Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Seismic response analyses of the pile foundation of the abutment on the soft soil layer

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ABSTRACT: The purpose of this study is to obtain the seismic response of the abutment on the liquefaction ground. Especially, the bending moment of the piles and the horizontal displacement of the abutment are focused on. Firstly, from the analytical results by using the periodical wave, the bending moment and the displacement of the piles on the liquefaction ground becomes larger than the ones on the non-liquefaction ground. Secondary, from the analytical results by using the observed seismic wave, the behaviour of the piles and the abutment changes with the periodic characteristic of the seismic wave and the characteristics of the ground. Therefore, it is needed to use some input seismic waves when the abutment on the liquefaction ground is designed.

1 INTRODUCTION

In the 2011 off the Pacific Coast of Tohoku earthquake, the step due to subsidence of the backfill soil of the abutment and the horizontal movement of the abutment were observed because the lateral flow was generated in the soft ground because of the severe ground excitation. In this study, to grasp the amount of the subsidence of the soil or the horizontal displacement of the abutment, effective stress analyses on the soft ground were conducted. In the analyses, the physical properties value of the soil, the location of the soft ground layer (the liquefaction layer) and the characteristic of the input seismic waves are changed.

2 ANALYTICAL CONDITION FOR 2 DIMENSIONAL EFFECTIVE STRESS ANALYSIS

The analyses are conducted by the general-purpose software "FLIP" based on the finite element theory (Iai, 1992). Figure 1 shows the model of the soil layers and Table 1 shows the characteristic values of the soil layers. Table 2 shows the horizontal stiffness (Kn), the vertical stiffness (Ks) and angle of internal friction between the footing and the ground or between the piles and the ground. Table 3 shows the material values of the piles. The properties of the joint elements as shown in Table 2 are determined by the design examples of the harbour structures. The surface of the groundwater level is set to be the bottom surface of the footing. The boundary condition of both sides of the model and bottom of the model is set to be the viscous boundary.

Layer 3 (N-value is 2) is supposed to be the liquefaction layer. Numerical integration method is adopted as Willson's θ method ($\theta = 1.4$) and Rayleigh damping ($\alpha = 0$, $\beta = 0.002$) is adopted in this analysis. The abutment is modelled as the linear plane element, the pile is modelled as the linear beam element and the soil is modelled as the effective stress model based on the multiple shear mechanism (Towhata, 1985). In this model, the top of the pile is fixed perfectly with the bottom of the footing. The viscous boundary condition is given to the bottom and the both side of the soil layers model. To reproduce that the soil move through between the piles, the nonlinear spring element connected between the pile and the soil layer are installed. The input wave is the sine wave whose maximum velocity is 50cm/sec. To keep the input energy constant, the period of the sine wave is only changed. Figure 2

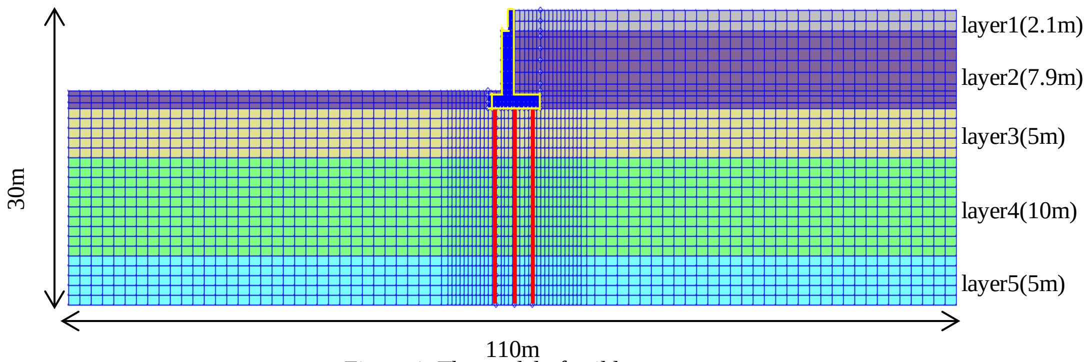


Figure 1. The model of soil layer

Table 1. The physical property of the ground model

Gronud layer	D	N	ρ_t	σ_{ma}'	G_{ma}	φ_f	φ_p	Liquefaction parameter				
	Thickness	N-value	Density	Effective confining pressure	Shear modulus	Shear resistance angle	Phase change angle					
	(m)	-	(t/m^3)	(kPa)	(kPa)	(°)	(°)	S1	W1	P1	P2	C1
Layer1	2.1	5	1.8	14	42202	39	-	-	-	-	-	-
Layer2	7.9	10	1.8	80	67613	39	-	-	-	-	-	-
Layer3	5	2	2	151	22632	37	28	0.005	3.476	0.5	1.123	1.6
Layer4	10	10	2	206	67613	38	-	-	-	-	-	-
Layer5	5	20	2	261	108326	39	-	-	-	-	-	-

