INVESTIGATION OF SPREAD FOUNDATIONS ON LIQUEFIED RECLAIMED GROUND AFTER THE 1995 HYOGOKEN-NANBU EARTHQUAKE

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ABSTRACT : During the 1995 Hyogoken-Nanbu earthquake, extensive liquefaction of soil occurred in the man-made Port and Rokko Islands. In these islands, there are a number of reinforced concreate buildings with shallow spread foundations resting on the liquefied reclaimed ground. After the earthquake, we investigated the fourteen selected spread foundation buildings in these islands. The results of our investigation can be summarized as follows : (1) The spread foundation buildings with a larger aspect ratio have a greater maximum angle increment of tilt. (2) Soil improvement appears to be effective on reducing the settlement of the buildings due to liquefaction during the earthquake. (3) The average settlement of the spread foundation buildings are considerably small. The relationship between the settlement and width of buildings observed in the 1964 Niigata earthquake in Japan was not found from our investigation results.

KEYWORDS : ground improvement ; 1995 Hyogoken-Nanbu earthquake ; liquefaction ; man-made island ; settlement ; site investigation ; soft ground ; spread foundation.

1. INTRODUCTION

During the 1995 Hyogoken-Nanbu Earthquake, liquefaction on a massive scale occurred in the man-made Port and Rokko Islands. Port Island, to the south of Kobe City, is reclaimed land with an area of 436 ha and it was constructed between 1966 and 1981. It is a large marine city containing large scale container yards and port facilities and has a planned population of two hundred thousand residing in apartment buildings. Rokko Island with a reclaimed land area of 580 ha was constructed between 1972 and 1992 as a second marine city to the east of Port Island. (Ref. Fig.1).

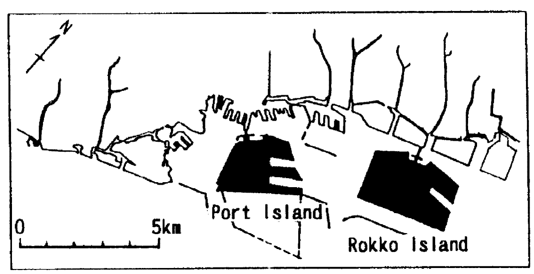


Fig.1. Location of Port and Rokko Islands.

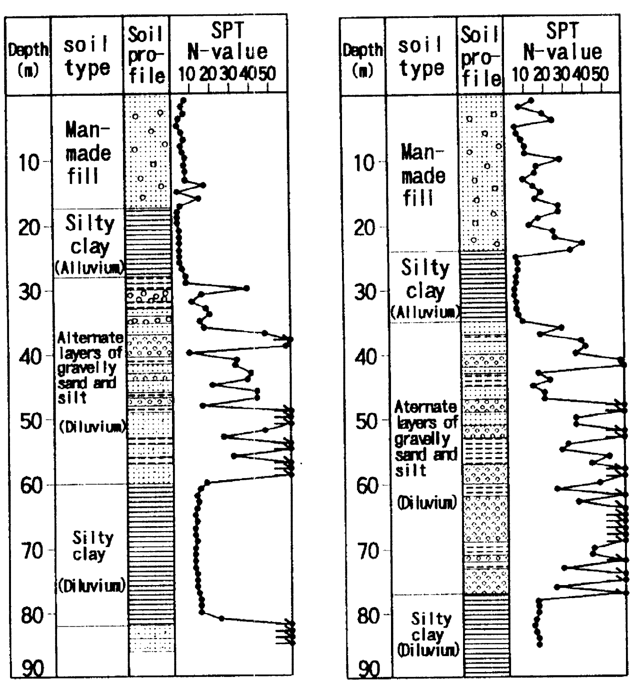
In both islands, there are a number of reinforced concrete buildings with shallow spread foundations such as mat foundation, continuous or individual foundation resting on the liquefied reclaimed layer. After the earthquake, buildings with spread foundations were investigated. Their settlement, tilting and structural damage in the superstructure were investigated to obtain a better understanding of the interaction between building behavior and ground behavior.

