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Numerical Simulations for the Port Structures Damaged Due to Ground Motion During the 2011 Off the Pacific Coast of Tohoku Earthquake

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ABSTRACT

Many port structures were damaged over a wide area by the 2011 off the Pacific Coast of Tohoku earthquake. Especially the quay walls damaged by both the ground motion and the tsunami were observed more remarkably in the south of the epicenter. Although it is supposed that the damage due to liquefaction before the tsunami induced severer damage, it is unknown how severely liquefaction and damage to the quay walls occurred during the earthquake. In order to clarify it, this study examined some numerical simulations using the strain space multiple mechanism model (called the cocktail glass model) as a geotechnical constitutive model for the port structures. Based on the results of this study, it was found that the cocktail glass model taking permeability into account is applicable to evaluate seismic performance such as deformation of the port structures against strong and long duration ground motion.

Introduction

Many port structures were damaged over a wide area by the 2011 off the Pacific Coast of Tohoku earthquake. Especially the quay walls damaged by both the ground motion and the tsunami were observed more remarkably in the south of the epicenter (e.g. Takahashi et al., 2011). As the reason for that the damage was concentrated in the south side, it is supposed that the characteristics of the source rupture process of the earthquake and sites are influential. As for the mechanism of damage to the quay walls, it is supposed that the damage due to liquefaction before the tsunami induced severer damage. However, the evidences of the liquefaction and the damage to the port structures due to the ground motions have disappeared by the tsunami. Therefore, it is important to predict soil liquefaction and damage to the port structures due to the ground motion by taking property of the ground motion into account. In order to clarify how severely soil liquefaction occurred and analyze the mechanism of damage to the quay walls due to the ground motions, this study examined some numerical simulations using the strain space multiple mechanism model (one of these models is called the cocktail glass model) as a geotechnical constitutive model (Iai et al., 2011). Since the duration of the ground motion induced the damage to the port structures was longer than 100sec, it is valuable to use the cocktail glass model taking permeability in saturated soil into account as well as dilatancy. This model has been developed by Iai et al. (2011) recently, but there are only a few examples that

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verify the applicability for various earth structures and for various ground motions. Therefore, the port structures for simulation in this study were selected from the quay walls whose damage has been investigated well in order to verify the applicability of this model.

Quay walls for simulation

The locations of the quay walls for simulation are shown in Figure 1. Soma port and Onahama port are located at about 170km and 215km from the epicenter of the earthquake respectively. After the earthquake and the tsunami, whose height was more than 9m in Soma port and more than 3m in Onahama port, several quay walls were seriously damaged due to both the earthquake and the tsunami in each port. In Soma port, the quay wall of the steel pipe sheet pile type in No.2-wharf was selected for simulation. This quay wall did not suffer serious damage in comparison with other damaged quay walls in this port. In Onahama port, in the same way as Soma port, the quay walls of the steel pipe sheet pile type in No.3-wharf and the caisson type in No.5-wharf were selected for simulation. The Cross sections and deformation of these quay walls are shown in Figure 2. The horizontal displacement has been measured as a distance from the reference point where movement was not observed after the earthquake in each quay wall. The vertical displacement has been measured excluding the vertical component of the diastrophism.

