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CORRECTION OF ORIENTATION ERROR OF BOREHOLE STRONG MOTION ARRAY RECORDS OBTAINED DURING THE SOUTH HYOGO EARTHQUAKE OF JAN.17, 1995

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The orientation error of accelrographs in borehole array stations was discussed using the records obtained during the South Hyogo Earthquake of Jan.17, 1995. The four stations, three of them located on reclaimed land and the other on stiff ground, were selected. The displacement orbits on the horizontal plane were carefully examined, and significant orientation errors were detected. The significance of the correction of orientation error was discussed. The effective stress-based 2D and/or 3D liquefaction analyses were applied for one of the array stations. It was demonstrated that the method could reproduce the records well in the case that the orientation-corrected base motion was used as the input motion.

Key Words *: orientation error, array records, borehole observation system, displacement orbit, liquefaction analysis, ground motion amplification, the South Hyogo Earthquake of Jan.17, 1995*

1. INTRODUCTION

In the last two decades, a number of strong motion array observation systems have been implemented in Japan . There is no doubt that the ground motions obtained in array systems play essential roles in the development of earthquake engineering since it is possible: 1) to study the effect of the local soil conditions to the amplification characteristics of the surface layers by the vertical array systems; 2) to study the evolution and/or attenuation of the ground motion by the plane or 3D-array systems; and 3) to examine the capability and limitations of numerical simulation methods based on the observed records by array systems.

However, one of the authors have experienced that it is often the case that the orientation of buried seismographs are not necessarily correct as they are intended. For example, **Table 1** summarizes the orientation error noticed through the careful comparisons of displacement orbits of the ground motions on the NS-EW plane at various depths[1),2)]. **Photo 1** shows typical bore-hole type accelerograph with three component sensors (one for UD, and the others for two perpendicular horizontal directions). **Photo 2** shows aluminium rods used to install the accelerograph at specified depths and in specified directions.

It can be found from **Table 1** that the orientation error was detected at greater depths,

Table 1 Summary of buried direction errors of accelerographs.

accelerograph ID	depth GL.(m)	error* (deg.)	Reference
A-6	- 17	10	Ohishi(1984)
A-5	- 50	36	"
FGA3	- 1	- 17	Kamata(1987)
YGA1	- 48	30	"
MGA1	- 48	- 14	"
PI1	- 83	22	present study
TRC3	- 0	180**	present study
TRC1	- 97	46	present study
TPS2	- 25	- 20	present study
TPS1	- 100	16	present study
KPS3	- 0	180***	present study
KPS2	- 25	67	present study
KPS1	- 100	46	present study

notations
PI : Port Island Borehole Array Station, Dept. of Urban Development, Kobe City
TRC : Technical Research Center- Borehole Array Station, Kansai Electric Power Company
TPS : Takasago Power Station- Borehole Array Station, Kansai Electric Power Company
KPS : Kainan Port Sub-station- Borehole Array Station, Kansai Electric Power Company
* : positive number in counterclockwise direction
** : orientation error in NS component only
*** : orientation error in EW component only

Photo 1 Typical Borehole Type Accelerograph with 3-component Sensors (one for UD, and the others for two perpendicular horizontal directions).

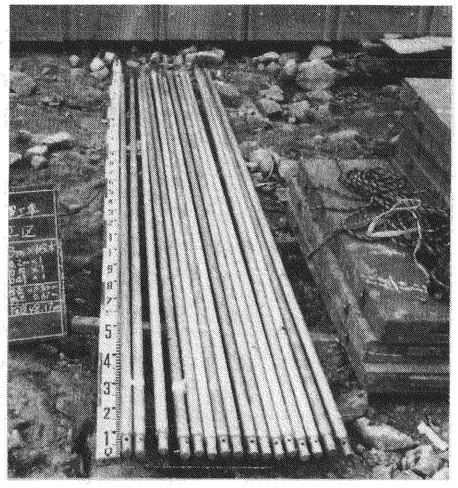


Photo 2 Aluminium Rods used to install the accelerograph at specified depths and in specified directions.

which suggests that the error might have been caused by the torsion of the rods used to install the accelerographs. Yamazaki, Lu, and Katayama[3] reported the significant orientation error of the seismographs in the Chiba dense array system, and proposed a method of the orientation error estimation for borehole array records. There is no doubt that the first task after obtaining records from any array system is to check the validity of the orientation of the seismographs.

The ground motion records during the South Hyogo Earthquake on January 17, 1995, which caused "The Great Hanshin-Awaji Earthquake Disaster," were obtained at a number of observation stations. They include the records from several borehole array stations. Preliminary reports regarding the nonlinear ground motion amplification based on the borehole array records has been published[4], however, the orientation error of the underground accelerographs has not been specified. The correction of the orientation error for the borehole records are of special importance, since 1) the error sometimes affects the frequency characteristics of amplification function obtained from original array records, and 2) the underground records might be used for various objectives, such as the input ground motion for the estimation of ground response in damaged areas.

In the present paper, attention is mainly paid to four sets of borehole array records obtained in the following locations:

1) northeast part of the Port Island, one of the reclaimed islands in Kobe City [PI]
2) Technical Research Center of Kansai Electric Power Company, in Amagasaki City [TRC]

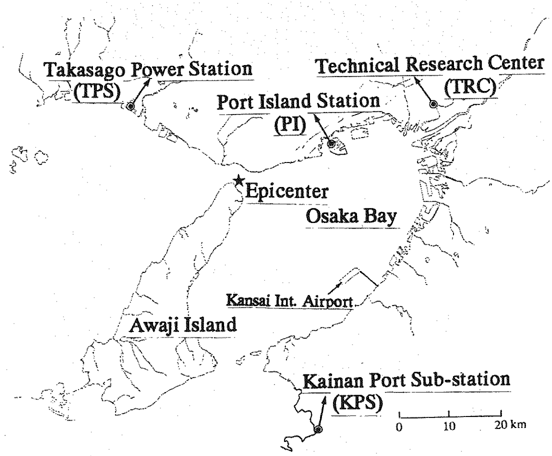


Fig.1 Location of Borehole Array Observation Stations.