This report describes the investigation and its results. Also, included is a discussion on the relationship between building damage and scale of building in terms of tilting angle and ground settlement. Finally, the results of this investigation are compared with observations made in the 1964 Niigata Earthquake in Japan.

2. GROUND CONDITION

Figure 2 shows the typical soil profile in Port and Rokko Islands. Both islands have almost the same soil profile of reclaimed layer, alluvial clay layer (old seabed), upper diluvial layer, diluvial clay layer and lower diluvial layer from the surface to the bottom. The thickness of the upper diluvial layer in Rokko Island is slightly thicker than that in Port Island. The reclaimed layer in Port Island is 15 to 25 m thick and it mainly consists of decomposed granite soil from the Rokko Mountains while that in Rokko Island is 20 to 25 m thick and is mainly composed of sandy soil from mudstone of the Kobe and Osaka layers groups except the northern part of the island. The groundwater level of the two islands was about from 3 m to 8 m deep below the ground level.

Figure 3 shows the distribution of grain size of the reclaimed layer in the two islands. The fine sand content of the fill material in Rokko Island is larger than that in Port Island. In the center of the reclaimed area of Port Island, sand drain and pre-loading methods had been applied to promote consolidation of the alluvial clay layer, and in some areas vibration compaction was applied to the reclaimed layer. In Rokko Island sand drains were employed at the center of the reclaimed area to promote consolidation of the alluvial clay layer and in some buildings sites sand compaction pile method was applied to the reclaimed layer. The soil improvement methods and the improved areas are illustrated in Fig. 4.



(a) Port Island (b) Rokko Island

Fig.2. Typical soil profile in Port and Rokko Islands.

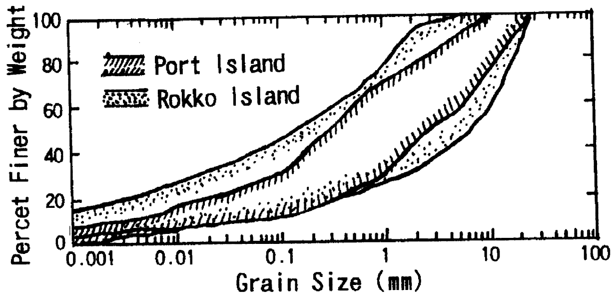
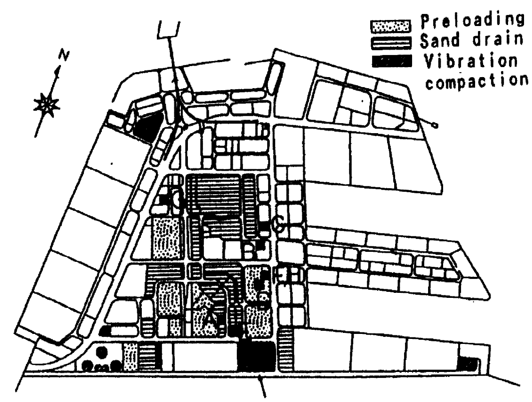
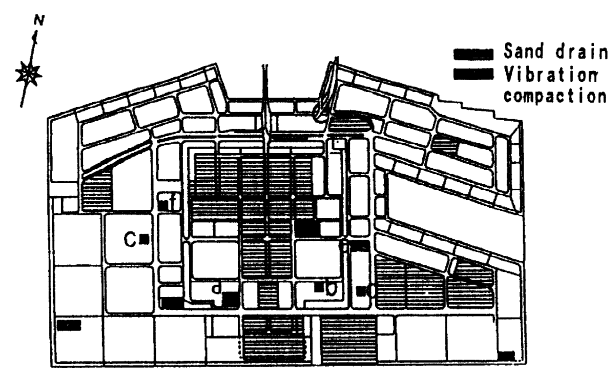


Fig.3. Grain size distribution curves of soils used for landfilling in Port and Rokko Islands (after Takenaka Corporation, 1995).



(a) Port Island



(b) Rokko Island

Fig.4. Ground improved area and location of investigated buildings.

