ISSN 2541-223X
Volume 4 2022

THE EFFECT OF SUBSURFACE PRESSURE TO THE PORE WATER PRESSURE AND EFFECTIVE STRESS ON SIDOARJO MUD VOLCANO

Kezia Ruus[1*], Ahmad Rifa'i[1], Agus Darmawan Adi[1]

[1]Universitas Gadjah Mada, Sleman, Indonesia, 55281

ABSTRACT
The Sidoarjo mud volcano is a geological disaster which still erupting after 16 years located in a densely populated. The eruption of Sidoarjo mud volcano is the longest continous disaster that Indonesia has ever experienced. It is known that there is overpressure in subsurface that propagated to the surface throught faults. However, the overpressure generation leads to the increase of pore water pressure, so the effective soil stress decreases. This study aims to estimate the change of pore water pressure and effective stress on the subgrade of Sidoarjo mud volcano due to the subsurface pressure. Furthermore, this study considers the existing embankment and excess pore water pressure due to the consolidation process using Finite Element Method. The results show high active pore water pressure in these area is around -580 kPa, due to the consolidation process is -372 kPa and the contribution of subsurface pressure is -208 kPa. The anomaly of effective stress occur from a depth of -13 m to -30 m. Thus, the reduction of effective stress is around 6%-56% from the ideal conditions with the largest reduction occurred at a depth of -30 m.

Keywords: subsurface pressure, pore water pressure, effective stress

1. INTRODUCTION
The Sidoarjo mud volcano is a geological disaster which still erupting after 16 years located in a densely populated. It started erupting in May 2006 and located in the Porong District of Sidoarjo, East Java. The flow rate of Sidoarjo mud volcano is up to 180 000 m3/day at the beginning of the eruption [1] and it has covered over 700 hectares of land [2]. The eruption of Sidoarjo mud volcano is the longest continous disaster that Indonesia has ever experienced.
One of the hypotheses developed based on the analysis of theoritical pressure regarding the cause of the mudflow is the eruption triggered by overpressure in Kalibeng formations may have propagated to the surface [3]–[5]. It supported by the research conducted by Tanikawa et al 2010, which evaluated and estimated the change and distributions of pore pressure at the Sidoarjo mud volcano. Thus, the numerical basin analysis and laboratory data showed the high overpressure that was produced below the Upper Kalibeng Formation and nearly reached the lithostatic level so that the pressure from the deep formation can reach the surface [6]. However, the overpressure generation leads to the increase of pore water pressure, so the effective soil stress will be reduced [6], [7]. The dynamics of subsurface geology have an impact on the problems that exist in the Sidoarjo mud volcano area. The rapid land subsidence that occur in this area has been estimated using the remote sensing [8]–[10].

[1*]Corresponding email: keziaruus1996@mail.ugm.ac.id
DOI: https://doi.org/10.20885/icsbe.vol4.art36

A homogeneous earth dams has built around the eruption to reduce the impact of mudflow with a total height and length of the embankment are 11 m and 14430 m (Figure 1), respectively [11]. The material eruption of Sidoarjo mud volcano classified as a high plasticity silt (MH) based on USCS classification. Thus, the behaviour of compressibility material need special treatment to deal with it [12]. Since the beginning of the embankment construction, it has experienced many failures due to land subsidence [13] with a total of thirty two failure events in 2007 to 2008 [14].

The study on LUSI embankment has been widely undertaken nowadays to evaluate stability and failure mode [13]–[16]. This study focused on the subgrade of the Sidoarjo mud volcano embankment to estimate increasing the pore water pressure induced by the subsurface pressure and its contribution to the effective soil stress based on Cone Penetration Test with Pore Water Pressure Measurement (CPTu) investigation data using Finite Element Method. Furthermore, this study considers the existing embankment and excess pore water pressure induced by the consolidation process.

