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EARTHQUAKE BEHAVIOR OF THE SURFACE LAYER AT TOKYO BAY AREA DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE USING THE DOWNHOLE ARRAY OBSERVATION RECORDS

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ABSTRACT: Underground motions within a hard diluvial stratum were obtained in the March 11th the 2011 off the pacific coast of Tohoku earthquake at a downhole in the Tokyo Bay area, which has suffered serious sand-liquefaction over its long $42km^2$ stretch. It is one of the sites of the seismic network carried out along the subway of the Tokyo Bay area since 1976. The seismometers comprised of the accelerometer of 3 components were installed in 3 depths. The seismometer of the deepest depth was installed in the diluvial sand deposit equivalent to the base layer. The motions in the diluvial sand deposit are characterized by their (1) long duration times with 6 to 8s components surpassing others, (2) moderate amplitude of $51.1cm/s^2$ in PGA, which is estimated to have resulted in moderate average strains of 8 to 9 $\times 10^{-4}$ and 5 to 7 $\times 10^{-4}$ over shallow -2 to -30m and deep -30 to -77m soil deposits, respectively. The peak strain reached in the interior of soil was estimated to be about 2×10^{-3}.

Key Words: Downhole array observation, Tokyo bay area, Non-linear, ground motion, the 2011 off the pacific coast of Tohoku earthquake

INTRODUCTION

On 11th March 2011, the 2011 off the pacific coast of Tohoku earthquake (hereafter Great East Japan Earthquake) was happened in the subduction zone of the Pacific offing of the Tohoku region, Japan. The area of the source area is regarded as around 500km × 200km or more over. The characteristic ground motion that has a long duration time due to large source area was observed at many sites around Japan including near source area (Furumura et al. 2011 and Kamae and Kawabe 2011).

The characteristic ground motion was also observed in Tokyo which is a little far from source area. Maximum seismic intensity of 5+ was observed many places in Tokyo (JMA 2011). This is the second earthquake that seismic intensity 5+ was observed in Tokyo except the island after 1926. The house damage in Tokyo was serious, such as 13 complete destruction, half destruction 190 and partially destruction 4,016 (FDMA 2011). And a lot of liquefaction occurred in the reclaimed land along the Tokyo bay and caused heavy damage to embedded lifelines and dwelling houses. These damages are regarded as the typical damage of urban area in our country where an urban area developed on the soft ground such as the alluvion ground. It is important to clarify ground behavior and nonlinear characteristic at Tokyo bay area during the Great East Japan Earthquake for the earthquake disaster mitigation of the urban area in Japan against future earthquake.

Konagai Laboratory, IIS, the University of Tokyo has performed downhole array observation in 2 sites on the reclaimed land in Tokyo bay area. In the Shinkiba site, seismometers were installed in the 3 depths including an engineering base. Furthermore, soil investigation was carried out at this site, and soil properties including non-linear property become clear. Fig.1 shows location of Shinkiba site with other observation sites (K-NET of the National Research Institute for Earth Science and Disaster Prevention and Bureau of Port and Harbor, Tokyo Metropolitan Government).

In this paper, firstly we introduce a summary of the Shinkiba downhole array observation including an observation system and soil profile. Next, we report earthquake behavior of the surface layer at Tokyo bay area during earthquake from observation records and earthquake response analysis.

