Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

INFLUENCE OF THE EARTHQUAKE MOTION CHARACTERISTICS ON THE GROUND SETTLEMENT BEHAVIOR DUE TO LIQUEFACTION

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ABSTRACT: Influences of the earthquake motion characteristics, such as peak acceleration amplitude, duration or wave form, on the settlement of ground occurred after liquefaction is described in this paper. Firstly, results of a series of centrifuge experiments are presented. Secondly, improvement of the effective stress analysis program in terms of the re-consolidation characteristics after liquefaction is discussed. Finally, ground settlement during the Great East Japan earthquake is simulated utilizing the program.

Key Words: Great East Japan earthquake, liquefaction, settlement, centrifuge experiment, effective stress analysis

INTRODUCTION

Severe damages were reported around Tokyo bay area during the Great East Japan earthquake, occurred on 11th of March, 2011. In spite of moderate peak acceleration of the ground motions (NIED 2011a), severe damages on infrastructure due to liquefaction were found especially on reclaimed land around Tokyo bay (JGS 2011b), and affected to recovery. Many researchers pointed out that severe liquefaction damages were partly due to the long duration of the earthquake motion. Therefore, this research focuses on the influence of earthquake motion characteristics, such as peak acceleration, duration or wave form, on the settlement of ground due to liquefaction.

Researches on the post-liquefaction settlement behavior of sandy ground have been performed by many researchers based on laboratory tests (Nagase 1988, Yoshida 1994). Ishihara et.al (1992) proposed a practical method to predict the post-liquefaction settlement in terms of the maximum shear strain of the liquefied sand strata experienced during the earthquake. Numerical research efforts were also performed, however, it is suggested many technical issues need to be improved for quantitative prediction on this problem. The code verification performed by the Earthquake Engineering Committee of JSCE is one of the major works (JSCE 2003), and pointed out there is large variation in terms of predicted settlements by numerical procedures at present.

In this paper, firstly, results of a series of centrifuge experiments, reproduced liquefaction under various earthquake motions on ideal ground condition are presented (Ikeda 2006). Secondly, improvement of the effective stress analysis program in terms of the re-consolidation characteristics after liquefaction is discussed (Higuchi 2007). Finally, ground settlement during the Great East Japan earthquake is simulated utilizing this program.

CENTRIFUGE EXPERIMENT

Test Procedure

Shake table tests were carried out under the 40g (392m/s^2) centrifugal gravity utilizing Obayashi centrifuge, which equips 2.2m x1.07m shake table (Matsuda 2002).

Fig. 1 shows the profile of the model ground and the layout of instruments. Model sand deposit is consisted of #7 silica sand (D_{50}=0.15mm) with Dr=50%, which is pluviated into the lamina container through the pore fluid. Methylcellulose solution (40mPa*s) is used as pore fluid to satisfy the similitude of pore water dissipation. Dimensions of the model ground are 440mm long, 300mm in width and 315mm deep, which equivalent to 17.6 m long, 12m in with and 12.6m deep respectively in prototype scale.(Without any notice, discussion will be referred at the prototype scale, hereafter.) Note that the depth of the sand deposit is 11.6m (290mm). Accelerometers and pore pressure transducers are instrumented in the ground. Ground settlements are measured by the laser displacement transducers at four point of the ground surface.

After finishing the model ground preparation, pre-consolidation process (on-flight self weight consolidation) is performed under 40g centrifugal gravity.

Table 1 shows summary of parameters of the shake table tests. Each relative density Dr on the table is derived from prepared ground model measurement, as well as Max. Acceleration values are performed peak acceleration observed at the shake table tests.

Because this experiment is focused on the characteristics of input motions, 2 different input motions are chosen, as shown in Fig. 2(a) and (b). One is the Port Island motion (CDIT 1997), representative motion among the inland earthquake, and the other is Akita motion (JGA 2000), representative motion among the plate boundary earthquake. Duration of Port Island motion is about 20s (second; hereafter), and that of Akita motion is about 80s. 4 experiments were performed, twice on each input motion, as shown in Table 1. The maximum acceleration amplitude is chosen as level 2 (Severe Earthquake; L2, hereafter) and level 1 (Operation Earthquake; L1, hereafter) motion.

