EVALUATION OF THE SEISMIC PERFORMANCE OF DUAL ANCHORED SHEET PILE WALL

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SUMMARY:
The dual anchored sheet pile wall method has been developed for the purpose of increasing a front water depth and improvement of seismic resistance of existing quay walls by providing additional anchors in the lower level of them to reduce a flexural moment of the sheet piles and a tension of the anchors. The authors firstly conducted the centrifuge experiments with a scale model to investigate the seismic behaviour of the dual anchored sheet pile wall. Then, the two dimensional effective stress analyses were conducted to investigate the applicability on evaluating the seismic performance of the dual anchored sheet pile wall prior to the actual application.

Keywords: Seismic retrofit, quay wall, centrifuge, effective stress analysis

1. INTRODUCTION

Recently, demand of increasing a front water depth of existing quay-walls due to increasing size of cargo ships or from the view point of reservation of marine transportation during post earthquake disaster restoration in Japan, the dual anchored sheet pile wall method (DASPW method, here after) has been developed. Although there are several existing reinforcement methods such as additional piles or soil improvement of backfill for seismic retrofitting of quay-walls, construction works affect regular function, such as cargo handling and storage capability, of quays and aprons. Under Ground Efficient Tie-rod System (**Figure 1.1**, UGETS, here after), developed by the joint research project initiated by public and private sectors in Japan, is one of retrofitting construction methods. This method consists of additional tie members, which installed by the high precise small-caliber drilling machine, and anchor structures. Utilizing this method, it is able to reinforce existing quay-walls without depressing function of quays.

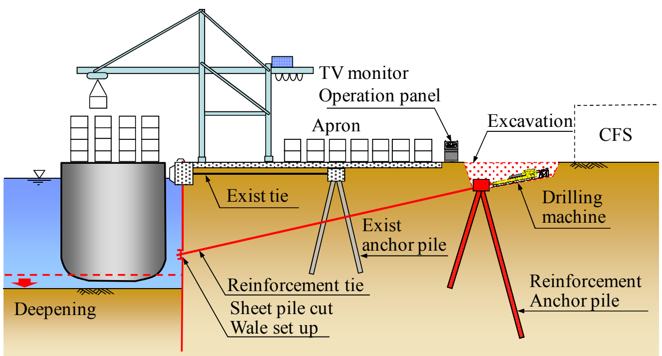


Figure 1.1 Conceptual drawing of the dual anchored sheet pile wall method (constructed by UGETS)

Although essential functions of the dual anchored sheet pile wall method has been confirmed (Morikawa, 2011), because of its complex structural system, limited technical information exists to evaluate the seismic behaviour and the retrofit performance of the quay-walls with anchors at two different levels.
Therefore, the authors firstly conducted the centrifuge experiments with a scale model to investigate the seismic behaviour of the dual anchored sheet pile wall. Then, the two dimensional effective stress analyses were conducted to investigate the applicability on evaluating the seismic performance of the dual anchored sheet pile wall prior to the actual application.

2. CENTRIFUGE EXPERIMENTS

2.1. Purpose

Sheet pile quay-wall consists of sheet pile, tie and anchor structure. Because most members are installed in the ground, seismic response is governed by the soil-structure interaction. Centrifuge experiment is suitable method to investigate the interaction between the structure and the ground. Therefore, the seismic performance of the DASPW method is investigated by conducting shake table tests under the centrifugal gravity.

2.2. Basic investigation for additional tie system

Preliminary centrifuge tests were conducted under the 50g (1g=9.81m/s^2) to investigate the efficiency of the additional tie system. Because different types of the tie arrangement are assumed in application, two models were chosen. One is the horizontal reinforcement tie system and another is the slanting reinforcement tie system, as illustrated in **Figure 2.1** and **Figure 2.2**.

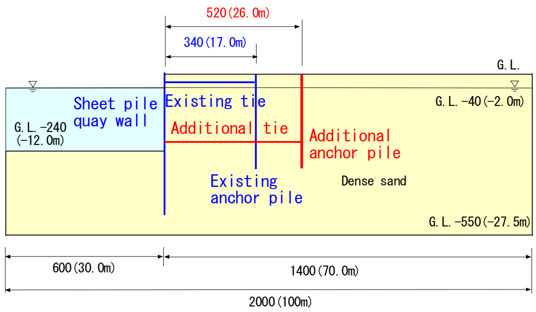


Figure 2.1 Model P1 (Horizontal reinforcement tie)

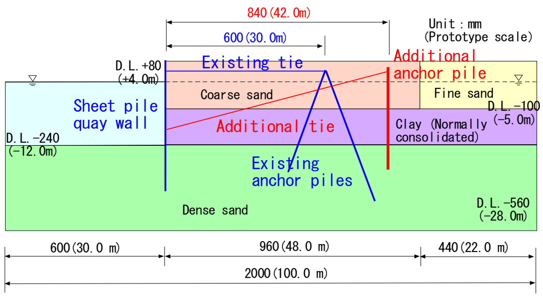


Figure 2.2 Model P2 (Slanting reinforcement tie)

One of the major findings is shown as **Table 2.1**, which shows the force share of the reinforcement tie members before (Static) and during the earthquake (Dynamic increment). Slanting reinforcement tie model could not burden large portion of the axial force of the existing tie compared to the horizontal reinforcement tie model. Therefore, the reduction effect on section force of the quay-wall may decline. Although consistency of the ground and tie length are different in each model, that is mainly due to the flexure of the additional anchor structure and the relative displacement between the quay and the additional anchor. Thus, it is pointed out that rigid anchor structure is suitable for DASPW method.

