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Research Paper

Potential failure of Soekarno Bridge Foundation Cause of Liquefaction

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ABSTRACT

Earthquake occurring may trigger many secondary hazards. One of those hazards is liquefaction which is a phenomenon where part of soil loses it stiffness due to cyclic load. This paper evaluates the liquefaction potential of Ir. Soekarno Bridge located in Manado, Indonesia using its own soil properties acquired from standard penetration test (SPT). Using Simplified Seed & Idriss (1971) as the basis method, based on this method, if the safety factor value exceeds one, the soil has a liquefaction potential. Calculation were done using NovoLiq software with the peak ground acceleration (PGA) = 0.732 g and shallow water table. Analysis result by applying previous soil and earthquake parameters shows that there is a potential of liquefaction on the bridge's foundation at the layer I ~ II (0 ~ 12m). Further analysis of the foundation stability against liquefaction using Pile Group GEO5 software shows there is increasing of horizontal displacement by 19.4 mm at service load, settlement increase by 0.7 mm at service load, and bearing capacity wearing off equal to 19008.45 kN. Based on analysis results, we conclude that the Ir. Soekarno Bridge have a potential of liquefaction during 7.5 Mw earthquake

1. Introduction

Geographically, Manado city is located between three earth's main tectonic plates that are Pacific plate, Indo-Australian plate, and Philippines plate. For this reason, earthquakes are prone to happen in the area. Thus, structural safety against earthquakes is important. Earthquake occurring may cause failure to the soil below like losing the bearing capacity or the stiffness. Such failures can be classified as Liquefaction. Liquefaction is an event where a soil acts like fluid caused by an earthquake or cyclic load occurred on a saturated soil that then increases its pore water pressure exceeding the vertical stress and reducing the effective stress until zero. This event may cause punching shear, fissure, landslide, and settlement. Recent examples are Palu, Donggala and the regions around at 2018, where a 7.4 Mw earthquake triggered liquefaction in a residential area. Based on the proximity of the city and tectonic plates, Manado is as prone to liquefaction as Palu city. Soekarno Bridge is located in this city, and currently is the largest bridge in the area with 1.127 meter wide size. This bridge is built on sandy silt and dense sand with shallow water table.

2. Liquefaction

Liquefaction is a condition where a soil losses it's shear strength as an effect of pore water pressure increase and effective overburden pressure decrease in a soil, which usually caused by cyclic load. If cohesionless soil or loose sand receives continuous

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cyclic load at a very short time, it will reduce the density of the soil and increase its pore water pressure which results in liquefaction.

cyclic load can be interpreted as earthquake on a saturated soil which may trigger dissipation to happen. Dissipation will increase the pore water pressure of a soil. If the pore water pressure keeps increasing causing effective stress and soil's stiffness to decrease, then the soil will act like a liquid. This condition is called liquefaction.

Events above can be explained from effective stress equation below :

$$\sigma' v = \sigma - u \qquad [1]$$

Where,

$\sigma' v$: vertical over burden stress (kN/m^2)

σ : vertical total stress (kN/m^2)

u : pore water pressure (kN/m^2)

And from shear strength equation below :

$$S = c' + \sigma' v \tan \varphi \qquad [2]$$

Where,

S : shear strength (kN/m^2)
c' : effective cohesion (kN/m^2)
$\sigma' v$: vertical over burden stress (kN/m^2)
φ' : effective friction angle (°)

From both equations it can be deduced that if there is an increase of pore water pressure until the value equals to the total vertical stress, effective stress becomes zero, reducing shear strength. It becomes worse if the soil didn't have cohesion. This soil condition is where liquefaction mostly will occur.