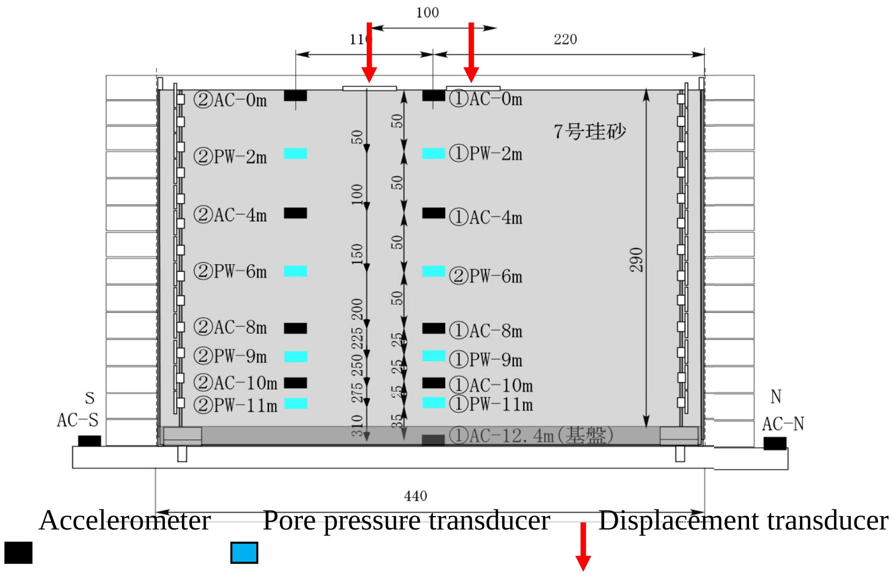
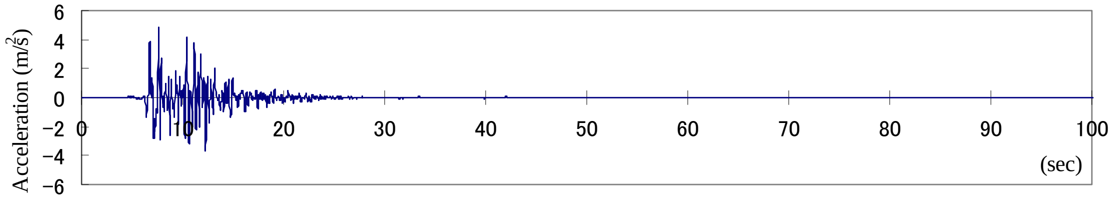
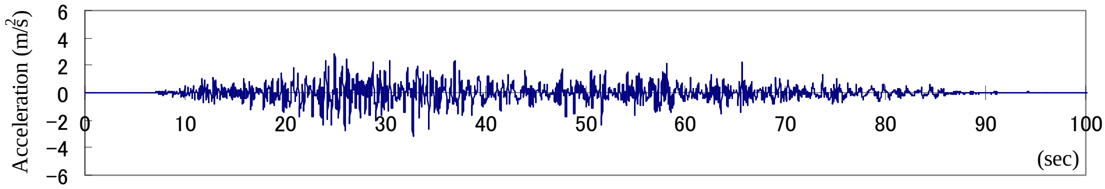


Fig. 1 Profile of the centrifuge model ground and the layout of instruments (Model scale: mm)



(a) Port Island (Recorded L-2 motion)



(a) Akita (Recorded L-2 motion)
Fig. 2 Time histories of input motions

Table 1 Summary of test conditions

Case	1(PI-L2)	2(PI-L1)	3(Akita-L2)	4(Akita-L1)
Input motion	Port island		Akita	
Duration (s)	20		80	
Relative density Dr (%)	58.5	43.1	48.2	52.7
Max. Acceleration (m/s^2)	4.85	2.00	3.11	1.60

Test Results

Final settlements of the ground surface recorded during the centrifuge experiments are summarized in Table 2. Settlements are measured at 4 point around the center of the model ground, and average number is shown in the Table. Settlements observed at Akita motion, which has longer duration, are larger than that of observed at Port Island motion, which show larger peak acceleration, on both L1 and L2 shake event.

Table 2 Ground surface settlement

Case	1(PI-L2)	2(PI-L1)	3(Akita-L2)	4(Akita-L1)
Input motion	Port Island		Akita	
Ground settlement (cm)	29	12	32	17

Time histories of the ground surface settlement and maximum excess pore water pressure ratio (PPR, hereafter) at the depth of GL=-6.0m are shown in Figure 3 and Fig. 4, respectively.

Liquefaction is defined as condition as PPR>0.95, and PPR is defined as follows,

$$PPR = \Delta u / \sigma_v' \tag{1}$$

in which, Δu: excess pore water pressure, σ_v': overburden effective stress, respectively.

Settlement time histories stabilized about 1,000s after the shake event at the L1 motions, while these still move at the L2 motions. Compared the shape of the settlement time histories with that of the PPR time histories, it is seen that as the period of duration of PPR dissipation is longer, larger final settlement is performed, instead of Case 1.

To investigate the liquefaction extent in the ground, PPR distributions throughout the sand deposit are compared as Fig. 5. It is seen that liquefaction is occurred at any depth in both Case 1 (PI-L2) and Case 3 (Akita-L2), which correspond to the L2 motions. In cases of using L1 motions, Case 2 (PI-L1) and Case 4 (Akita-L1), PPR<0.95 are seen at deep part of the sand deposit in Case 2.

Maximum shear strain distribution throughout the sand deposit is shown in Fig. 6. Shear strain of each sand layer is calculated utilizing the acceleration time histories recorded at the tests. Same as previously described by Ishihara, as larger the maximum shear strain, ground settlement become bigger. Although the largest strain is seen in Case2 (PI-L2) at the bottom, average shear strain throughout the sand deposit is bigger in Case4 (Akita-L2), at which the largest settlement occurred.