Table 2.1. Force share of the reinforcement tie members before and during the earthquake

Model	P1	P2
Static	1.0	0.17
Dynamic (Increment)	2.0	0.10

*Static force of the existing tie member is 1.0.

2.3. Centrifuge test on conceptual model

Basing on the preliminary studies, a 12m deep (front water depth is DL=-9.5m after deepening) conceptual quay model as illustrated in **Figure 2.3** was proposed as the prototype. Original quay (front water depth is DL=-7.5m) has sheet pile type quay-wall with batter piles anchor structure. Batter piles anchor structure is also applied for the reinforced anchor structure.

The seismic performance of the DASPW method was investigated by comparing the dynamic response of the reinforced model and that of the unreinforced model. **Figure 2.4** is the photo of the model during preparation. Reinforced section and unreinforced section were simultaneously prepared.

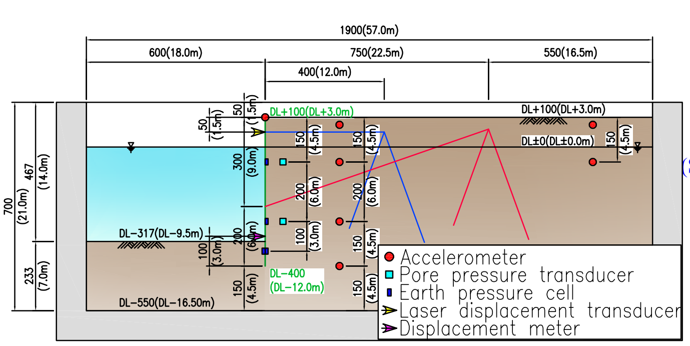


Figure 2.3 Conceptual DASPW model
(Buttered anchor and slanting reinforcement tie)

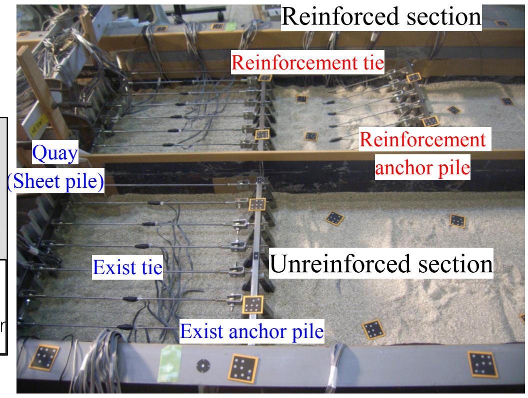


Figure 2.4 Photo of the model during preparation

2.3.1. Test conditions

Shake table tests were conducted under the 30*g* centrifugal gravity. According to the similitude shown in **Table 2.2**, member sections were determined as **Table 2.3**. Followings were considered in application of the similitude to the modeling of the structures.

(a) Sheet pile: equivalent in the bending stiffness
(b) Buttered anchor pile: equivalent in the circumference (axial stiffness of the soil-pile system)
(c) Tie member: equivalent in the axial stiffness (area)

Table 2.2 Similitude of the centrifuge (30*g*)

Items	Symbol	Similarity (*Ng*)	Scale (30*g*)
Length	l	$1/N$	1 / 30
Density	ρ	1	1
Strain	ε	1	1
Acceleration	α	N	30
Velocity	v	1	1
Displacement	d	$1/N$	1 / 30
Stress	σ	1	1
Time	t	$1/N$	1 / 30
Frequency	f	N	30
Bending stiffness	EI	$1/N^4$	$1/30^4$
Axial stiffness	EA	$1/N^2$	$1/30^2$

Table 2.3 Summaries of modeling

Structure		Prototype	Scaled model
Exist member	Sheet pile	Sheet-pile VL	Thin steel sheet (wave form)
		h=200mm	h=67mm
	Anchor pile	H-section steel @1.5m	Steel bar @50mm
		388×402×15×15	front:8×10 back:13×13
	Tie	Tie rod φ42	φ3mm Steel rod
		@1.5m	@50mm
Reinforcement member	Anchor pile	H-section steel @1.5m	Steel bar @50mm
		400×400×13×21	front:10×10 back:14×14
	Tie	Tie rope TR-180	φ3mm Steel rod
		@1.5m	@50mm

2.3.2. Model preparation

Model grounds were prepared in the steel rigid container with the dimension of L=1900mm (57m in prototype), W=400mm (12m) and H=700mm (21m). Because the assumed ground condition was stiff sand as N=30, coarse silica sand (D_{50}=1.2mm) was used and compacted as Dr=80% (ρ_s=2g/cm^3). As liquefaction was not considered in this research, water was used as pore fluid.