Table 1. Soil Properties

Thickness of Layer (m)	GWT (m)	Depth (m)	N-SPT	Soil Type	Ɣsat (kN/m3)	ϕ	c (kN/m2)	E (kN/m2)
0-10		4	4	Soft to Medium Clayey Sandy Silt	16	2	25	6000
		6	9		16			
		9	12		16			
10-12		12	35	Medium Dense Silty Fine Sand	16	28	10	8000
12-20		15	47	Dense Silty Sand	17	30	15	70800
		17	46		17			
20-28		21	60	Very Dense Sand	17	30	15	85000
		24	60		17			
28-32		30	56	Very Dense Silty Sand	17	35	15	85000
32-47.5		33	40	Dense Silty Sand	17.5	30	20	60000
		36	38		17.5			
		39	39		17.5			
		43	36		17.5			
		45	34		17.5			
		47.5	35		17.5			

3. Method on liquefaction analysis

The method used to analyze liquefaction potential on this research is an empirical correlation method using Seed et. al,.(1983) There are two parameters in this analysis; Cyclic Stress Ratio (CSR) which is the soil stress ratio from cyclic load, and Cyclic Resistance Ratio (CRR) which is the soil tolerance ratio against cyclic loads. There are two analysis methods, lab test and calculation approach. The calculation method to find the liquefaction value is done by comparing the CSR and CRR parameter

$$FS = \frac{CRR}{CSR} \qquad [3]$$

If,
FS < 1, potentially will happen
FS = 1, critical condition
FS > 1, potentially won't happen

4. Soil Properties

Soil properties for the site is based on Standard Penetration Test (SPT). **Table 1** shows soil properties of the bridge's pylon