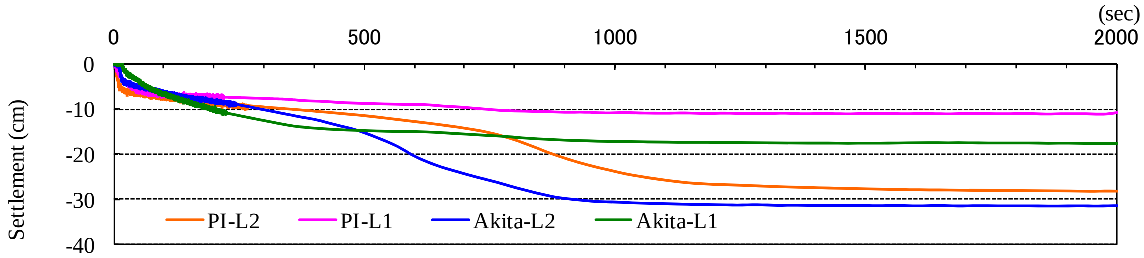


Fig. 3 Time histories of ground surface settlement

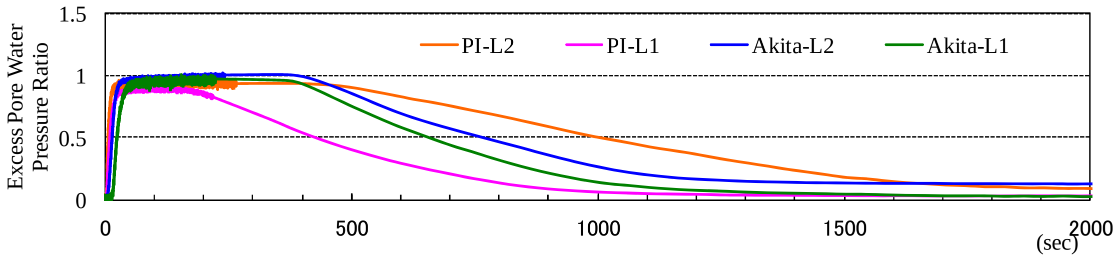


Fig. 4 Time histories of PPR (GL=-6.0m)

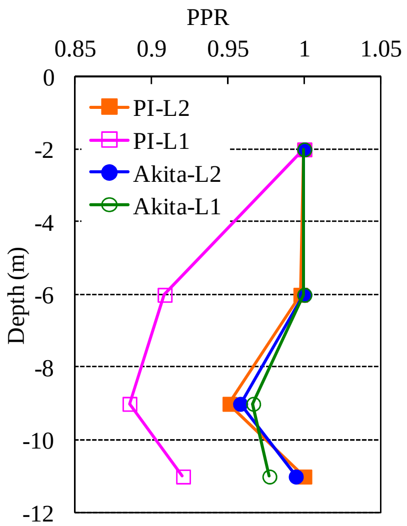


Fig.5 Maximum PPR distribution throughout the sand deposit

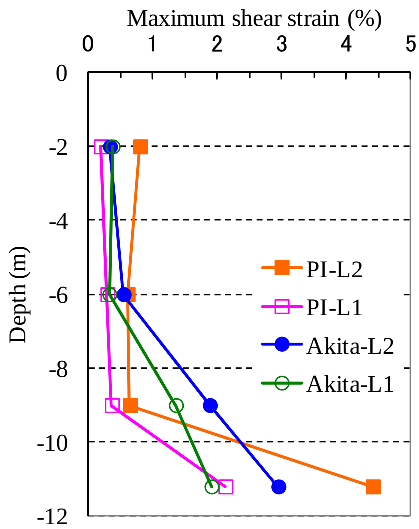


Fig.6 Maximum shear strain distribution throughout the sand deposit

IMPROVEMENT OF THE EFFECTIVE STRESS ANALYSIS PROGRAM

Settlement behavior of the liquefied sandy ground was simulated utilizing the dynamic effective stress analysis program. The program was improved by adopting the volumetric compression model after liquefaction, which is affected by the accumulated shear strain of sand deposit during un-drained cyclic shear process. Applicability of the improved program is discussed by simulating the centrifuge experiments conducted previously described.

Effective stress analysis program

The dynamic effective stress analysis program, named "EFECT" developed by Ito, et.al (1995) is utilized. This program is based on the dynamic characteristics of porous media developed by Biot (1962). Matsuoka's constitutive model for sand and clay (1987) is adopted as the constitutive model of sand, as well as introducing parameters for concerning the cyclic loading process.

Post liquefaction settlement model

Re-consolidation volumetric strain model proposed by Sento, et.al (2004) is adopted for the dynamic effective stress program, described above. This model is based on the relation between the volumetric compression characteristics and the experienced un-drained cyclic shear process evaluated by the re-consolidation test after liquefaction. Followings are major characteristics of the model.

(a) It is experimentally found that post-liquefaction re-consolidation characteristics of sand are similar to the normal consolidation process.
(b) Accumulated shear strain is used as an index to characterize the post-liquefaction volumetric compression.