To simulate the actual moment (M) - curvature (ϕ) relationship of the quay sheet pile, wave form thin steel sheets were used as the sheet pile model.

Accelerometers and pore pressure transducers were instrumented in the ground. Displacements of quays were measured by the laser displacement transducers at the top and by LVDTs at the seabed level. Strain gauges were placed on the quay sheet piles, ties and anchor piles, as shown in **Figure 2.5**.

2.3.3. Testing procedures
On the execution of the centrifuge experiments, following processes were implemented prior to the shake table test.

Step 1: Centrifugal gravity of 25*g* was applied to the model to simulate the initial stress condition of the original quay (DL=-7.5m) without connecting additional tie member and existing sheet pile quay-wall. The model ground and structures were deformed due to the ground deformation generated by centrifugal force. Initial stresses were also generated on the existing tie members.

Step 2: Centrifugal gravity was released to connect additional tie members to existing quay-wall. Then, centrifugal gravity of 30*g* was applied to model to simulate the initial stress condition of the deepening quay (DL=-9.5m).

The authors assumed that the stress increment of the additional member connected after the Step 2 is mostly affected by the deepening effect because exist members are previously affected by the deformation caused by Step 1.

Earthquake motion chosen for the input motion for the shake table tests is shown in **Figure 2.6**. One of these is the artificial design motion applied for high earthquake-resistance port facilities, and the other is recorded motion at Takamatsu wharf, port of Sendai, during the 2008 Iwate-Miyagi inland earthquake. Sequence of the shake table tests are illustrated in **Figure 2.7**. 4 shake events were performed under 30*g* in terms of the maximum acceleration amplitude of input motions.

Because the initial values (ex, initial stress) of each event may change due to the accumulation of the recorded values during the shake event as illustrated in **Figure 2.7**, evaluation data of each shake event, which will be discussed in regard to the seismic performance, were processed as the sum of the initial values at CASE-000 and the seismic drift portions (increments) during the shake event.