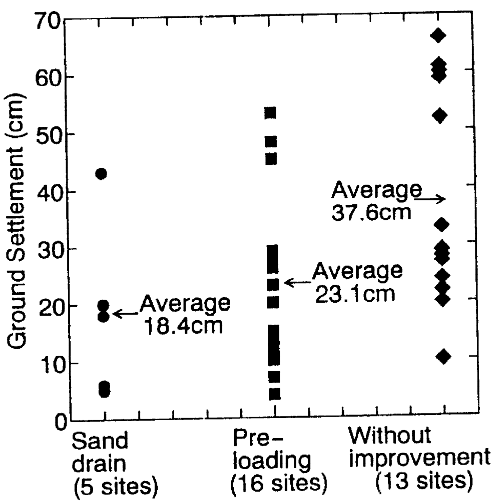
3. SETTLEMENT OF THE RECLAIMED LAYER DUE TO LIQUEFACTION

In the 1995 Hyogoken-Nanbu Earthquake sand boil, mud pumping and compaction of the reclaimed layer due to liquefaction caused ground settlement in Port and Rokko Islands.

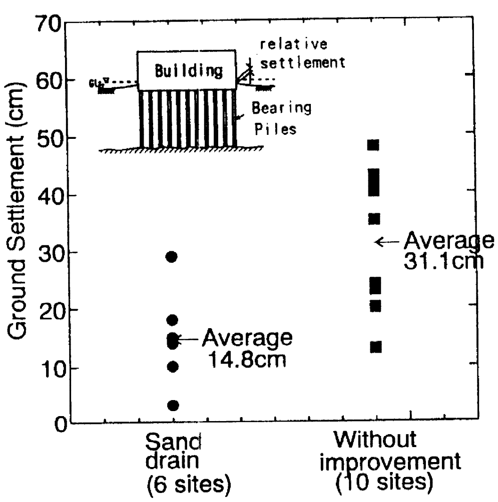
Figure 5 shows the relative ground settlement of the reclaimed layer as estimated from the vertical gaps between the ground surface and the base of the building founded on point bearing piles. The relative ground settlement near buildings varied from 5 to 70 cm in Port Island and from 3 to 50 cm in Rokko Island respectively. In measuring settlement, we tried to estimate the settlement caused by the earthquake and exclude continuing settlement due to consolidation of the clay layer. Areas where the reclaimed layer was improved by sand drain and pre-loading methods show smaller relative ground settlement than areas without any improvement.

Figure 6 shows the settlement measured with differential settlement gauges at points in Port and Rokko Islands shown in the figure.

Figure 6 (a) shows the time history of settlement in the last ten years at ground surface and bottom of the reclaimed layer (20 m below the ground surface) in Port Island. The measuring point is located on a road without any improvement. Assuming that the measuring point at 90 m below the ground surface did not settle, the reclaimed layer is seen to be compressed 22 cm by the earthquake. Figure 6 (b) shows the time history of settlement at various depths at a measuring site in Rokko Island on reclaimed layer which was not improved. Assuming that at this site there was no settlement at a depth of 110 m below the ground surface, the reclaimed layer is seen to be compressed 3 cm by the earthquake.