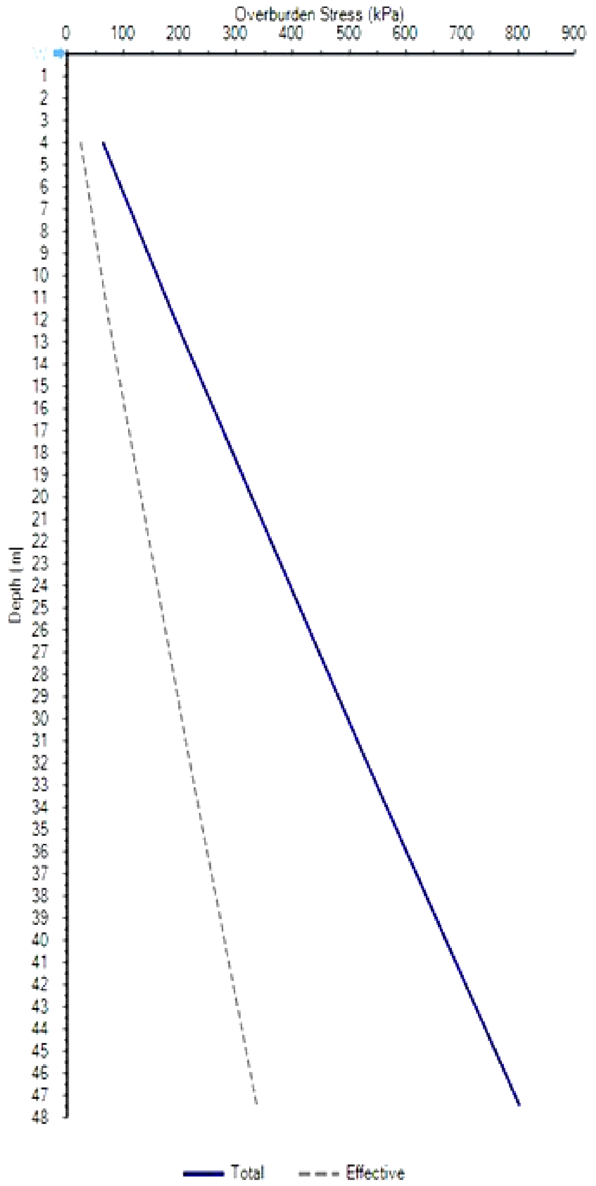

Fig. 1. Soil strength vs. Depth

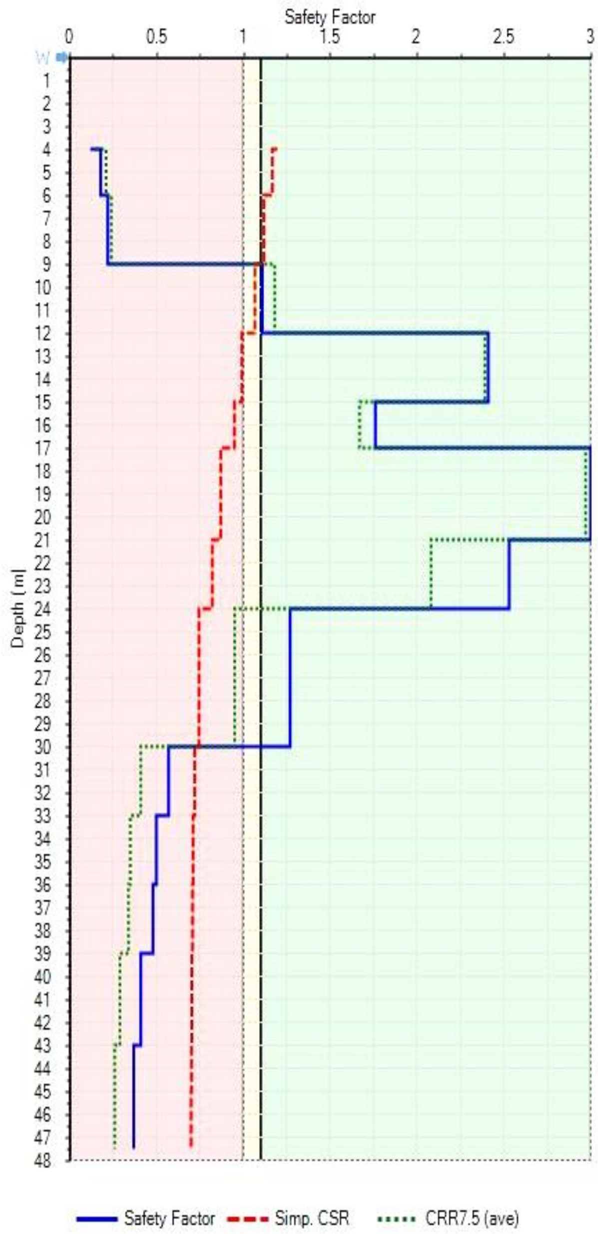

Fig. 2. Safety Factor (Mw = 7.5)

5. Liquefaction analysis

Liquefaction analysis is done using NovoLiq software. These following earthquake used 7.5 (**Fig. 2**), 7.6 (**Fig. 3**), 7.7 (**Fig. 4**), and 7.8 Mw earthquake model (Fig.4) in its analysis. The parameter used in the analysis is Cyclic Stress Ratio (CSR) which is based on the site's Peak Ground Acceleration (PGA).

Method used to determine CSR is based on Simplified Seed & Idriss (1971). This method is used in every layer and every magnitude reference. (**Fig 1**) also shows the soil strength compared to the depth.