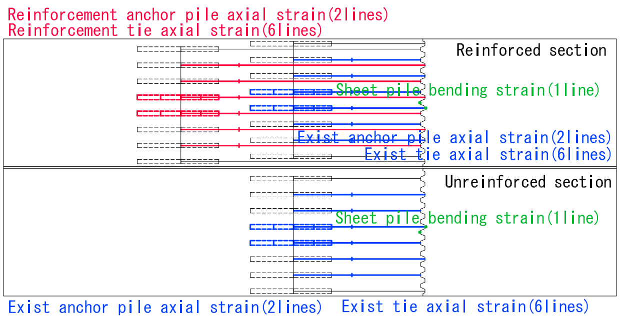


Figure 2.5 Instrumentation plan of strain gauges

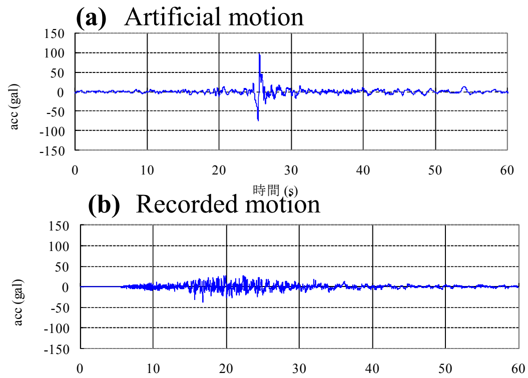


Figure 2.6 Input motions for shake table tests

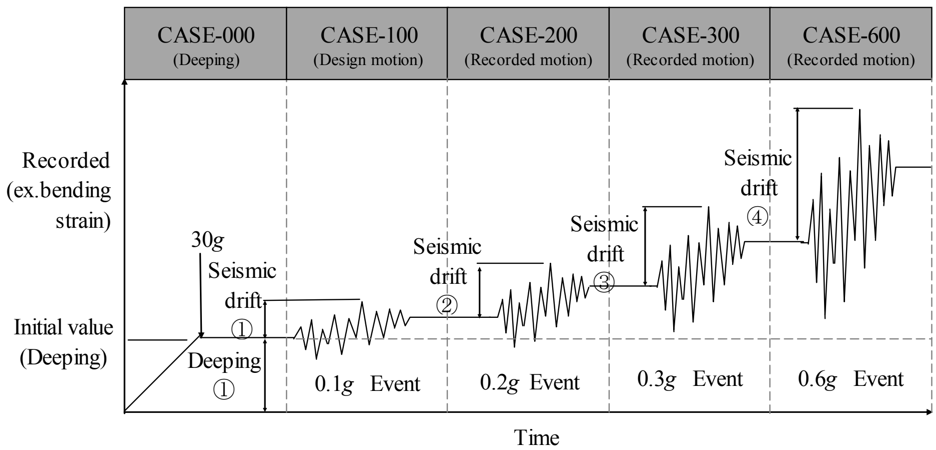


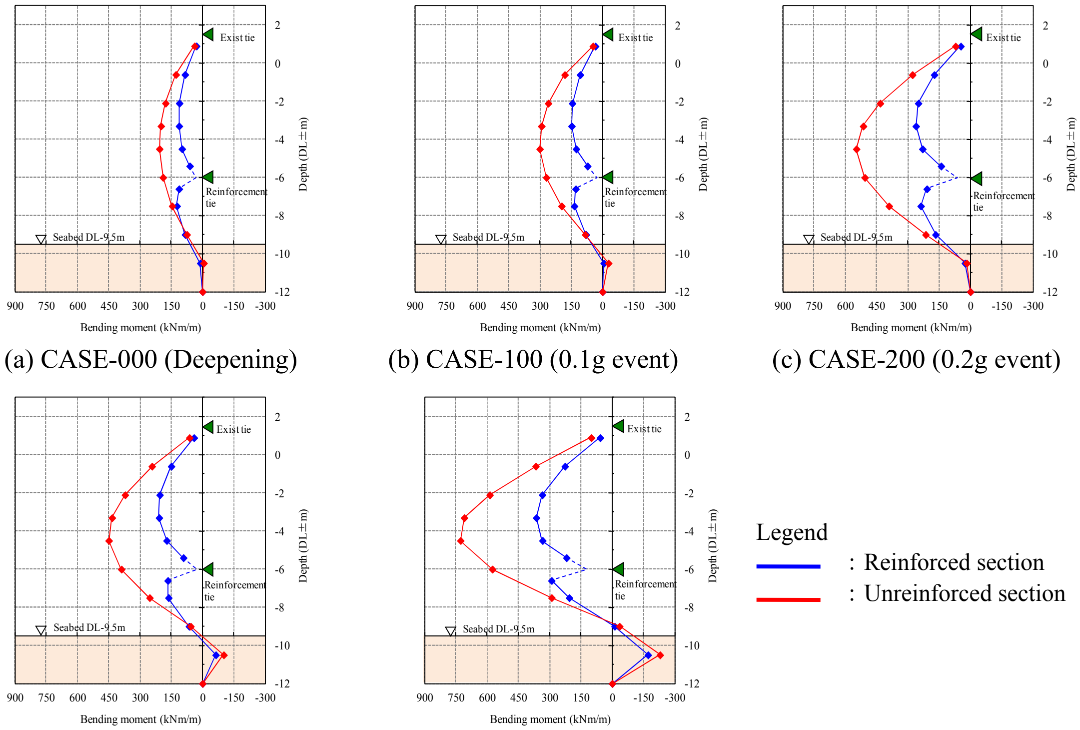
Figure 2.7 Sequence of the shake table tests and the evaluation data processing

2.4. Test results

As previously mentioned, the seismic performance of the DASPW method will be discussed by comparing the dynamic response of the reinforced model and the unreinforced model. Representative responses, because that strongly affect to quay stabilities, displacement and bending moment of quay-walls, and axial force on the ties will be mainly presented and discussed. Note that further discussion will be referred at the prototype scale without any notice.

2.4.1. Bending moment of the quay-wall

Maximum bending moment distributions throughout the quay-wall are arranged. Both deepening case (CASE-000) and shake event cases are compared in **Figure 2.8**. It is seen that the bending moment of the reinforced quay-wall is reduced at the depth of DL=-6.0m, where reinforcement ties are attached, in every case compared to the unreinforced case. Because that attached position was determined with regard to the bending moment distribution of the un-reinforced model, efficient improvement is seen. Improvement effect is also seen at other part of the quay-wall, in addition. As shown in **Table 2.4**, reduction of the bending moment amplitude is about 50% (M/M_o) at most.



(a) CASE-000 (Deepening) (b) CASE-100 (0.1g event) (c) CASE-200 (0.2g event)

(d) CASE-300 (0.3g event) (e) CASE-600 (0.6g event)

Figure 2.8 Comparison of the maximum bending moment distributions throughout the quay-wall

Table 2.4 Comparison of the maximum bending moment

Experiment case		CASE-000	CASE-100	CASE-200	CASE-300	CASE-600
Peak acceleration		(Deepening)	0.1*g*	0.2*g*	0.3*g*	0.6*g*
Maximum bending moment	Unreinforced section M_0 (kNm/m)	207	301	547	449	728
	Reinforced section M (kNm/m)	123	148	261	208	364
Ratio M/M_0		0.59	0.49	0.48	0.46	0.50

2.4.2. Axial force of ties

As previously shown in **Figure 2.5**, axial strains of 6 ties in each section were measured. Thus, average axial force will be used for discussion.

Maximum axial force of both deepening case and shake event cases are compared in **Figure 2.9** and **Table 2.5**. Although tension force became larger in proportion to the input acceleration magnitude up to 0.2*g* event, increment became smaller at 0.3*g* and 0.6*g* event.

