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LIQUEFACTION ANALYSIS OF ROAD EMBANKMENT IN PIDIE JAYA DUE TO ACEH EARTHQUAKE IN 2016

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ABSTRACT: The 6.5 Mw Aceh earthquake has been struck the north-east part of Sumatra Island on 7 December 2016. The strong quake was at a depth of 13 km and categorized as a shallow earthquake. The earthquake has caused many damages to the roads as results of lateral spreading in Pidie Jaya Regency. This study is conducted to analyze the liquefaction phenomena that caused lateral spreading on the Pidie Jaya roads. All of the soil data for the analysis were taken from the field of the affected area. First, the soil data are analyzed to examine whether the soil sediment has the potential to liquefaction under the earthquake. Then the detailed analysis to observe the phenomenon of liquefaction on a particular road embankment is conducted with the use of numerical computer program. This study shows that for particular soil sediment which has liquefaction potential, the structure stability analyses need to consider liquefaction circumstance at a certain level. Finally, a reasonable geo-construction analysis is suggested for preventive measures of liquefaction.

Keywords: Earthquake, Liquefaction, Road Embankment, Numerical Analysis

1. INTRODUCTION

Sumatra is an island with great earthquake potential. There are at least two big geological conditions that become the main source of seismicity in this island. The first source is coming from the subduction boundaries of Asian continental plates and the Indian Ocean Plate on the western side of the Sumatra island. The second source is the main fault that crosses along the middle of the Sumatra Island, named Semangko fault. Both seismic sources have caused major earthquakes that occurred at the beginning of this century.

The first earthquake that includes destructive earthquakes on Sumatran Island in this century is the Aceh earthquake in 2004. This earthquake resulted in a phenomenal huge tsunami that opened wide the attention all people around the world. Then in 2005, there was the Nias earthquake on the western side of Sumatra which has resulted in liquefaction in some places on that Island [1]. The next is Bengkulu earthquake that happened in 2007 which also caused more than one-meter tsunami. The Bengkulu earthquake also resulted in liquefaction in several places in Bengkulu [1]. Then the Padang earthquake in 2009 which resulted in liquefaction in many places in Padang [2]. In 2010, the Mentawai earthquake occurred on the west-central side of Sumatra Island. This earthquake also caused a destructive tsunami in the Mentawai Island. Finally, the Pidie-Aceh earthquake in the eastern part of the north Sumatra Island happened at the end of 2016. Pidie earthquake located in the eastern part of the Aceh province in the Sumatra. The Pidie earthquake occurred on December 7, 2016. Pidie earthquake magnitude is 6.5 Mw at a shallow depth of 13 km (Fig.1).

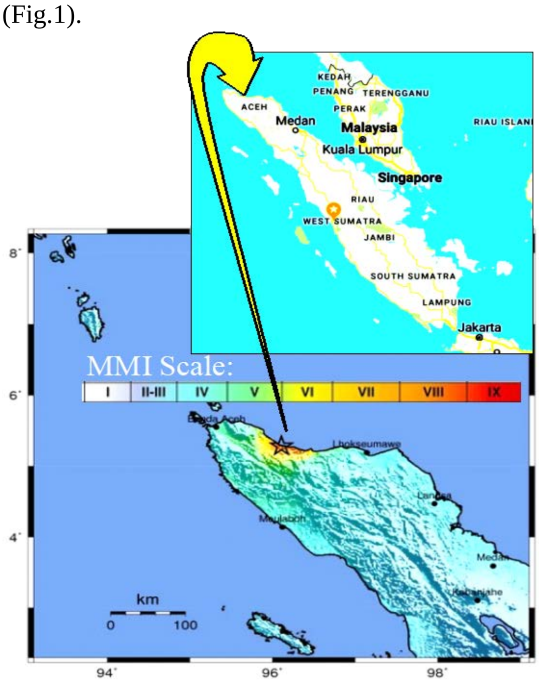

Fig.1 M 6.5 Earthquake 2016 in Pidie [3]

Soon after the earthquake, researchers did study many aspects related to the earthquake and one of them has been reporting the surface deformation in Pidie (Fig.2). This study remarked the deformations of the ground surface have relation to the liquefaction [3]. Another study tried to convince the relationship between the phenomena of liquefaction to the Poisson's Ratio value in Meurah Dua Distric of Pidie Jaya. This premature study estimating the soil type based on the Poisson's ratio taken from Table 1 [4]. The value of Poisson's ratio was determined based on the test results of compression-wave velocity (Vp) and shear-wave velocity value (Vs). The velocities tests were conducted through seismic refraction method and Multichannel Analysis of Surface Wave.