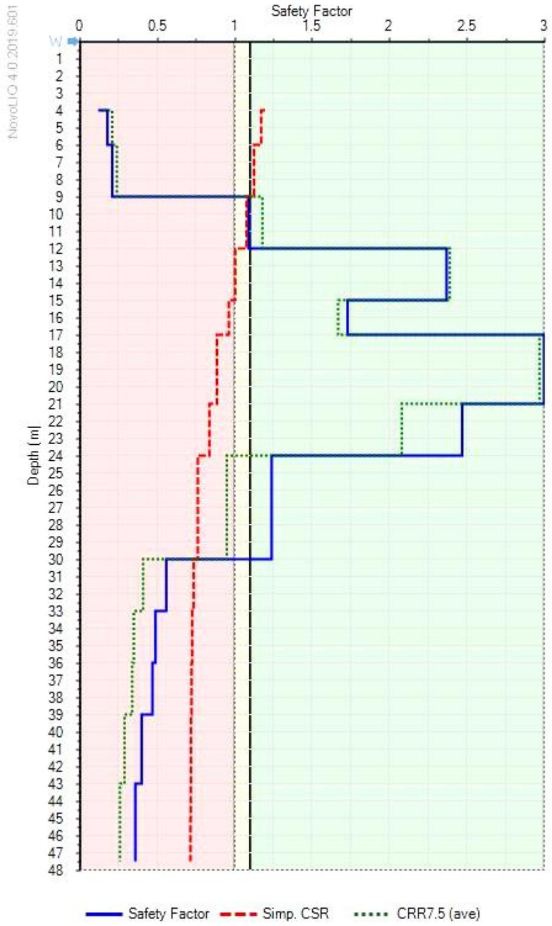

Fig. 3. Safety Factor (Mw = 7.6)

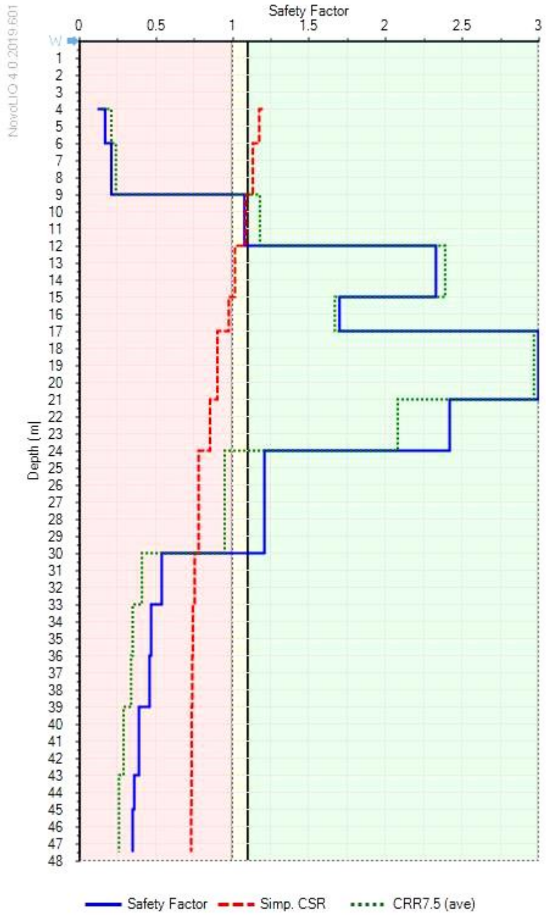

Fig. 4. Safety Factor (Mw = 7.7)

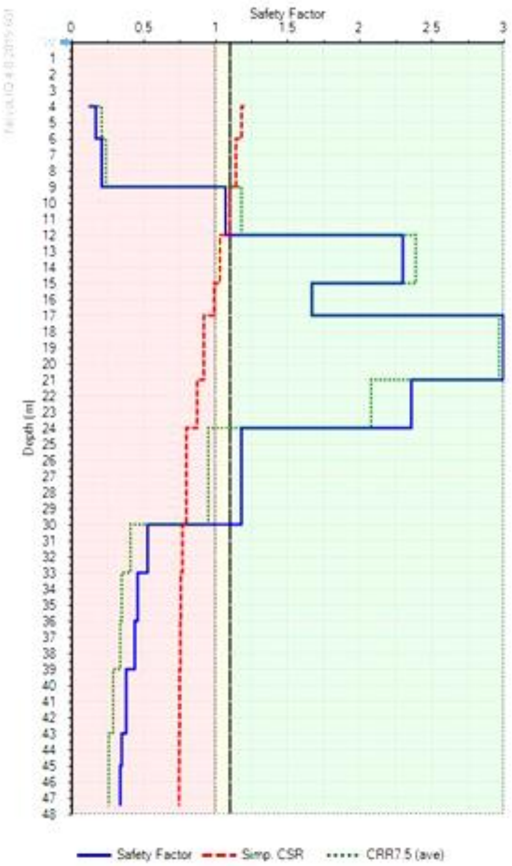

Fig. 5. Safety Factor (Mw = 7.8)