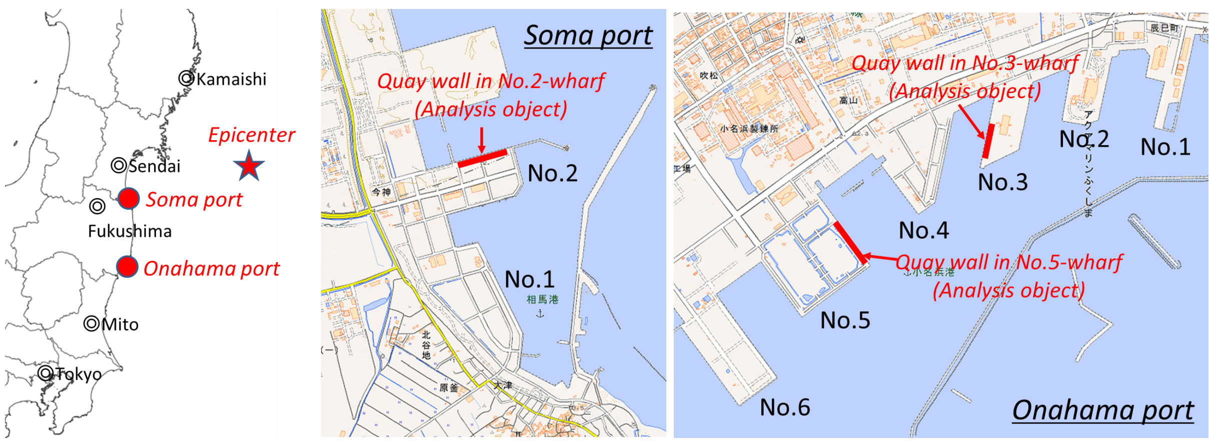

Figure 1. Locations of the quay walls for simulation

Ground motions

The acceleration time histories on the engineering base surface in Soma and Onahama port have been derived by Nozu et al. (2011) from the strong motion records and the site characteristics. Their acceleration time histories and acceleration response spectra of dumping ratio 5% in the normal direction to the quay walls line are shown in Figure 3. As shown in the figure, the peak acceleration as well as the response spectrum in Soma port is smaller than both of the two quay walls in Onahama port, even if Soma port is nearer the epicenter in comparison with Onahama port. In addition, the two peak accelerations as well as the two response spectra in Onahama port are different from each other even in the same port.