Table 2. The physical property of the joint element

	Static analysis			Dynamic analysis		
	Kn	Ks	φj	Kn	Ks	φj
Side of footing	1000000	0	15	1000000	1000000	15
Base of footing	1000000	1000000	31	1000000	1000000	31
Pile	0	0	15	0	1000000	15

Table 3. The physical property of the piles

Density(t/m^3)	9.4
Poisson's ratio	0.3
Shear elastic modulus of rigidity(kN/m^2)	9.23×10^7
Diameter(m)	0.8
Cross-sectional area(m^2)	0.02469
Geometrical moment of inertia(m^4)	0.0019

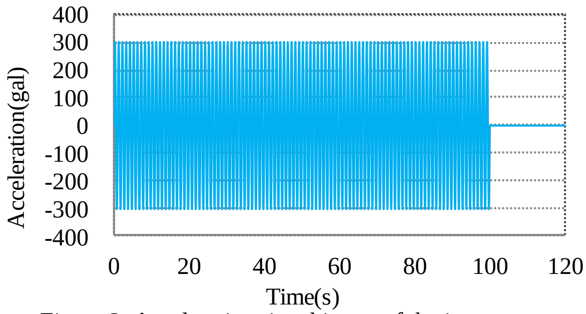


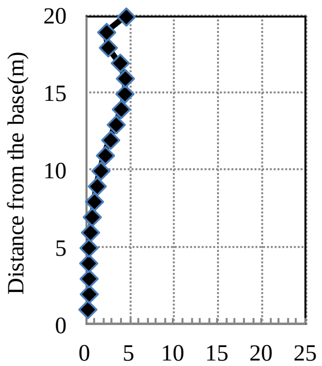
Figure 2. Acceleration time history of the input wave

shows an example of the input waves whose period is 1 second.

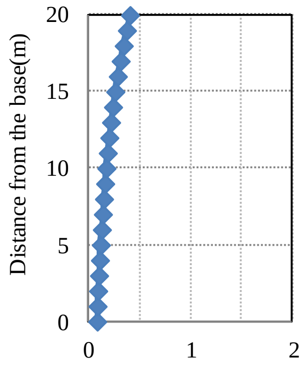
3 ANALYTICAL RESULT (IN THE CASE OF SINE WAVE)

3.1The effect of liquefaction

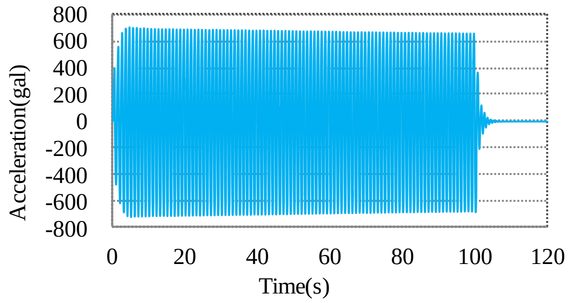
Firstly, the physical properties of layer 3 is regarded as the same ones of Layer 4. So liquefaction is not considered. Figure 3 shows the maximum bending moment of the pile, the maximum displacement of the pile and the time history of the ground surface acceleration. The period of the input wave is 1 second. Likewise, Figure 4 shows the results in the case that the N-value of Layer 3 is 2 and the period of the input wave is 1 second. Liquefaction occurred.in this case. Figure 5 shows the deformation figures at the end of the analysis. By the generation of liquefaction, the response acceleration of the ground surface



Max moment(MN・m)



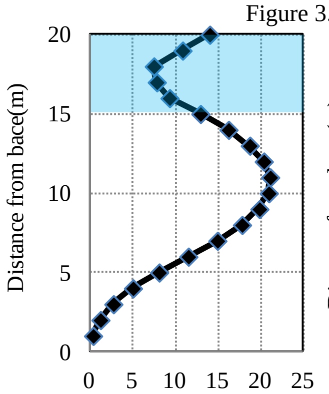
Max displacement(m)