Table 2 Soil Profile and System Layout for Port Island Borehole Array Station (Kobe City Development Bureau).

depth (m)	soil type	P-velocity (km/sec)	S-velocity (km/sec)	Poisson's ratio	location of seismometer
0 - 2.0	sandy gravel	0.26	0.170	0.127	◉ GL -0.0m
2.0 - 5.0	sandy gravel	0.33	0.170	0.319	
5.0 - 12.6	sandy gravel	0.78	0.210	0.461	
12.6 - 19.0	sand with gravel	1.48	0.210	0.490	◉ GL -16.0 m
19.0 - 27.0	alluvial clay	1.18	0.180	0.488	
27.0 - 33.0	alluvial sand	1.33	0.245	0.482	◉ GL -32.0 m
33.0 - 50.0	sand with gravel	1.53	0.305	0.479	
50.0 - 61.0	diluvial sand	1.61	0.350	0.475	
61.0 - 79.0	diluvial clay	1.61	0.303	0.482	
79.0 - 85.0	sand with gravel	2.00	0.320	0.487	◉ GL -83.0 m

3) Kainan Port sub-station of Kansai Electric Power Company, in Kainan City [KPS], and
4) Takasago Power station of Kansai Electric Power Company, in Takasago City [TPS]

The objective of the present paper is as follows; Firstly, to examine the orientation error of the accelerographs for these array stations, and to show the amplification characteristics of the sites based on the corrected records. Secondly, to examine the effect of correction of orientation error to the numerical ground response analysis[5], which deals with 2D/3D liquefaction simulation.

2.CORRECTION OF ORIENTATION ERROR OF BOREHOLE RECORDS

Herein, the four sets of borehole array records obtained during the South Hyogo Earthquake of Jan. 17, 1995 are examined. **Fig.1** shows the locations of these array stations. The epicentral distance for these stations are, Δ=21 km (PI), 43 km (TRC), 53 km (KPS), and 26 km (TPS).

The major points of correction of orientation error in this study are summarized as follows.

1) The displacement orbits on a horizontal plane obtained from the integration of the filtered accelerograms are used for the estimation of the orientation error. The frequency range of the filter with the flat-amplitude is fixed between 0.15 and 20.0 Hz. The advantage to use displacement orbits is that the predominant ground motion, which consists of relatively low frequency contents and are not affected by the local soil condition in between burried accelerographs, can be examined.
2) The orentation error is examined on the basis of the careful investigation by using the overlaied displacement orbits. The orientation error of the buried accelerographs are estimated on the assumption that the orientation of a accelerograph on the ground surface is correctly set. Namely, the relative inclination angle of predominant motion compared with the ground surface motion is examined.
3) The orientation error regarding the vertical direction is not dealt with in this study, since it is general that the burried accelerographs are fixed much more correctly in the vertical direction than in the horizontal direction[3].

(1) Port Island Borehole Array Records: Kobe City Development Bureau [PI]

The borehole array observation system installed in Port Island, Kobe City, recorded ground motions which included liquefaction phenomenon in the surface reclaimed layer. **Table 2** shows the layout of the array system as well as the soil profile at the station.

To examine the orientation error of the buried accelerographs, displacement orbits on the horizontal(NS-EW) plane at 4 depths during 10 to 20 seconds are prepared as shown in **Fig.2**. The time histories of the displacements were calculated from the acceleration records using FFT and a trapezoidal digital filter with a flat amplitude in the frequency range of 0.15 - 20.0 Hz. From the comparisons of the four figures (**Figs.2**(a) to (d)), it may be stated that the error of the buried direction of the accelerograph at GL.-83m exists in the range between 15 to 25 degrees counter-clockwise.

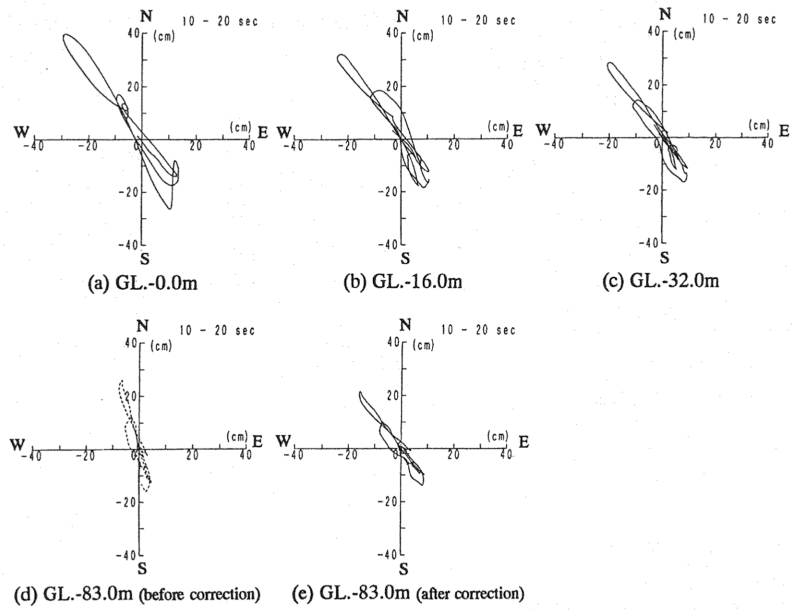


Fig.2 Displacement orbits at various depths (Port Island, Kobe City, 10-20 sec, 0.15-20.0 Hz).

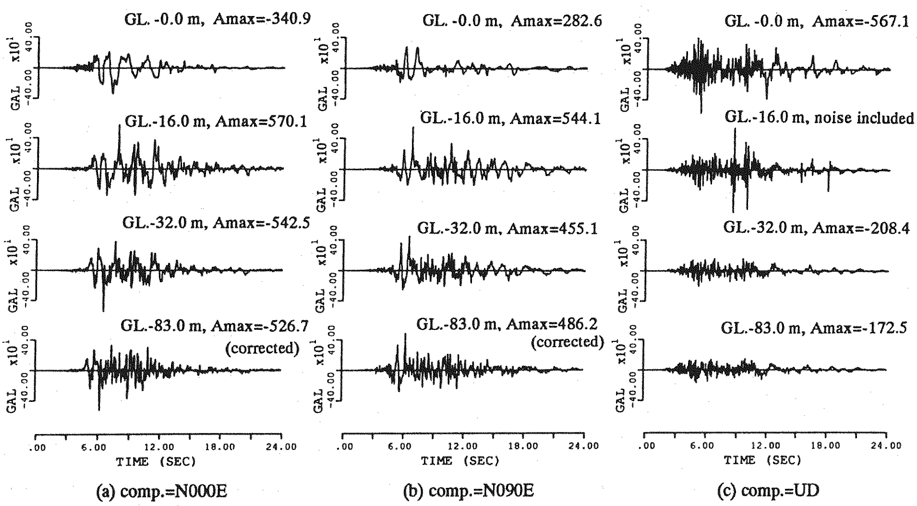


Fig.3 Acceleration Time Histories (Port Island, Kobe City Development Bureau).