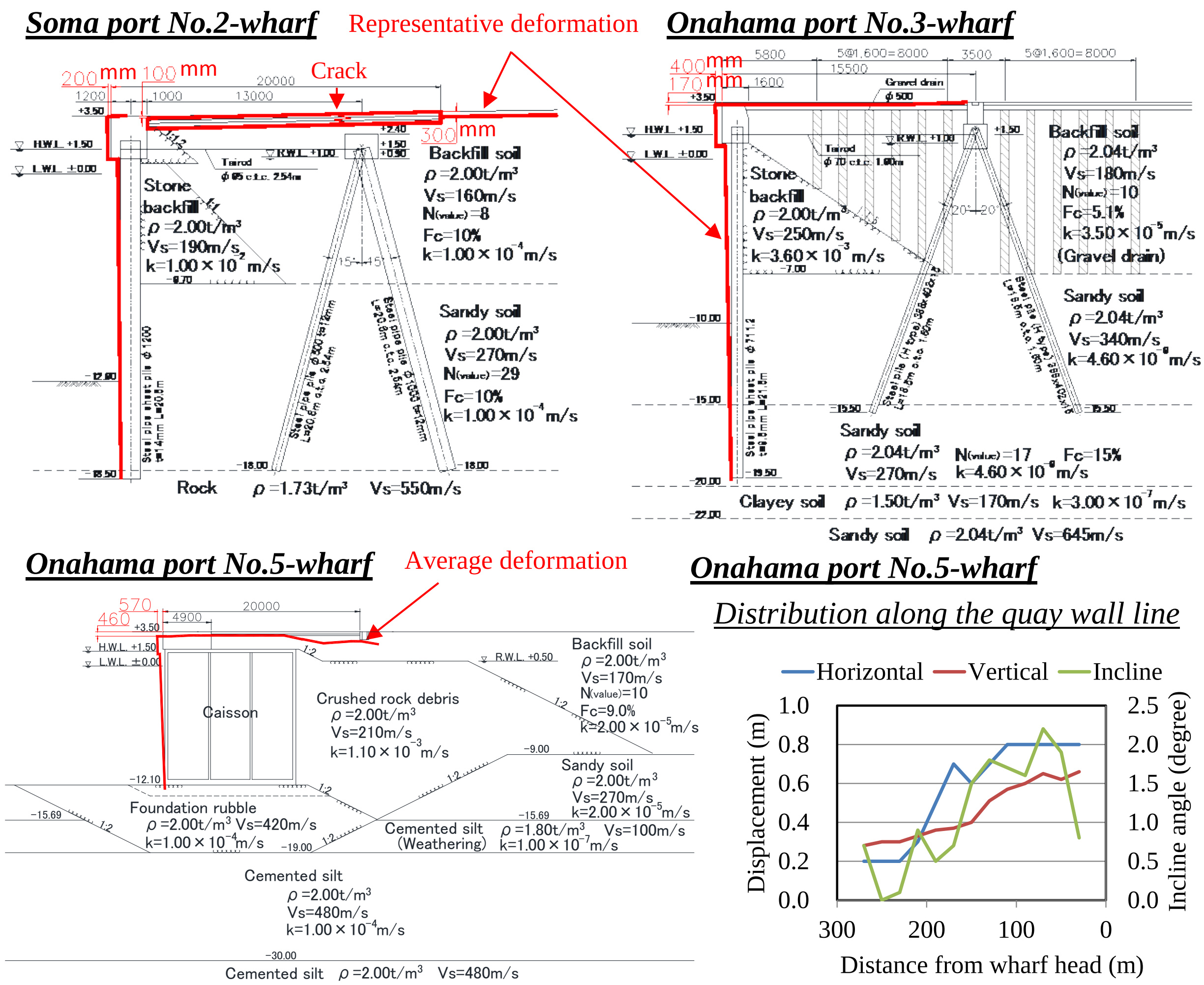

Figure 2. Cross sections and deformations of the quay walls for simulation

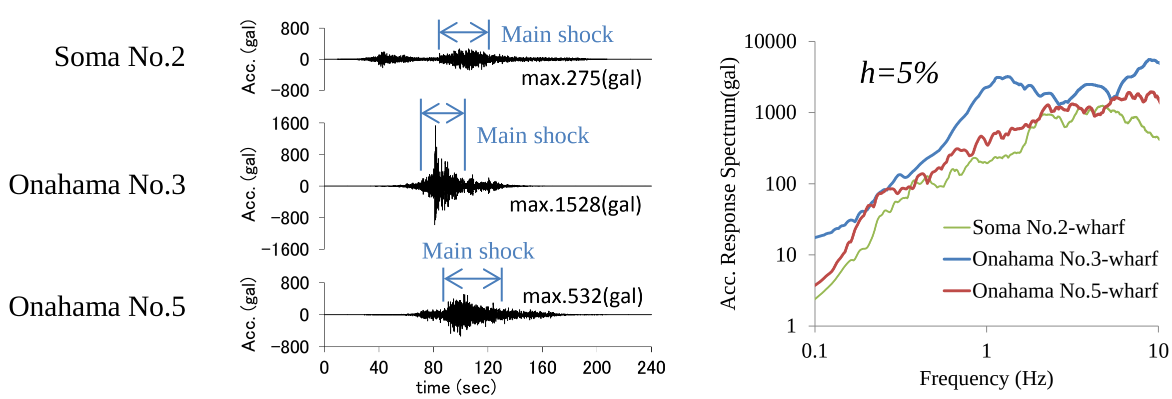

Figure 3. Ground motions at the sites of the quay walls

Conditions for numerical simulation

In the two-dimensional finite element analysis program used in this study, not only the cocktail glass model but also another type of the strain space multiple mechanism model (called the multi-spring model) has been implemented (Iai et al., 1990). In addition, the other various type elements have been implemented in this program so that complex soil-structure-foundation-water interaction can be taken into account. Although the multi-spring model is valid only under undrained condition without permeability, this model has been used in the analysis of numerous problems in practice for evaluating the seismic performance of geotechnical works (e.g. Iai et al., 1993, Iai et al., 1998) by the reason that it is applicable to evaluate seismic performance against short duration ground motion. In this study, in order to evaluate the permeability effect and compare with such an applicable model, numerical simulations using both the cocktail glass model and the multi-spring model were performed.