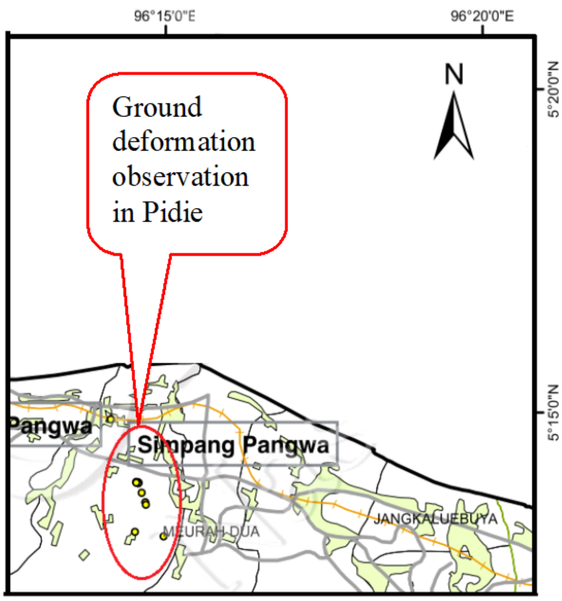

Fig.2 Deformation in Pidie [3]

Table 1 Poisson's Ratio range [4]

No.	Soil Types	Poisson's Ratio
1.	Satturated Clay	0,40-0,50
2.	Un-saturated Clay	0,10-0,30
3.	Clayey Sand	0,20-0,30
4.	Silt	0,30-0,35
5.	Dense Sand	0,20-0,40
6.	Coarse Sand	0,15
7.	Fine Sand	0,25
8.	Boulders	0,10-0,40

2. DAMAGE IN PIDIE 2016

The Pidie 2016 earthquake has caused damages in many access roads in terms of settlement od bridge abutment (Fig.3) and cracks in the road surfaces (Fig.7). Those infrastructure damages are illustrated in Fig.4 and Fig.8 respectively. The crack on roads was caused by liquefaction in the underground soils. The cracks mostly extended along the surface of the road, although there are several crossed through the road. The liquefaction and lateral spreading in some districts of Pidie Jaya are indicated by sand boil at the lower side of the road body (Fig. 7). Liquefactions that caused cracks and settlement of the access roads have also reported being widespread in Pidie region [3].

Fig.3 Settlement on the road in Pidie 2016

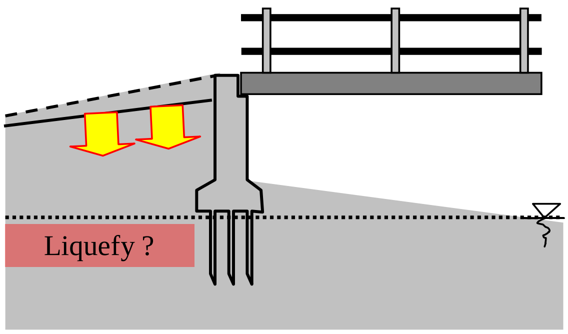

Fig.4 Settlement on the road in Pidie 2016

Fig. 5 Sand boiling due to Aceh earthquake 2016

Fig. 7 Cracks on road in Pidie 2016

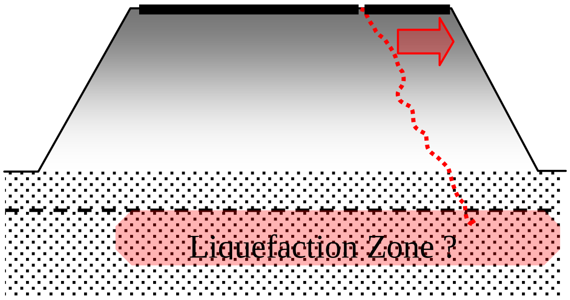

Fig. 8 Cracks on road in Pidie 2016

The studies of liquefaction, in general, have been done a lot [4], [5], [6]. In this paper, the damage in road embankment due to liquefaction is discussed. The soil and geometric data for that purposes are adopted from field test investigation in Pidie district of the Aceh province.

