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Seismic Ground Settlement and Deformation Behavior of Reclaimed Lands in the 1995 Kobe Earthquake

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ABSTRACT

After the 1995 Kobe Earthquake, particular attention has been paid on the settlement observed at reclaimed lands located at between Osaka and Kobe, in reference to their geological characteristics.

In this paper, the ground surface elevations before and after the 1995 Kobe Earthquake were compared to evaluate the seismic ground settlement of reclaimed lands. Calculated settlements by using an available empirical formula were compared with measured ones.

A further study was carried out to investigate the seismic ground settlement calculated by using a numerical simulation program called "FLIP" at a selected reclaimed land. In reference to the data available from published papers on seismic ground settlement as measured, attempts were made to identify in a practical manner such settlement with the degree of the earthquake recorded at each reclaimed lands as well as the grain size and N value of the filled layer there. The proposed method for estimating seismic ground settlement caused by earthquake is estimated for its applicability and accuracy by using a simulation program.

INTRODUCTION

Many reclaimed lands have been constructed along the northeast shoreline of Osaka Bay, including Port Island, Rokko Island, Maishima, Yumeshima, Sakishima and Kansai International Airport Island. Some of these islands have been constructed by waste disposals.

The 1995 Kobe Earthquake that struck the southern part of Hyogo prefecture, Japan brought many severe damages. The geotechnical phenomena that caused the damages were mainly soil liquefaction and ground settlement and spreading, which were commonly found at reclaimed lands. Most damages at reclaimed lands were concentrated on structures of port facilities. They include such damages as displaced caissons composing of revetments and embankments, collapsed cranes and buildings on the ground with lateral displacement and liquefaction. At inner areas of the reclaimed lands located far from the shoreline, such phenomena as sand boils and ground settlement were commonly observed. The settlements were as large as several tens of centimeters in some parts (Japanese Geotechnical Society, 1996, 1998).

In this paper, attempts are made to mainly analyze the behavior of the seismic ground settlement and the liquefaction phenomenon in the reclaimed lands in the 1995 Kobe Earthquake. Firstly, in reference to the measured data available from published papers on seismic ground settlement, attempts are made to identify seismic ground settlements with the intensity of the Earthquake recorded at each reclaimed lands as well as the fines content and N-value of filled materials in a practical manner. Secondly, to calculate seismic ground settlement arising from an Earthquake, this proposed method is verified for its applicability and accuracy by using numerical simulation program called "FLIP".

LOCATIONS OF RECLAIMED LANDS RELATED TO THIS STUDY

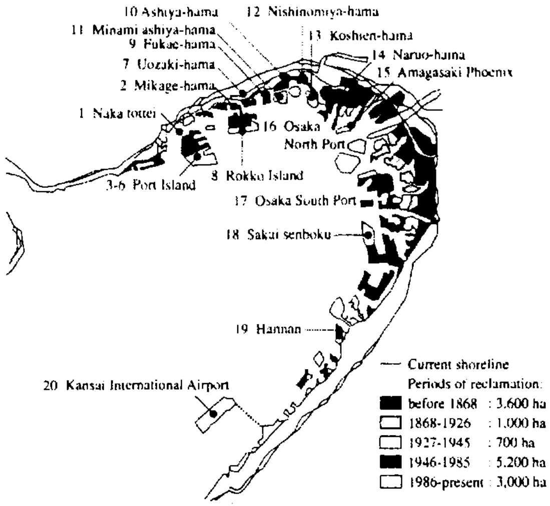

Fig.1 Reclaimed lands in Osaka Bay area

Fig.1 shows the locations and construction period of reclaimed lands in the Osaka Bay area. Reclaimed lands related to this study are constructed along the shoreline of Osaka Bay, including such man-made islands as Port Island, Rokko Island and Kansai International Airport Island. Some of these islands have been used as disposal sites. Particular attention was paid to the seismic ground settlement observed at the reclaimed lands located at between Osaka and Kobe, in reference to these geological characteristics. Seismic ground settlements were concentrated on the reclaimed lands and their enough data were available from numerous reports on the Earthquake damages.