Soil conditions

The composition and the main properties of the soils at each quay wall are shown in each cross section in Figure 2. The shear velocity (Vs) of each soil was calculated at the center of the depth of each layer using the relationship between shear velocity, density and shear modulus. The shear modulus, except that of the stone backfill and the foundation rubble, was calculated using the method proposed by Morita et al. (1997). In this method, SPT N-value, which was obtained from each layer in each wharf, is used. The shear velocity of the stone backfill and foundation rubble was calculated in the center of the depth of each layer, based on the shear modulus which was obtained assuming that the shear velocity is 300m/s at the effective mean stress of 98kPa, and that the shear modulus varies with the effective mean stress raised to the power law of 0.5. The soils considering liquefaction are the backfill soils at all of the quay walls, the sandy soil at the quay wall in Soma No.2-wharf and the sandy soil layered on the elevation -15m to -20m at the quay wall in Onahama No.3-wharf. The liquefaction properties and the multi-spring model parameters of their soils were obtained using the method proposed by Morita et al. (1997). In this method, SPT N-value and fine fraction content (Fc) are used. The cocktail glass model parameters were also obtained so that the liquefaction properties of the cocktail glass model could match those of the multi-spring model. At the quay wall in Onahama No.3-wharf, a part of the backfill soil has been improved by gravel drain. In order to evaluate the drain effect of the gravel drain, two simulation cases, whether the back fill soil is improved by the gravel drain or not, were conducted in this study. At the quay wall in Onahama No.5-wharf, the crushed rock debris has been backfilled behind the caisson. As it is supposed that the dilatancy of this debris affects the settlement on the ground surface, the simulation case using the dilatancy property provided by Yamazaki et al. (2012) was also conducted.

Structural modelling

The structural modelling concept for the caisson type and the steel pipe sheet pile type quay wall are shown in Figure 4. In the case of the caisson type, the joint element was used for the contact surface between caisson and soil, and between caisson and foundation. This joint element for the contact surface between two objects can consider contact or non-contact in the normal direction to the contact surface and friction in the parallel direction to the contact surface. In the case of

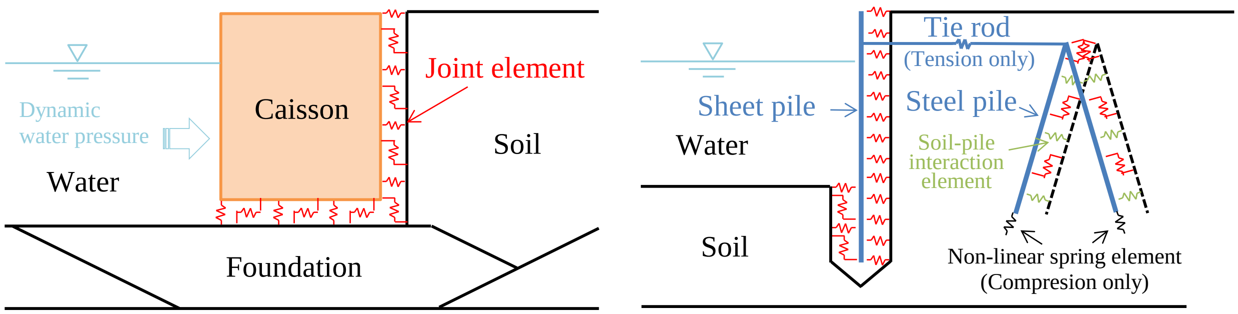

Figure 4. Structural modelling concept (Left: Caisson type, Right: Steel pipe sheet pile type)