3. ROAD EMBANKMENT CASE IN PIDIE

The soil data for the purposes of numerical analysis in this study was adopted from the results of the Dutch Cone Penetration test (CPT) data as shown in Table 2 and Fig. 9. Based on that data it can be seen that the soil on the site has a small tip resistance on the near surface to a depth of several meters. The soil type at that location is obtained by analyzing the Friction Ratio (R_f) values of the CPT results. Furthermore, the value of the cones resistances and the friction ratios are plotted together on the soil type chart. The results show that the sandy soil dominates the near-surface soil layer (Fig. 10). While the rest is estimated to be a cohesive layer in terms of silt or clay mixtures [7]. The site location is on the edge of the river with relatively shallow groundwater level. This situation makes the land in that location will be in water-saturated condition.

In the performed numerical simulations, the soil layer is simply divided into two parts, the top layer with the cone average resistance of 25 kg/cm^2 and the bottom one with an average cone resistance of 200 kg/cm^2. Further, the modulus of soil modulus, E and the shear angle, ϕ and others parameters for the analysis is calculated based on the total constraint resistance, q_t, the cone resistance, q_c, of the total and effective overburden stress of σ_{vo} and σ_{vo}' with the correlation parameter α_E, using the following equation [7]:

$$E = \alpha_E (q_t - \sigma_{vo}) \quad (1)$$

$$\tan \phi' = \frac{1}{2.68}\left[\log\left(\frac{q_c}{\sigma'_{vo}}\right) + 0.29\right] \quad (2)$$

Table 2 CPT Test results

Dept (m)	CPT-1 q_c (kg/cm^2)	CPT-1 R_f (%)	CPT-2 q_c (kg/cm^2)	CPT-2 R_f (%)
0	0	0	0	0
0.2	40	1.25	25	2
0.4	30	1.67	30	1.67
0.6	25	2	25	2
0.8	25	2	25	2
1	25	2	20	2.5
1.2	30	1	15	2
1.4	25	1.2	30	1.67
1.6	25	2	35	1.43
1.8	25	2	40	1.25
2	25	2	45	0.67
2.2	20	2.5	35	0.86
2.4	25	2	180	0.56
2.6	30	3.33	150	0.67
2.8	180	2.22	190	1.05
3	220	1.36	180	1.11
3.2	245	0.2	210	0.71

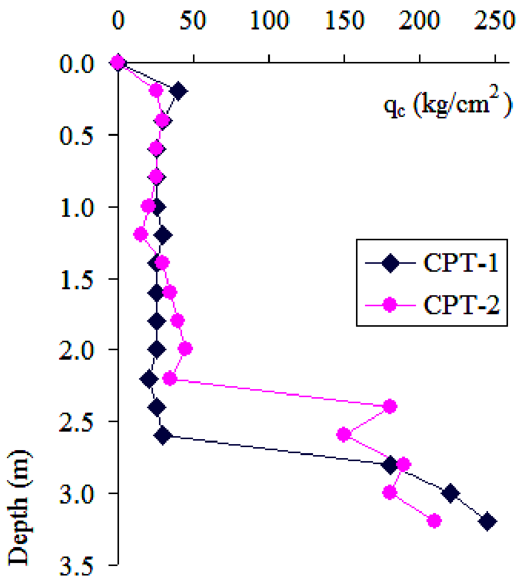

Fig. 9 Cone Penetration Test Data in Pidie

The results of the correlation calculations of the mechanical parameters for the numerical analysis are shown in Table 3.