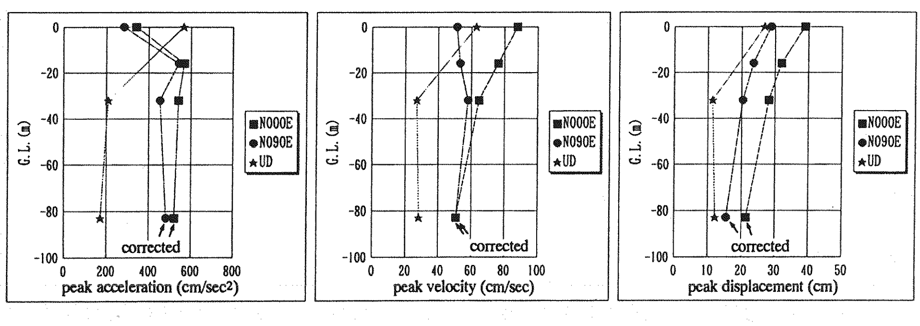


Fig.4 Distribution of Peak Ground Motions (Port Island, Kobe City Development Bureau)

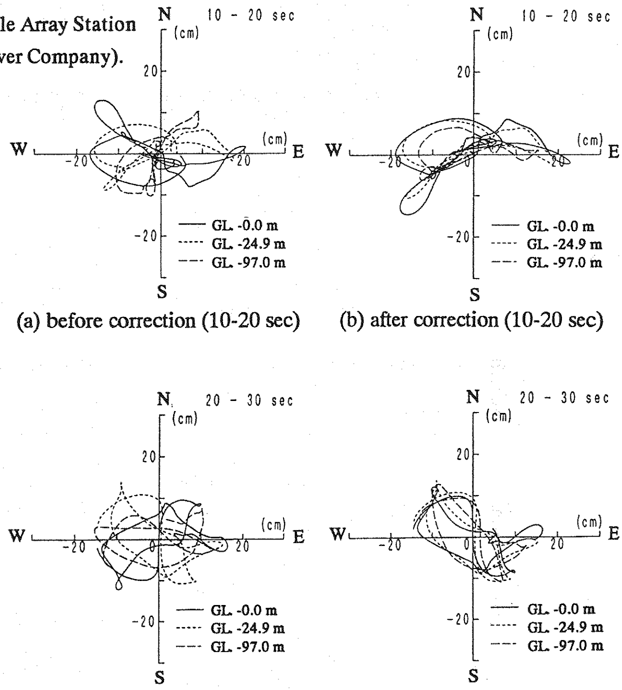
Table 3 Variation of Peak Ground Motions at Port Island Borehole Array Station (Kobe City Development Bureau).

	peak acc. (cm/sec)			peak vel. (cm/sec)			peak displ. (cm)		
	NS	EW	UD	NS	EW	UD	NS	EW	UD
GL. 0.0m	-340.9	282.6	-567.1	-88.8	-51.1	-62.8	39.7	-29.6	26.9
GL. -16.0m	570.1	544.1	547.5	-76.7	-53.3	-33.5	32.0	-24.1	-18.2
GL. -32.0m	-542.5	455.1	-208.4	-65.0	-58.2	-27.1	28.4	-20.8	11.5
GL. -83.0m	-670.5 -526.7★	-304.6 486.2★	-172.5	66.2 50.7★	-28.8 -51.1★	-28.4	25.9 21.6★	12.0 -16.0★	12.2

★peak value for orientation- corrected time histories

Table 4 Soil Profile and System Layout for TRC Borehole Array Station (Technical Research Center, Kansai Electric Power Company).

depth (m)	density (g/cm³)	P-velocity (km/sec)	S-velocity (km/sec)	Poisson's ratio	location of seismometer
0 - 2	1.4	0.42	0.098	0.471	◉ GL -0.0m
2 - 3	1.4	0.84	0.117	0.490	
3 - 5	1.7	0.84	0.117	0.490	
5 - 7	1.7	1.18	0.117	0.495	
7 - 8	1.7	1.39	0.149	0.494	
8 - 11	1.6	1.39	0.149	0.494	
11 - 12	2.0	1.39	0.342	0.468	
12 - 17	2.0	1.61	0.342	0.476	
17 - 18	2.0	1.61	0.222	0.490	
18 - 20	2.0	1.61	0.154	0.495	
20 - 21	2.0	1.61	0.400	0.467	
21 - 27	2.0	2.00	0.400	0.479	◉ GL -24.9m
27 - 30	2.0	1.90	0.400	0.477	
30 - 33	2.0	1.90	0.375	0.480	
33 - 39	1.7	1.90	0.375	0.480	
39 - 42	1.7	1.54	0.231	0.488	
42 - 45	2.0	1.54	0.286	0.482	
45 - 52	2.0	1.87	0.255	0.491	
52 - 54	2.0	1.39	0.222	0.487	
54 - 58	2.0	1.39	0.177	0.492	
58 - 60	2.0	1.39	0.222	0.487	
60 - 67	2.0	1.60	0.389	0.469	
67 - 74	2.0	1.60	0.333	0.477	
74 - 75	2.0	1.60	0.303	0.481	
75 - 94	2.0	1.44	0.303	0.477	
94 - 95	2.0	1.44	0.455	0.445	
95 - 100	2.0	2.17	0.455	0.477	◉ GL -97.0m



(a) before correction (10-20 sec) (b) after correction (10-20 sec)

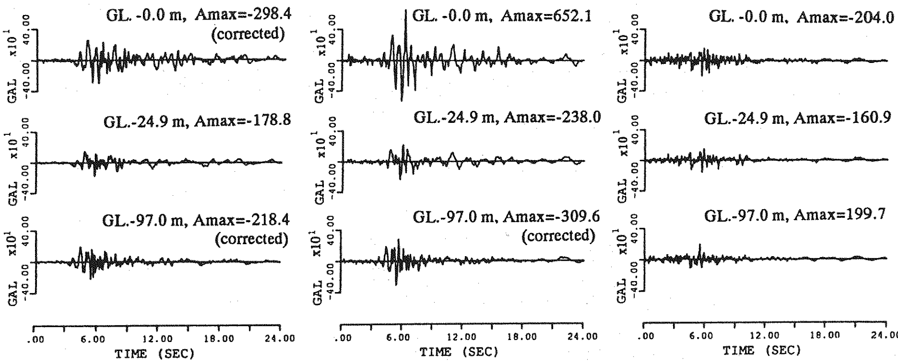
(c) before correction (20-30 sec) (d) after correction (20-30 sec)

Fig.5 Displacement Orbits (Technical Research Center, Kansai Electric Power Company).