the steel pipe sheet pile type, the different types of the joint element were used for the each contact surface as shown in Figure 4. For the front of the steel pipe sheet pile, the type considering both contact/non-contact and friction was used. For the back of the steel pipe sheet pile, only the contact/non-contact type was used. For the surface along the anchored steel piles, only the friction type was used. However, at the present study, it is unknown what frictional resistance angle is appropriate for this type of joint element. In this study, the two simulation cases using 15degree as a wall friction angle and 40degree as a contact soil internal friction angle were considered at the quay wall in Soma No.2-wharf. In the case of the steel pipe sheet pile type, the other three type elements were used. The first one is the non-linear spring element with tension only for the tie rod. The second one is the non-liner spring element with compression only that can consider the interactive action between the soil and the bottom of the anchored steel pile. The third one is the soil-pile interactive action spring element that can consider the interactive action between the soil and the side of the anchored steel pile in the normal direction to the axis of the pile. In order to take dynamic water pressure into account, the water element was also used in the cases of all quay wall types. The caisson was modelled with a linear elastic material. The steel pipe sheet pile and the anchored steel piles were modelled by a non-linear beam element, in order to appropriately evaluate seismic performance of the quay wall structures even when their stresses exceed over the yield stress.

Simulation cases

Table 1 shows the simulation cases in this study. In the table, “Multi” is to use the multi-spring model, “Ctgl” is to use the cocktail glass model, “Friction15” and “Friction40” are to use 15degree and 40degree as a frictional resistance along an anchored steel pile respectively, “Gravel” is to take gravel drain in backfill soil into account, and “CDR-dilatancy” is to take dilatancy of crushed rock debris into account.

Table 1. Simulation cases in this study

Quay wall	Case-1	Case-2	Case-3
Soma No.2-wharf	Multi;Friction40	Ctgl;Friction15	Ctgl;Friction40
Onahama No.3-wharf	Multi;Friction15	Ctgl;Friction15	Ctgl;Friction15;Gravel
Onahama No.5-wharf	Multi	Ctgl	Ctgl;CRD-dilatancy

Numerical simulation results

The simulated results in Soma No.2-wharf are shown in Figure 5. In the figure, the excess pore water pressure is that at the time of 240sec after the ground motion, and the lateral displacement and the settlement are those at the time when the excess pore water pressure has dissipated perfectly except Case-1. The lateral displacement in Case-1 is coincident with the observed value. This indicates that the multi-spring model is applicable to evaluate the lateral displacement even if the duration of ground motion is longer than 100sec, but only if the peak ground acceleration of ground motion is less than about 300gal (in this case, 275gal). The reason for that the settlement in Case-1 is less than the observed value is that this model cannot take permeability into account. On the other hand, both the simulated settlement and lateral displacement in Case-3 are coincident with the observed values, but those in Case-2 are greater than the observed values. These indicate that the cocktail glass model is applicable to evaluate the deformation of the quay wall if an appropriate frictional resistance angle is used. Although the excess pore water pressure ratio at the time of main shock is omitted due to the limited space in this paper, it is almost 1.0 in the backfill soil in both Case-2 and Case-3. Based on these results, it is indicated that the deformation at the quay wall in Soma No.2-wharf was induced by the liquefaction of the backfill soil during the earthquake and the excess pore water pressure had dissipated before the tsunami.