Table 3 Average values of soil parameters

Parameter	Layer 1	Layer 2
Soil modulus, E (kN/m^2)	22000	29700
Poisson's ratio, μ	0.4	0.3
Friction angle, ϕ (degree)	40	48
Unit weight, γ (kN/m^3)	17.5	18.5

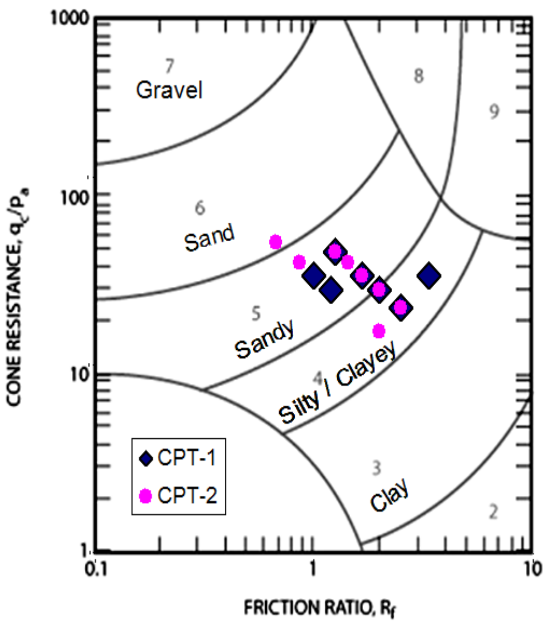

Fig.10 Soil type chart

4. ANALYSES AND RESULTS

In order to investigate the stability of the road embankment against liquefaction, a finite element model of the road embankment on the ground is constructed. The road embankment is made of sandy clay material with a unit weight of 18 kN/m^3, the soil cohesion of 1200 kN/m^2, the internal friction angle of 10^O and 29000 kN/m^2 of soil modulus. The numerical modeling in this study was done by using the numerical computer program [8]. Road pile is placed right above ground surface with two types of soil layers. The soil parameters for the model are shown in Table 3. Groundwater table is at the depth of 1m from the ground surface. The geometry of the finite element model is shown in Fig.11.

The stability of the embankment due to the liquefaction is investigated in two stages. The first stage, the model is executed with its self-weight. At this stage, the condition of the model is referred to as the normal state. The next stage is considering the liquefaction condition in which the increasing pore water pressures happen in the saturated soil mass. In this stage, the pore water pressure due to liquefaction phenomenon is determined by doubling it from its normal condition. Furthermore, to investigate the stresses in the under the ground, two points are selected that is at a depth of 2m and a depth of 4m from the ground surface.

In the first stage, the displacement pattern due to its self-weight is shown in Fig.12. In this condition, the maximum calculated settlement is 0.002m. The value is relatively small and indicates that the embankment is in stable condition with a safety factor of 5.8 which is considered as a good value for the embankment stability.

Furthermore, in the second stage, the pore water pressure on the saturated soil mass is increased by two times from its normal condition. In this condition, the calculated settlement on the embankment is 0.002m. The value is the same as it in the normal condition. The safety factor in this second condition is 4.7 which indicates the stable state is generally safe. The soil mass in this second stage has tensile stresses at the top of the embankment surface and plastic conditions have occurred in the ground under the embankment (Fig.13). The possible pattern of collapse of this embankment model is estimated as in Fig.14.