From the careful investigation by using the overlaied displacement orbits, it was concluded that the accelerograph at GL. -83m was rotated about 22 degrees from the proposed orientation. This assumption was also confirmed through the comparisons of the displacement orbits in other time ranges. **Fig.2**(e) shows the displacement orbit based on the orientation- corrected time histories. Namely, the correction of the digital records can be performed by the rotation of the coordinates. To perform the operations mentioned in this paragraph efficiently, two sets of programs[6),7)] were used.

The peak accelerations of the original time histories are Amax= -670.5 cm/sec^2 (NS) and -304.6 cm/sec^2 (EW), and those of the orientation-corrected time histories are Amax= -526.7 (NS) and 486.2 (EW). **Fig.3** shows the acceleration time histories for each ground level including corrected time histories at GL.-83m. In **Fig.3** the drastic change in frequency content during the first S-wave phase, around 6 seconds on time axis, can be noticed. It is observed that the strong spikes are contained in the UD component at GL.-16m. Some electric noise occurred in the system could be one of the reasons for these strong spikes.

Fig.4 shows the amplification characteristics of peak acceleration, velocity, and displacement. In **Fig.4** the absolute peak values are given. These peak values are listed in **Table 3** with those for the original time histories at GL.-83.0m.



(a) comp.=N-S (b) comp.=E-W (c) comp.=U-D

Fig.6 Acceleration Time Histories (Technical Research Center, Kansai Electric Power Company).

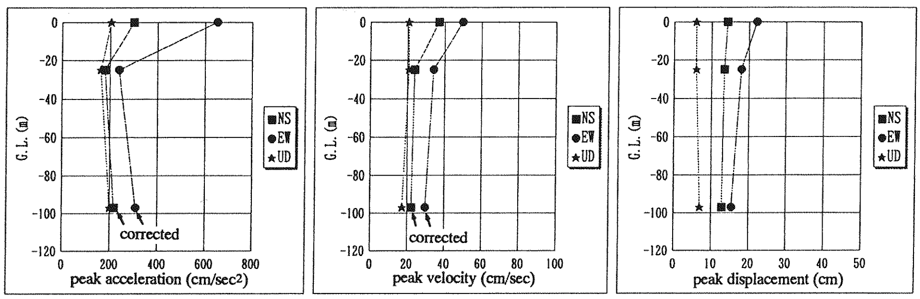


Fig.7 Distribution of Peak Ground Motions (Technical Research Center, Kansai Electric Power Company).

Table 5 Variation of Peak Ground Motions at TRC Borehole Array Station (Technical Research Center, Kansai Electric Power Company).

	peak acc. (cm/sec²)			peak vel. (cm/sec)			peak displ. (cm)		
	NS	EW	UD	NS	EW	UD	NS	EW	UD
GL. 0.0m	298.4 -298.4★	652.1	-204.0	-37.2	-49.4	20.8	14.5	22.8	-6.0
GL. -24.9m	-178.8	-238.0	-160.9	-24.3	34.5	21.0	13.8	18.8	-6.0
GL. -97.0m	-292.5 -218.4★	319.9 -309.6★	199.7	30.6 -22.5★	20.3 29.8★	17.6	-13.5 12.9★	-15.4 15.4★	-7.0

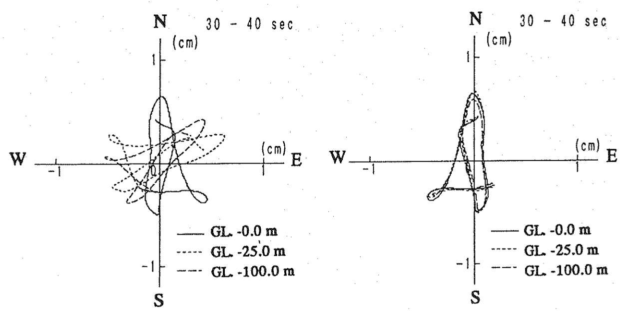
★peak value for orientation- corrected time histories

(2) Technical Research Center Borehole Array Records: Kansai Electric Power Company [TRC]

The borehole array station at Technical research center, Kansai Electric Power Company in Amagasaki City, obtained the records from the earthquake. **Table 4** shows the layout of the array system as well as the soil profils. Compared with the soil profile in **Table 2**, the ground condition of this station is found to be relatively stiff.

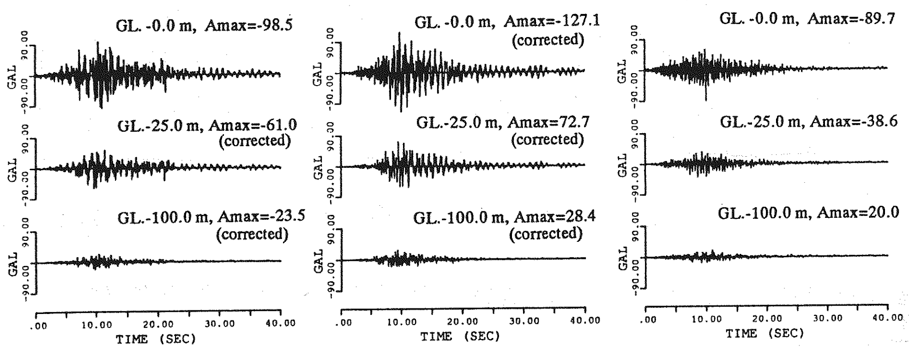
Figs.5(a) and (c) show the displacement orbits at 3 depths obtained from the original time histories: (a) during 10 to 20 seconds, and (c) during 20 to 30 seconds. From careful comparisons of the displacement orbits, the error of the buried direction was detected as listed in **Table 1**. **Figs.5**(b) and (d) show the displacement orbits obtained from the orientation-corrected time histories. It may be seen in **Figs.5**(b) and (d) that the orbits in the three depths show reasonable agreements.