Because the force increment shared by the reinforcement tie, it is seen that the axial force acting on the exist tie at the reinforced section (T') is reduced up to 70% during the earthquake event, and reduced to 60% due to deepening, compared to the tie axial force on the unreinforced section (T_o). According to the **Table 2.5**, it is verified that share of the axial force acting on the reinforcement tie (T) is more than 50% (T/T' is larger than 1) on the reinforced section. On the other hand, it is pointed out that total force acting on the ties in reinforced section (T'+T) became larger than that of the unreinforced section (T_o). This is due to the increasing of the stiffness and the strength of the reinforced quay wall by the additional anchor system.

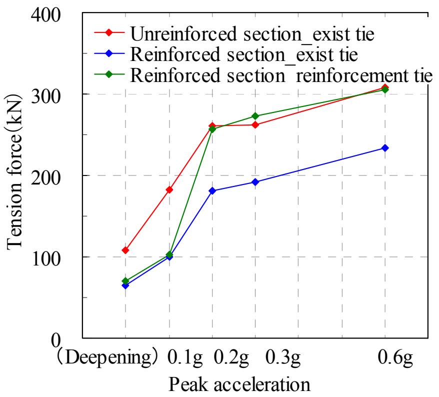


Figure 2.9 Comparison of the maximum axial force of ties (Tension)

Table 2.5 Comparison of the maximum axial force of ties and share of total force

Experiment case		CASE-000	CASE-100	CASE-200	CASE-300	CASE-600
Peak acceleration		(Deepe-ning)	0.1g	0.2g	0.3g	0.6g
Unreinforced section	Exist tie T_0 (kN)	108	182	261	262	308
Reinforced section	Exist tie T' (kN)	64	100	180	192	233
	Reinforcement tie T (kN)	71	102	256	273	305
T'+T		135	202	436	465	538
Reducion T'／T_0		0.59	0.55	0.69	0.73	0.76
Share of total tensile force T／T'		1.11	1.02	1.42	1.42	1.31
Total tensile force increment (T'+T)／T_0		1.25	1.11	1.67	1.77	1.75

2.4.3. Displacement of the quay-wall

Maximum displacements of the quay-wall are shown in **Figure 2.10**. Displacements of the seabed are presented in addition to the anchor section of the exist tie of the quay-wall. Due to the reinforcement, reductions of the horizontal displacement are seen on the anchor section of existing ties, as well as the seabed. Different from the axial force responses of ties, horizontal displacement of the quay-wall became larger in proportion to the input acceleration magnitude in both sections. According to the displacement difference between the anchor section and the seabed, magnitude of the seaward rotation of the quay-wall on the reinforced section is larger than that of the un-reinforced section.

Figure 2.11 shows the displacement vector distributions of quay-walls and the back yard ground surface determined by image analysis. Vertical deformation of the ground surface is also reduced on the reinforced section. In addition, the deformation dispersed in the reinforced section, while the deformation is locally concentrated in the un-reinforced section. This will be strong advantage on the reservation of marine transportation during post earthquake recovery.

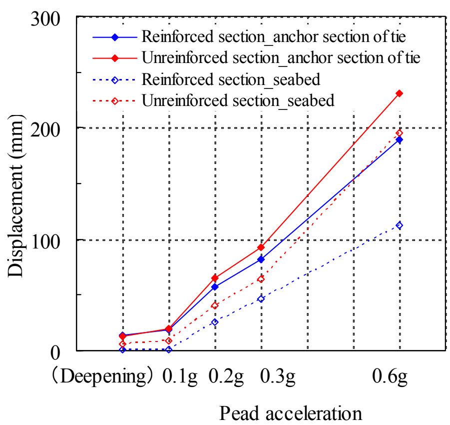


Figure 2.10 Comparison of the maximum horizontal displacement of quay-wall (Sea ward +)

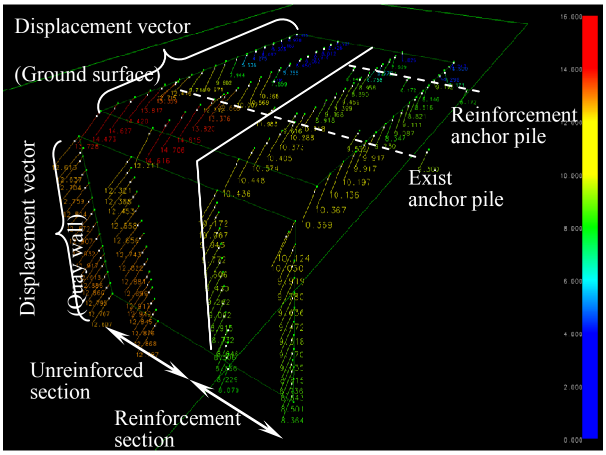


Figure 2.11 Deformation of quay-walls and back yards determined by image analysis (Sea ward: left)

3. NUMERICAL SIMULATION

Numerical simulation utilizing the two dimensional effective stress analyses were conducted to investigate the applicability of the code on evaluating the seismic performance of the dual anchored sheet pile wall (DASPW) prior to the actual application.