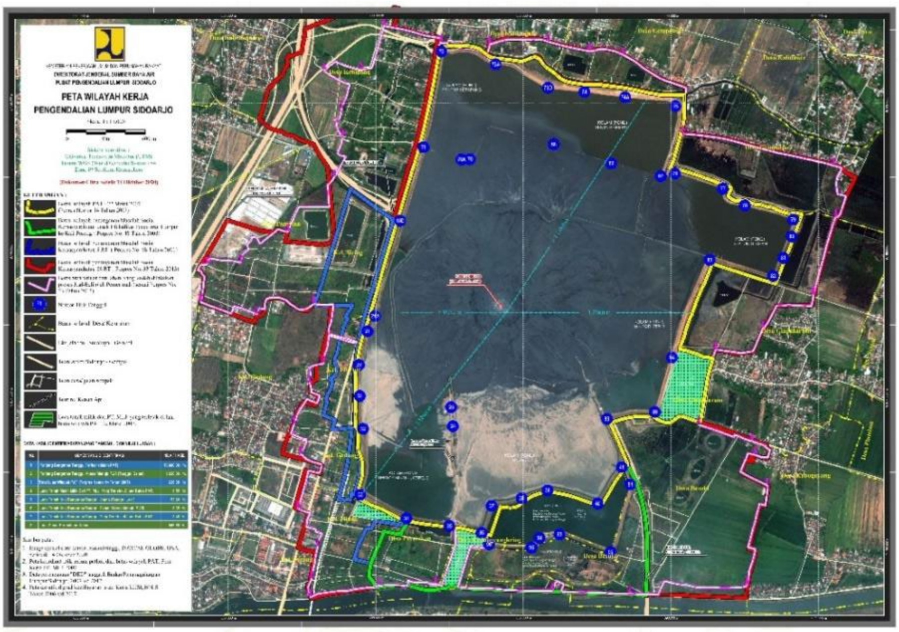


Figure 1. Sidoarjo Mud Volcano Area [11]

2. THEORETICAL BACKGROUND

2.1. Stresses in The Soil

In conditions where the soil is saturated, the pore water pressure that fills the cavity will affects the soil. The hydrostatic pore water pressure acting on the soil due to the presence of ground water table. The pore pressure (u) value is equal to zero at the ground water table and will increase linearly with increasing depth. [17]. The formulation of the concept of effective stress is most often attributed to Terzaghi (1923) who gives the relationship between the three stresses acting on the soil [18]. The vertical stress of soil can be calculated simply by multiplying the mass of the overlying material with depth, the vertical stress is

$$\sigma_v = \gamma_{sat} z \qquad (1)$$

where γ_{sat} is the saturated unit weight of soil and the Z is the soil depth. The pore water pressure values below the water table is

$$u = \gamma_w Z \tag{2}$$

where the γ_w is the unit weight of water and Z is the soil depth. The effective stress of soil can be defined according to equations 1-2 is

$$\begin{aligned} \sigma_v' &= \sigma_v - u \\ &= z\gamma_{sat} - z\gamma_w \\ &= (\gamma_{sat} - \gamma_w) z = \gamma' z \end{aligned} \tag{3}$$

where the γ' is the unsaturated unit weight of soil. This equation showed, the effective stress will increase as the pore water pressure decrease.

2.2. Stress Distribution

The 2V:1H (vertical to horizontal) method is the simplest approach to determine stress distribution at a depth proposed by Boussinesq. This method assume that the sregion the load acts over will increase geometrically with depth [19]. The unit stress decreases due to the same vertical load being distributed over a much larger area at depth as depicted in the Figure 2

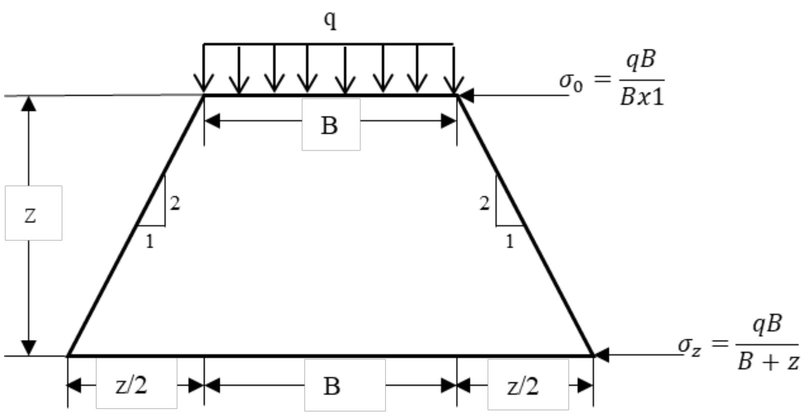


Figure 2. The Stress Distribution of The 2V:1H Method [20]