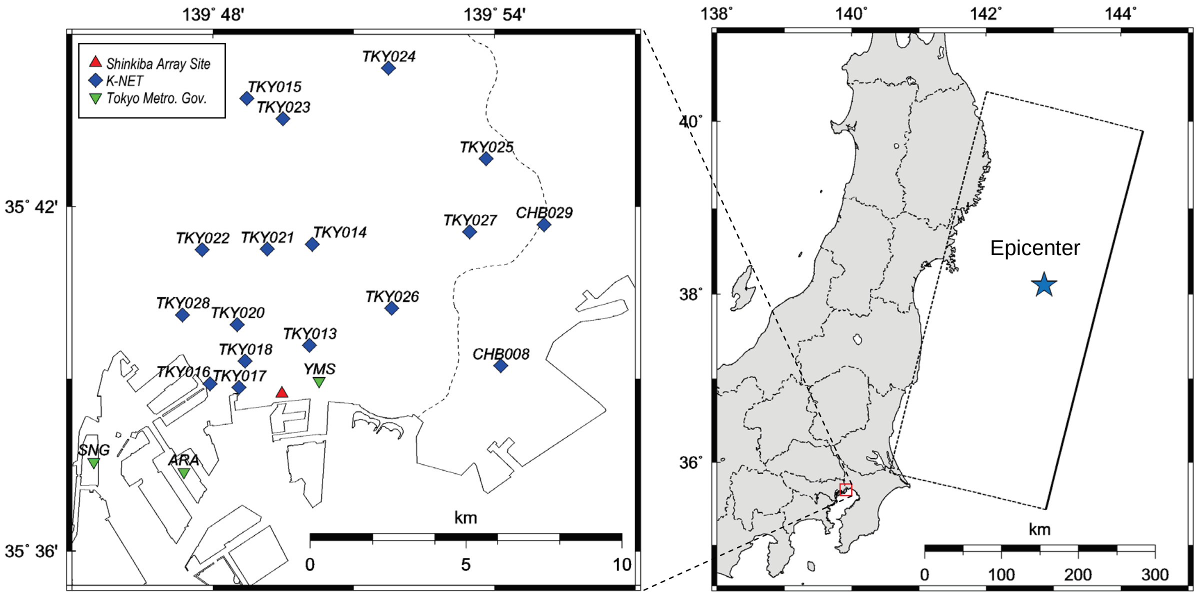


Fig. 1 Location of seismic observation sites in Tokyo bay area.
A red filled triangle indicate Shinkiba site.

SHINKIBA DOWNHOLE ARRAY OBSERVATION

The Shinkiba site is one of the seismometry sites carried out along the subway of the Tokyo bay area since 1976. Fig.1 shows location of Shinkiba site. The ground around the Shinkiba site was filled up with the dredging sand from 1961 to 1970 (Endoh 2004 and Tokyo Geotechnical Construction Association 2004).

Fig.2 shows soil profile based on boring investigation. Soil deposits of G.L. to G.L.-7m is reclaimed soil, therefore the depth of the sea bottom before reclamation is considered as G.L.-7m. G.L.-7m to -37.2m is Yurakucho layer of alluvium stratum. The layer deeper than G.L.-37.2m is diluvium stratum. G.L.-37.2m to -56.0m is No.7 layer. Lower No.7 layer at G.L.-53.5m to -56.0m is a humus silt layer, but the SPT-N value is relatively high (SPT-N value ≈ 30). Because the upper part of To layer is composed of sand deposit, an SPT-N value is high. The Ed layer is hard gravel deposit, and the SPT-N value over 50. Therefore, Ed layer is regarded as the engineering base layer. Fig.3 shows geological cross-section at Tokyo bay area around Shinkiba site.

The Great East Japan Earthquake has caused sand-liquefaction over a long streach of reclaimed lands along the coast of Tokyo bay. According to the survey by Konagai Laboratory, intense liquefaction was found around Shinkiba station of Tokyo Metropolitan subway that is 350m away from Shinkiba site, but was not found Shinkiba site (Konagai et al. 2011). Fig.4 shows liquefaction findings around Shinkiba site by MLIT and JGS (Kanto Regional Bureau, MLIT and JGS 2011). In these findings, the liquefaction is not found around Sinkiba site. We can understand that a liquefaction area and a non-liquefaction area are separated with clarity in this area. The cause is regarded as the difference of the material for reclamation, detailed study and survey will be necessary in future.

The SA-355CT (Type A) of Tokyo Sokushin Co., Ltd, is used for the seismometer of Shinkiba downhole array observation, it is installed in three depth of G.L.-2m (surface layer), G.L.-30m (middle layer) and G.L.-77m (base layer). Each seismometer also can observe 3 components acceleration at the same time. The seismometer is installed to agree with a magnet direction. However, seismometers of G.L.-30m and G.L.-77m have orientation error (Ikeda et al. 2011). Table 1 shows orientation error for the seismometer of G.L.-2m. There may be an orientation error in a seismometer of G.L.-2m, but does not correct it. Therefore, N-S component shows Y direction and E-W component shows X direction respectively.