3.1. Procedures

3.1.1. Numerical code

2D Dynamic FEM code "FLIP" developed basing on the effective stress theory, was used for the simulation. The constitutive model for soil, named "Multi-spring model" developed for simulating the liquefaction phenomena by Iai (1990), was introduced to the code.

3.1.2. Model

Simulations model was prepared in model scale as shown in **Figure 3.1**. Because of utilizing the rigid container in the centrifuge experiment, rigid boundary condition was applied to the FEM on both base and side of the model. Model parameters were configured in accordance with structural properties of model members and the dynamic characteristics of sand. Beam elements were utilized for structural members. Initial stress analyses, conducted prior to the dynamic analyses, were performed in accordance with the model preparation and the centrifugation process, as discussed in section *2.3.3*.

3.1.3. Simulation case

Simulations were conducted on CASE-A200 and CASE-A600 of the centrifuge experiments, as shown in **Table 3.1**. Input motions were derived from the recorded data at the shake table during the experiment, as shown in **Figure 3.2**.

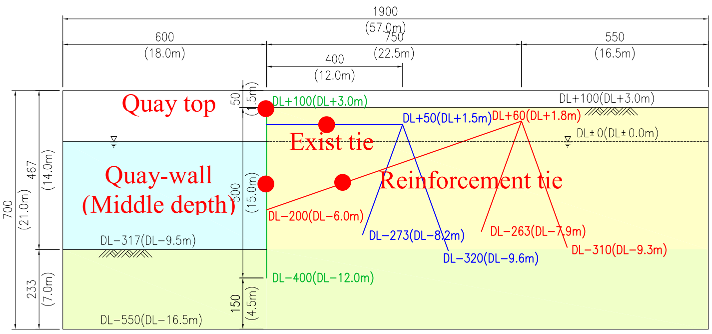


Figure 3.1 Simulation model and locations of major outputs for comparison

Table 3.1 Simulation case

FLIP case	Peak acceleration	Notes
CASE-A200	72.6 m/s^2	Simulation of CASE-200 (0.2g)
CASE-A600	218.7 m/s^2	Simulation of CASE-600 (0.6g)

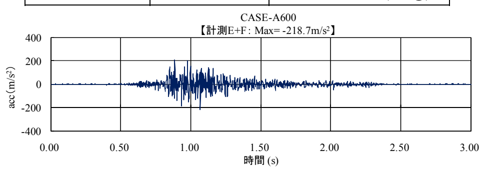


Figure 3.2 Input motion (CASE-A600)

3.2. Result

3.2.1. Responses of the model

To confirm the dynamic response of the model, deformation of whole model at CASE-A200 is shown in **Figure 3.3**. Deformation in both quay-wall and back yard are similar to the deformation determined by after measurement, as shown in **Figure 2.11**. Displacements of the quay-wall are similar in both tie anchor section and seabed, about 50mm, with comparing that of shown in **Figure 2.10**.
Time histories of representative responses at CASE-A200, acceleration, displacement, bending moment of the quay-wall and axial force of existing tie, compared with the experiment results, are shown, in **Figure 3.4**. There are good agreement between the experimental data and analytical results on acceleration and horizontal displacement responses of the quay top. Analysed dynamic responses (oscillation components) of the bending moment of the quay-wall and both ties are also similar to that of recorded in the experiment, as well. It is pointed out that difference between the analyzed responses and the recorded responses are mainly due to the initial condition, which was calculated by the initial stress analysis. Therefore, initial stress condition should be carefully investigated with regard to the stability and safety of the quay.

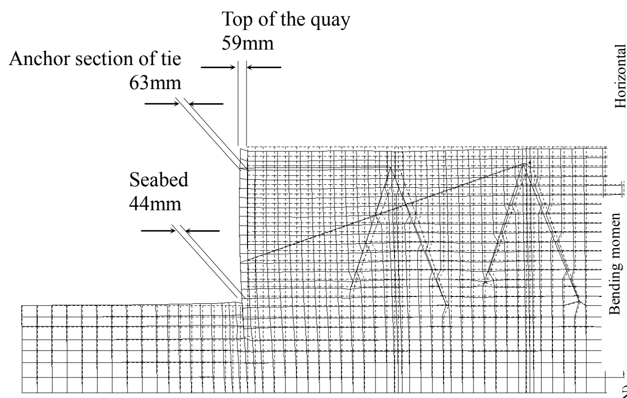
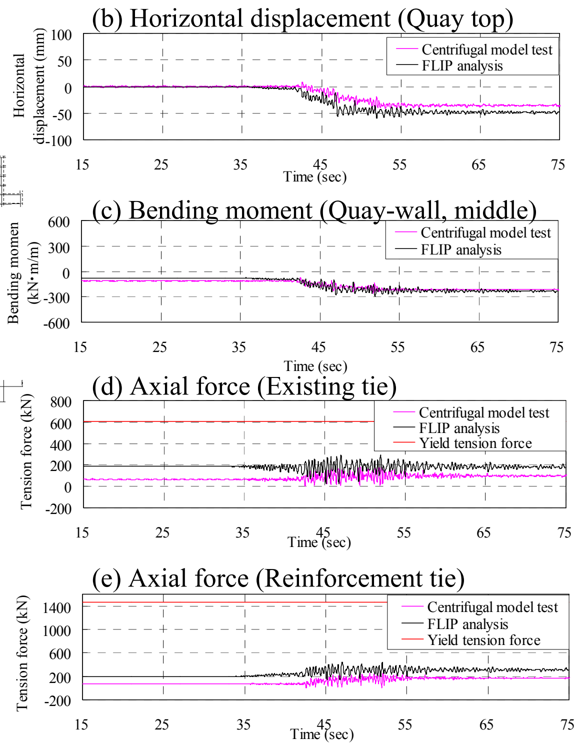