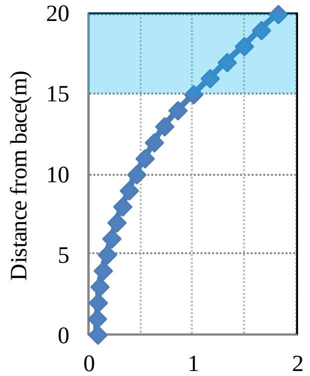
(c) Acceleration time history at the ground surface

(a) Max moment of the pile (b) Max displacement of the pile

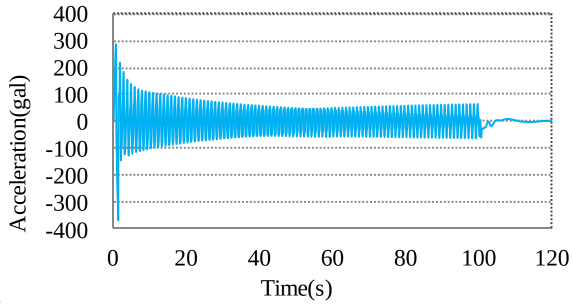
Figure 3. Result of this analysis (Input wave's period:1.0s, Non-liquefaction layer)



Max moment(MN・m)



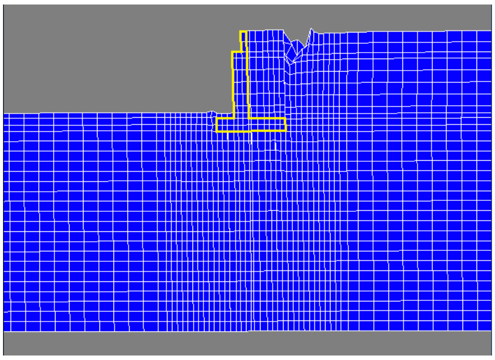
Max displacement(m)



(c) Acceleration time history at the top of embankment

(a) Max moment of the pile (b) Max displacement of the pile

Figure 4. Result of this analysis (Input wave's period:1.0s, liquefaction layer)


(a) Non-liquefaction

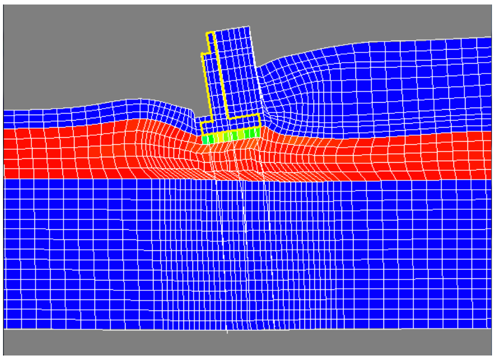
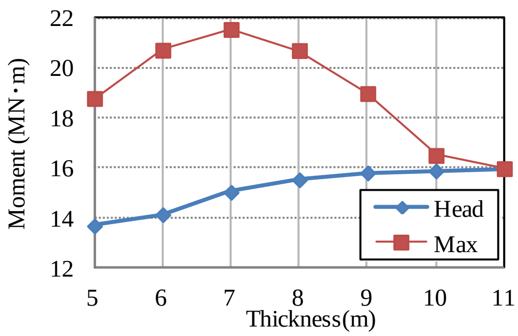
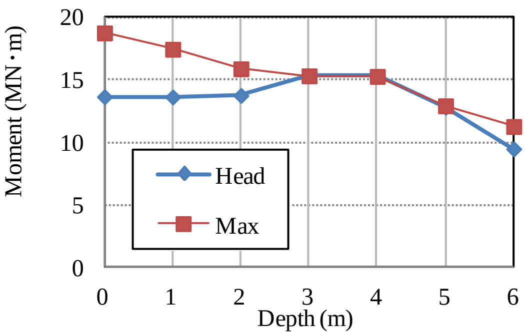

(b) Liquefaction

Figure 5. Deformation diagram(deformation ratio:1.0)

is reduced drastically, however, the abutment is fallen forward and the ground at the backside of the abutment is settled down. By considering the liquefied layer, that is, by considering the different physical properties of the soil layer, the bending moment and displacement of pile in this analytical model increases 3 times. Moreover, the maximum point of the bending moment of the pile is not the top of the pile when the liquefaction occurred. Therefore, it is necessary to grasp the location of the liquefaction layer when the structural design is conducted.