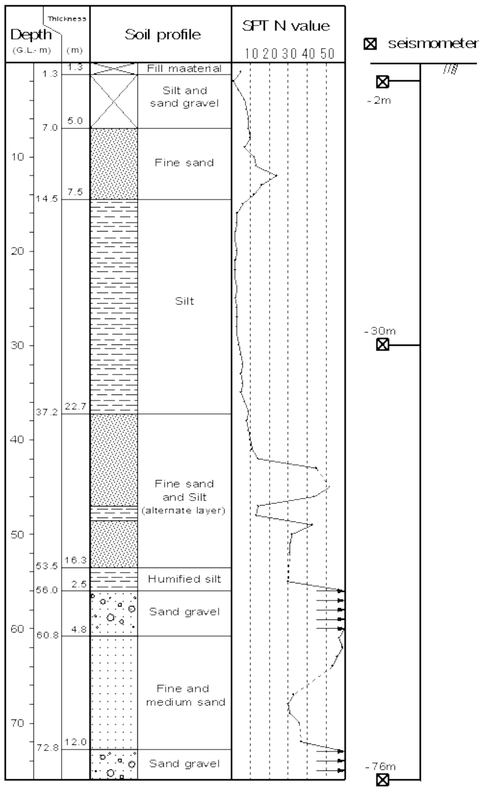
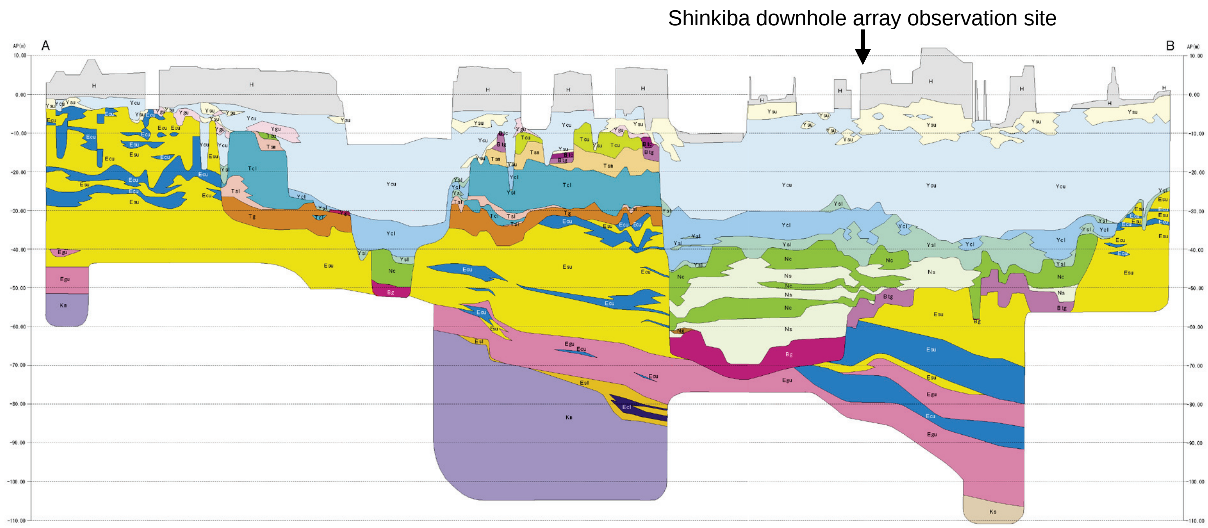


Fig. 2 Soil profile at Shinkiba site and installation depth of the seismometers.

Table 1 Orientation error of seismometer for the G.L.-2m

Depth	Orientation error
G.L.-30m	2
G.L.-77m	31

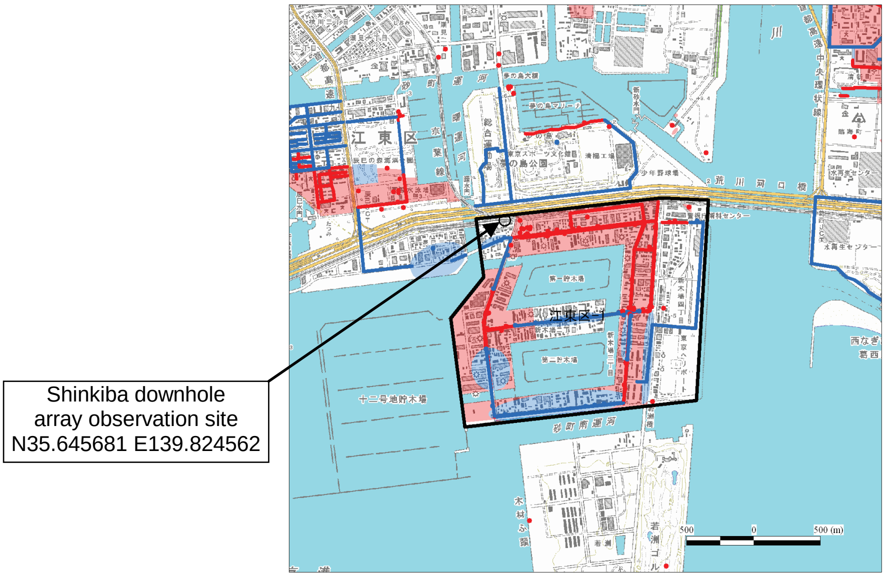
Sing of orientation error: + Counter clockwise direction
- Clock wise direction



Holocene
- Reclaimed layer
- Yuraku cho Layer(Sandy)
- Yuraku cho Layer(Cohesive)
- Yuraku cho Layer(Sandy)
- Yuraku cho Layer(Cohesive)

Pleistocene
- No.7 Layer(Sandy)
- No.7 Layer(Cohesive)
- Buried terrace sediment(Sandy gravel))
- Edo gawa layer(Sandy)
- Edo gawa layer(Cohesive)
- Edo gawa layer(Sandy gravel)

Fig. 3 Geological cross-section around downhole array observation site



- Sand boiling or Water gushes out were observed
- Sand boiling or Water gushes out were not observed
- Liquefaction area
- Non-Liquefaction area