2.3. Consolidation

Consolidation is associated with the changes in effective stress, resulting from a changes in pore water pressure. On the application of external or internal loads, there is an increase in pore water pressure through the soil which is known as excess pore pressure [21]. An increse in pore water pressure occurs immediately after loads applied to saturated soil. The expulsion of water from the pores is accompanied by volumetric strain and the increasing of effective stress. The correlation between compression index of consolidation (Cc), initial void ratio (e0) and physical soil properties can be used to predict effective stress due to consolidation process in Sidoarjo mud volcano [22]. The terzaghi's one-dimensional consolidation theory can be used for estimating the total consolidation settlement [19]

$$S_c = C_c \frac{H}{1+e_0} \log \frac{p_1'}{p_0'} \tag{4}$$

where Sc is the total consolidation settlement, Cc is compression index, H is the initial thickness, e0 is the initial void ratio, P1' is the initial vertical effective soil stress, and P0' is the final vertical effective soil stress. During the consolidation process, the total settlement is associated with the dissipation of excess pore water pressure as a time function [23]. Thus, it is also used to estimate the rate of consolidation settlement.

$$T = \frac{C_v t}{H_t^2} \tag{5}$$

where T is the time rate of consolidation with a dimensionless measure of time, Ht is the length of the longest pore water drainage path, and Cv is the coefficient of consolidation.

3. MATERIAL AND METHOD

3.1. Method

The pore pressure analysis of the subgrade of the Sidoarjo mud volcano embankment has been carried out by the finite element method using Plaxis program under the plane strain condition. The Mohr-Coulomb model was used as an initial solution to the problem considered. Consolidation and plastic calculation in Plaxis have been undertaken to estimate the change of pore water pressure and effective stress. Comparison of analytical calculations and finite element method is used as a verification of modeling. Three types of sequence analysis were investigated in this study, i.e: the change of pore pressure due to the consolidation process, subsurface modeling and analysis based on CPTu investigation data, and the effective soil stress analysis induced by the subsurface pressure.

3.2. Geometry Model and Soil Properties

An embankment of Sidoarjo mud volcano is considered in this modeling as a load above the soil surface which causes the consolidation process and changes to the pore water pressure. Furthermore, the ground is modeled into five layers based on the soil investigations in the laboratory. The embankment and soil modeling are using Mohr Coloumb failure criteria under the plane strain conditions. Thus, the geometry model of the embankment is seen in Figure 3 There are five parameters applied in this modeling effective cohesion (c'), poisson ratio (υ), effective friction (ϕ'), modulus of elasticity (E) and permeability coefficient (kx/ky) [24]. The soil properties are shown in Table 1 as adopted from soil laboratory test result [11], [25]

Table 1. Soil Material Properties [25]

Material	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Embankment	Mud
γ_{unsat} (kN/m^3)	13,24	13,73	11,38	7,75	7,45	18,63	14
γ_{sat} (kN/m^3)	18,14	18,44	16,67	14,61	14,42	19,40	15
$k_x = k_y$ (m/day)	5,46 x10^{-3}	8,64 x10^{-2}	1,47 x10^{-2}	4,84 x10^{-4}	4,57x10^{-4}	2,42x10^{-2}	8,64x10^{-4}
E (kN/m^2)	3848	10162	11247	4045	3354	5750	1000
c' (kN/m^2)	49,33	9,87	17,76	22,69	8,88	10,06	3
ϕ	13	35	29	5	5	26,97	5,46

(deg)

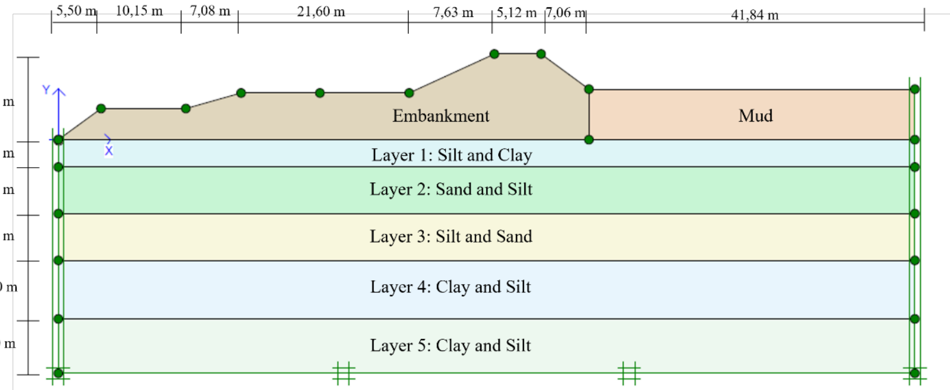


Figure 3. Geometry Model of Sidoarjo Mud Volcano Embankment

4. RESULT AND DISCUSSION

4.1. Geotechnical Investigation

The Standard Penetration Test (SPT) was carried out to determine the soil classification of embankment and ground particularly the north side area of Sidoarjo mud volcano[11], [25]. The results show the embankment consist of sandy silt while the subgrade materials consist of silty clay, sandy silt, silty sand, and clay silty soils from the top to the bottom soil layer, respectively (Figure 4)