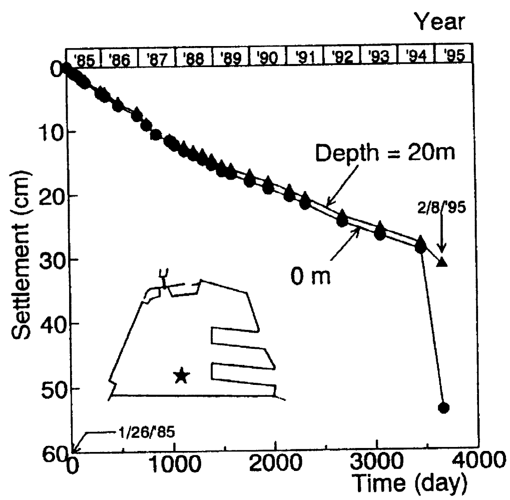


(a) Port Island

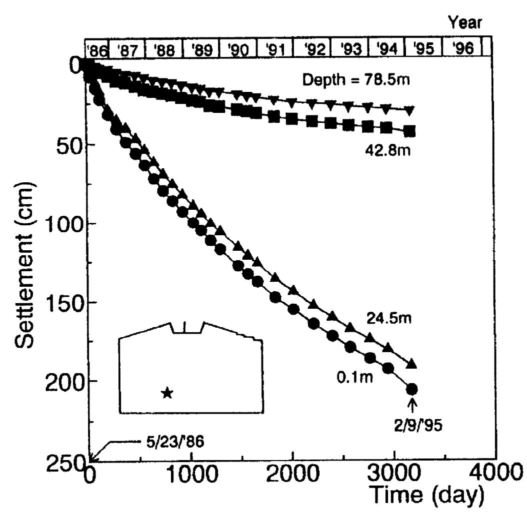


(b) Rokko Island

Fig.5. Effects of soil improvement on ground settlement in Port and Rokko Islands.



(a) Port Island (after Hirai et al., 1995)



(b) Rokko Island (after Mine et al., 1995)

Fig.6. Time history of ground settlement measured with differential settlement gauges in Port and Rokko Islands.

4. OUTLINE OF INVESTIGATION OF BUILDINGS WITH SPREAD FOUNDATIONS

In Port and Rokko Islands eight and six selected buildings with spread foundations were surveyed respectively. The locations of the buildings are shown in Fig. 4. The buildings were first investigated externally. Then leveling was conducted at points which could be safely assumed to have been horizontal before the earthquake such as the upper end of the first floor tile joints on external columns of the buildings.

At six buildings with spread foundations located near the central part of Rokko Island, leveling has been regularly conducted since the completion of their construction. Therefore, absolute settlement was obtained using data from leveling before and after the earthquake.

The control elevation for leveling after the earthquake was taken to be the bench mark at one of the piers of the Rokko Bridge founded on pneumatic caissons.

5. RESULTS OF INVESTIGATION OF BUILDINGS WITH SPREAD FOUNDATIONS

The outline of the eight surveyed buildings in Port Island and the results of the investigation are shown in Fig. 7 and Table 1. The aspect ratios of the buildings (building height over square root of horizontal sectional area of the building) vary from 0.23 to 0.65. The average relative settlement shown in Table 1 is the average difference in elevation at corner points obtained from the results of leveling. The average relative settlement (which does not include the uniform settlement component) ranges from several centimeters to tens of centimeters. The increase in tilting angle of the building is also shown in Table 1.

Although a maximum tilting angle of approximately 1/100 rad was observed in some buildings, little damage was seen in these buildings by visual inspection. All buildings remain in service up to now.

The outline of the six surveyed buildings in Rokko Island and the results of the investigation are shown in Fig. 8 and Table 2. The six buildings except Building f have mat foundation and the supporting reclaimed layer had been improved by the sand compaction pile method. The improved portion under the foundation is shown shaded in Fig. 8.

The aspect ratios of the buildings range from 0.20 to 0.55. As these buildings have been continuously surveyed, the elevations at the corners of the buildings before and after the earthquake are used to calculate the average absolute settlements from which the continuing settlement due to consolidation is subtracted.