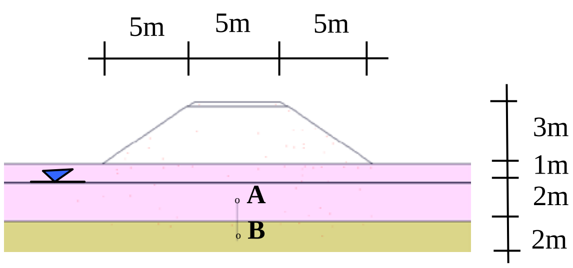

Fig.11 Numerical model

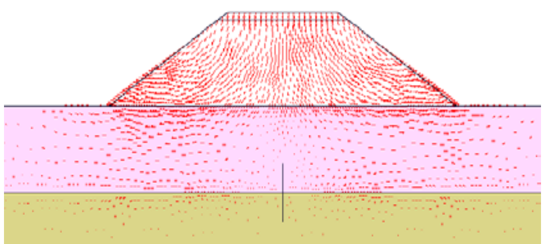

Fig.12 Displacement due to self-weight

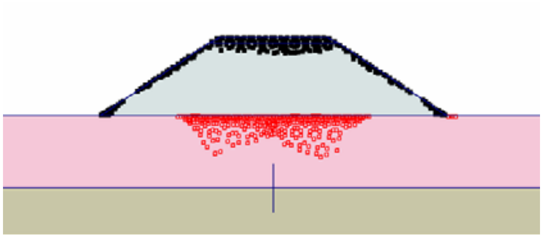

Fig.13 Plastic state due to self-weight

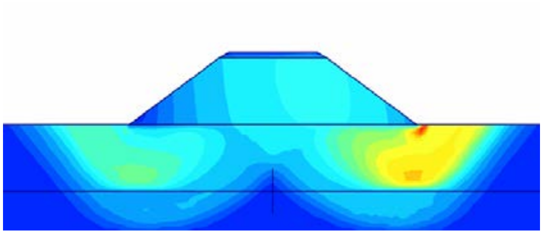

Fig.14 Failure pattern of the embankment

In this analysis, it is also given a simulation of increased pore water pressure up to 2.5 times the normal state. At the pore pressure of that value, the ground under the embankment is collapsed. The safety factor under this condition is 0.4 which is indicating the embankment is not in the stable condition anymore.

The numerical simulations also show that instability condition, the construction suddenly collapse with the increased pore water pressure more than twice in its initial condition (Fig.15). In the actual circumstances, this condition indicates that the liquefaction due to an earthquake will result in a sudden collapse of construction. This is certainly very dangerous since the sudden collapse of construction has given no time for the evacuation action. Although the excess pore water pressures can be monitored with geotechnical equipment, the collapsed condition remains unexpected in certain circumstance. Therefore, in that such cases, a careful analysis of the construction stability is more necessarily important than the installation of monitoring equipment.

Based on these results, it can also be understood that damage and collapse to the embankment of the road can occur suddenly when the pore water increases to a certain incremental value from its normal condition. If this increased pore water pressure has passed away, the embankment will return to its original state. Therefore, the improvement of the road can be done to restore it to its original condition.

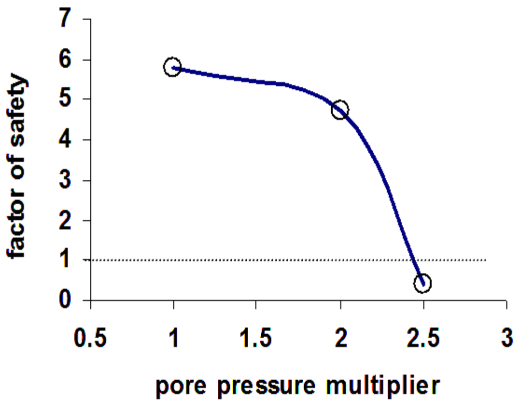

Fig.15 Stability due to incremental pore pressure

5. CONCLUSIONS

The earthquake that struck Aceh in 2016 has caused damage to a number of road embankment in Pidie Jaya. In order to investigate the effects of that phenomenon on the road embankment stability, the simulation of an increase in pore water pressure caused by liquefaction was discussed here. The original ground data was adopted based on cone penetration test results in The Pidie Jaya District - Aceh.

The results of this study indicate that the increase in pore water pressure due to liquefaction can reduce the stability of road embankment. The increased pore water pressure, at a certain time, will result in the loss of stability of the construction suddenly. This indicates that the damage and collapse occurring due to liquefaction and lateral spreading can occur at a short time during the earthquake. Soon after the earthquake passed away, the excess water pressure due to liquefaction returns to its normal state, the embankment construction will also be stable again but in damaged condition. For that then the improvement can be done to restore the road condition to function as normal.

Based on the results in this study it can also be suggested the importance of conducting stability analysis of the construction by considering the liquefaction triggered pore water pressure due to a selected earthquake. Since the sudden collapse phenomenon happens in a very short time, monitoring equipment installation for early warning for such case purposes seems to be less recommended.

6. ACKNOWLEDGMENTS

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