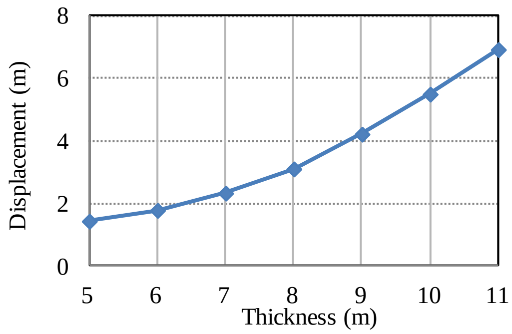


(a) Thickness is changed

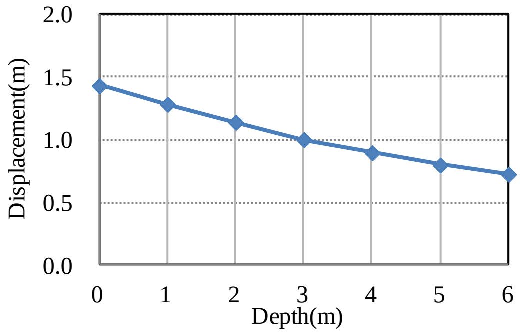


(b) Depth is changed

Figure 6. Correlations between the liquefactuin layer's thickness or depth and the moment



(a) Thickness is changed



(b) Depth is changed

Figure 7. Correlations between the liquefaction layer's thickness or depth and the displacement of the pier

3.2 The effect of the location and thickness of the liquefaction layer

Secondly, the location and the thickness of the liquefaction layer is changed. The depth of the liquefaction layer (Layer 3) means the depth from the basement of the footing. Figure 6 shows the relationship between the bending moment and the location and the thickness of the liquefaction layer and Figure 7 shows the relationship between the displacement of the top of the pile and the location and the thickness of the liquefaction layer. From Figure 6(a), the maximum value of the bending moment is the case that the thickness of the liquefaction layer is 7 meter. It is found that the bending moment is not always proportional to the thickness of the liquefaction layer. The displacement of the top of the pile increased drastically so that it is necessary to grasp the location of the liquefaction layer when the structural design is conducted.

4 ANALYTICAL RESULT (OBSERVED SEISMIC WAVES)

Three observed seismic waves are prepared in this analysis. These seismic waves are recorded in the 2011 off the Pacific Coast of Tohoku Earthquake. Firstly, the observed seismic waves at the ground surface are converted to the acceleration at the engineering foundation. Figure 8 shows the time history of the acceleration at the engineering foundation and the Fourier spectrum of the waves. The Fourier amplitude of the Soma wave dominants at the wide range. On the other hand, the Fourier amplitude of the Tsukidate wave dominants at the short period range and one of the Ogawa wave dominants at the long period range.

Figure 9 shows the relationship between maximum bending moment and the thickness of the liquefaction layer and the relationship between the displacement of the top of the pile and the thickness of the liquefaction layer. Figure 10 shows the horizontal displacement of the abutment and the subsidence of the backfill soil of the abutment. As for the response of the pier, the displacement increases with an increase in thickness of the liquefaction layer, however, the bending moment decreases in the case of the Ogawa wave. The Ogawa wave contains a lot of long period waves. The component of the long period dissipate when seismic wave pass through the liquefaction layer (the soft soil layer). So, the response acceleration of the abutment becomes small. As for the bending moment, the period