Fig.6 shows the acceleration time histories for each ground level, including the corrected time histories at GL.-0.0m and -97.0m. **Fig.7** shows the amplification characteristics of peak acceleration, velocity, and displacement. These peak values are listed in **Table 5** with those for original records. Compared with the result in **Fig.4**, the



(a) before correction (30-40 sec) (b) after correction (30-40 sec)

Fig.8 Displacement Orbits (Kainan Port Sub-station, Kansai Electric Power Company).



(a) comp.=NS (b) comp.=EW (c) comp.=UD

Fig.9 Acceleration Time Histories (Kainan Port Sub-station, Kansai Electric Power Company).

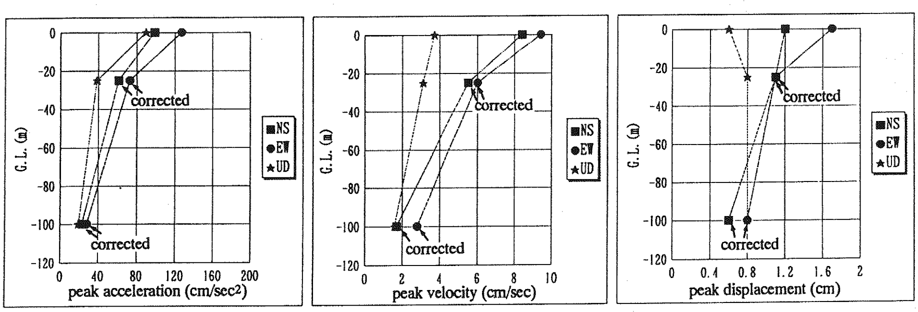


Fig.10 Distribution of Peak Ground Motions (Kainan Port Sub-station, Kansai Electric Power Company).

ground motion is strongly amplified at this station even in high frequency contents, which is mainly due to the stiff ground condition.

(3) Kainan Port Sub-station Borehole Array Records: Kansai Electric Power Company [KPS]

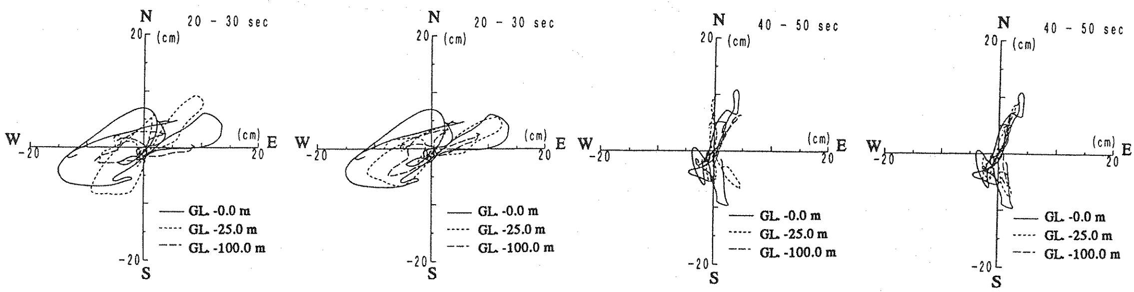
The borehole array station at Kainan Port, in Wakayama Prefecture, obtained the records from the earthquake. The formation of the observation system is nearly the same as that for TRC. The accelerographs are installed on the ground (reclaimed land), at GL.-25m (alluvial clay), and at GL.-100m (rock). **Figs.8**(a) and (b) show the displacement orbits at 3 depths during 30 to 40 seconds: (a) those from original time histories, and (b) those from orientation-corrected time histories. To detect the buried direction error clearly, a narrower digital filter with flat frequency range of 0.15 to 0.5 Hz was used. The orientation error was obtained as listed in **Table 1**.

Fig.9 shows the acceleration time histories for each ground level, including the corrected time histories. **Fig.10** shows the amplification characteristics of peak acceleration, velocity, and displacement. It is observed that the amplification characteristics is quite different between that for UD component and those for two horizontal

Table 6 Variation of Peak Ground Motions at KPS Borehole Array Station (Kainan Port Sub-station, Kansai Electric Power Company).

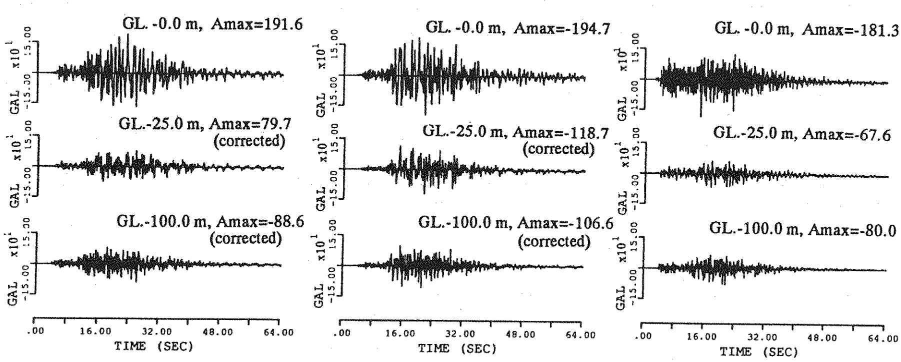
	peak acc. (cm/sec)			peak vel. (cm/sec)			peak displ. (cm)		
	NS	EW	UD	NS	EW	UD	NS	EW	UD
GL. 0.0m	-98.5	127.1 -127.1★	-89.7	8.4	-9.4 9.4★	3.7	-1.2	1.7 -1.7★	0.6
GL. -25.0m	-71.8 -61.0★	-59.5 72.7★	-38.6	5.8 -5.5★	-4.9 -6.0★	3.1	1.2 1.1★	1.0 -1.1★	0.8
GL. -100.0m	-26.1 23.5★	-24.9 28.4★	20.0	-2.9 -1.7★	1.8 2.8★	1.6	0.9 0.6★	0.6 -0.8★	0.8

★peak value for orientation- corrected time histories



(a) before correction (20-30 sec) (b) after correction (20-30 sec) (c) before correction (40-50 sec) (d) after correction (40-50 sec)

Fig.11 Displacement Orbits (Takasago Power Station, Kansai Electric Power Company).



(a) comp.=NS (b) comp.=EW (c) comp.=UD

Fig.12 Acceleration Time Histories (Takasago Power Station, Kansai Electric Power Company).

components. These peak values are listed in **Table 6** with those for original records.