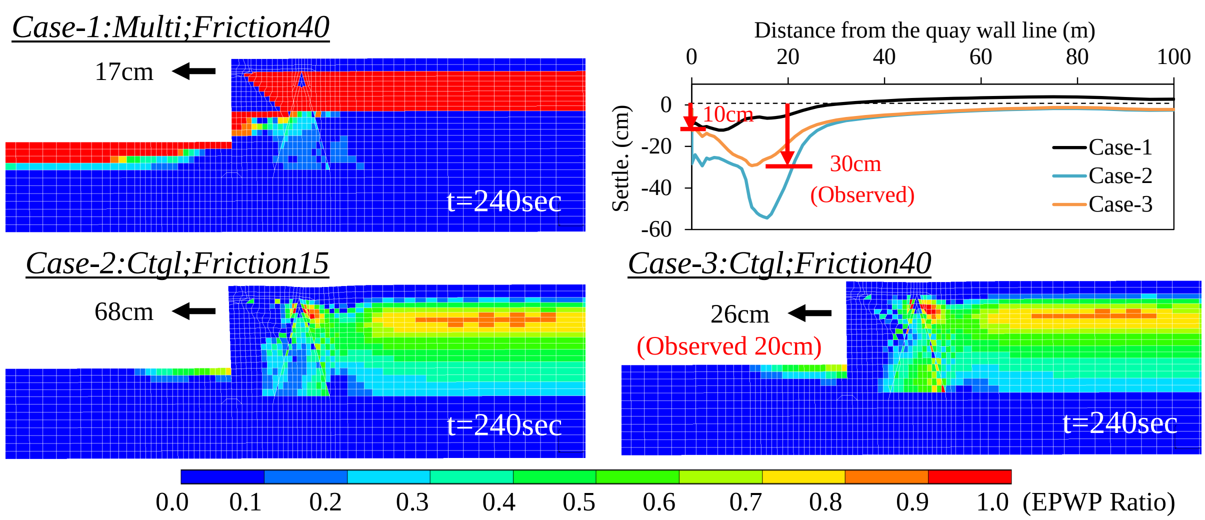

Figure 5. Simulated deformation and excess pore water pressure ratio in Soma No.2-wharf

The simulated results in Onahama No.3-wharf are shown in Figure 6. The contents of this figure are the same as Soma No.2-wharf. Although the excess water pressure ratio at the time of main shock is omitted, it is almost 1.0 in the backfill soil in all cases. The lateral displacement in Case-1 using the multi-spring model is larger than that in Case-2 using the cocktail glass model. On the other hand, the lateral displacement in Case-3 taking gravel drain into account is about 1/1.5 times of that in Case-2 and closer to the observed value than that in Case-2. As for the time until when the excess pore water pressure in the backfill soil has perfectly dissipated in Case-3, it is shorter than that in Case-2. These results indicate that the gravel drain in the backfill soil can reduce the damage due to the strong and long duration ground motion even if the liquefaction occurs.

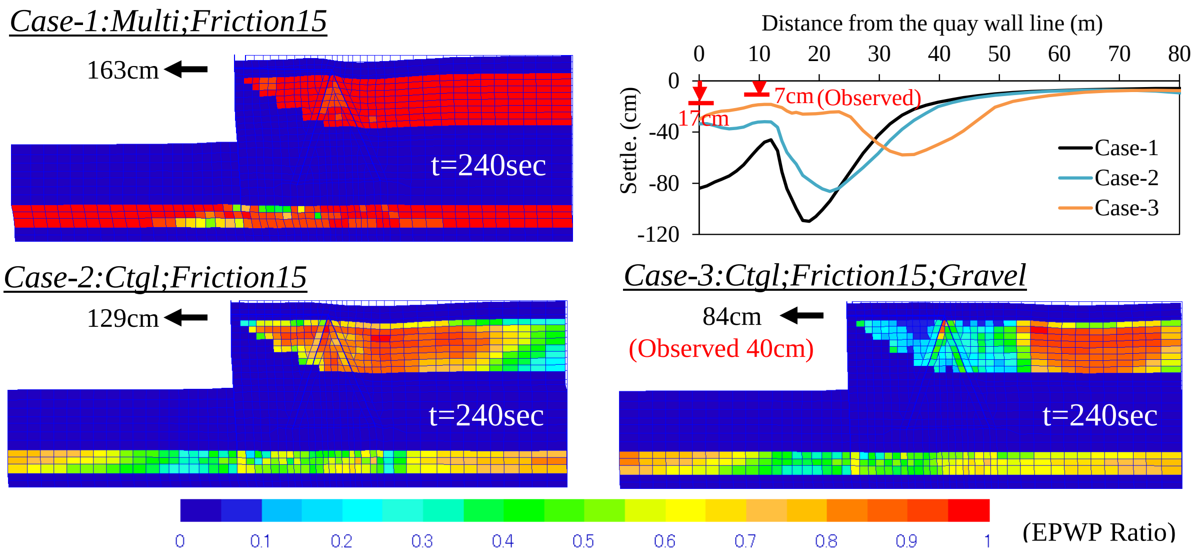

Figure 6. Simulated deformation and excess pore water pressure ratio in Onahama No.3-wharf