The average absolute settlement including a

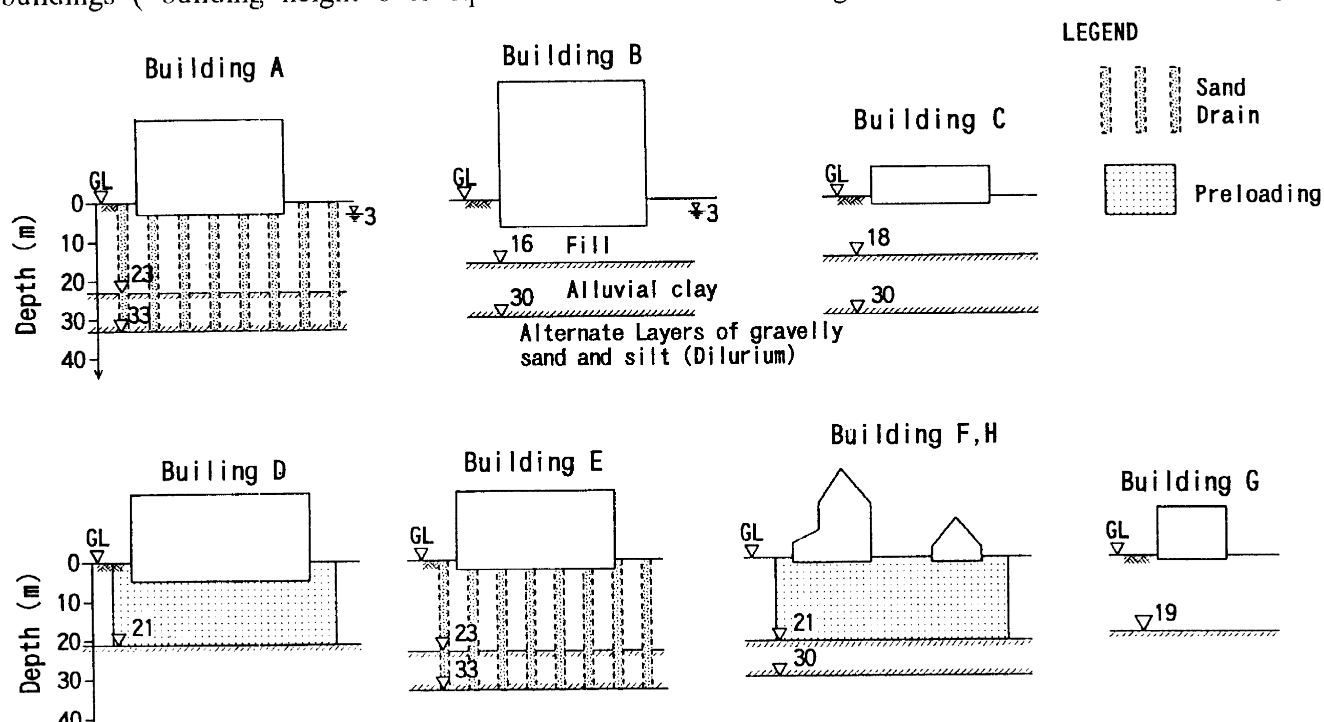


Fig.7. Outline of eight investigated buildings in Port Island.

Table 1. Investigation results of eight buildings in Port Island.

Building No.	No. of stories	Width of building B(m)	Length of building L(m)	Height of building H(m)	Type of foundation	Depth of foundation D_f(m)	Aspect ratio[d]	Type of Soil improvement	Average relative settlement (cm)	Maximum tilting angle increment (rad)	Remarks
A	6	38	185	22	Mat	2.9	0.26	Sand drain	8.3	1/680	
B	7+B[a]	37	65	30	Mat	7.0	0.60	–[e]	13.6	1/242	Marked non-uniformity of building load
C	2	30	36	7	Mat	1.8	0.23	–	6.9	1/384[f]	
D	4+B	46	100	17	Mat	4.5	0.25	Preloading	3.5	1/629[f]	
E	4	40	51	18	Mat	1.9	0.40	Sand drain	4.7	1/511	
F	4	20	26	15	Cont.[b]	1.2	0.65	Preloading	7.2	1/109[f]	Marked non-uniformity of building load
G	3	18	21	12	Ind.[c]	1.1	0.60	–	7.7	1/107[f]	
H	2	13	26	6	Ind.	1.2	0.34	Preloading	2.7	1/322[f]	

a)With basement, b)Continuous footing, c)Individual footing, d)=$H/\sqrt{B \times L}$, e)Without improvement, f)Not angle increment but angle