Table 2. Safety Factor

Depth (m)	Liquefaction Safety Factor			
	Mw=7.5	Mw=7.6	Mw=7.7	Mw=7.8
4	0.12	0.12	0.12	0.12
6	0.18	0.18	0.17	0.17
9	0.22	0.21	0.21	0.21
12	1.11	1.09	1.08	1.07
15	2.41	2.37	2.33	2.3
17	1.76	1.73	1.7	1.67
21	3	3	3	3
24	2.53	2.47	2.42	2.36
30	1.27	1.24	1.21	1.18
33	0.57	0.56	0.54	0.53
36	0.5	0.49	0.47	0.46
39	0.48	0.47	0.46	0.44
43	0.41	0.4	0.39	0.38
45	0.37	0.36	0.36	0.35
47.5	0.37	0.36	0.35	0.34

6. Foundation Modeling

Foundation modeling is made with the help of Pile Group GEO5 software, software based on Finite Element (Spring) and analytical method. To model a foundation, required inputs are pile group foundation alignment and its geometry data. The total of piles used in the bridge's pylon foundation are 89 piles with varying diameter. However, in this model, the diameter used was 1 meter and the length used was 41 meter for all piles for sampling purposes. Based on the result of previous liquefaction analysis, there is a potential of liquefaction on the first and second layer with variety of earthquake magnitudes, So each soil conditions is modeled into stages in the Geo5 software.

7. Effect evaluation of liquefaction occurring to the pylon's foundation

In this evaluation, GEO5 software was used. This software uses semi-finite element method (FEM) and creates modelling test of foundation condition in different stages. Data needed for input such as soil property, foundation geometric, foundation alignment, and loads simulated on the foundation. The parameters used in the models are shown in **Fig. 6** and **Table 3**

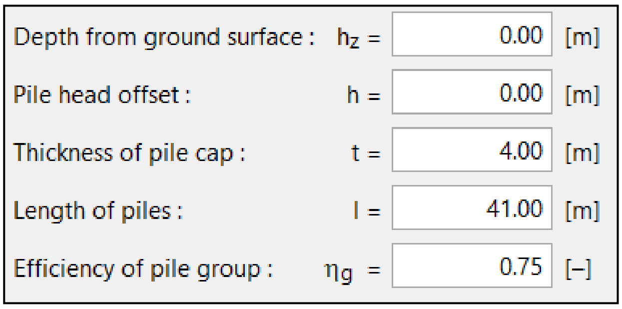

Fig 6. Foundation Geometric Input Window

Table 3. Safety Factor

Soil's Type	Ysat kN/m3	ϕ	c kPa	ηh MN/m3	E Mpa	v
Soft to Medium Clayey Silt	16	2	25	5.56	6	0.3
Medium Dense Silty Fine Sand	16	28	10	16.68	8	0.3
Dense Silty Sand (1)	17	30	15	34.75	70.8	0.3
Very Dense Sand	17	30	15	34.75	85	0.3
Very Dense Silty Sand	17.5	35	15	34.75	85	0.3
Dense Silty Sand (2)	17.5	30	20	34.75	60	0.3
Liquefy Soil	16	1	1	0.1	1	0.3

Based on liquefaction analysis result, the first and second soil layers (0 – 12m) have liquefaction potential. Soil models are divided into stages of conditions for each liquefied soil layer. Liquefied soil layers loses it's stiffness due to liquefaction, thus soil parameters for these layers are reduced to close to zero.