The Cone Penetration Test with Pore Water Pressure Measurement (CPTu) investigation was obtained to find out the existing pore water pressure conditions. Furthermore, the investigation was carried out on the surface of the embankment with a total of 5 measurement points [11]. The result shows there is an anomaly in the pore water pressure on the north side area of Sidoarjo mud volcano. The highest pore water pressure occurred in this area with an increase up to -380 kPa from normal conditions of -200 kPa with extreme pore pressure around -580 kPa (Figure 5). The results indicate that the increasing of pore water pressure occurred by the consolidation process where the residual pore pressure has not been dissipated and there is a contribution from subsurface pressure. Thus, the effective soil stress will decrease as pore water pressure increases.

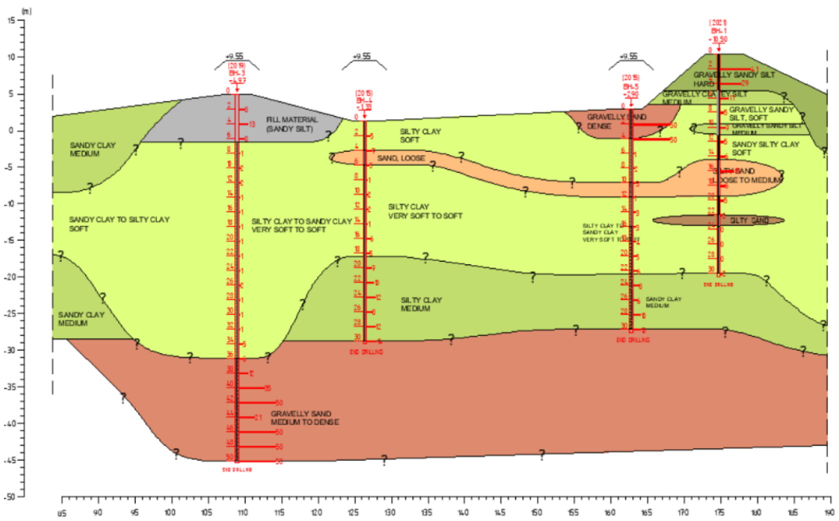


Figure 4. Soil Stratigraphy in The North Side of Sidoarjo Mud Volcano [11]

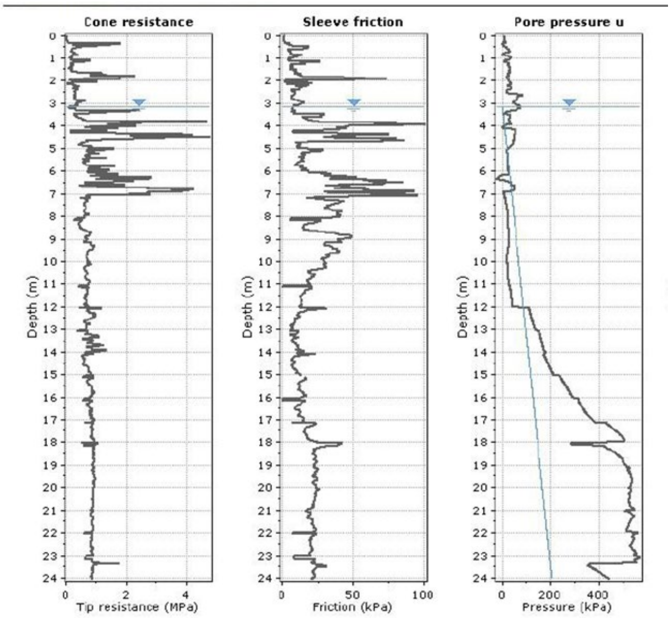
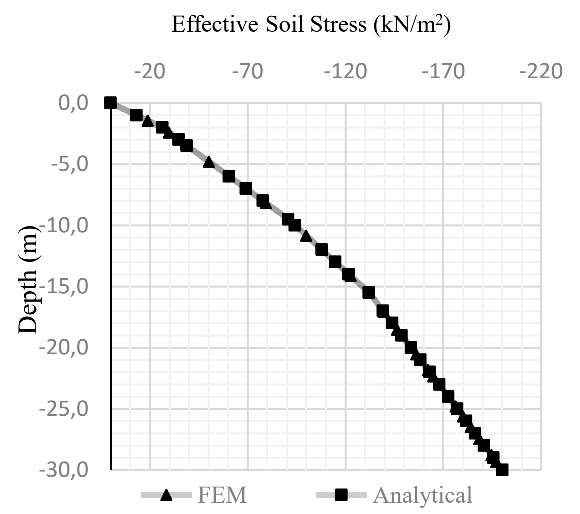


