Study on Reinforcement of Fishery Harbor Wharf against the Nankai Trough Earthquake

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ABSTRACT

The Great East Japan Earthquake has implied the big potential all over Japan for earthquakes with magnitude 9.0. In the Great East Japan Earthquake, ports and fishing ports played an important role in (1) transportation of emergency supplies after the earthquake, (2) early recovery of marine products lifting and distribution functions. Kochi Prefecture has approximately 713 km coastal-line on which 88 fishing ports are scattered and 46,000 people live in this area. The fishing ports are very important as the life base of local populace for the relief activity, restoration-reconstruction and business continuity plan. The fishing ports are desired to maintain function when subject to the earthquake motion and tsunami of the Nankai Earthquake. In Kochi Prefecture, not only major ports but also fishing ports are proposed to be used as earthquake resistant quay walls in the event of a disaster. This research was executed for the Kaminokae Fishing Village, which is a typical district of the local fishing port in Kochi Prefecture. In the preparation of the earthquake resistant wharf, low construction cost and a short construction term would be anticipated. One of the effective methods for the economical construction of an earthquake resistant wharf is the adoption of the press-in pile.

Keywords: *Fishery harbor wharf, Nankai Trough Earthquake, effective stress analysis, Liquefaction, Centrifuge*

1. Background and outline of the project

The Nankai Earthquakes, of which epicenters are in the Nankai Trough offshore in the Tosa Bay, have occurred repeatedly every 100-150 years. The Japan government officially announced that the next earthquake will occur with a 70% probability within the next 30 years.

According to “The second earthquake assessment of Kochi Prefecture”, it is assumed that the Nankai Earthquake ground motion has a maximum acceleration of 400 gals or more, long period waves with a period of 2-3 seconds, and continues for about 90 seconds (level Ⅰ). The height of the maximum tsunami is 6-10 m (Kochi Prefecture, 2005).

After the Great East Japan earthquake in 2011 had occurred, a Nankai Trough huge earthquake (M9.0 class) was assumed in Kochi Prefecture. It is assumed that the Nankai Earthquake ground motion has a maximum acceleration of 800 gals or more, a long period wave of 2-5 seconds, and continues for about 120-150 seconds(level Ⅱ). The height of the maximum tsunami is 10-34 m.

The Great East Japan Earthquake has implied a big earthquake potential all over Japan with a magnitude of 9.0. In the Great East Japan Earthquake, ports and fishing ports played an important role in (1) transportation of emergency supplies after the earthquake, (2) early recovery of marine products lifting and distribution functions.

Kochi Prefecture has approximately 713km of coast line on which 88 fishing ports are distributed and 46,000 people live in this area. The fishing ports are expected to suffer serious damage from the earthquake motion and the tsunami caused by the Nankai Earthquake (Okabayashi *et al*. 2004).

In Kochi Prefecture, not only major ports but also fishing ports are proposed to be used as earthquake resistant quay walls in the event of a disaster. The design of port structures such as breakwaters is to target level I earthquake ground motion, with a policy to compensate for level 2 earthquake motion by evacuation.

This research was executed for the Kaminokae Fishing Village, which is a typical district of the local fishing port in Kochi Prefecture. In this area, the strong possibility of liquefaction is observed in most of the area. (Ministry of Transport,1997) (Okabayashi *et al*. 2008).

Using the existing data, we examined the effect of liquefaction countermeasures on a construction method in which sheet pile and counterfort are connected by tie rods. (Japan Road Association, 2014) (Okabayashi *et al*. 2014).

2. Site condition and investigations

The points of borings in Kaminokae Fishing Village are shown in **Fig. 1**. The four borings (Nos. A-D) to reach the bedrock were performed in addition to 23 existing borings to confirm the soil strata for doing the necessary soil test.