Fig. 4 Liquefaction investigation results around Shinkiba downhole array observation site after the 2011 off pacific of Tohoku earthquake (Revised Kanto regional bureau, MLIT and JGS 2011)

OBSERVATION RECORDS AT THE SHINKIBA SITE DURING THE GREAT EAST JAPAN EARTHQUAKE

Fig.5 shows the waveforms of horizontal ground motions recorded at Shinkiba site during the Great East Japan earthquake. The origin of X-axis is 14:47:03 on March 11th, 2011 (JST). The velocity data and the displacement data were calculated from the acceleration data with bandpass-filtered (0.1-10.0Hz) by Fourier integration method. The acceleration amplitude becomes large at around 60 seconds and relatively-large amplitude continues until 140 seconds. The maximum amplitude occurs from 120 to 130 seconds. On the other hand, the displacement waveform shows different form from the acceleration waveform. The large amplitude of the displacement waveform continues until about 340 seconds.

Table 2 shows maximum amplitude of the observation records. The vertical component of G.L.-30m hasn't recorded for the instrumental trouble. PGA of each seismometers are 126.8cm/s^2 of G.L.-2m, 96.9cm/s^2 of G.L.-30m and 51.1cm/s^2 of G.L.-77m respectively. By amplification properties of the surface layer, PGA of shallow depth is bigger than deep depth. On the other hand, PGD of each seismometers are 10.6cm of G.L.-2m, 11.2cm of G.L.-30m and 9.7 of G.L.-77m respectively. PGD has an almost same value at three depths.

Fig.6 shows pseudo velocity response spectra (PVRS) of horizontal direction with damping factor of 0.05. The predominance of the long period component from 6 to 8s is seen in a PVRS. It was known that a surface wave with long period component occurred in the Kanto plain by basin structure of the Kanto district. When the Niigataken Chuetsu-oki Earthquake in 2007 occurred, a long period ground motion with 7 seconds predominance was observed in Tokyo. Therefore it is thought that a surface wave was included in ground motion at Shinkiba site.

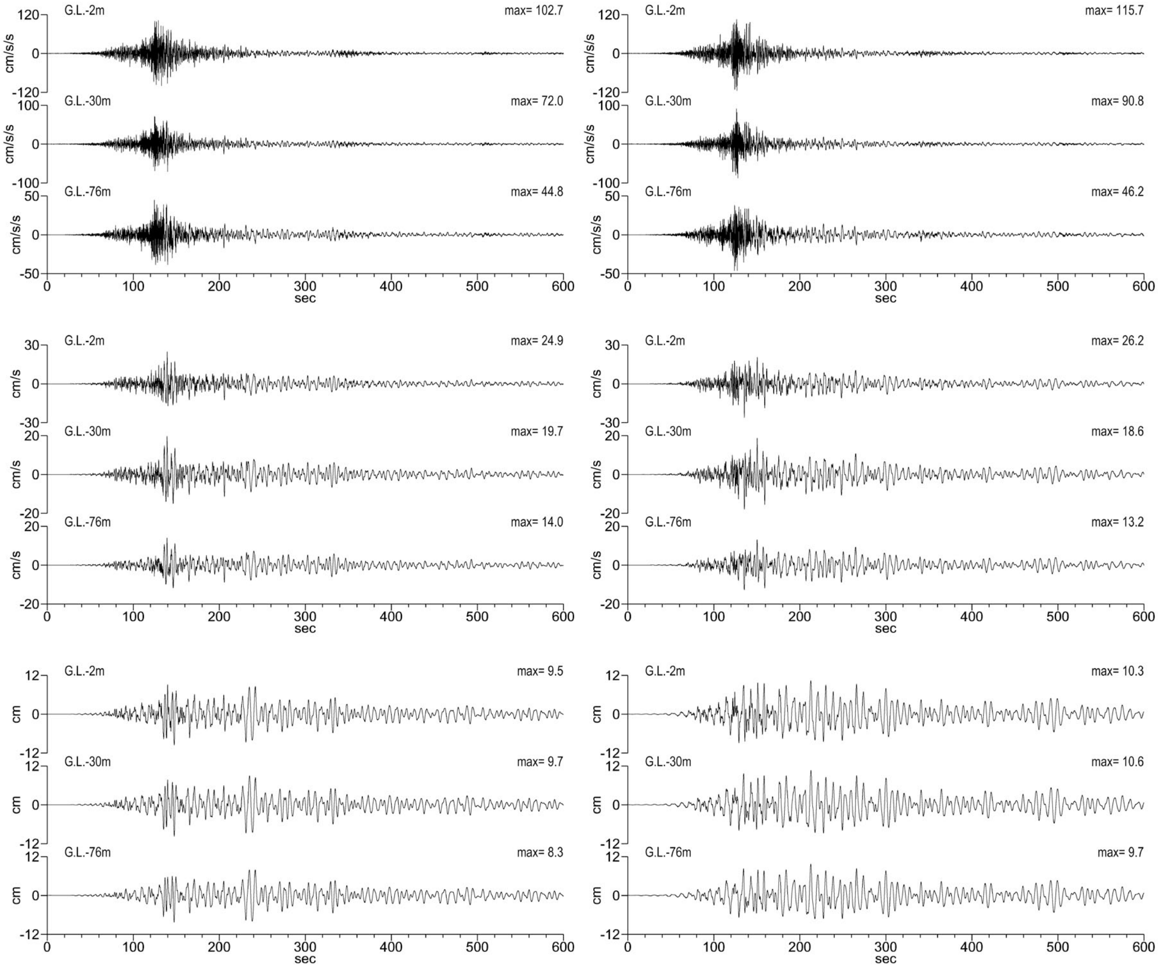
A broken line in Fig.6 is standard pseudo velocity response spectra (SPVRS) converted from standard acceleration response spectra of level 1 ground motion to use for collation of the earthquake-resistant performance of the land bridge (JRA 2002). The PVRS at G.L.-2m is at the same level as SPVRS.