EVALUATION OF SEISMIC ACCELERATION AT RECLAIMED LANDS

Most data on seismic vibration of ground during the Earthquake were taken at the ground surface of some reclaimed lands, except those recorded by the seismographs in vertical arrays at Port Island. Accordingly, they need some correlation for compensating the difference of vibration due to different seismic datum, particularly when evaluating seismic behavior of reclaimed lands on which no seismic data are available.

Distribution of the surface wave acceleration had already been assessed over the coastal areas along Osaka Bay by extrapolating the data taken at a relatively large number of sites. However, the reliable seismic data were taken only at a limited number of sites, and also their geological features vary each other to a greater extent. It is necessary, therefore, to evaluate seismic acceleration at each reclaimed land in a realistic manner by examining seismic vibration of ground transmitted from active fault to bottom of a filled layer, considering the damping effect.

Fukushima and Tanaka (1990) proposed an empirical formula for calculating the maximum horizontal acceleration at a given distance from the active fault in which an earthquake originates. The formula which is applicable to earthquakes in Japan and the seismic vibration in the neighborhood of its epicenter, is expressed as follows:

$$\mathrm{Log}A=0.41M\log(R+0.032\times10^{0.41M})+0.0034R+1.30 \quad (1)$$

A: the maximum acceleration (gal)
M: the magnitude of earthquake
R: the distance from the active fault in which an earthquake originates (km)

The formula in Eq. (1) is often used to estimate the maximum horizontal acceleration on a Pleistocene layer or an alluvial layer not deeper than 25 m.

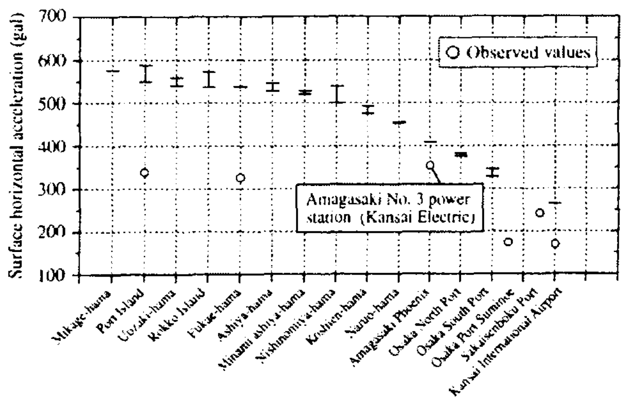

Fig.2 Estimated maximum horizontal accelerations together with measured ones

Therefore, the acceleration at each reclaimed land can be calculated by using this formula, and the results are shown in Fig.2, including some measured values. In this figure, names of these reclaimed lands are arranged in order according to the distance from active fault. It is noted from this figure that at the locations far from the active fault, the estimated values approximately agree with the measured ones. However, at the locations close to the active fault, the measured values are fairly smaller than the estimated ones. This phenomenon was caused by the damping effect of horizontal vibration. Therefore, it is noted that in case of applying Eq. (1) to reclaimed lands, the maximum horizontal acceleration should be reduced by about 200 gals at closer locations from the active fault.

SETTLEMENT CHARACTERISTICS OF THE RECLAIMED LANDS

Soil liquefaction that occurred at many sites in the reclaimed lands along Osaka Bay proved to be one of the major causes of damages to various kinds of structures.

Referring to available measured data on seismic ground settlement, attempts were made to correlate the seismic ground settlement with the intensity of the Earthquakes as well as the fines content and N value of filled materials.

Comparison between Measured and Calculated Ground Settlements

Data on such geotechnical characteristics as fines content and N value of soils at each reclaimed land, as well as measured seismic ground settlement were collected from various relevant publications. The settlement data for many reclaimed lands as shown in Table 1 were taken at locations relatively far from the shoreline without effect of lateral spreading of ground.
Measured seismic ground settlements given in Table 1 were estimated from the data obtained by means of level surveys and GPS surveys before and after the 1995 Kobe Earthquake.