(4) Takasago Power Station Borehole Array Records: Kansai Electric Power Company [TPS]

The borehole array system at Takasago power station, in Takasago City, obtained the records from the earthquake. The formation of the system is just the same as that at KPS. The accelerographs are installed at GL.-0.0m (reclaimed land), at GL.-25m (sandy gravel), and at GL. -100m (rock). **Figs.11**(a) and (c) show the displacement orbits at 3 depths obtained from the original time histories: (a) during 20 to 30 seconds, and (c) during 40 to 50 seconds.

The orientation error detected from the orbits are summarized in **Table 1**. **Figs.11**(b) and (d) show the displacement orbits obtained from the orientation-corrected time histories. **Fig.12** shows the acceleration time histories for each ground level, including the corrected time histories. **Fig.13** shows the amplification characteristics of peak ground motions. It is observed that the peak acceleration for UD component was significantly amplified, and this is quite the same result as shown in **Fig.10**. These

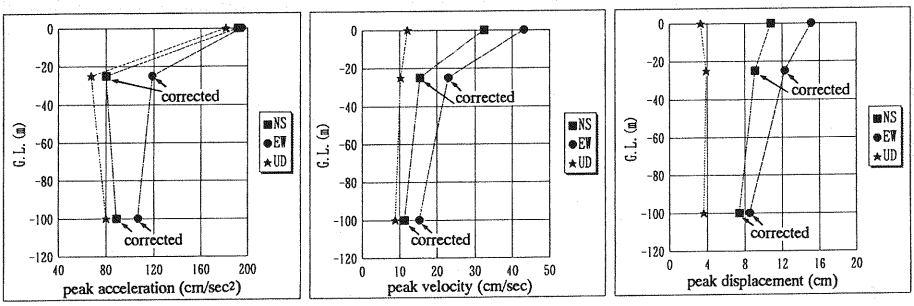


Fig.13 Distribution of Peak Ground Motions (Takasago Power Station, Kansai Electric Power Company).

Table 7 Variation of Peak Ground Motions at TPS Borehole Array Station (Takasago Power Station, Kansai Electric Power Company).

	peak acc. (cm/sec^2)			peak vel. (cm/sec)			peak displ. (cm)		
	NS	EW	UD	NS	EW	UD	NS	EW	UD
GL. 0.0m	191.6	-194.7	-181.3	-32.4	-43.1	-12.1	10.8	-15.1	3.3
GL. -25.0m	105.6 79.7★	-105.3 -118.7★	-67.6	-20.4 15.4★	-20.7 -22.9★	10.2	9.7 9.1★	10.1 12.3★	-3.9
GL. -100.0m	-84.0 -88.6★	108.6 -106.6★	-80.0	10.9 11.3★	16.2 15.3★	-8.8	6.3 7.4★	8.9 8.5★	3.6

★ peak value for orientation- corrected time histories

peak values both for original and corrected are listed in **Table 7**.

As presented in the above, the orientation error of seismometers exists commonly in the borehole array observation systems. The examination of the orientation error of seismometers is indispensable since the ground motions generally contain a directivity, especially in the case of near field earthquakes.

3. EFFECT OF ORIENTATION CORRECTION TO 2D AND 3D LIQUEFACTION ANALYSIS

Using the effective stress-based 2-D and/or 3-D liquefaction analysis method, the ground response analyses at Port Island are carried out to reproduce the liquefaction induced damping of the horizontal motion and large amplification of the vertical motion in the reclaimed ground. The effects of the correction of orientation error to the numerical results are discussed based on the simulated and measured results.

Table 8 Parameters for Numerical Analysis (Port Island Borehole Array Station).

Depth (GL m)	Soil Layer	Unit Weight tf/m$_3$ (N-Value)	Void Ratio e	Vs m/sec	Poisson's Ratio ν	Coefficient of Permeability m/sec	Liquefaction Strength N=10	Liquefaction Strength N=30
▲ 0.0 – -5.0	Sandy Gravel (Reclaimed)	1.9 (5.2)	0.80	170	0.25	—		
-5.0 – -12.6	Sandy Gravel (Reclaimed)	1.9 (6.5)	0.80	210	0.25	4.0×10^{-4}	0.16	0.13
-12.6 – -19.0 (-16m)▲	Sand withGravel (Reclaimed)	1.9 (6.5)	0.80	210	0.25	4.0×10^{-4}	0.16	0.13
-19.0 – -27.0	Alluvial Clay	1.6 (3.5)	1.20	180	0.30	1.0×10^{-8}	—	—
-27.0 – -33.0 ▲(-32m)	Alluvial Sand	1.9 (13.5)	0.75	245	0.25	1.0×10^{-4}	0.35	0.25
-33.0 – -50.0	Diluvial Sand with Gravel	1.9 (36.5)	0.72	305	0.25	1.0×10^{-4}	0.40	0.30
-50.0 – -61.0	Diluvial Sand	1.9 (61.9)	0.70	350	0.25	1.0×10^{-4}	—	—
-61.0 – -79.0	Diluvial Clay	1.6 (11.7)	1.00	303	0.30	1.0×10^{-8}	—	—
-79.0 – -83.0 ▲(-83m)	Diluvial Sand with Gravel	1.9 (61.9)	0.70	320	0.25	1.0×10^{-4}	—	—

NOTE 1. ▲ Seismometer 2. K_o=0.5

(1) Summary of numerical method

The constitutive model in the present study is based on the concept of the non-linear kinematic hardening rule, which had originally been used in the field of metal plasticity[8]. Oka et al.[9] derived a cyclic elasto-plastic constitutive model for sand through use of the concept of non-linear kinematic hardening. Tateishi et al.[10] incorporated a new stress dilatancy relationship and cumulative strain dependent characteristic of the shear modulus to modify the original model. Such a constitutive model is formulated under the three-dimensional stress conditions in the present study. The validity of the constitutive model has been verified by the experimental evidences from the hollow cylindrical torsion tests under various stress conditions.

This constitutive model is then incorporated into a coupled finite element- finite difference (FEM- FDM) numerical method[5] for the liquefaction analysis of a fluid-saturated ground.