Table 3 shows comparison of the total volumetric strain during post-liquefaction re-consolidation evaluated by the adopted model and the compression model originally adopted on the program "EFECT". Test calculation results of volumetric strain accumulation are also shown. Schematic drawings of the volume change process during and after liquefaction by each evaluation model are shown in Fig. 7.

Table 3 Total volumetric strain during post-liquefaction re-consolidation

Model	Adopted model	EFECT (Sand)[3)]
Volumetric strain increment	$d\varepsilon_v = \frac{0.434C_c}{1+e_0}\frac{dp}{p+p_i}$ $d\varepsilon_v$: Volumetric strain increment C_c :Compression index e_0 : Initial void ratio p :Normal effective stress p_i :New parameter	$d\varepsilon_v = \frac{C_c}{1+e_0}\frac{1}{\sqrt{p_a}}\frac{1}{2}\frac{dp}{\sqrt{p}}$ $d\varepsilon_v$: Volumetric strain increment C_c :Compression index e_0 : Initial void ratio p :Normal effective stress p_0 :Initial effective stress p_a :Atmospheric pressure ($=98kPa$)
Post-liquefaction volumetric strain accumulation (p=0 through p_0)	$\varepsilon_v = \int_0^{p_0}\frac{0.434C_c}{1+e_0}\frac{dp}{p+p_i} = \frac{C_c}{1+e_0}\log_{10}\left(\frac{p_0+p_i}{p_i}\right)$	$\varepsilon_v = \int_0^{p_0}\frac{C_c}{1+e_0}\frac{1}{\sqrt{p_a}}\frac{1}{2}\frac{dp}{\sqrt{p}} = \frac{C_c}{1+e_0}\sqrt{\frac{p_0}{p_a}}$
Test calculation results of volumetric strain accumulation (p_0=98kPa)	5 (p_i=10^{-5}kPa) 1 (p_i=10kPa)	1 (p_a=98kPa)

A new parameter p_i, defined as eq. (2) is introduced to evaluate the volumetric strain relate with the experienced shear strain during the cyclic shear. Parameter x in eq. (2) is defined as eq. (3), which related with the accumulated shear strain. Accumulated shear strain defined as eq. (4) is introduced as the experienced shear index in this model. Therefore, as larger the shear process experienced, larger volumetric strain is evaluated.

$$p_i = p_0 \times 10^{-x} \tag{2}$$

$$x = \frac{a\gamma_{acm}}{1+\gamma_{acm}/b} \tag{3}$$

Here, *a* and *b* are parameters to fit the volumetric change characteristics of sand.

$$\gamma_{acn} = \int_0^t |\dot{\gamma}(t)| dt \tag{4}$$

Here, $|\dot{\gamma}(t)|$ is defined as the shear strain velocity at time t.

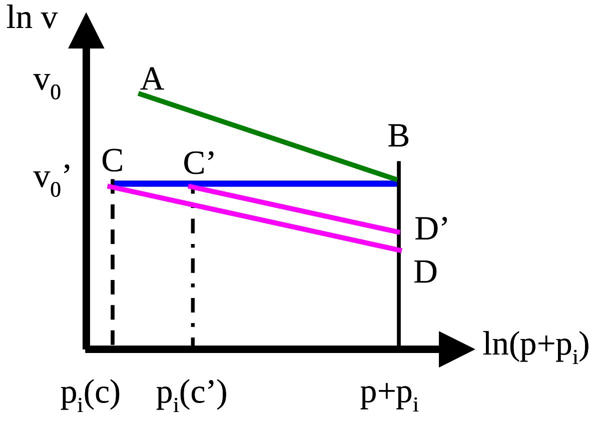


Fig. 7 Schematic drawings of the volume change process during and after liquefaction

Accumulated shear strain throughout the soil deposit in the centrifuge experiments are shown in Fig. 8. Largest accumulated shear strain is seen in Case3 (Akita-L2) instead of Case1 (PI-L2), in which the largest maximum shear strain was observed, as shown in Fig. 6. Compared the accumulated shear strain distribution in the ground with that of the maximum shear strain, relatively larger values are observed throughout the soil deposit in cases selected Akita motion, which has longer duration, as input motion at experiments.

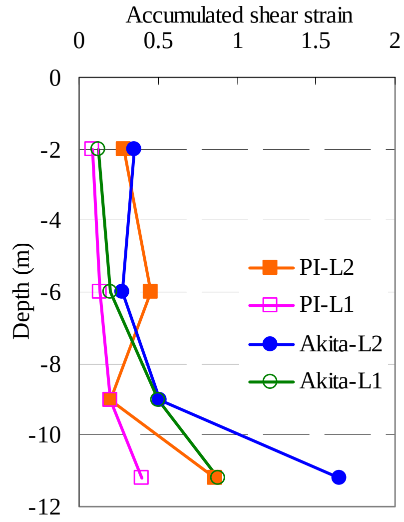


Fig. 8 Accumulated shear strain throughout the soil deposit at the centrifuge experiments

Simulation of the post liquefaction settlement

Numerical simulations were conducted to access performance of the new settlement model. Centrifuge experiments discussed are simulated and compared in terms of the ground surface settlement.