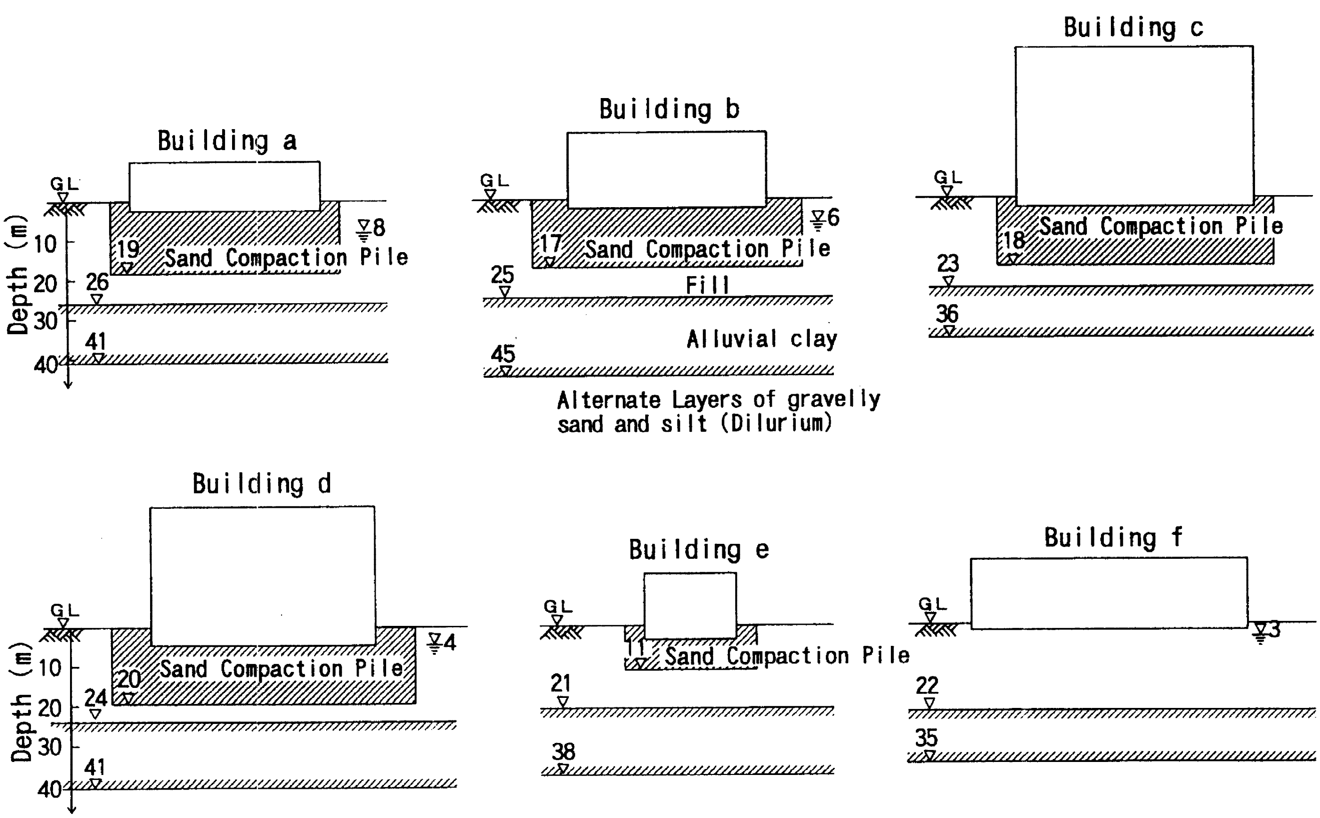


Fig.8. Outline of six investigated buildings in Rokko Island.

Table 2. Investigation results of six buildings in Rokko Island.