Table 1 Data of seismic ground settlement at reclaimed lands

Reclamation site	Subsidence surveyed (cm)	Surface displacement measurement method
Naka tottei	South revetment 50-70 East revetment 20-30	Leveling-based
Mikage-hama	20-30	Amount of relative subsidence
Port Island	av.	Leveling-based
	Approx. 30	Leveling-based
	20-30	Leveling-based
	20-31	
	18.4-30.0	
	8-23	Amount of relative subsidence
	0	
Uozaki-hama	35-70	GPS survey-based
Rokko Island	0-20	GPS survey-based
Fukae-hama	25	GPS survey-based
Ashiya-hama	Approx. 30	Amount of relative subsidence
Minami ashiya-hama		Leveling-based
	20-55	GPS survey-based
Nishinomiya-hama	35-40	Amount of relative subsidence
		GPS survey-based
Koshien-hama		GPS survey-based
Naruo-hama	0-4	GPS survey-based
Amagasaki Phoenix		GPS survey-based
Osaka North Port	3.3-4.1	Leveling-based
Osaka South Port	0.0-2.0	Leveling-based
Kansai International Airport		

In this section, the seismic ground settlements were calculated by using the liquefaction index FL given in the Guide Line of the Revised Manual (JSSMFE, 1993). FL is represented by the ratio of Lmax and Rmax, both of which signify the maximum resistance ratio and seismic shear stress ratio at each depth, respectively. Fig.3 shows the relationship between measured and calculated seismic ground settlements. In Fig.3, a fairy good agreement seems to exist between the two. However, all the data measured at Rokko Island (taken through level survey at its central and southern parts) are smaller than those calculated. This is because Rokko Island except the northern area was reclaimed mainly by soils from Kobe groups which include greater fines content than in other materials.

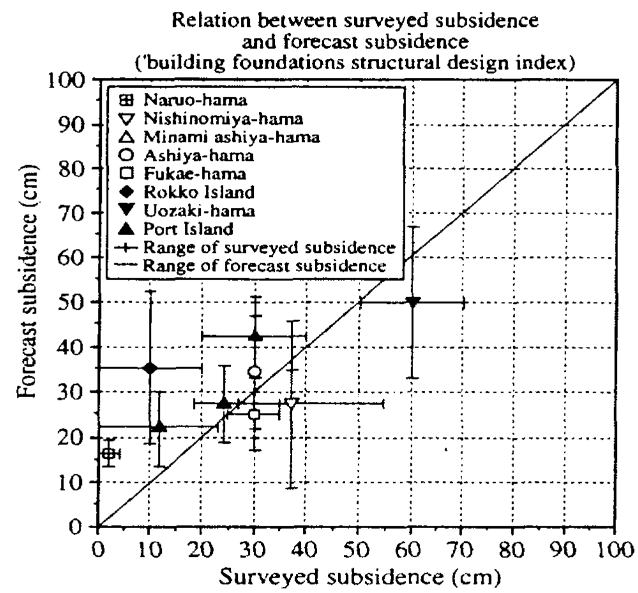

Fig.3 Relationship between measured and calculated seismic ground settlement

Seismic Ground Settlement and Intensity of Sand Boil

To establish the correlation between the measured seismic ground settlements given in Table 1 and the intensity of sand boil, a survey was conducted at each reclaimed land. The intensity of sand boil is defined herein as the percentage of the area with sand boil per a unit area. A report (Kobe Development Bureau, 1995) is available on traces of sand boil at Rokko Island and Port Island. Sand boils were extensive at locations where a larger seismic ground settlement was measured.

Fig.4 shows the relationship between the intensity of sand boil and measured compressive strain of ground (i.e. measured ground settlement / thickness of the filled layer). Despite of a relatively large scattering, the data indicate that the compressive strain of ground increases as increasing the intensity of sand boil.