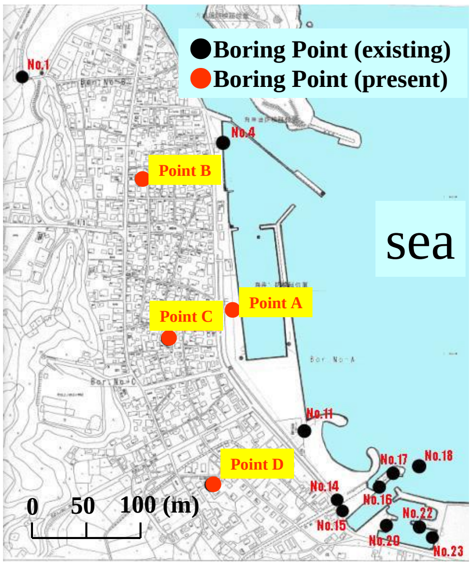

Fig. 1 Soil investigation point at Kaminokae

The strata consist of six layers of which the soil test results are shown in Table 1. The geologic column and the distribution of N value of point A are shown in **Fig. 2**.
In addition, frozen undisturbed samples were taken in the layers at point A to perform cyclic triaxial compression tests and to examine the possibility of liquefaction (Okabayashi *et al*. 2008). The samplings of soil were done at the following depths:

1). 8.5-10.5m at the second layer (sand)
2). 10.8-17m at the third layer(silt)
3). 21.8-24.0m at the fifth layer (silt)

Table 1. Grain size analysis

Silt mixing Sandy gravel	Fine fraction content : FC(%)	13.475
	D_{10} (mm)	0.0238
	D_{50} (mm)	4.2969
	Plasticity index : I_p	9.3
Sand	Fine fraction content : FC(%)	28.8
	D_{10} (mm)	0.046
	D_{50} (mm)	0.129
	Plasticity index : I_p	-
Silt	Fine fraction content : FC(%)	84.4
	D_{10} (mm)	0.001
	D_{50} (mm)	0.0137
	Plasticity index : I_p	25.15
Volcanic ash	Fine fraction content : FC(%)	38.7
	D_{10} (mm)	0.0042
	D_{50} (mm)	0.1096
	Plasticity index : I_p	-
Silt	Fine fraction content : FC(%)	96.2
	D_{10} (mm)	0.001
	D_{50} (mm)	0.0049
	Plasticity index : I_p	28.25
Silt mixing Sandy gravel	Fine fraction content : FC(%)	22.4
	D_{10} (mm)	0.0078
	D_{50} (mm)	1.4828
	Plasticity index : I_p	8.35

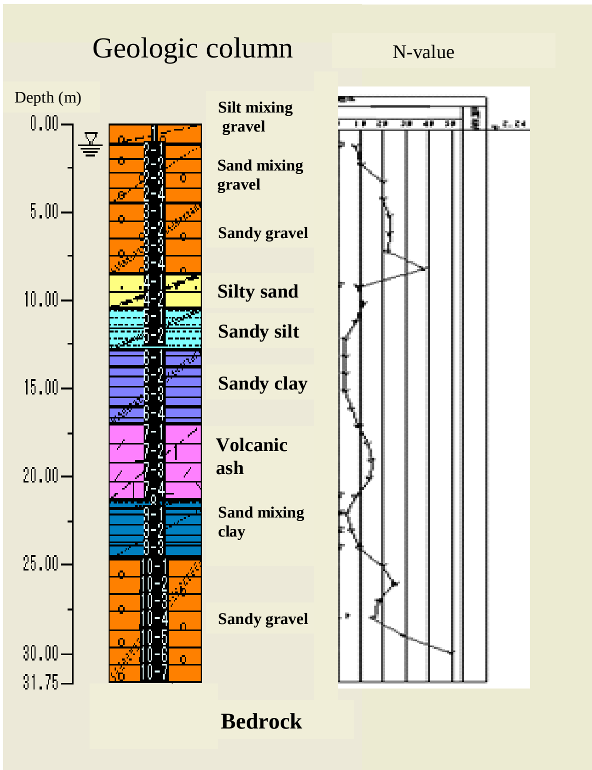

Fig. 2 Boring log (Point A)

Fig. 3 shows the cross section and strata profile for the analytical model. Three layers subjected to the liquefaction strength test are shown with shadow.

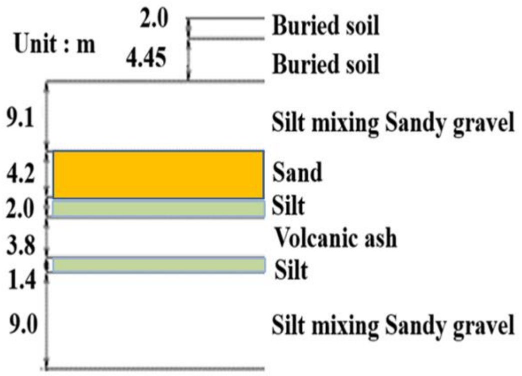

Fig. 3 Stratum of the ground

Element simulations were carried out based on liquefaction resistance curve. We found a fitting curves, and determined analysis parameters. **Fig. 4** shows the test result of liquefaction strength and fitting curve. **Table 2** shows analysis parameters of three layers obtained by element simulations.