Building No.	No. of stories	Width of building B(m)	Length of building L(m)	Height of building H(m)	Type of foundation	Depth of foundation D_f(m)	Aspect ratio [c)]	Type of Soil improvement	Average absolute settlement (cm)	Maximum tilting angle increment (rad)	Remarks
a	2	48	54	10	Mat	2.5	0.20	S.C.P.[d)] 700φ l=16m, @2.0m□	1.9	1/2666	Floating foundation
b	4	50	110	16	Mat	2.3	0.22	S.C.P. 700φ l=15m, @2.0m□	4.5	1/760	Semi-floating foundation
c	6+B[a)]	60	80	38	Mat	2.5	0.55	S.C.P. 700φ l=15m, @2.3m□	4.2	1/1701	Semi-floating foundation
d	5	57	112	31	Mat	4.5	0.39	S.C.P. 700φ l=15m, @1.8m□	2.0	1/1764	Floating foundation
e	3+B	23	26	13	Mat	3.4	0.55	S.C.P. 700φ l=16m, @2.5m□	12.6	1/1003	Floating foundation
f	2	70	88	18	Ind.[b)]	1.5	0.30	–[e)]	20.3	1/800	

a)With basement, b)Individual footing, c)=$H/\sqrt{B \times L}$, d)Sand compaction Pile, e)Without improvement

uniform settlement component ranges from 2 to 20 cm. The increase in tilting angle of the building is also shown in Table 2. The maximum angle increment of tilt is found to be smaller than 1/760 rad.

6. DISCUSSIONS

6.1 Effects of Aspect Ratio of Buildings on Angle of Tilt.

When we discuss building damage in Port and Rokko Islands, one point we should keep in mind is that while extensive liquefaction occurred in almost the entire area of Port Island, severe liquefaction was limited to the northern part of Rokko Island.

Figure 9 shows the relationship between aspect ratio and maximum increase in tilting angle for buildings shown in Fig.7 and Fig.8. The increase in tilting angle is obtained as the difference of tilting angles before and after the earthquake. The symbol * in the figure indicates that the value is the maximum tilting angle measured after the earthquake because the tilting angle before the earthquake is not available.

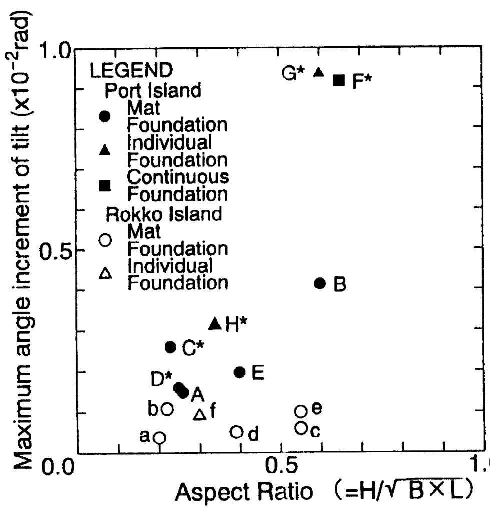


Fig.9. Effects of aspect ratio of buildings on angle increment of tilt.

When the relationship between maximum tilting angle and aspect ratio of buildings is examined, it is found that in Port Island spread foundation buildings with a larger aspect ratio have a greater maximum angle increment of tilt. This tendency is more obvious when the building is supported on a continuous or individual foundation or the building has the marked non-uniformity of the load intensity. The results indicate that the aspect ratio of buildings greatly affects the angle increment of tilt. However, in Rokko Island, the maximum angle increment of tilt of the spread foundation buildings does not increase with aspect ratio and remains relatively small even at larger aspect ratios. The reasons for the small angle increment of tilt and the insensitivity of maximum angle increment of tilt to aspect ratio are considered to be the following:

1) Severe liquefaction did not occur in the central part of Rokko Island because of the difference on the fill materials between the two islands.

2) Some building sites in Rokko Island had been improved by the sand compaction pile method and all buildings except Building f have mat foundations as the countermeasures against long-term settkement.

6.2 Effects of Soil Improvement on Settlement of the Buildings in Rokko Island.

Figure 10 shows the relationship between thickness of un-improved reclaimed layer under spread foundations and average absolute settlement of the buildings in Rokko Island. As the reclaimed layer is improved to deeper depths the un-improved layer becomes thinner and the average absolute settlement of buildings becomes smaller. Therefore, soil improvement is seen to be effective on reducing the average absolute settlement of the buildings.