Fig.7 shows transfer function of G.L.-2m for G.L.-77m. The transfer function means the Fourier spectrum ratio smoothed in Parzen window with bandwidth of 0.2Hz. The red line indicates the Great East Japan Earthquake and blue line indicate small earthquake (M3.8, 9th May 2010). PGA of G.L.-77m of the small earthquake is less than 2cm/s^2. The predominate frequency of the small earthquake and the Great East Japan Earthquake is 0.83Hz and 0.74Hz respectively. It is estimated that surface layer become nonlinearity during the Great East Japan Earthquake and shear stiffness decreased. Equation (1) is derived by 1/4 wavelength rule when we supposed that behavior of the surface layer controlled by a primary mode.

$$G^* = \frac{G_s}{G_w} = \left(\frac{f_s}{f_w}\right)^2 \tag{1}$$

Where, G^* is decreasing rate of shear stiffness, *Gs* and *Gw* are shear stiffness at strong event and weak event, *fs* and *fw* are predominate frequency at strong event and weak event. The decreasing rate of shear stiffness is estimated 0.8 by equation (1).

Similarly, we estimate maximum shear strain of the surface layer using maximum relative displacement and distance between the seismometer of the top and bottom. Table 3 shows maximum relative displacement and maximum shear strain. The maximum shear strains are less than 10^{-3}. Therefore it is thought that the nonlinearity which occurred on the ground of the Shinkiba site during the Great East Japan Earthquake was not so large.



(a)Y direction (b)X direction

Fig.5 Waveform of observation record at Shinkiba site from main event

Table 2 Maximum amplitude of observation record at Shinkiba site during the Great East Japan earthquake

Depth	PGA(cm/s^2)				PGV(cm/s)				PGD(cm)			
G.L.	X	Y	XY_{max}	Z	X	Y	XY_{max}	Z	X	Y	XY_{max}	Z
-2m	102.7	115.7	126.8	60.4	24.9	26.2	26.5	6.6	9.5	10.3	10.6	3.5
-30m	72.0	90.8	96.9	-	19.7	18.6	20.0	-	9.7	10.6	11.2	-
-77m	44.8	46.2	51.1	27.4	14.0	13.2	14.2	4.8	8.3	9.7	9.7	3.2

XY_{max}: $(X^2+Y^2)^{0.5}{}_{max}$

The UD record of G.L.-30m haven't recorded for the instrumental trouble

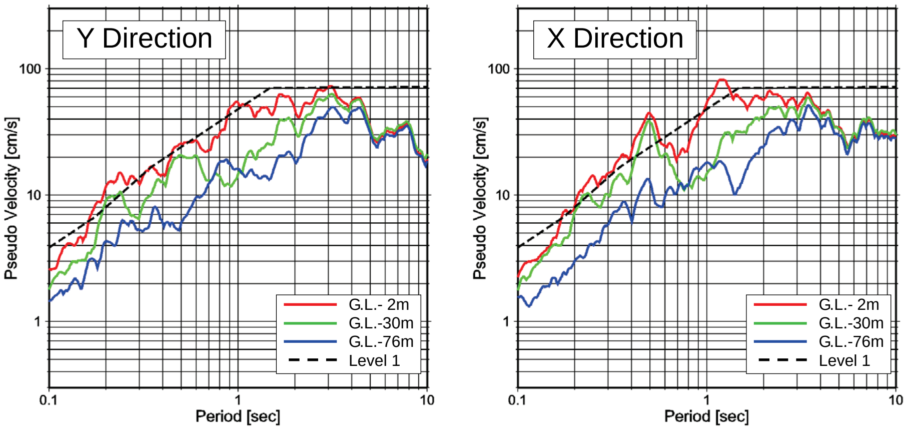


Fig.6 Pseudo velocity response spectra (PVRS) with damping ratio of 0.05 of ground motion recorded at Shinkiba site during the Great East Japan earthquake. The standard pseudo velocity spectra of Level 1 ground motion of Specifications for Highway Bridges (Japan Road Association 2002) is indicated in a broken line.