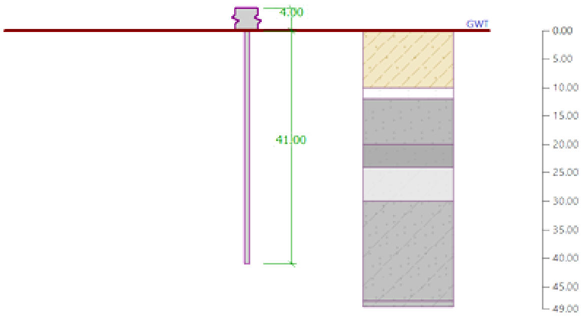

Fig 7. Stage 1 Soil Profiles
(No liquefaction occurred)

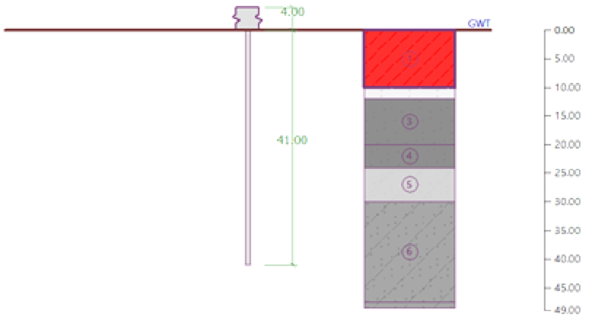

Fig 8. Stage 2 Soil Profiles
(Liquefaction on the first layer)

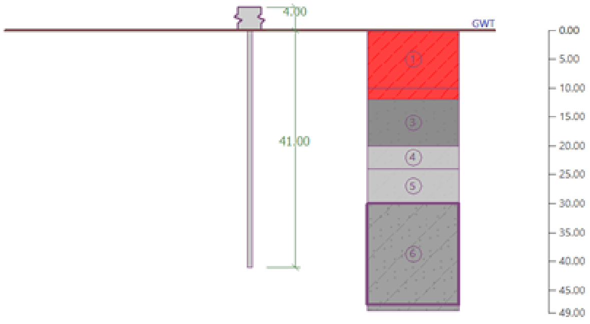

Fig 9. Stage 3 Soil Profiles
(Liquefaction on the first and second layer)