Figure 3.3 Deformation of whole model
(Maximum deformation, CASE-A200)



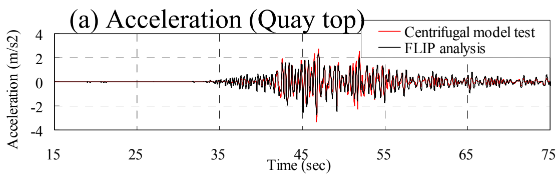


Figure 3.4 Representative time history responses of the FLIP analysis (CASE-A200)

3.2.2. Summaries of dynamic responses

Summaries of compared maximum seismic responses on CASE-A200 and CASE-A600 are shown in **Table 3.2**. Followings are pointed out.

(1) Acceleration responses of quay-wall are slightly small in the analyses.
(2) Horizontal displacements on the quay-wall are about 20% to 80% larger in the analyses.
(3) Bending moments of the quay-wall and axial forces generated on ties are about 20% to 90% larger in the analyses, as well.
(4) Axial forces acting on anchor piles are 1.3 times to 4.7 times larger in the analyses.

Table 3.2 Summaries of compared seismic responses on CASE-A200 and CASE-A600

Items		CASE-A200 (0.2g event) Analysis (A)	CASE-A200 (0.2g event) Experiment (B)	CASE-A200 (0.2g event) Ratio (A/B)	CASE-A600 (0.6g event) Analysis (A)	CASE-A600 (0.6g event) Experiment (B)	CASE-A600 (0.6g event) Ratio (A/B)	Notes
Acceleration amplitude of top of the quay (m/s^2)		2.76	3.36	0.82	4.87	5.05	0.96	
Horizontal displacement (mm)	Anchor section of exist tie	-63	-44	1.43	-213	-176	1.21	Only increment during seismic event
	Seabed	-44	-25	1.77	-144	-111	1.29	
Maximum bending moment of quay-wall sheet pile (kNm/m)		293	261	1.12	447	364	1.23	Section force of deepening + Increment during seismic event
Maximum axial force of exist tie (kN/tie)	Exist tie	292	180	1.62	378	233	1.62	
	Reinforcement tie	444	256	1.73	590	305	1.94	
Maximum axial force of exist anchor pile (kN/pile)	Compression force	-460	-189	2.44	-595	-300	1.98	
	Tension force	461	323	1.43	595	451	1.32	
Maximum axial force of reinforcement anchor pile	Compression force	-722	-154	4.69	-952	-269	3.54	
	Tension force	544	264	2.06	711	405	1.76	

As mentioned in previous section, difference between the analyzed responses and the recorded responses are mainly due to the initial stresses. In spite of this, analyzed oscillation components are well simulated that of recorded in the experiment.

Major cause of divergence on the initial stress of the structures between the experiment and the analyses are presumed as follows.

(a) There are differences on the estimation of the ground stiffness for the initial stress analysis during the centrifugation process. Although actual ground stiffness is gradually increased in proportion to the centrifuge gravity, stiffness assumed for the initial stress analysis is the final values after the centrifugation. Therefore, stiffness of the ground, especially at the tip of the anchor pile, is over estimated and large initial stress is generated on the piles.

(b) Because shake events were conducted in sequence at the centrifuge experiment, initial stress conditions are adjusted to the initial values after the centrifugation for processing the experiment data. Thus, initial condition is different in the experiment and the analysis.

With regard to these conditions, analyzed member responses are lower enough in terms of the strength or the elastic limit of the member.

4. APPLICATION FOR THE SITE

Basing on these researches, DASPW method was applied to the seismic retrofit project carried out at the port of Sendai and completed in November, 2010. On the 11th of March, 2011, the port of Sendai was smashed by the 2011 Great East Japan Earthquake. Fortunately, the quay applied this method had no damage and utilized for the restoration operation soon after.