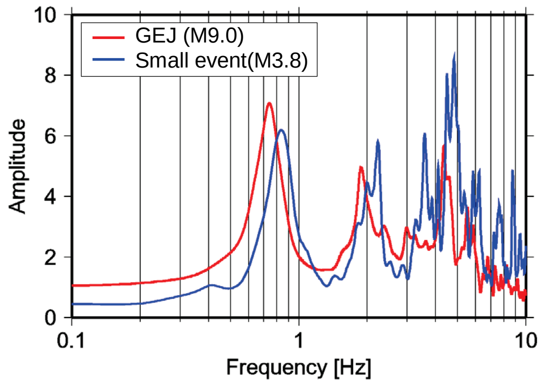


Fig.7 Comparison between the Great East Japan earthquake (M9.0) and small event(M3.8) transfer function

Table 3 The relative displacement calculated from observation record and maximum shear strain calculated from relative displacement

Depth of seismometer		Maximum relative displacement(cm)		Maximum shear strain	
upper	Bottom	Y-direction	X-direction	Y-direction	X-direction
G.L.-2m	G.L.-30m	2.30	2.49	8.2×10^{-4}	8.9×10^{-4}
G.L.-30m	G.L.-77m	2.25	3.05	4.9×10^{-4}	6.6×10^{-4}

EVALUATION OF THE EARTHQUAKE BEHAVIOR OF THE SURFACE LAYER BASED ON THE EARTHQUAKE RESPONSE ANALYSIS

Soil investigation including laboratory test using the sample taken from boring hole was carried out at the Shinkiba site, and data to set a parameter necessary for earthquake response analysis were provided. We attempted to estimate earthquake behavior of the surface layer from earthquake response analysis. The equivalent linear analysis (P. B. Schnabel et al. 1972) is selected for earthquake response analysis method because the level of maximum shear strain of surface layer is about 10^{-3} (Nishimoto and Ikeda 2011). Table 4 shows analysis model for equivalent linear analysis. The analysis model is comprised of 13 layers based on soil profile. Nonlinear property obtained laboratory test for the sample taken from 9 depths on the site. Fig.10 shows nonlinear property used in this study.

Fig.11 shows depth distribution of maximum acceleration, maximum velocity, maximum displacement, maximum shear strain and decreasing rate of shear stiffness (G/Go). G/Go is evaluated from the convergence value of the equivalent linear analysis. The black filled circle overwritten on a distribution is an observation result. The analysis results of maximum response can almost reproduce an observation results. The average maximum shear strain calculated from observation record is superimposed on the depth distribution.

The average shear strain of G.L.-2m to -30m and G.L.-30m to -77m calculated from earthquake response analysis are 6.6×10^{-4} and 4.8×10^{-4} respectively, these values are consistent with average shear strain calculated from observation record. The range of decreasing rate of shear stiffness is 0.71 to 0.91 and average is 0.83, this average value is in good agreement with estimation value from equation (1)

Fig.12 shows waveforms that superimposed an analysis on the observation. The PVRS with damping factor of 0.05 at G.L.-2m and G.L.-30m are shown in Fig.13. The analysis results can almost reproduce an observed one.

As a result of these considerations, it is thought that the earthquake behavior of the Shinkiba site during the East Japan earthquake can almost reproduce by earthquake response analysis using equivalent linear analysis. It is thought that the maximum shear strain is 1.3×10^{-3} and the surface layer didn't happen rapid nonlinear during the Great East Japan Earthquake. The maximum shear strain to occur in the sand layer where liquidizing is 5×10^{-4}. This result is consistent with the liquefaction investigation result that is not finding liquefaction around Shinkiba site.