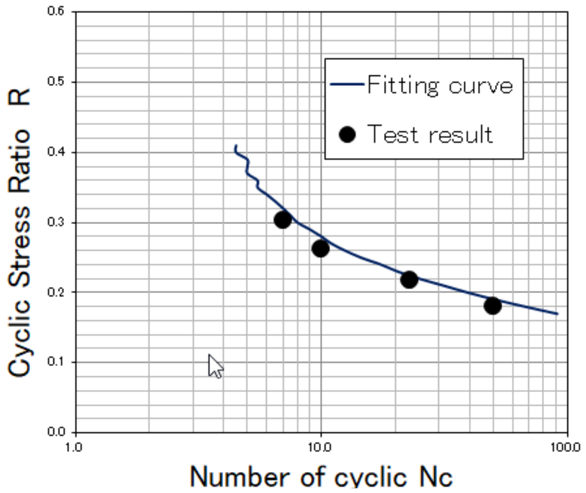

Fig.4 liquefaction strength

3. Effective stress analysis for the Sheet pile quay wall

The Computer Program for Liquefaction Analysis LIQCA was used for analyses. The analysis method is an effective stress analysis method.

Fig. 5 shows the example of analysis model. This structure comprised a sheet pile wall and counterfort connected with a tie rod at the top, which was employed in the restoration of a damaged wharf in the Akita Port due to the Nihonkai-Chubu earthquake in 1983.

Table 3 shows the physical properties of the sheet pile wall, the counterfort and the tie rod.

Table 2. List of parameters

		Sand	Silt mixing Sandy gravel	Silt
Dry density(g/cm^3)	ρd	1.423	1.3735	1.434
Wet density(g/cm^3)	ρt	1.8377	1.8761	1.9201
Void ratio	e	0.9088	1.031	0.9963
degree of saturation(%)	Sr	87.1	99	97.4
specific gravity of soil particle	Gs	2.7162	2.7896	2.863
Wet unitweight(KN/m^3)	γt	18.0093	18.3853	18.817
initial void ratio	e0	1.0533	1.0472	1.029
N value	N	13.05	4.9688	8
Poisson's ratio	ν	0.3251	0.3429	0.3425
velocity of S-wave(m/s)	Vs	188.3476	136.5125	160
effective overburden pressure(KN/m^2)	σv'	161.5	217.34	376.44
angle of shear resistance(°)	φ'	36.2216	33.5697	33.6252
SINφ'		0.5909	0.5530	0.5538
coefficient of earth pressure at rest	K0	0.4816	0.5218	0.5209
compression index	λ	0.0024	0.0365	0.0268
expansion index	Κ	0.0002	0.0036	0.0027
overconsolidation ratio	OCR*	1	1	1
Curing function 1	B0*	1390	3178	3900
Curing function 2	B1*	10	31.3	35
Curing function 3	Cf	0	0	0
plastic strain	γrP＊	0.011	0	0
elastic strain	γrE＊	1.2	0.15	0.055
coefficient of dilatancy 1	D0*	0.0001	0.005	0.002
coefficient of dilatancy 2	n	2.5	1	7.5
anisotropy	Cd	2000	2000	2000

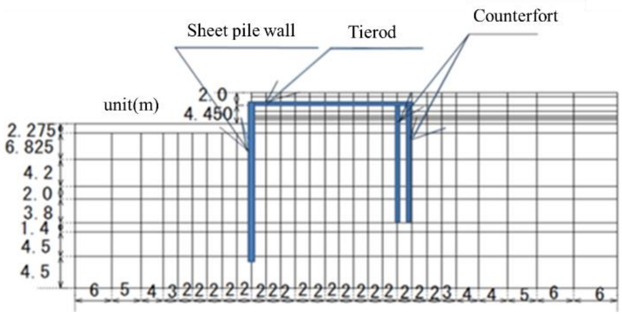

Fig. 5 Analysis model with improvement

Table 3. The physical properties of the steel

	E(Pa)	A(m^2)	I(m^4)	ρ(g/cm^3)
Sheet pile wall	2.10E+08	3.06E-02	8.60E-04	7.5
Counterfort	2.10E+08	5.80E-03	3.95E-04	7.5
Tie rod	2.10E+08	1.59E-03	0	7.5

The steel sheet pilings, the counterfort and the tie rod were modelled as beam elements. The steel sheet pile was a VI_L type, the counterfort was a steel pipe pile with Φ 550mm and a board thickness of 12mm.