Fig. 9 shows the model used in the simulation. A 1D FEM soil column model, consists of solid elements with plane strain condition is adopted. Only the vertical movement is allowed for liquid phase in this model. Initial shear stiffness of the model is determined by the model ground period measured at small excitation test in the centrifuge. Major soil parameters are shown in Table 4, which were obtained from laboratory element tests on the sand used in the centrifuge experiment. Result of the liquefaction test simulation performed under the cyclic simple shear condition utilizing these parameters is shown in Fig. 10.

Parameters governing the volumetric strain characteristics a and b are determined basing on the result of the laboratory test executed with sand used in the centrifuge experiment. Fig. 11 shows the test result and the fitted result on the relations between the volumetric strain after the liquefaction (re-consolidation volumetric strain) and the accumulated shear strain during cyclic shear. Parameters are chosen as a=10 and b=0.5, respectively, and about 3% maximum volumetric strain is expected in this case.

Simulations were performed on 4 cases, and recorded acceleration time histories on the shaking table are utilized. To calculate the re-consolidation settlement, duration of the analyses is chosen as 4,000s as to stabilize the re-consolidation process.

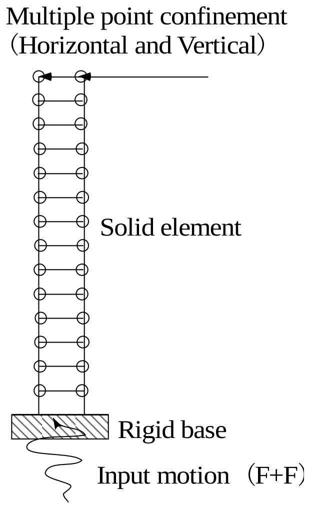


Fig. 9 Simulation model

Table 4 Major soil parameters used in the simulation

Void ratio	e_0	0.87
Parameter for dilatancy characteristics	λ	1.20
	μ	0.21
Friction angle	ϕ_f	37°
Compression index	C_c	0.0150
Poisson ratio	ν	0.33
Permeability (m/s)	k	8.0x10^{-5}

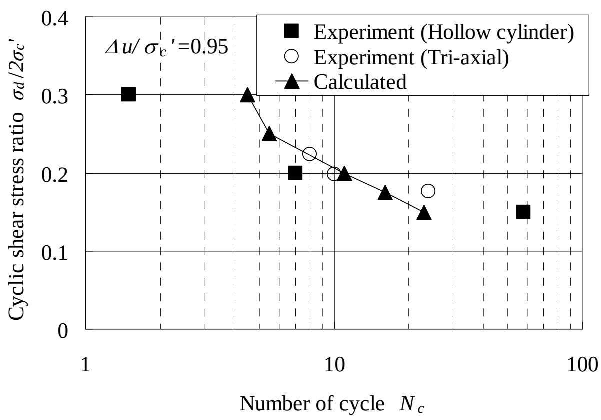


Fig.10 Result of the liquefaction test simulation

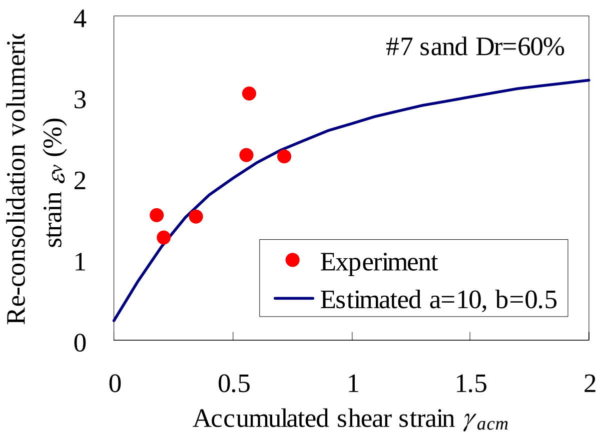


Fig. 11 Relations between the re-consolidation volumetric strain after the liquefaction and the accumulated shear strain during cyclic shear

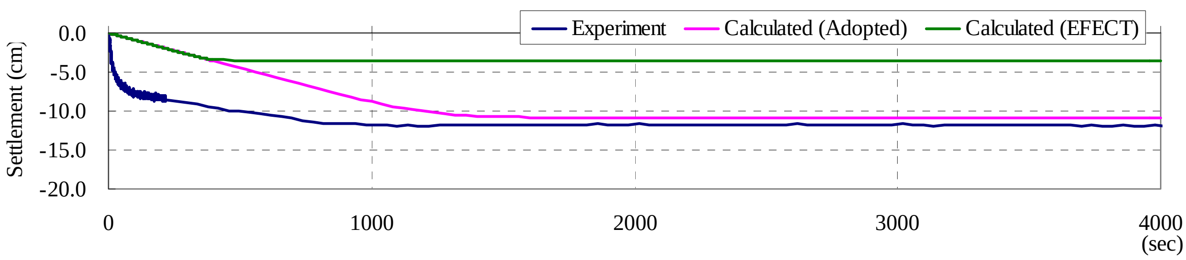
Calculated final settlements of the ground surface are summarized in Table 5. Settlements calculated by the adopted model became larger than that of calculated by the original model. Settlements calculated at L1 event (Case 2 and Case 4; Maximum acceleration is smaller than 2m/s^2) become close to that observed at experiments. Comparison of these cases, settlement calculated at Akita motion, which has longer duration, is larger than that of observed at Port Island motion, which shows larger peak acceleration. In Case1 and Case 3, at which L2 motion were used, settlement become larger than L1 event and original EFECT model, but still smaller than that of observed at experiments. Because of the re-consolidation characteristics of sand is derived from the sand specimen with Dr=60%, which is denser than the model ground, these results may be affected.