Table 4 Model parameters for earthquake response analysis (equivalent linear analysis) at Shinkiba site

No.	Soil profile	Thickness (m)	Dense (t/m^3)	Vs (m/s)	G (kN/m^2)	Non-linearly
1	Fill	5.0	1.80	95	16245	Type1
2	Fill	7.5	1.85	125	28906	Type1
3	Fine sand	5.5	1.85	170	53465	Type2
4	Silt	10.0	1.70	155	40843	Type3
5	Silt	9.0	1.55	140	30380	Type4
6	Silt	4.2	1.60	160	40960	Type4
7	Fine sand	3.8	1.85	235	102166	Type5
8	Fine sand	1.5	1.90	235	104928	Type5
9	Silt	7.5	1.70	290	142970	Type8
10	Fine sand	9.7	1.90	290	159790	Type6
11	Sand and gravel	7.1	1.95	400	312000	Type7
12	Sand	4.2	1.75	300	157500	Type8
13	Sand and gravel	5.0	2.00	400	320000	Linear
14	Base	-	2.00	400	320000	

Vs: Shear wave velocity, G: Shear stiffness

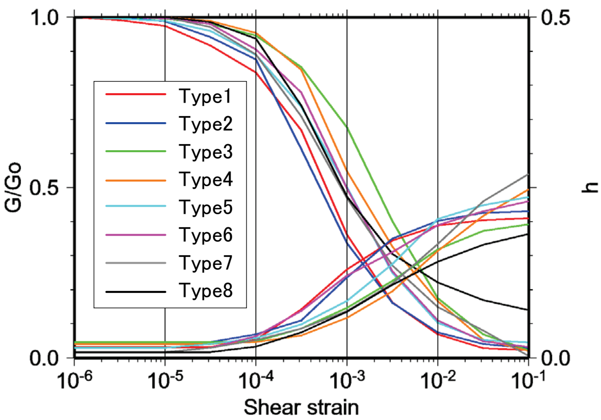


Fig.10 Nonlinear properties which are G/Go – γ and h -γ of each layers

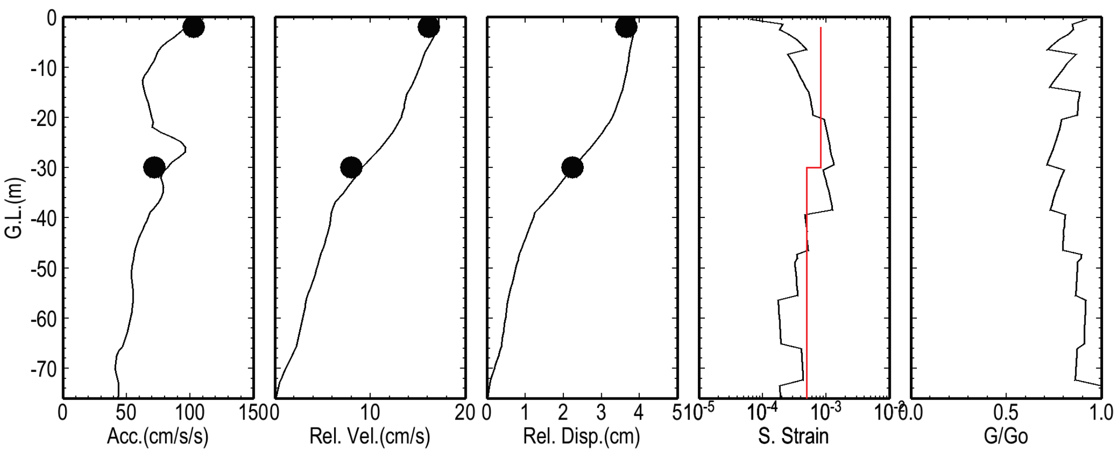


Fig.11 Depth distribution of maximum response calculated by earthquake response analysis.
A filled circle and red line had indicated observation results.

