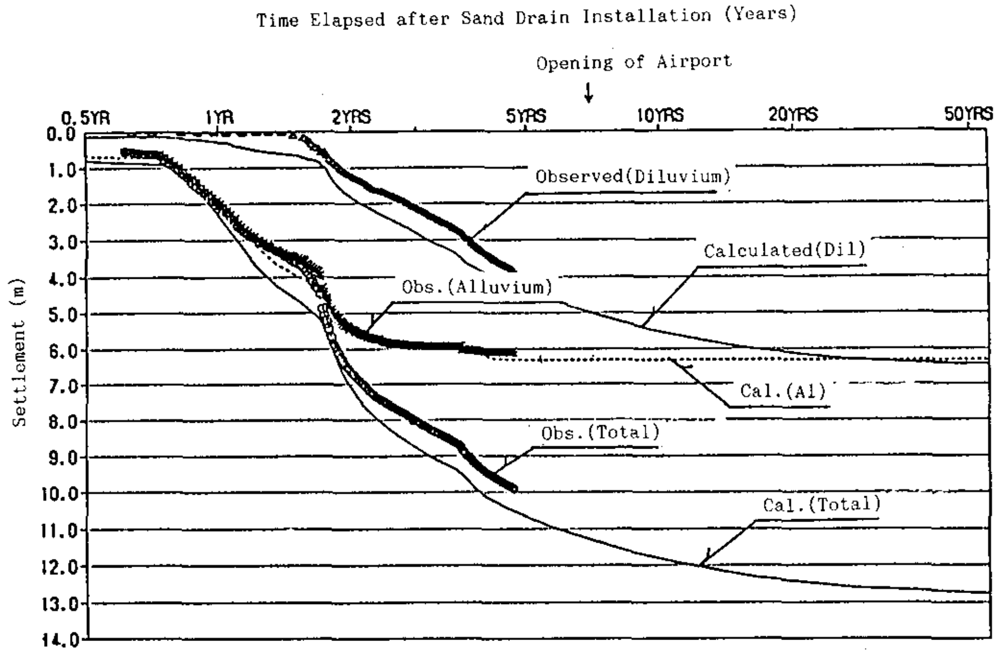


Fig. 3-11 Total Settlement and Settlement of the Diluvium Observed at Point K in the Pilot Area; the Time Axis in Logarithmic Scale. (KIA Co, Ltd.)

with reasonable accuracy the settlement behavior of a soft clay stratum even when it is stabilized by vertical drains.

Observed data shows that compressions taking place at great depths become a major source of settlement after consolidation of the alluvial clay layer is substantially completed in a relatively short period of time having been accelerated by vertical drains installed in it.

A large artificial island consisting of a thick reclamation fill placed over a wide area produces a significant stress increase that does not diminish with depth and increases the effective stress exceeding the preconsolidation pressure of overconsolidated diluvial clay causing a significant compression to a depth far greater than that contemplated previously.

It is highly desirable to provide a full-size pilot reclamation area well in advance so that long-term settlement behaviors are actually observed as well as stability of fill, effectiveness of stabilization measures such as vertical drains and other construction problems.

An accurate assessment of settlement both during and after construction is essential to estimate and secure the volume of fill required, to forecast the date of completion of the project and also to provide in advance appropriate measures to cope with excessive post-construction settlements. The amount of fill involved is so enormous it is vitally related to the cost of the project.

With the present state of knowledge and technology, it is both technically and economically feasible to construct a large-scale island at an offshore site at such a great depth of water with such a great magnitude of settlement as was once considered just impossible.

REFERENCES

Akagi, T.(1991). Large settlements of the Kansai International Airport Island, Panelist Report, Theme 4, Ninth Asian Regional Conf. on Soil Mech. and Found. Eng., Bangkok, 4p.

Akai, K., Nakaseko, K., Matsui, T., Kamon, M., Tanaka, Y. and Suwa, S.(1991). Geotechnical properties of marine clays in Osaka Bay, Proc. Geo-Coast '91, 5-10, Yokohama.

Arai, Y., Oikawa, K. and Yamagata, N.(1991). Large-scale sand drain works for the Kansai International Airport Island, Proc. Geo-Coast '91, 281-286, Yokohama.

Endo, H., Oikawa, K., Komatsu, A. and Kobayashi, M.(1991). Settlement of diluvial clay layers caused by a large scale man-made island, Proc. Geo-Coast '91, 177-182, Yokohama.

Fujishima, K. and Aoyama, M.(1992). Container berths and foundations for cranes, Kisoko, Vol. 20, No. 5, 22-29.(in Japanese).

Japan Society of Civil Engineers.(1991). Construction engineering for artificial islands, JSCE, 106p.(in Japanese).

Japan Society of Civil Engineers.(1992). Kansai International Airport Project, JSCE, 80p., Presented to the 1992 ASCE Convention, New York, U. S. A.

Kanazawa, H., Ikeda, T. and Takimi, M.(1989). Foundations in Rokko Island, Kisoko, Vol. 17, No. 7, 63-71.(in Japanese).

Kanda, K., Suzuki, S. and Yamagata, N.(1991). Offshore soil investigation at the Kansai International Airport, Proc. Geo-Coast '91, 33-38, Yokohama.

Kobe, The City of, (1981). Port Island-15 years of construction of a marine city, 496p.(in Japanese).

Komatsu, A., Oikawa, K. and Iwasaki, M.(1991). Kansai International Airport - Construction of Airport Island, Tsuchi-to-Kiso, Vol. 39, No. 5, 25-36. (in Japanese).

Oikawa, K., Nakaoka, K., Jimbo, N. and Kawata, S. (1989). Effect of Plastic Board Drain Method to Improve the Soft Clay Stratum in the Kansai International Airport, Proc., 24th Annual Convention. the Japanese Society of SMFE, Vol. 3, Paper No. 701, 1903-1908. (in Japanese).

Oikawa, K. and Endo, H.(1990). Construction of a large-scale man-made island for the Kansai International Airport, Proc. Kansai International Geotech Forum '90, 55-69, Osaka.

Tohma, T. and Yamamoto, S.(1990). Construction of the Kansai International Airport, Civil Engineering in Japan, 1990, Vol. 29, Japan Society of Civil Engineers, 28-44.