Fig. 12 show comparisons of observed and calculated ground surface settlement time histories at Case2 and Case 4. Periods of settlement duration are about 1,000s in both observed settlement and calculated settlement by the adopted model in Case 2, in spite that of the original model is about 300s. Duration get longer in Case 4 than that of Case 2, moreover, due to the input motion characteristics. Although settlements rapidly increased at the beginning of the observed time histories, which correspond to the duration of shake events, shape of the post-liquefaction settlement increment relate with re-consolidation is mostly reproduced by the analysis adopted a new re-consolidation model.

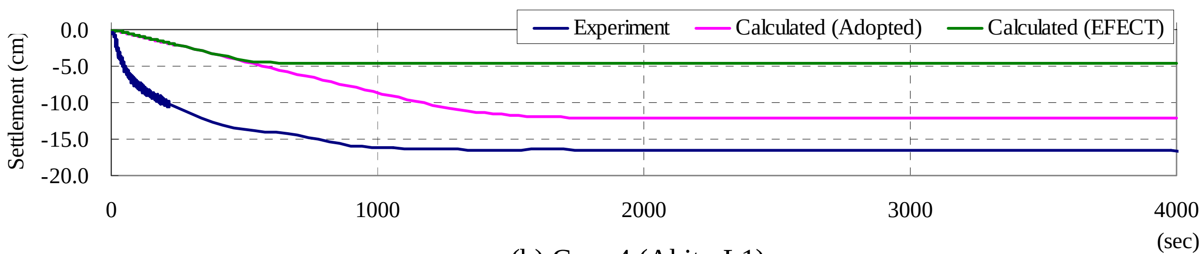
Fig. 13 show comparisons of observed and calculated PPR time histories in Case 2. Due to the estimated volumetric strain became larger induced by the adopted model, the period of duration of excess pore water pressure dissipation became longer than the original model. In addition, it is seen that the duration became longer than that of observed in the experiment. Further discussion is necessary on this point in terms of the permeability characteristics of the soil during liquefaction (Kazama 2003).

Table 5 Ground surface settlement

Case		1(PI-L2)	2(PI-L1)	3(Akita-L2)	4(Akita-L1)
Input motion		Port Island		Akita	
Max. Acceleration (cm/s^2)		485	200	311	160
Calculated settlement (cm)	Adopted model	16.9	10.8	14.6	12.1
	EFECT (original)	4.7	3.6	4.5	4.6
Observed settlement (cm)		29	12	32	17



(a) Case 2 (PI-L1)



(b) Case 4 (Akita-L1)

Fig. 12 Comparisons of ground surface settlement time histories

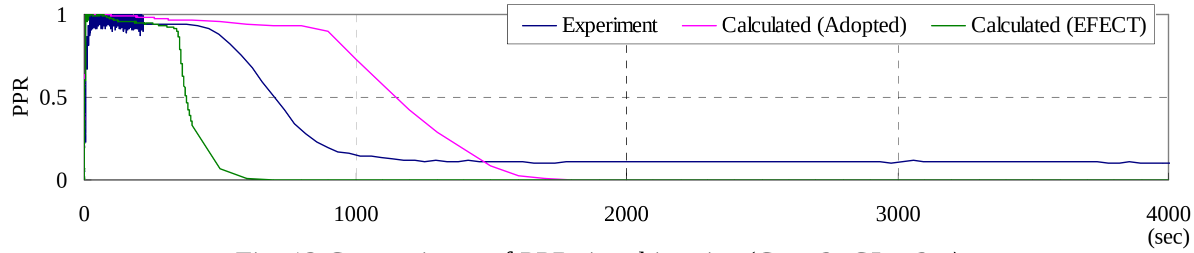


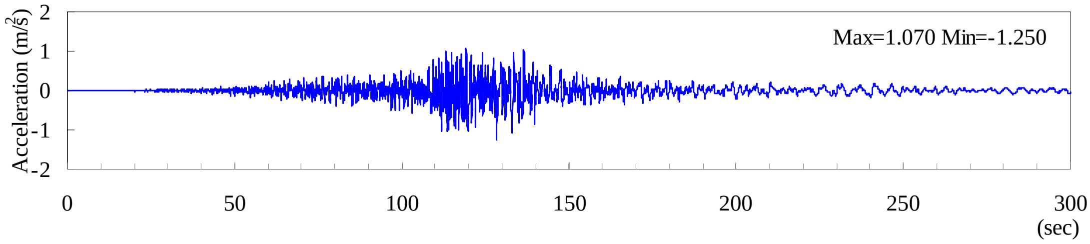
Fig. 13 Comparisons of PPR time histories (Case 2: GL=-2m)