4.1. Seismic design of Raijin wharf

Because of the demand of landing and loading usage of larger car carrier, deepening of the quay were planned at Raijin wharf on the port of Sendai, Miyagi prefecture (**Figure 4.1**). Representative cross section plan of Raijin wharf after deepening is shown in **Figure 4.2.**

Figure 4.1 Photo of Raijin wharf on port of Sendai

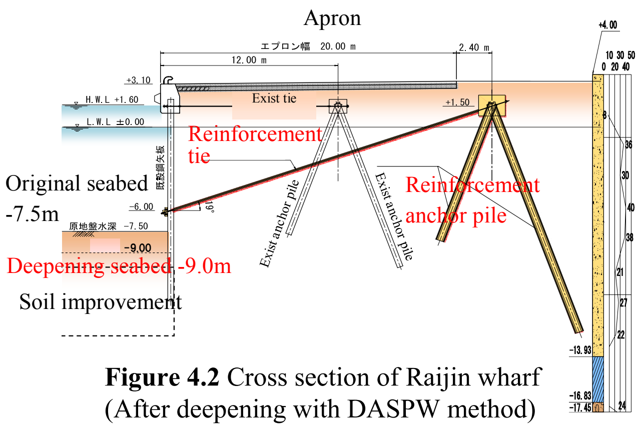


Figure 4.2 Cross section of Raijin wharf (After deepening with DASPW method)

Due to the demand of landing of larger car carriers, it was planned that seabed of the wharf lowered to DL=-9.0m from DL=-7.5m, on the section of about 400m, after completion of the project. The wharf is also required to retrofit as a high earthquake-resistance facility for post earthquake disaster restoration. In addition, execution of the construction work was required under port operations. Thus, DASPW method by UGETS was chosen as retrofitting work.

Seismic coefficient for the operation base earthquake was set as k_h=0.14. Because of the excavated wharf, the ground condition is stiff enough. Thus, liquefaction was not expected on this site. Residual horizontal displacement of the wharf allowed after the severe earthquake was set as 300mm.

Dynamic response analysis, utilizing the code “FLIP” was required for the verification of the seismic performance in case of the severe earthquake (Level-2). 4 motions, expected Miyagiken-oki earthquakes were the one among of these, were proposed for this purpose. The motions were defined at the base stratum (Soft rock, Vs=530m/s). At most 160mm residual horizontal displacement of the wharf was found from the result of FLIP analysis performed with these motions.

4.2. Verification

4.2.1. Damage due to earthquake

Seismic intensity of an upper 6 and 8m high tsunami attack in succession by the 2011 Great East Japan

Earthquake, surrounding area of port of Sendai was seriously damaged. Though minor settlement was observed at the apron, no major damage was found on the quay-wall, as shown in **Figure 4.3**.

4.2.2. Comparison of observed and design seismic motions

Seismic motions used for the seismic design, as mentioned in previous section, and observed motions near the site are compared. One is the strong motions recorded during the 2011 Great East Japan Earthquake at K-net Shiogama station (MYG012). Another is the estimated base strong motion at Takasago wharf, opposite side of the port, by PARI (2011).

Comparison of the acceleration responses of base motions are shown in **Figure 4.4**. As it is seen, responses of observed motions are almost equivalent to the design motion spectra. This is consistent with the minor damage of the Raijin wharf at the 2011 Great East Japan Earthquake.

Figure 4.3 Photo of Raijin wharf afer earthquake and tsunami attack
(Photo was taken on 2011, March, 14)

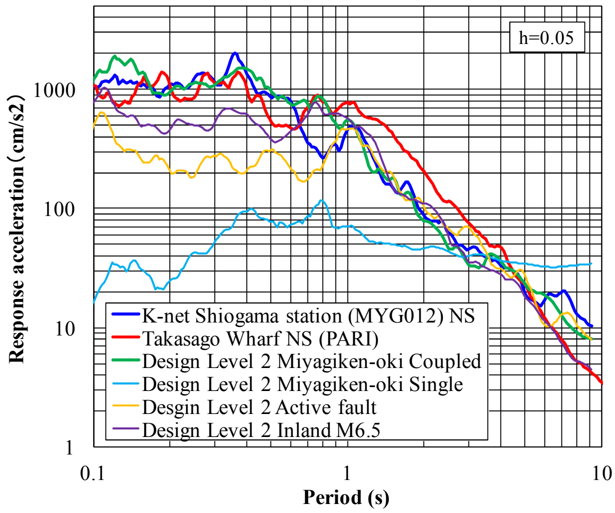


Figure 4.4 Comparison of the acceleration responses of base motions

5. CONCLUSIONS

Following are concluded by this research.

(a) By applying the DASPW method, bending moment of the quay-wall can be reduced by 50%.
(b) By applying the DASPW method, axial force of existing ties can be reduced by 30%.
(c) From a view point of quay-wall deformation, rigid anchor structure, such as buttered pile is suitable for DASPW.
(d) Dynamic responses of the DASPW observed in the centrifuge test were well simulated by the dynamic FEM code FLIP. Thus, the applicability of the code was verified.
(e) Seismic performance of the applied DASPW is verified by comparing the acceleration responses of observed severe earthquake motions on site and that of design motions.

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