The steel sheet pile and the ground, and the counterfort and the ground, were connected using a joint element. The joint element was assumed that a friction angle of 15 degrees. These joint elements considered slip only.

The ground was assumed to be the same as **Fig. 2** and **Fig. 3** and used plane strain elements. The penetration depth of the sheet pile was to the center of the silt mixing sandy gravel layer.

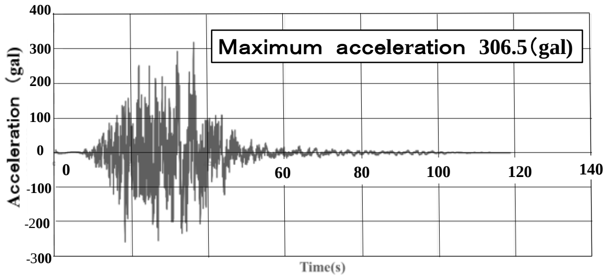

Fig. 6 Seismic base motion (level Ⅰ)

The seismic waves profiles on the engineering bedrock (N value : 50 or more) at Kaminokae area were based on new assumptions in Kochi prefecture.
The magnitude of earthquake was 8.4. **Fig. 6** shows the input seismic wave used for the seismic response analysis.

Fig. 7 shows the analysis results for the model without improvement and with improvement. “Without improvement” indicates the case of the natural ground, and “with improvement” shows the case reinforced by sheet pile wall and counterfort.

Maximum horizontal displacements were approximately 2.1m and 0.6m, respectively.

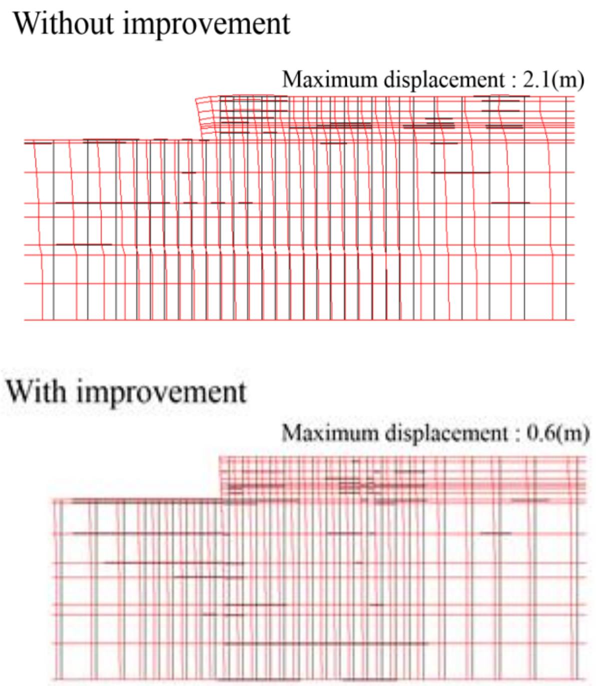

Fig. 7 Horizontal displacement

Fig.8 shows the ratio of excess pore water pressure without improvement and with improvement. The ratio is defined by the ratio of excess water pressure to the overburden pressure. Even when countermeasures were taken, it can be seen that excess pore water pressure is generated between the sheet pile wall and counterfort.