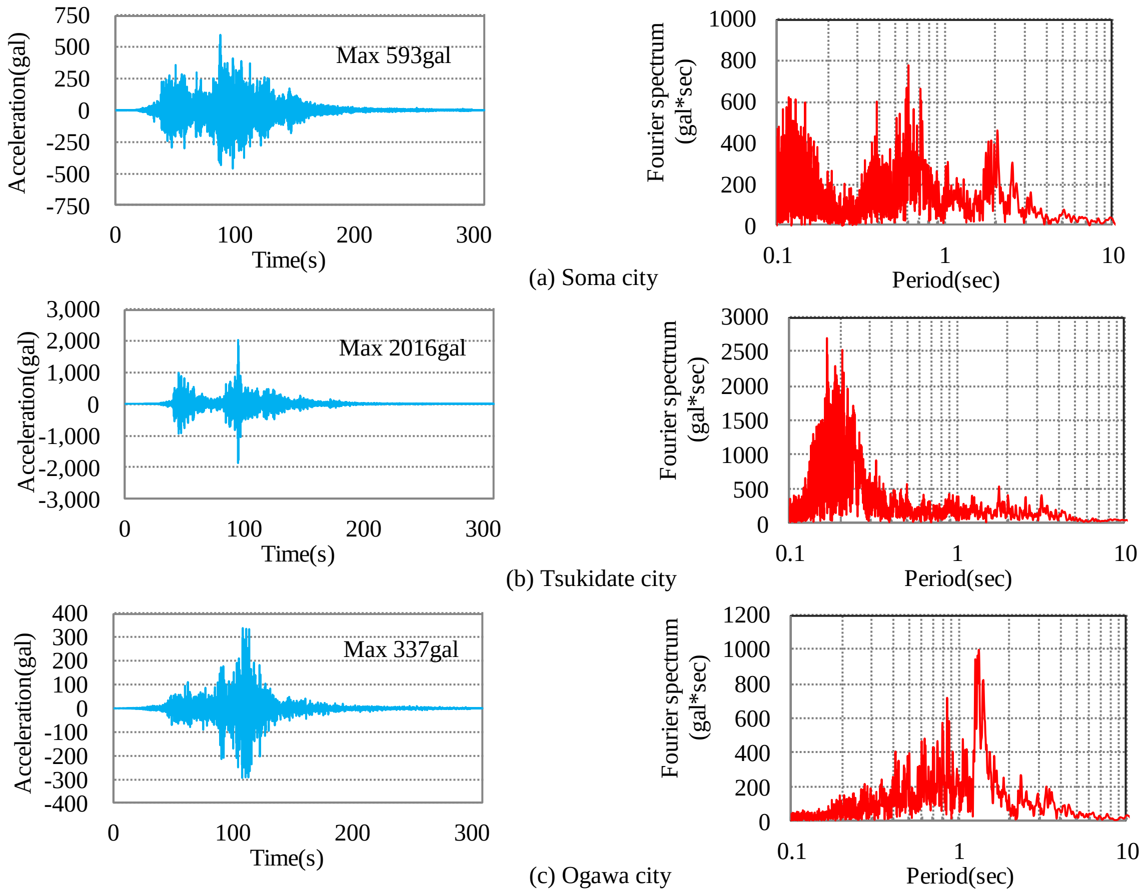


Figure 8. Acceleration time history and Fourier spectrum of the input waves

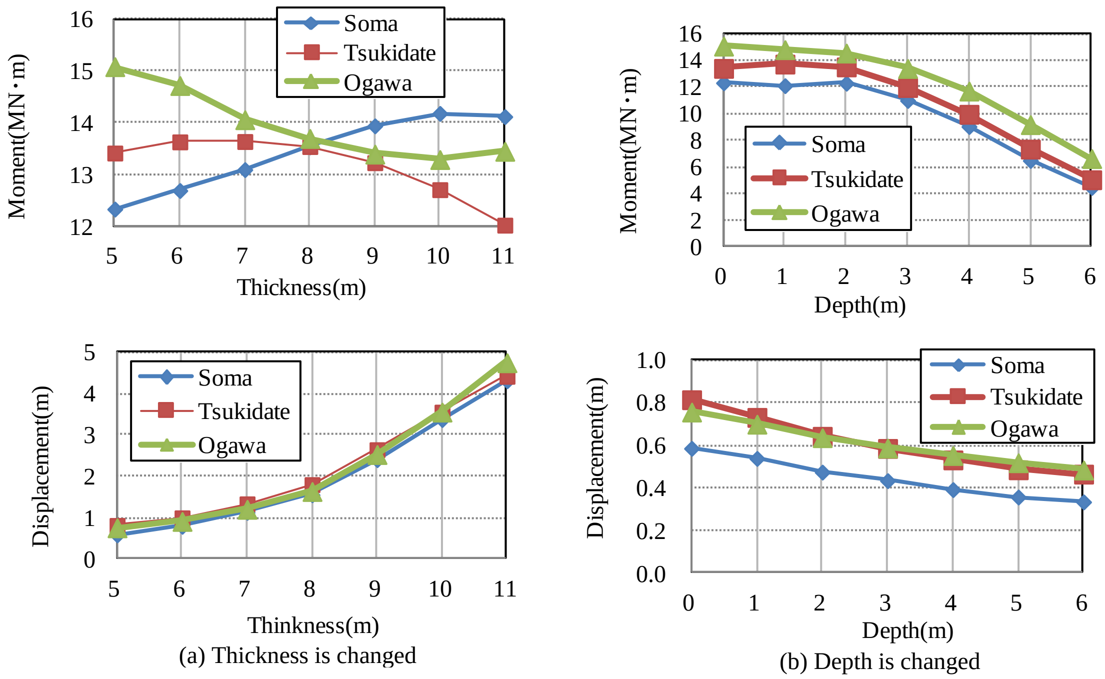
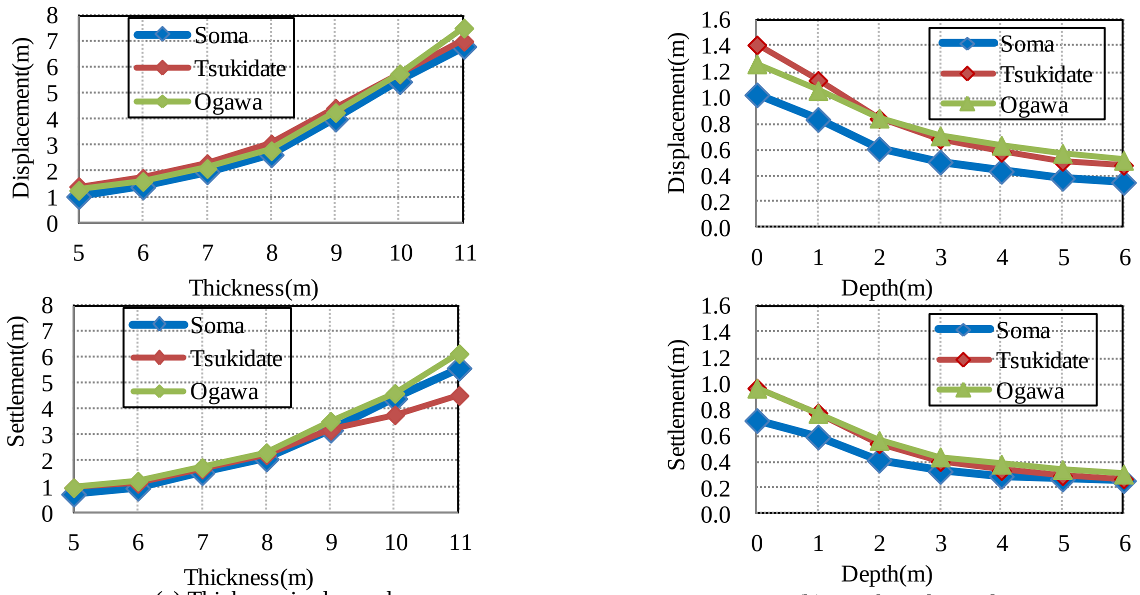