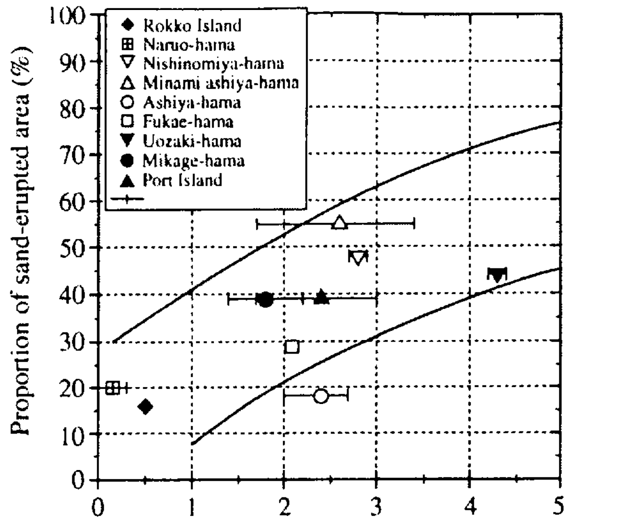

Fig.4 Relationship between intensity of sand boil and measured compressive strain of ground

EVALUATING SEISMIC GROUND SETTLEMENTS OF RECLAIMED LAND BY USING DYNAMIC ANALYSIS METHOD

In this chapter, the above-mentioned method for estimating the seismic ground settlements is verified for its applicability and accuracy by using a numerical simulation program called "FLIP". This program developed in 1988 by the Port and Harbor Research Institute, Ministry of Transport (Iai, 1989). This can provide a dynamic effective stress analysis in a given ground, by taking into account the effective stress reduction due to excess pore pressure increase as well as shear modulus decrease in the process to liquefaction when subjected to an earthquake. The program can also evaluate not only liquefaction potential but also residual strain in the ground.

To estimate the amount of seismic ground settlement after liquefaction using the result of numerical simulations, a correlation between the safety factor FL against soil liquefaction and the volumetric strain at soil which occurs as water is squeezed out of the liquefied soil is used. The safety factor FL was calculated by using two criteria; one provided in the "Guidelines for Structure Foundation Design" (1988), and the other given in the "Instruction Manual for Road Bridges" (1996), while the relative density Dr was worked out in accordance with a formula proposed by Tokimatsu and Yoshimi (1983). The fines content Fc that is needed to calculated FL and Dr was assumed to be 5% for those soils identified as decomposed granite, and 15% for those composed of other materials.

In verifying the proposed method, attention is paid to the maximum shearing strain and maximum excess pore pressure ratio (residual excess pore pressure ratio), which can be obtained by the relationships between these and the volumetric strain (See Fig.5 and Fig.6). These relationships will be described later in detail.

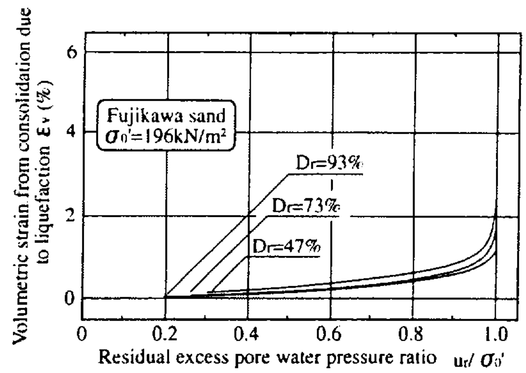

Fig.5 Relationship between maximum shear strain and volumetric strain

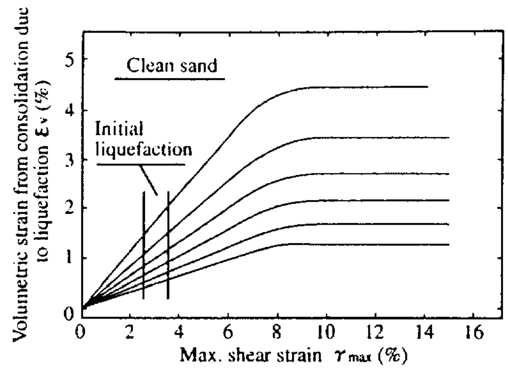

Fig.6 Relationship between residual excess pore pressure ratio and volumetric strain

Analytical Conditions

The filled layer at the central part of Fukaehama was selected as an object of analysis because enough data of soil properties at the site were available. Fig.7 shows the finite element mesh of the analytical ground. Table 2 shows the various parameters of soil characteristics which were used for the analysis. The seismic record of the Earthquake is presented at the bottom of the layer. Fig.8 shows the Kobe Earthquake Wave PI 79 NS Base, which had been worked out based on the seismic data recorded both at surface and underground during the 1995 Kobe Earthquake. The applied seismic record is fixed by modifying the maximum horizontal acceleration of this wave to 538 gal which is the estimated maximum horizontal acceleration at the site for analysis.