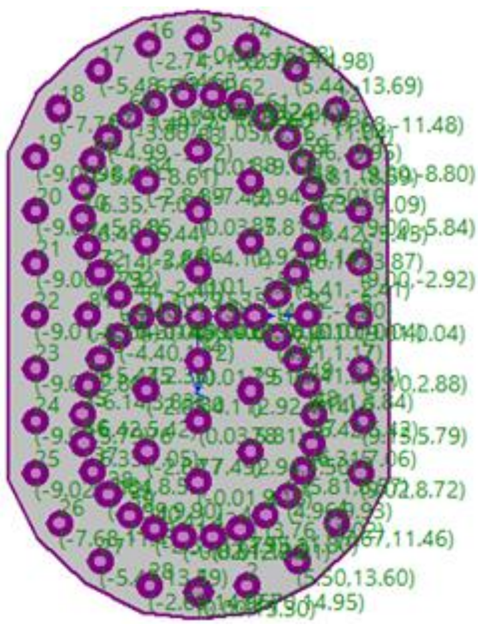

Fig 10. Pile group alignment

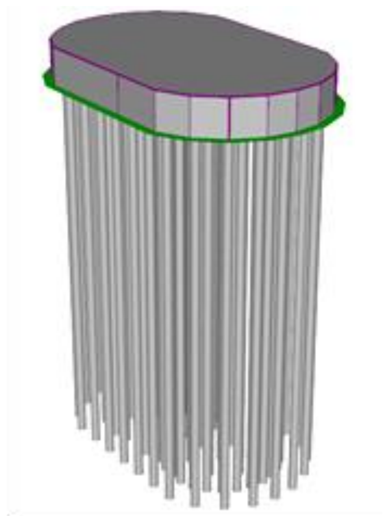

Fig 11. Pile cap of phylon Ir. Soekarno cable-stayed bridge

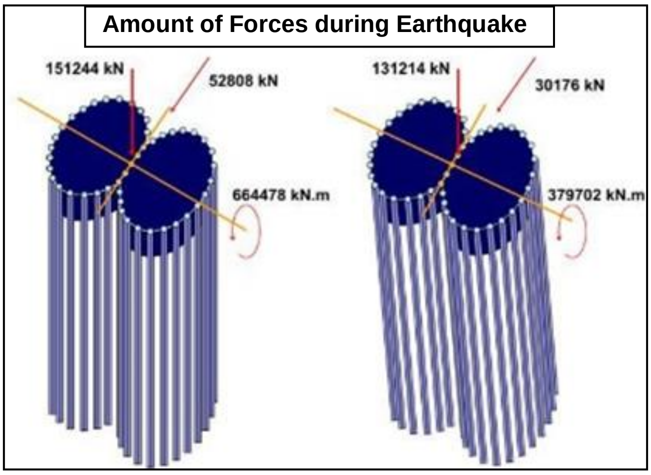

Fig 12. Pile group loads (without pile cap weight)

Fig. 13, 14, 15 shows displacement for each stage.

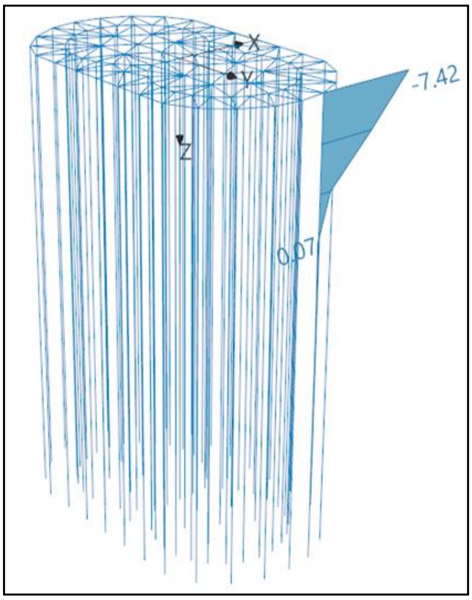

Fig 13. Pile cap horizontal displacement (stage 1)

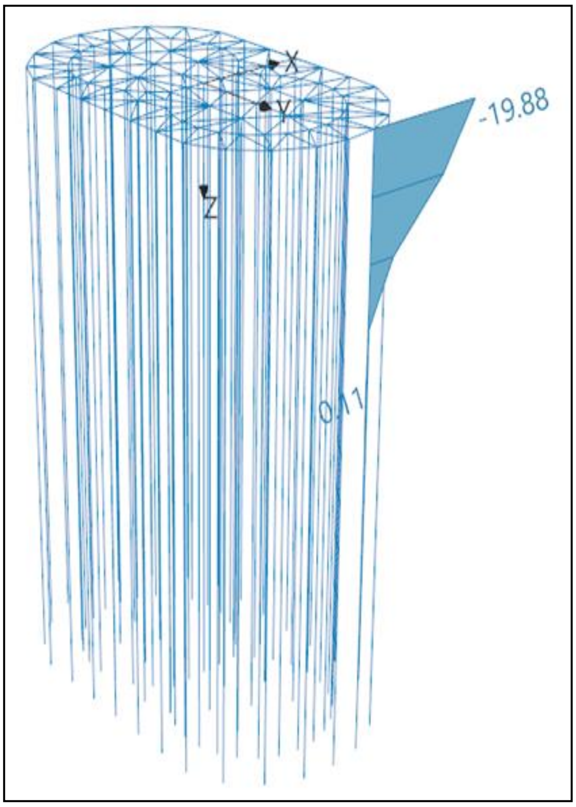

Fig 14. Pile cap horizontal displacement (stage 2)