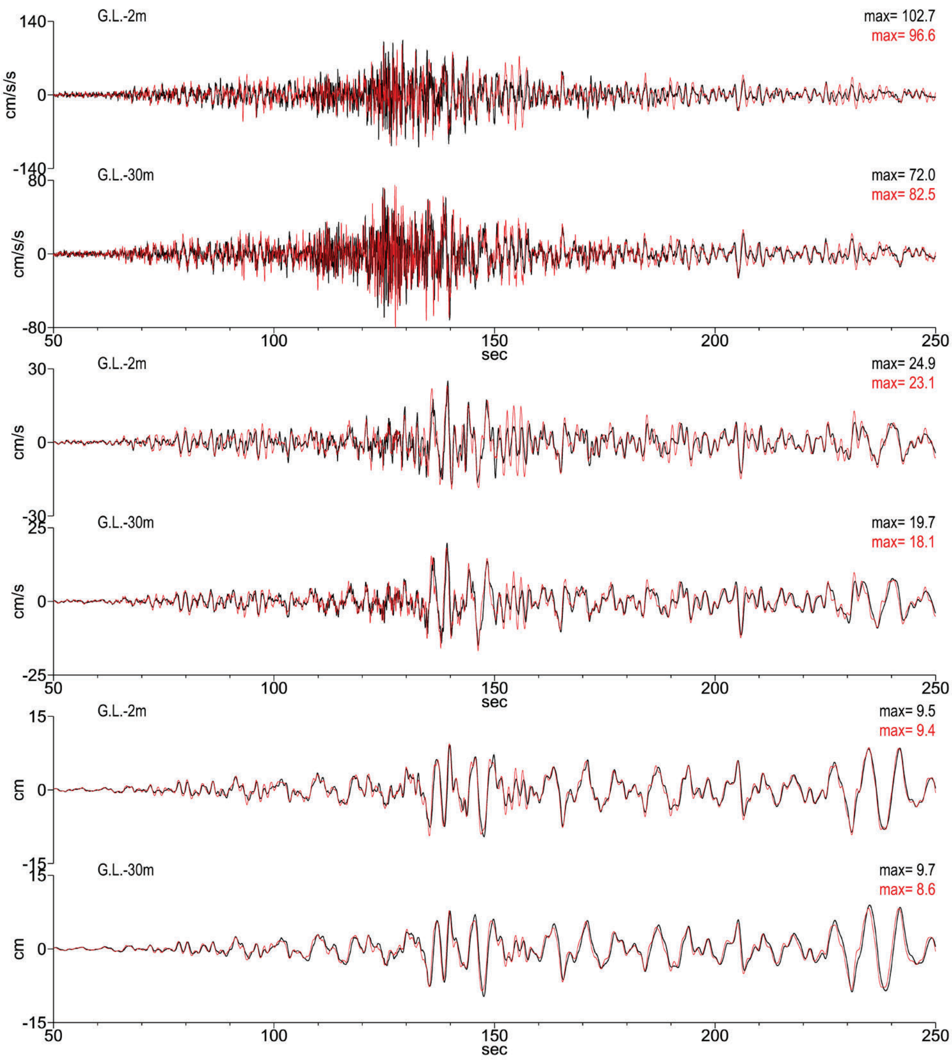
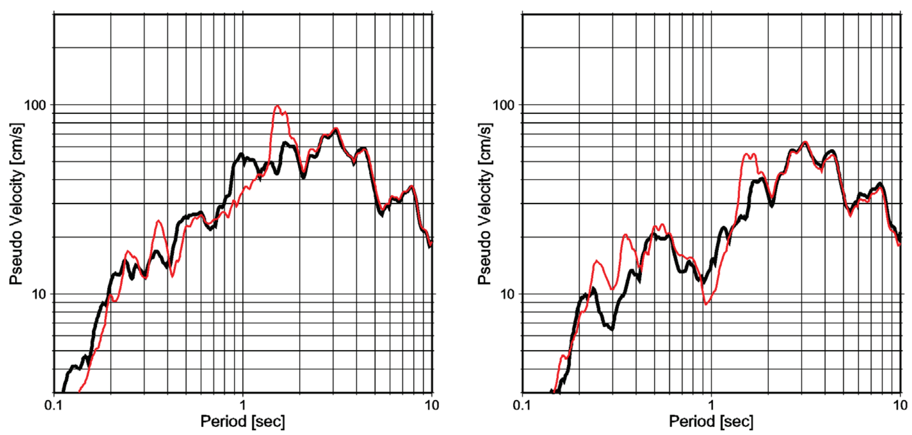


Fig. 12 Comparison of an observation waveform and an analysis waveform at G.L.-2m and G.L.-30m. A black line means observation and a red line means analysis.



(a) G.L.-2m (b) G.L.-30m

Fig.13 Comparison of the pseudo velocity response spectra (PVRS) with damping factor of 0.05 of the analyzed motion and observed motion at G.L.-2m and G.L.-30m. A black line means observation and a red line means analysis.

CONCLUSIONS

This paper evaluated the earthquake behavior of surface layer at Tokyo bay area during the Great East Japan Earthquake from downhole array observation records and earthquake response analysis using equivalent linear analysis. The results are as follows.

(1) Horizontal maximum acceleration is 126.8cm/s^2 of G.L.-2m, 96.9cm/s^2 of G.L.-30m and 51.1cm/s^2 of G.L.-77m.
(2) The pseudo velocity response spectra at G.L.-2m is at the same level as standard pseudo velocity response spectra of earthquake ground motion of level 1 to use for collation of the earthquake-resistant performance of the land bridge.
(3) The predominance of the long period components were seen in an observation record of the 3 depths. It was thought the influence of the surface wave caused by the basin structure in the Kanto district.
(4) Maximum shear strain during the Great East Japan Earthquake is estimated about 8 to 9×10^{-4} of G.L.-2m to -30m and 5 to 7×10^{-4} of G.L.-30m to G.L.-77m by observation records. Similarly, the decreasing ratio of shear stiffness is estimated to be around 0.8 times for initial value.
(5) Maximum shear strain of the surface layer estimated by earthquake response analysis is 1.3 $\times10^{-3}$.Therfore, It is thought that the surface layer didn't show the rapid nonlinearity during the Great East Japan Earthquake. This result is consistent with the liquefaction investigation result that is not finding liquefaction around Shinkiba site.

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