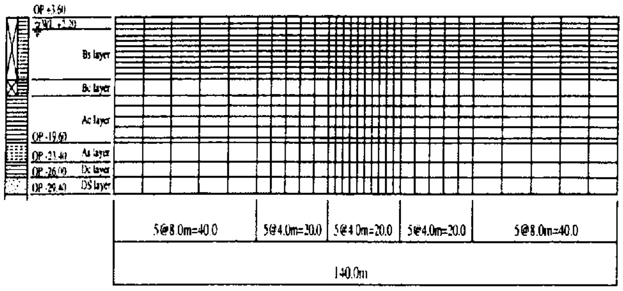

Fig. 7 Finite element model of ground

Table 2 Various parameters of soils used in analysis

Material no	Soil layer	Depth of top of soil layer (m)	Depth of base of soil layer (m)	Wet unit weight γ_t (t/m³)	Effective overburden pressure σ_v' (kgf/cm²)	N-value N	Fine content Fc (%)	Equiv. N-value $N_{0.66}$	Poisson's ratio ν	Initial shear plasticity (rigidity) Gm (tf/m²)	Initial bulk elastic modulus Km (tf/m²)	Porosity n	Internal friction angle ϕ_f (°)	Conversion angle ϕ_p (°)	Liquefaction parameters S1	w1	p1	p2	modulus proportionate to shear space c1
1	Bs	0.0	1.3	1.8	0.117	6	14	8.9	0.30	4870	10552	0.45							
2	Bs	1.3	2.2	1.8	0.315	6	14	7.7	0.30	4870	10552	0.45							
3	Bs	2.2	3.5	2.0	0.461	6	14	6.9	0.30	4870	10552	0.45	39	28	0.005	8.06	0.5	0.93	1.30
4	Bs	3.5	4.5	2.0	0.576	5	14	5.3	0.30	4302	9321	0.45	36	28	0.005	6.69	0.5	0.99	1.60
5	Bs	4.5	5.5	2.0	0.676	4	13	3.9	0.30	3698	8008	0.45	39	28	0.005	5.69	0.5	1.03	1.60
6	Bs	5.5	6.5	2.0	0.778	4	4	3.6	0.30	3698	8008	0.45	39	28	0.005	1.19	0.5	1.15	1.60
7	Bs	6.5	7.5	2.0	0.878	3	5	2.4	0.30	3040	6587	0.45	39	28	0.005	0.96	0.5	1.17	1.60
8	Bs	7.5	8.5	2.0	0.976	3	5	2.2	0.30	3040	6587	0.45	39	28	0.005	0.93	0.5	1.18	1.60
9	Bs	8.5	9.5	2.0	1.076	18	8	14.8	0.30	10279	22271	0.45	41	28	0.005	20.15	0.5	0.92	1.30
10	Bs	9.5	10.5	2.0	1.176	18	8	14.1	0.30	10279	22271	0.45	41	28	0.005	18.58	0.5	0.94	1.30
11	Bs	10.5	11.6	2.0	1.281	24	8	18.3	0.30	12500	27083	0.45	41	28	0.005	20.24	0.5	0.89	1.30
12	Bc	11.6	14.6	1.7	1.441	3	100	1.2	0.45	3040	29387	0.55							
13	Ac	14.6	16.5	1.7	1.613	3	100	0.9	0.45	3040	29387	0.55							
14	Ac	16.5	18.5	1.7	1.749	3	100	0.7	0.45	3040	29387	0.55							
15	Ac	18.5	20.5	1.7	1.889	3	100	0.5	0.45	3040	29387	0.55							
16	Ac	20.5	22.5	1.7	2.029	3	100	0.3	0.45	3040	29387	0.55							
17	Ac	22.5	23.4	1.7	2.130	6	100	2.1	0.45	4870	43077	0.55							
18	As	23.4	27.0	2.0	2.342	27	–	14.3	0.30	13542	29341	0.45							
19	Dc	27.0	30.0	1.7	2.627	13	100	5.3	0.45	8238	70634	0.55							
20	Ds	30.0	33.0	2.0	2.882	43	–	20.6	0.30	18583	40283	0.45							