Figure 9. The maximum moment and displacement of top of the pile on each earthquake

characteristic of the seismic wave has a lot of influence so that it is very important to investigate the response of the structure by using the different period characteristics of seismic waves. From Figure 10, it is found that in this modelled ground, in the case that liquefaction layer thickness is 5m and the liquefaction layer lies immediately below abutment foundation, the subsidence of the backfill soil of the abutment will be about 1m. There is a possibility that the emergency vehicles cannot pass through the bridge immediately after the earthquake



(a) Thickness is changed

(b) Depth is changed

Figure 10. The displacement of top of the abutment and settlement of backfill soil of abutment on each earthquake

5 CONCLUDING REMARKS

In this study, firstly, the numerical analyses by using the periodical wave were conducted. Secondary, from the analyses by using the observed seismic wave were conducted. The results are obtained as follows,

- In the analysis by a sine wave, by considering the liquefied layer, that is, by considering the different physical properties of the soil layer, the bending moment and displacement of pile in this analytical model increases 3 times.
- If it is not considered a liquefaction layer, although occurrence location of the maximum bending moment was always pile head, by considering the liquefaction layer, for the magnitude of the bending moment acting on the pile, it is rare to become the largest at the top of the pier, also, liquefaction layer thickness did not hold the relationship that becomes larger as thick if thicker. That is, on calculating the bending moment acting on the pile, it is need to grasp the ground conditions correctly and to focus on not only the pile head but also the upper and lower layers of the liquefied layer.
- In the case that the liquefaction layer is considered, as for the displacement of the pile head, liquefaction layer thickness is thick or the position of the liquefaction layer is shallower, it is found that displacement is increased.
- Only liquefaction layer thickness changes, it is found that ground motion that takes the maximum value of the bending moment acting on the pile changes. For the bending moment acting on the pile foundation, it is necessary to consider in the ground motion with a variety of period characteristics.
- In this modelled ground, in the case that liquefaction layer thickness is 5m and the liquefaction layer lies immediately below abutment foundation, the subsidence of the backfill soil of the abutment will be about 1m. There is a possibility that the emergency vehicles cannot pass through the bridge immediately after the earthquake.

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