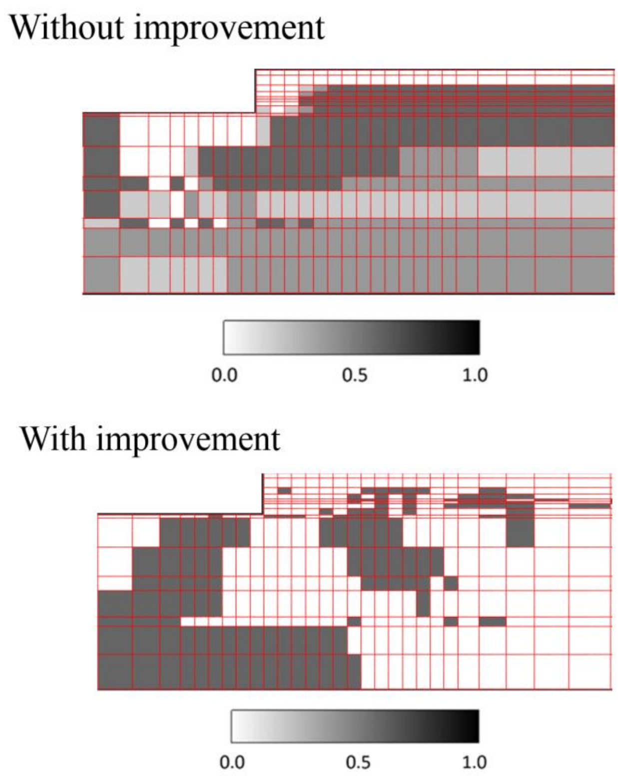

Fig. 8 Excess pore water pressure ratio

4. Centrifuge model tests for the Sheet pile quay wall

Fig. 9 shows the internal configuration of the centrifuge used in the experiment. The interior of the device consists of a platform with a shaking table, rotating spindle, rotating arm, counterweight and emergency brake. **Table 4** shows the basic specifications of the centrifuge.

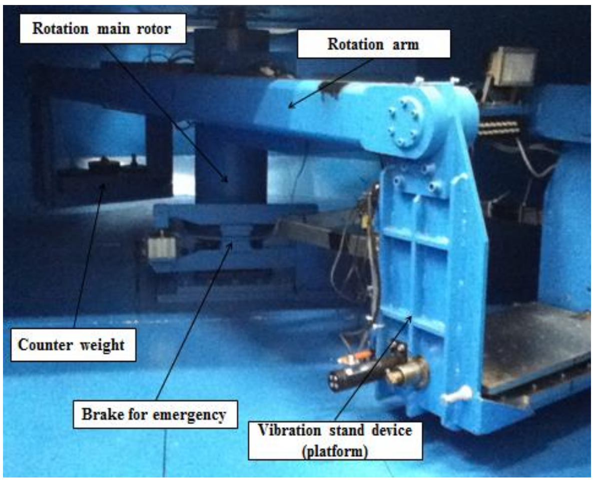

Fig. 9 Structure dynamic centrifuge

Table 4. Centrifuge specifications

Effective radius (mm)		1925
Depth (mm)		1700
Vibration table of dimensions (mm)		L550×B150
Experiment container size (mm)		L450×B150×H300
		L450×B139×H355
Maximum acceleration (G)		200
Maximum frequency (Hz)		30
Maximum displacement (mm)		30
Power of the drive motor (KW)		14
Measuring device	Switch box	50 channels
	Pressure sensor connector	30 channels

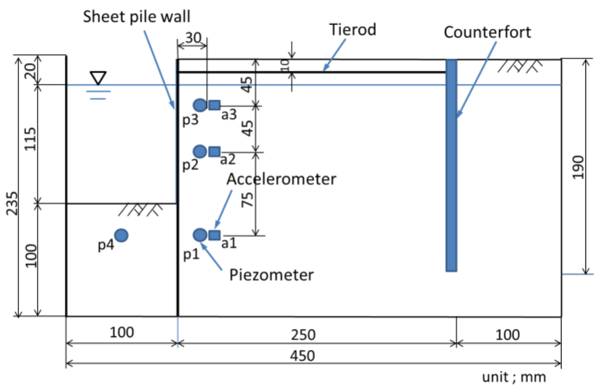

Fig. 10 Experimental model (Model scale)

4.1. Liquefaction experiment by centrifuge

In this research, liquefaction experiment is carried out by using the centrifuge. A model with a scale of 1/40 of the analytical model was prepared and experiments were conducted with a centrifugal force field of 40 G. **Fig. 10** shows the experiment model and the position of each sensor.

The backfill soil of the sheet pile was made with Toyoura sand with a relative density of 70%.At that time, the void ratio is 0.72 and the saturated density is 1.95 g / m ^{3}. The pore water was saturated with methylcellulose, which is 40 times more viscous than water. The counterforts were installed at intervals of 25 mm (1 m in actual size).

Fig. 11 shows photographs after the experiment in case of countermeasure work. Displacement of the sheet pile wall surface was about 2 mm (about 8 cm in terms of the real structure), and the deformation of the pile was controlled and the countermeasure effect was able to be confirmed.

4.2. Pore water pressure response

Time histories of excess pore water pressure are shown in **Fig.12.** From the results, the upper part of excess pore water pressures did not increase to overburden pressure level. Therefore, these measuring points were not completely liquefied.