SIMULATION OF THE GROUND SETTLEMENT DURING THE GREAT EAST JAPAN EARTHQUAKE

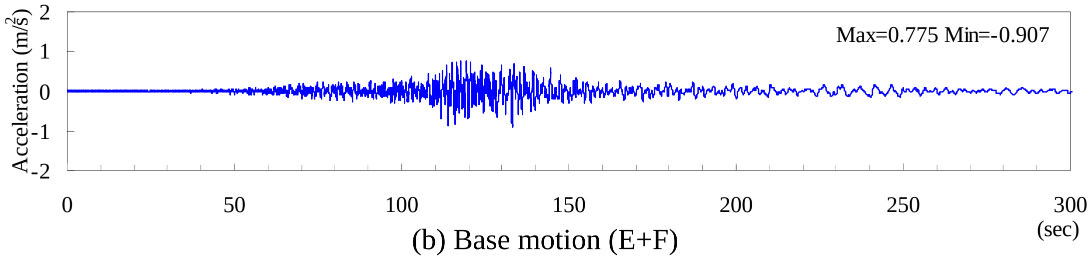
Procedures

Numerical model and procedures used here are same as same as previous chapter. Model ground was assumed as 15m deep soft sandy deposit, referred to the ground condition at Urayasu area (JGS 2011b). Soil parameters previously shown in Table 4 were used.

Earthquake motion recorded at Urayasu (CHB008NS, NIED 2011a) was chosen as the input motion for this simulation. Because Urayasu motion was recorded at the ground surface, base motion defined at the top of the silt layer underneath surface sand deposit was calculated by SHAKE. Both surface and base motions are shown in Fig. 14. Port Island motion is used, in addition, for comparison. Maximum acceleration amplitude of PI motion was set as same as Urayasu motion (about $1m/s^2$) in Case A and about $4.5m/s^2$,which is equivalent to the L2 motion, in Case B.



(a) Surface motion (Recorded motion)



(b) Base motion (E+F)

Fig. 14 Urayasu motion (CHB008NS)

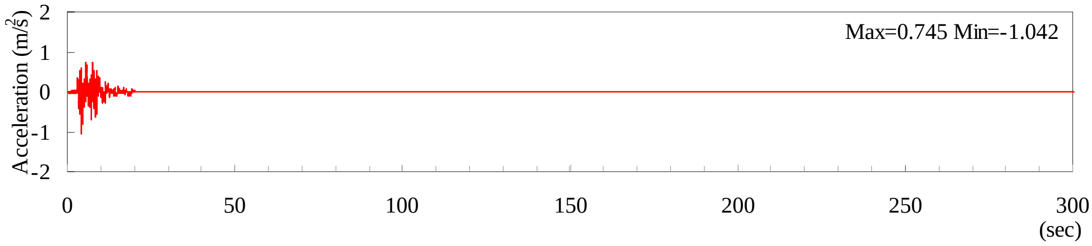


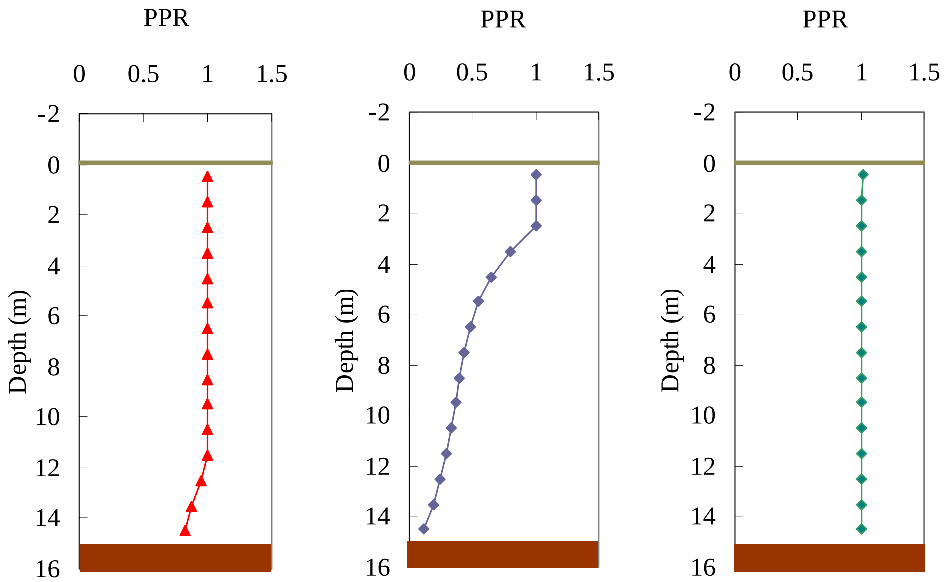
Fig. 15 Port Island motion (Base, E+F, Case A)

Results

Maximum excess pore pressure water ratio (PPR) distributions throughout the sand deposit are shown in Fig. 16. PPR of 1.0 are seen most part of the sand deposit in Urayasu case and Case B, at which L2 motion is applied. This suggests that Urayasu motion, with which the maximum acceleration is only 1m/s^2, affected to liquefaction as severe as the L2 motion. In Case A, on the other hand, only shallow part of the ground got liquefied.