Ground settlement was determined in terms of the volumetric strain in each grid element in accordance with the maximum shearing strain as calculated by the FLIP program, and by using the relationship between the maximum shearing strain and the volumetric strain shown in Fig.6. Volumetric strain of the soil also calculated based on the residual excess pore pressure ratio, by using the relationship shown in Fig.5.

Table 3 provides the analytical results. The upper five diagrams in Fig.9 shows the depth-wise distributions of N value, fines content and relative density, as well as those of the maximum shearing strain and maximum excess pore pressure ratio $\Delta u / \sigma_v'$, in which latter two items are calculated from the numerical analysis. While the lower three diagrams in Fig.9 shows the depth-wise distributions of the volumetric strain which are calculated by three methods, that is, a simplified method and methods based on the maximum shearing strain and the excess pore pressure ratio.

The analysis was conducted to verify the applicability of the proposed method by using the FLIP program. In conjunction with the relationship between maximum shearing stress and volumetric strain resulted in a settlement of 13.2 cm, while the same analysis, when conducted by using the relationship between residual excess pore water pressure ratio and volumetric strain, provide a settlement of 12.0 cm. In contrast to these results from the analysis, the settlement as calculated by using the proposed method was 32 cm while the measured settlement was 35 cm.

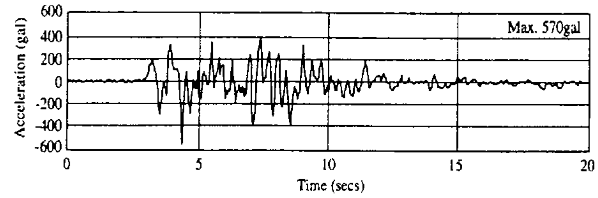

Fig.8 Kobe Earthquake Wave PI-79 NS Base

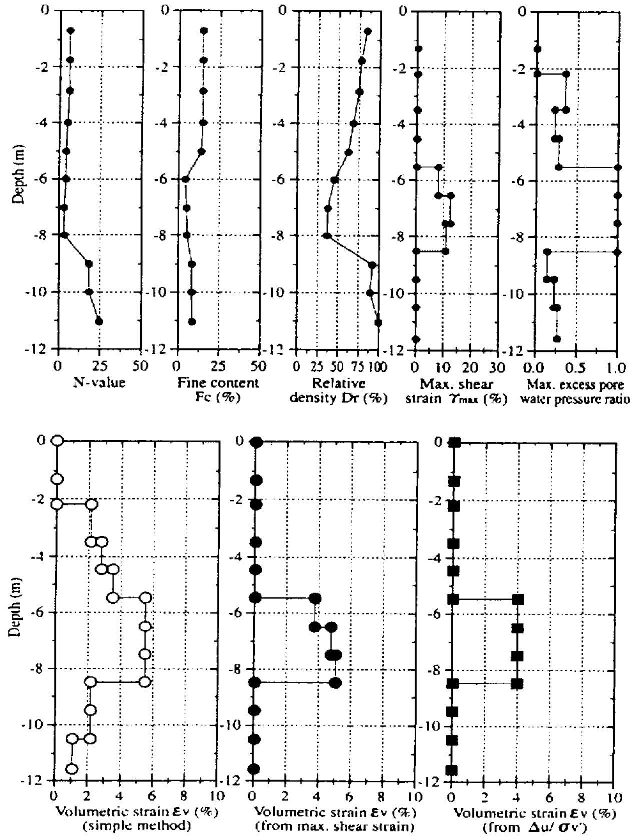

Fig. 9 Ground conditions and analytical results

From the three diagrams shown in the bottom half of Fig.9, the volumetric strains, each worked out in a different manner, are seen to be distributed depth-wise more or less in a similar pattern. The settlement determined by using the FLIP program, however, proved only half as large as that measured, or calculated by using proposed method. The discrepancy between the results from the method using the FLIP program and the settlement worked out by the proposed method attributed to the fact. Namely, the maximum shearing strain as provided by the former method was latter. When dealing with the soil layer with a large fine-grain (GL-2 to –6 m) and that having relative density (GL-8 to –10 m), both of which were assumed to have liquefied.

Table 3 Analysis results

Surface strain input acceleration: 538gal response: 482gal