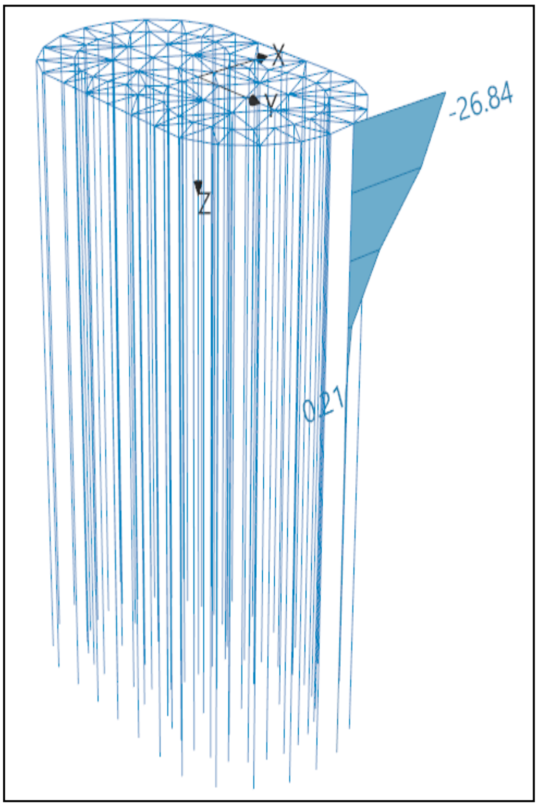

Fig. 15. Pile cap horizontal displacement (stage3)

Table 4. Foundation Stability Result

Stage	Vertical Bearing Capacity			Vertical Load		
1	23771.93	kN	>	188189.59	kN	TRUE
2	228377.31	kN	>	188189.59	kN	TRUE
3	218763.48	kN	>	188190.59	kN	TRUE
	Settlement of Pile Group			Allowable Settlement		
1	10.06	mm	<	25	mm	TRUE
2	11.01	mm	<	25	mm	TRUE
3	11.03	mm	<	25	mm	TRUE
	Horizontal Displacement of Pile Group			Allowable Displacement		
1	07.04	mm	<	25	mm	TRUE
2	19.08		<	25	mm	TRUE
3	26.08.00		<	25	mm	FALSE

8. Result

Based on the liquefaction potential analysis using local ground acceleration (Table 2), liquefaction happens on the I – II soil layers (0 – 12m) if 7.5 Mw or bigger earthquake occurred. Analysis result shows, bigger earthquake magnitudes and increasing peak ground acceleration (PGA) will increase liquefaction potential for a site. Based on the impact analysis of liquefaction on the pylon's foundation (Table 4), liquefied soil influenced foundation stability this is shown by the increase of horizontal displacement and settlement, and decrease of bearing capacity.

9. Conclusion

The soil surrounding Soekarno bridge's pylon foundation have the potential to liquefy during 7.5 Mw scale or larger scale earthquakes. soil improvement around the foundation is recommended to improve structural failure during liquefaction, such as installing stone column or granular pile. These may reduce horizontal displacement of the foundation's pilecaps, Micro piles may also be another alternatives to reduce displacements.

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Symbols and abbreviations

c'	Effective cohesion
CRR	Cyclic resistance ratio
CSR	Cyclic stress ratio
E	Modulus of elasticity soil
FS	Safety factor of liquefaction
GWT	Ground water table
Mw	Moment magnitude
N	Vertical load
PGA	Peak ground acceleration
S	Shear strength of soil
SPT	Standart penetration test
u	Water pore pressure
v	Poisson's ratio
γ	Unit weight of soil
γ'	Effective unit weight of soil
γsat	Saturated unit weight of soil
η	Efficiency of pile group
ηh	Subgrade's reaction modulus
σ'v	Effective vertical over – burden stress
σv	Vertical total over – burden stress
φ	Internal friction angle
φ'	Effective friction ang