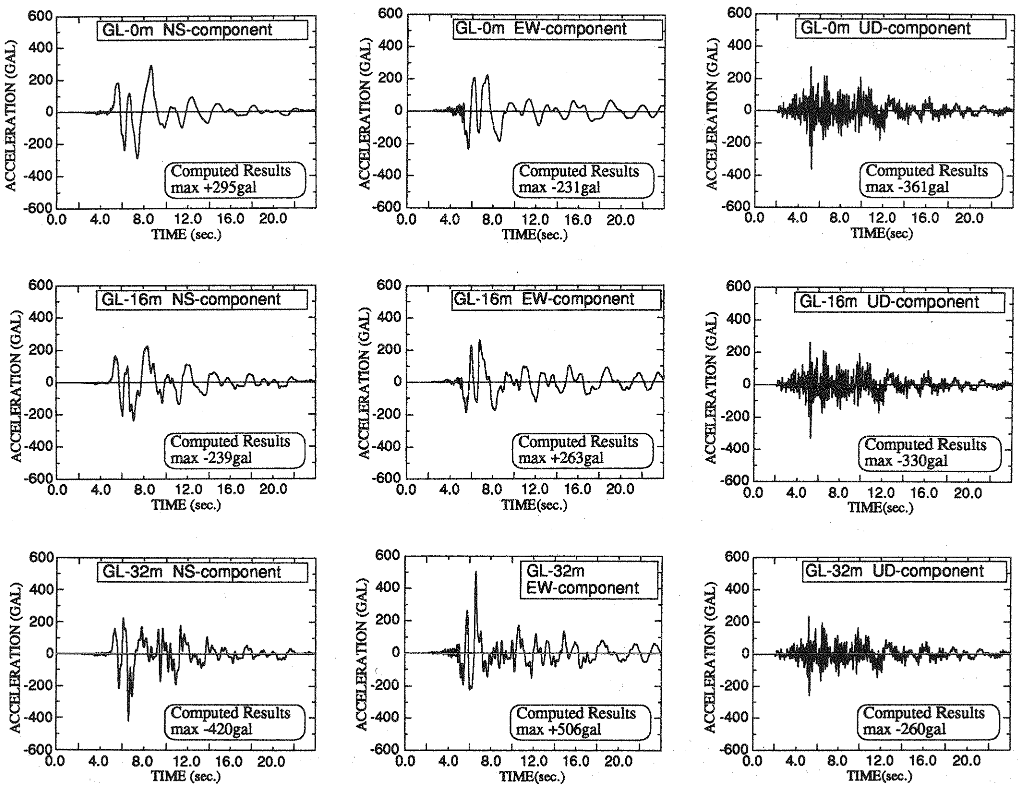


Fig.14 Simulated Acceleration Time Histories based on Corrected Input Motion.

Using a u-p (displacement of the solid phase and pore water pressure of the liquid phase) formulation, the numerical method is developed. The finite element method is used for the spatial discretization of the equilibrium equation, while the finite difference method is used for the spatial discretization of the continuity equation. Newmark's β-method is used for the time discretization of both equations. The applicability of the proposed numerical method to the actual ground (including a model ground by a centrifuge test) had been already verified by the previous studies[11),12)].

(2) Analytical condition

The single column ground model using the rectangular solid element mesh (39 elements and 160 nodes) is used for the analysis. Most numerical parameters for the analysis are determined based on the results of the past field investigations and laboratory tests. Some parameters which were not given in such past studies are assumed. List of basic parameters are shown in **Table 8**. Three components of acceleration records at GL-83m with and without correction are applied as the base input accelerations.

(3) Simulation results

The simulation results (time histories of response acceleration at GL-32m, 16m, and 0m) obtained from the orientation-corrected and original base accelerations are shown in **Figs.14** and **15**, respectively. Simulated results obtained from corrected base acceleration reproduce the measured record better than those from non-corrected base acceleration, as shown in **Figs.3**, **14**, and **15**. For the horizontal motion, peculiar phenomena due to liquefaction such as the damping of ground acceleration and the increase in long-period contents near the ground surface can be identified in **Figs. 14** and **15**. Since the compressibility of the fluid phase is assumed in this study, the amplification property in the vertical motion can be also reproduced as shown in **Figs. 14** and **15**.

The time histories of excess pore water pressure and mean effective stress path ($\sqrt{2J_2}/\sigma'_{m0} \sim \sigma'_m/\sigma'_{m0}$) in the simulated results with and without correction at typical sandy soil layers are shown in **Fig.16**. The computed results of excess pore water pressure-time histories with one

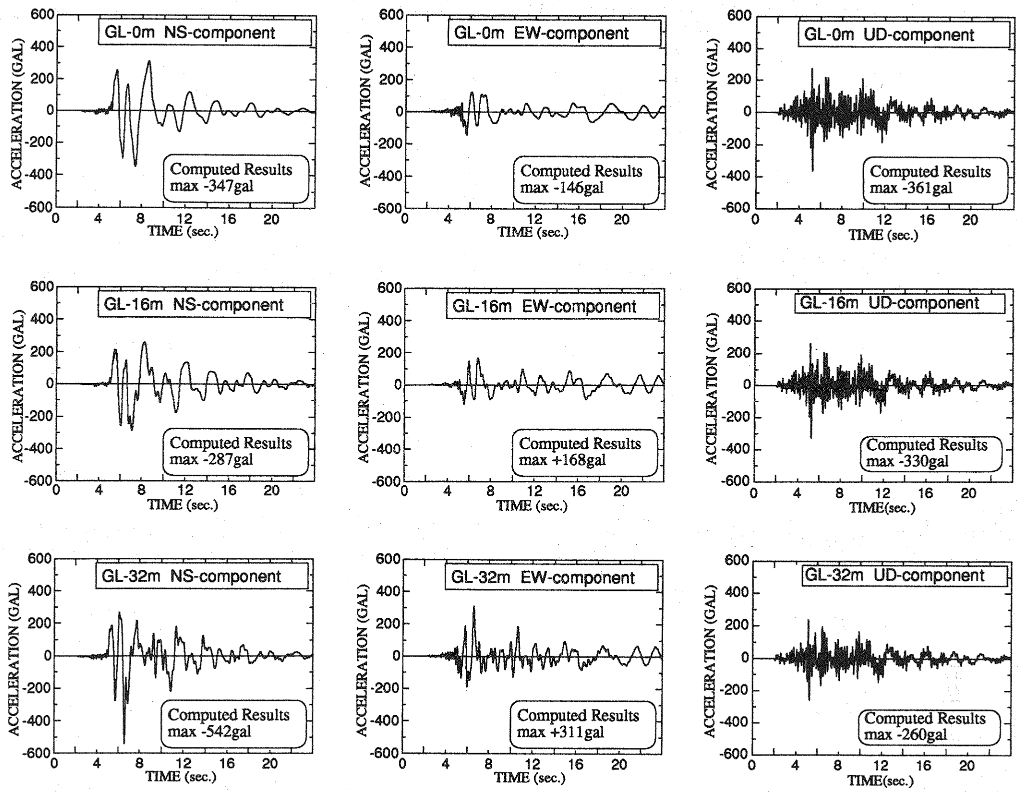


Fig.15 Simulated Acceleration Time Histories based on Original Input Motion.