Height DL (m)	Depth GL (m)	Measured depth (m)	N-value	Effective overburden pressure σ_v' (kgf/cm²)	Fine content Fc (%)	Standardized N-value N1	ΔNf	Relative density Dr (%)	Max. shear strain γ_{max}	Bulk strain ε_v (%)	Thickness of layer H (cm)	Amount of subsidence S (cm)		Element no.	Excess pore water pressure ratio, $\Delta u/\sigma_v'$	Bulk strain (%)	Thickness of layer H (cm)	Amount of subsidence S (cm)
3.5	0.0	0.85	6	0.117	14	12	6.8	85.3	0.0001	–	130	0.0		301	–	0.00	130	0.0
2.2	1.3	1.75	6	0.315	14	10	6.8	78.7	0.0002	–	90	0.0		302	–	0.00	90	0.0
1.3	2.2	2.85	6	0.461	14	9	6.8	75.1	0.0006	0.00	130	0.0		303	0.347	0.00	130	0.0
0.0	3.5	4.00	5	0.587	14	7	6.8	68.6	0.0006	0.00	100	0.0		304	0.219	0.00	100	0.0
-1.0	4.5	5.00	4	0.676	13	5	6.8	62.4	0.0008	0.00	100	0.0		305	0.261	0.00	100	0.0
-2.0	5.5	6.00	4	0.776	4	5	6.8	45.1	0.1609	3.80	100	3.8		306	0.993	4.00	100	4.0
-3.0	6.5	7.00	3	0.878	5	3	0.0	37.8	0.2489	4.85	100	4.8		307	0.993	4.00	100	4.0
-4.0	7.5	8.00	3	0.976	5	3	0.0	36.6	0.2160	5.00	100	5.0		308	0.994	4.00	100	4.0
-5.0	8.5	9.00	18	1.076	8	17	0.0	92.4	0.0001	0.00	100	0.0		309	0.142	0.00	100	0.0
-6.0	9.5	10.00	18	1.178	8	18	3.6	90.2	0.0006	0.00	100	0.0		310	0.218	0.00	100	0.0
-7.0	10.5	11.06	24	1.281	8	21	3.6	100.1	0.0006	0.00	110	0.0		311	0.25	0.00	110	0.0
-8.1	11.6									TOTAL	1160	13.6				TOTAL	1160	13.6

CONCLUSIONS

In this paper, estimating methods of the behavior of the seismic ground settlement and the liquefaction phenomenon in the reclaimed lands caused by 1995 Kobe Earthquake were reported. Major conclusions in this study are summarized as follows.

1. At the locations far from the active fault, the estimated acceleration values approximately agree with the measured ones. However, at the locations close to the active faults, the measured values are fairly smaller than the estimated ones.
2. A fairy good agreement except the northern area of Rokko Island seems to exist between the measured and calculated settlement by using the liquefaction index FL. This is because this area was mainly reclaimed by soils from Kobe groups which include greater fines content than in other materials.
3. Despite of a relatively large scattering, the data indicate that the compressive strain of ground increases as increasing the intensity of sand boil.
4. The proposed method was verified by using a program called "FLIP" provided volumetric strain in good agreement with that worked out from measured data, but it yields a smaller settlement that actually recorded.

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