Fig. 17 shows calculated time histories of the ground surface settlement. Final settlement observed in Urayasu case is 0.21m, which is the largest among these cases. Although the liquefied extent is same as Urayasu case, final settlement observed in Case B is smaller, about 0.13m. Therefore, it is concluded that effect of the duration of the earthquake event can be simulated reasonably by adopting the volumetric strain model considering the experienced shear strain during the earthquake event. Settlement observed in Case A is much smaller, about 0.02m, because of the limited liquefaction generation.

Fig. 18 shows time history of the PPR calculated in Urayasu case. It is seen that period of duration to dissipate the excess pore water pressure is more than 3,000s (45 minutes). It is pointed out that settlement became larger in Urayasu area due to the aftershock (M_w=7.7) happened about 29 minutes after the main shock (Fukutake 2011), because of the residual excess pore water pressure in the ground. Therefore, PPR characteristics shown in Fig. 18 follow that observation.



(a) Urayasu (PA=1m/s^2) (b) Case A (PI:PA=1m/s^2) (c) Case B (PI:4.5m/s^2)

Fig. 16 Comparison of PPR distribution throughout sand deposit

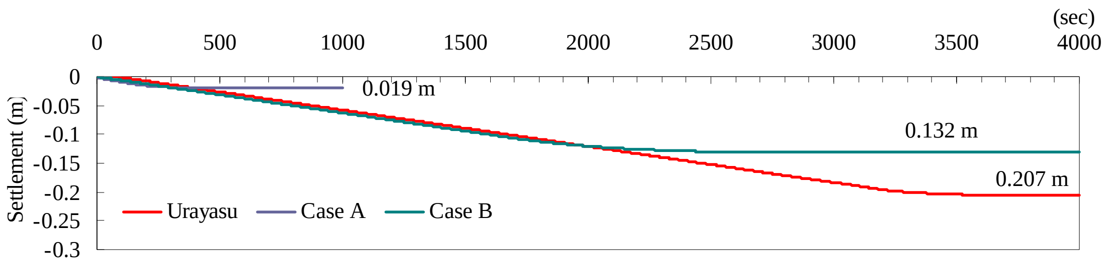


Fig. 17 Comparison of the ground surface settlement time histories

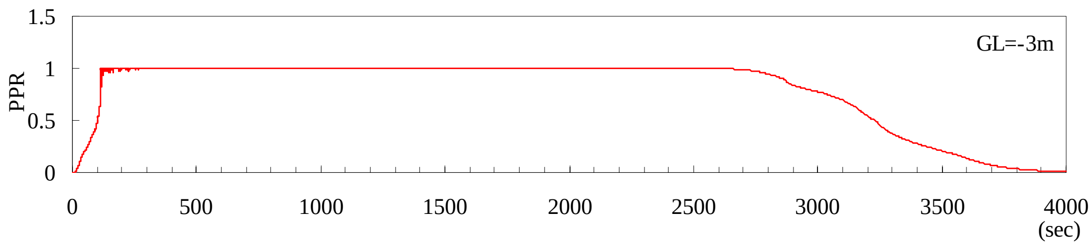


Fig. 18 PPR time history in Urayasu case (GL=-3m)

CONCLUSIONS

Followings are concluded from this research.

(a) By conducting the centrifuge experiments, it is found that the settlement characteristics of the ground surface due to liquefaction heavily affected by the duration of the earthquake motion, as well as the maximum acceleration. It is suggested that even if smaller maximum acceleration is expected, larger settlement may occur in case of the longer duration earthquake.
(b) By adopting the new volumetric strain estimation model into the effective stress program, predicted settlement characteristics is improved. Because the experienced shear strain during the earthquake is used as the index for the post-liquefaction volumetric strain estimation, dependency of the settlement in terms of the duration of the earthquake can be simulated reasonably. By comparing the estimated settlement by the simulation and the observed settlement in the centrifuge experiments, applicability of the model is confirmed.
(c) By utilizing the improved program, settlement characteristics of the liquefied ground around the Tokyo bay area during the Great East Japan Earthquake is estimated. It is found that the earthquake motion attacked Urayasu, even though its maximum acceleration is $1m/s^2$, show potential to give severe damage on the soft sandy reclaimed ground, as strong as L2 motion, because of the long duration.

ACKNOWLEDGMENTS

Earthquake record, observed at the Great East Japan Earthquake, utilized for the effective stress analyses is derived from k-net/NIED.

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(2011.12.02 Submitted)
(2012.xx.xx Accepted)