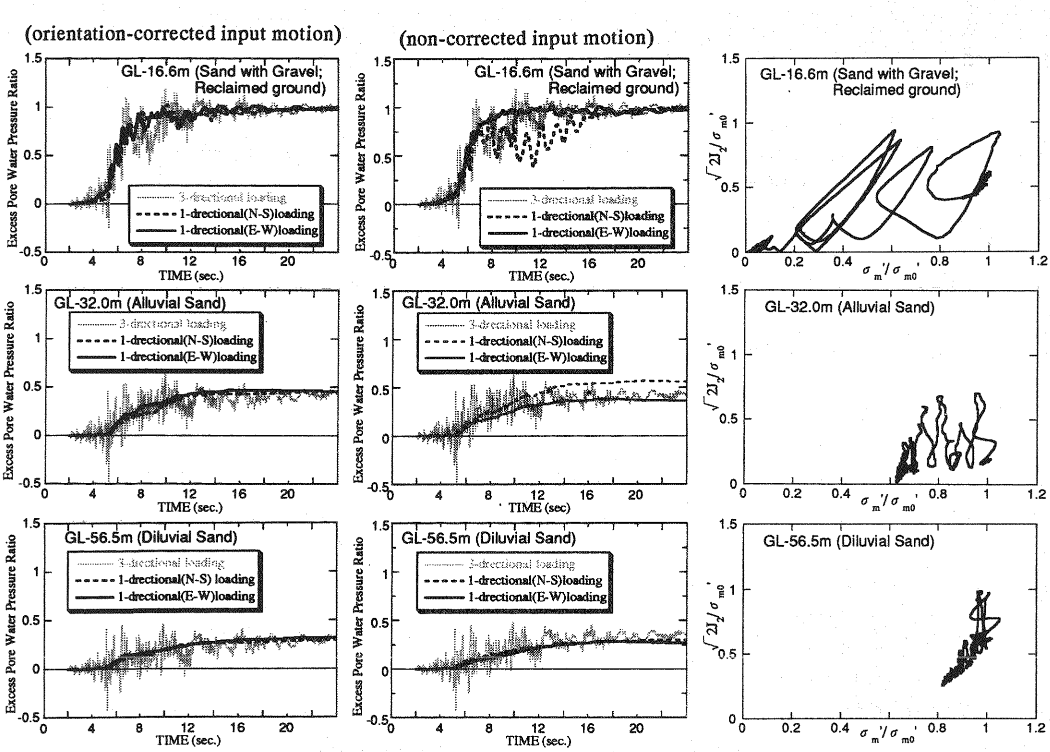


Fig.16 Time Histories of Excess Pore Water Pressure Ratio and Effective Stress Path in Numerical Analysis.

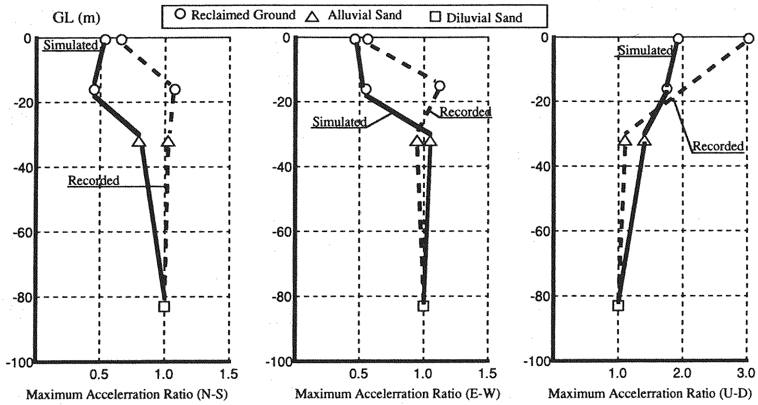


Fig.17 Distribution of Maximum Acceleration Ratio.

directional motion (N-S or E-W) are also depicted in **Fig.16**. When the simulation analyses are carried out with 2-D model or one directional motion in 3D model, the behavior of excess pore water pressure depends on the direction of input motion. For 3-D analysis, however, the time histories of excess pore water pressure calculated for three directional motions are same in simulations both for orientation-corrected and non-corrected input base motions.

The comparison of maximum acceleration ratio between measured record and simulated result for corrected base acceleration are shown in **Fig.17**. The maximum acceleration ratio is defined as the maximum acceleration at each level normalized by the maximum acceleration at GL-83m. The simulated amplification of the ground in the horizontal motion as well as in the vertical motion are found to be well reproduced except at GL-16m. The measured record at GL-16m has little reliability as mentioned on Chapter 2.(1), and the assumption of soil properties in the reclaimed ground might be rather different from real soil properties.

4.CONCLUSIONS

This paper presented the orientation error of the accelerographs in borehole array systems which obtained the records from the South Hyogo Earthquake of Jan. 17, 1995. The effect of the correction of orientation errors to the numerical response analysis of ground was emphasized using the Port Island array records which include the liquefaction phenomenon. The results may be summarized as follows.

(1) The study regarding the orientation error of seismometers in borehole array systems were briefly reviewed. It was pointed out that the orientation error was detected at greater depths, which might have been caused by the torsion of the rods used to install the seismometers.

(2) The four sets of borehole array records obtained during the South Hyogo Earthquake of Jan.17, 1995 were examined regarding the orientation error of the installed accel-erographs. They include the stations at reclaimed land where severe soil liquefaction occured as well as the station at the stiff ground. The displacement orbits on the horizontal plane obtained from the integration of the filtered accelerograms were used to examine the level of the orientation error. The orientation error of the buried accelerographs are estimated on the assumption that the orientation of a accelerograph on the ground surface is correctly set. The significant orientation errors were detected in all the sets of array records used in this study. The peak acceleration, velocity, and displacement both for original and corrected time histories were obtained, and the characteristics of ground motion amplification were demonstrated.

(3) The significance of the correction of orientation error was discussed. The effective stress-based 2D and/or 3D liquefaction analyses were applied to one of the borehole array stations where soil liquefaction occurred. It was demonstrated that the method could reproduce the records well in the case where the orientation-corrected base motion was used as the input motion.

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