Vertical axial strain defined as average absolute settlement divided by thickness of un-improved reclaimed layer is seen to range from 0.3 to 1.3%. The result of direct regression shown in the figure reveals a high correlation between average absolute settlement and thickness of un-improved reclaimed layer (with a correlation coefficient of 0.89).

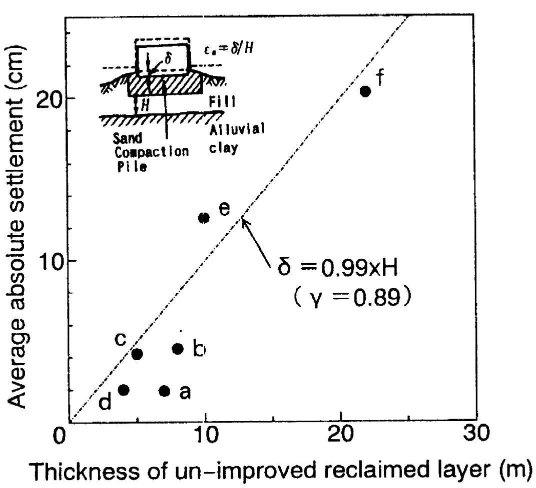


Fig.10. Relationship between thickness of un-improved reclaimed layer and average absolute settlement of buildings in Rokko Island.

6.3 Relationship Between Average Relative Settlement and Width of Buildings.

Figure 11 shows the relationship between average

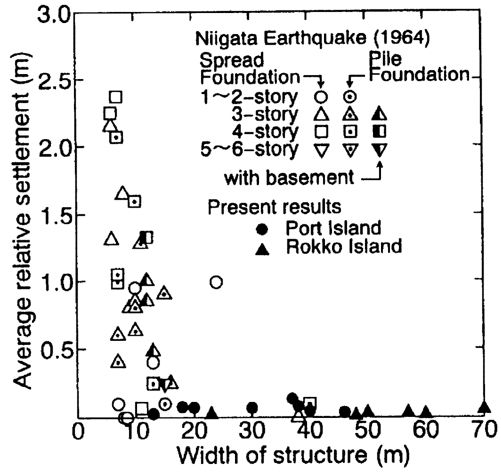


Fig.11. Relationship between average relative settlement and width of buildings (after Yoshimi and Tokimatsu, 1977).

relative settlement to ground surface and width of reinforced concrete buildings obtained from the survey results after the 1964 Niigata Earthquake. During the earthquake, the spread foundation buildings on loose and medium sand deposit of high groundwater level (about 1.0 m deep below the ground surface) suffered heavy damage in Nigata City and the maximum relative settlement of the buildings was 2.5 m. The relationship for spread foundation buildings obtained by our survey after the 1995 Hyogoken-Nanbu Earthquake is superimposed in this figure.

The relationship for the Niigata Earthquake shows a tendency of decreasing average relative settlement with increasing building width. However, in the Hyogoken-Nanbu Earthquake, the average relative settlement remained small irrespective of the building width in Port and Rokko Islands.

The reason for this is mainly considered to be the relatively deeper groundwater level in both islands from 3 m to 8 m deep below the ground surface. Therefore, the surface reclaimed layer near the buildings did not liquefy directly.

7. CONCLUSIONS

Based on these investigation results and discussions, it can be concluded as follows:

1) The maximum tilting angle is greatly affected by the aspect ratio of buildings in Port Island. Foundation type and the marked non-uniformity of the building load intensity also have a significant

influence on the tilting angle of buildings.

2) Soil improvement as the countermeasures against long-term settlement appears to be effective on reducing the average absolute settlement of the spread foundation buildings due to liquefaction during the earthquake.

3) The average relative settlement of spread foundation buildings in both islands are considerably small. The relationship between the average relative settlement and width of buildings observed in the 1964 Niigata Earthquake was not found from our investigation results after the 1995 Hyogoken-Nanbu Earthquake.

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