Fig. 11 Photographs after the experiment

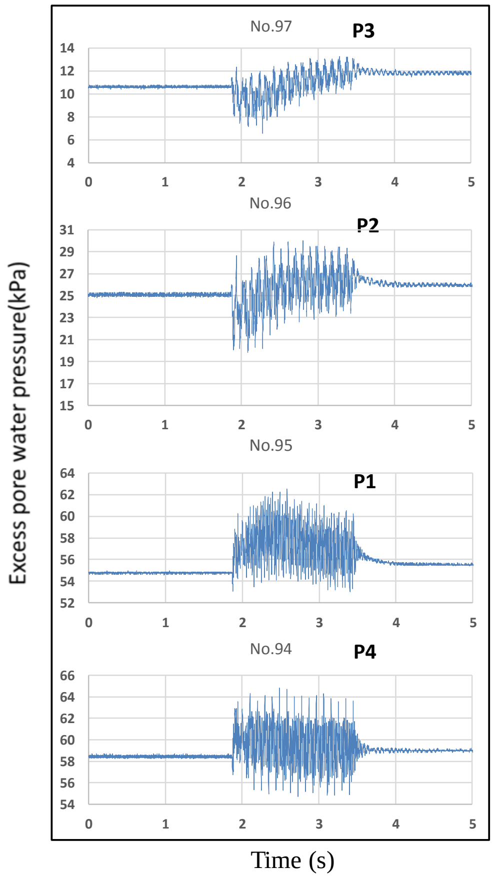

Fig. 12 Excess pore water pressure (Measured value)

Table 5. Pore water pressure and Overburden pressure

	Pore water pressure (kPa)	Overburden pressure (kPa)
P3	13.2	16.8
P2	30.0	33.7
P1	62.5	61.7
P4	64.8	56.3

Table 6. Acceleration Response

	Measured values (m/s^2)	Actual scale (gal)
a3	80.5	201.3
a2	70.7	176.9
a1	53.8	134.5
Input	20.1	67.8

Table 5 shows the relationship between the pore water pressure and overburden pressure. The pore water pressure of p2 and p3 did not increase to the overburden pressure level. But, the pore water pressure of p1 and p4 increased to the overburden pressure.

4.3. Acceleration response

Time histories of acceleration responses are shown in **Fig.13**. Accelerations have amplified from the input acceleration. **Table 6** shows measured values of acceleration responses and actual conversion values. It can be seen that the input wave is amplified as it is transmitted to the upper layer.

From these results, it became clear that this method has problems with dissipation of pore water pressure and amplification of seismic waves.

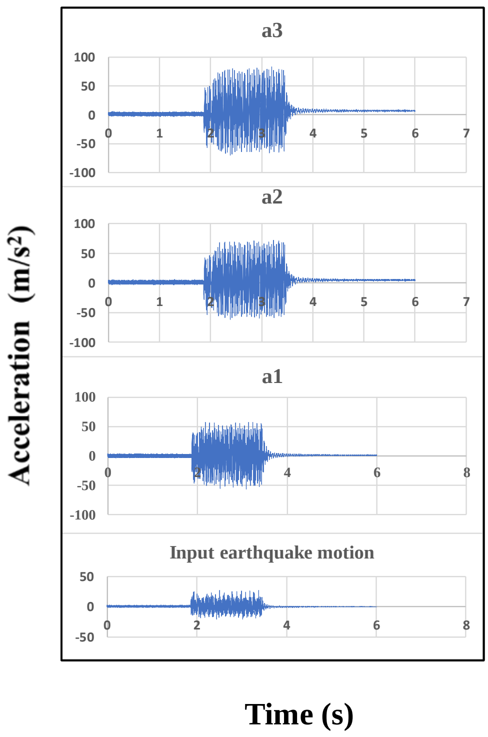

Fig.13 Acceleration response (Measured value)

5. Concluding remarks

The following conclusion were obtained ;

As a seismic reinforcement method for fishing port quay walls, the countermeasure method by sheet pile and counterfort is effective.

The countermeasure method using sheet pile and counterfort can be verified by seismic response analysis method by effective stress method and centrifuge model test.

The countermeasure method using sheet pile and counterfort is highly effective in suppressing deformation against earthquake. It is necessary to further investigate the dissipation of pore water pressure and the amplification of seismic waves.

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