The simulated results in Onahama No.5-wharf are shown in Figure 7. Although the lateral displacement and the incline angle of the caisson in Case-1 seem to be coincident with the observed values, the lateral displacements in the cases using the cocktail glass model (i.e. Case-2 and Case-3) are less than the observed minimum value (20cm). Considering that the multi-spring model cannot take permeability into account, the displacement of the caisson due to the liquefaction of the backfill soil in Case-1 must be greater than a true value. This means that the observed deformation of the caisson includes the deformation due to the scour in the foundation rubble while the tsunami. Based on these considerations, it is expected that the numerical simulation using the cocktail glass model can appropriately predict the deformation of the caisson due to the ground motion. In addition, the settlement on the backward ground surface of

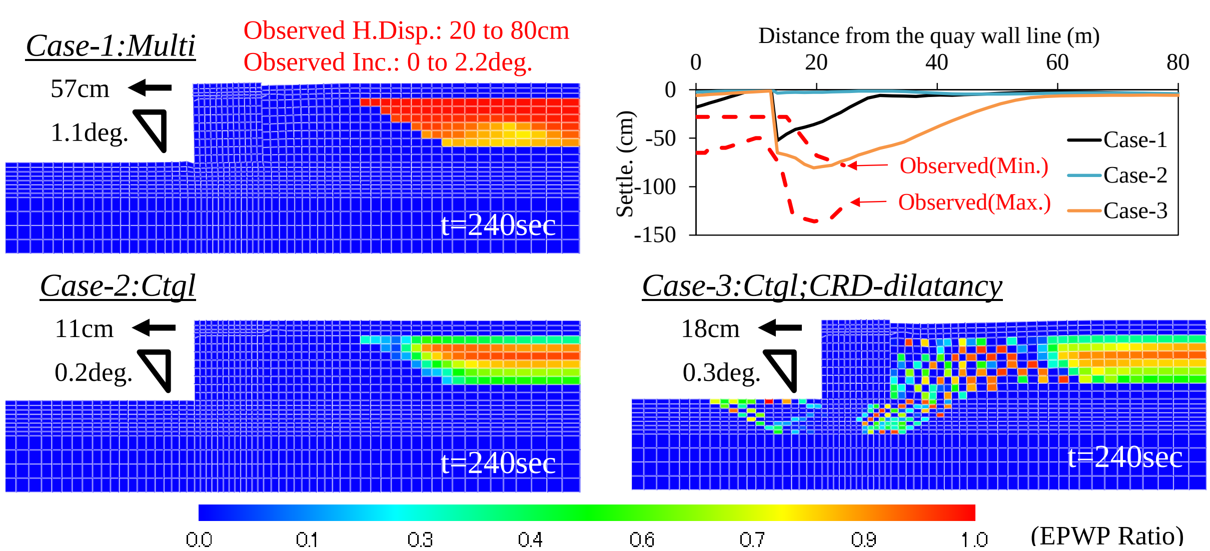

Figure 7. Simulated deformation and excess pore water pressure ratio in Onahama No.5-wharf

the caisson in Case-3 is coincident with the observed value. It indicates that it is necessary to take dilatancy into account for the crushed rock debris in numerical simulation.

Conclusions

The results obtained by the numerical simulations of the damaged port structures due to the ground motions using the strain space multiple mechanism model (i.e. the multi-spring model and the cocktail glass model) are summarized as follows. (1)It is indicated that the effect of the tsunami to the deformation of the quay walls can be reduced if the port structures retain the structural stability and the excess pore water pressure dissipated in the backfill soil before the tsunami, although the soil liquefaction occurred in wide area. (2)The multi-spring model limited to undrained condition is applicable to evaluate lateral deformation of the port structure against the ground motion of low peak ground acceleration even if the duration of the ground motion is longer than 100sec. (3)The cocktail glass model taking permeability into account is applicable to evaluate seismic performance such as deformation of the port structures against strong and long duration ground motion. However, it is necessary to use an appropriate frictional angle along anchored steel piles in the case of anchored sheet pile type, and an appropriate dilatancy property of the crushed rock debris in the case of the quay walls using this debris as backfill.

Acknowledgments

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