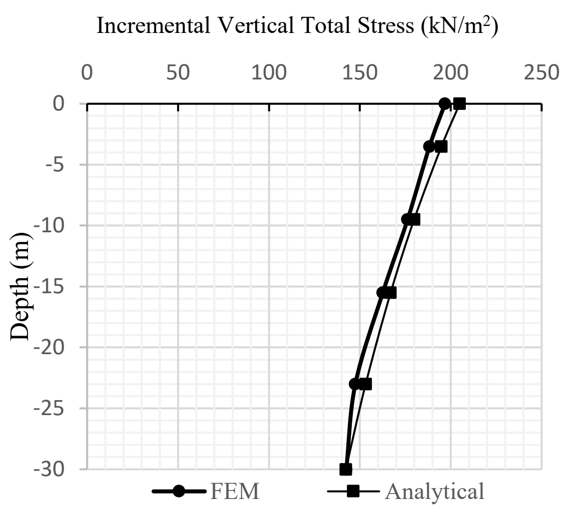
Figure 5. Pore Water Pressure Measurement [11]

4.2. Comparison Analytical Calculations with Finite Element Method

To validate soil models in Plaxis, the results of the Finite Element Method have been compared with the analytical calculations. Therefore, the analytical calculation of effective stress using equation 1-3 and the stress distribution using 2V:1H method have been conducted. The comparison of effective stress and stress distribution calculation between the two methods presented in Figure 6. Thus, the consolidation analysis also carried out to determine the total settlement and rate of consolidation using equation 4-5. The cummulative settlement of each layer after 3,41 years reaching -1,25 m in analytical calcuation, while the Finite Element Method results show the total settlement is -1,27 m with the rate of consolidation took 3,79 years. The comparison results of the methods showed that the Finite Element Method using Plaxis reasonably agreed with the analytical calculation.



(a)



(b)

Figure 6. Comparison The Analytical and FEM Calculations: (a) Effective Stress; (b) Stress Distribution

Table 2. The Analytical Calculation of Consolidation

Consolidation Settlement							Time Rate of Consolidation			
Layer	e_0	Cc	H_c m	σ'_0 kN/m^2	$\Delta\sigma'$ kN/m^2	Sc m	H_{dr} m	t_v U= 90%	c_v m^2/sec	t_{90} year
1	1,03	0,25	3,5	38,98	194,92	0,349				
2	0,93	0,11	6	90,76	179,86	0,177				
3	1,26	0,13	6	131,92	166,96	0,132	24	0,848	4,54E-06	3,41
4	2,29	0,49	7,5	167,92	153,23	0,315				
5	2,47	0,6	7	200,19	142,30	0,282				
Ultimate Consolidation Settlement (m)						-1,25	Time Rate of Consolidation (Year)			3,41

4.3. Pore Pressure Modeling and Analysis

Changes in pore water pressure due to subsurface pressure cannot be observed directly because there is a consolidation process that occurs in the subgrade of the embankment which affects the increase in pore water pressure. So that the calculation of pore pressure is performed in two stages, namely: the increasing of pore pressure due to the consolidation process using Plaxis and the subsurface pressure contribution based on the CPTu investigation data. The results of the consolidation analysis show that the extreme pore pressure at this stage is -372,27 kPa (Figure 7) while the CPTu is -580 kPa (Figure 5). With these conditions, it can be concluded that there is a contribution of subsurface pressure to the increasing pore pressure. The difference in pore water pressure values between the consolidation analysis and the CPTu is assumed as a contribution of subsurface pressure, which is -280 kPa. Thus, the analysis results are presented in the Table 3.

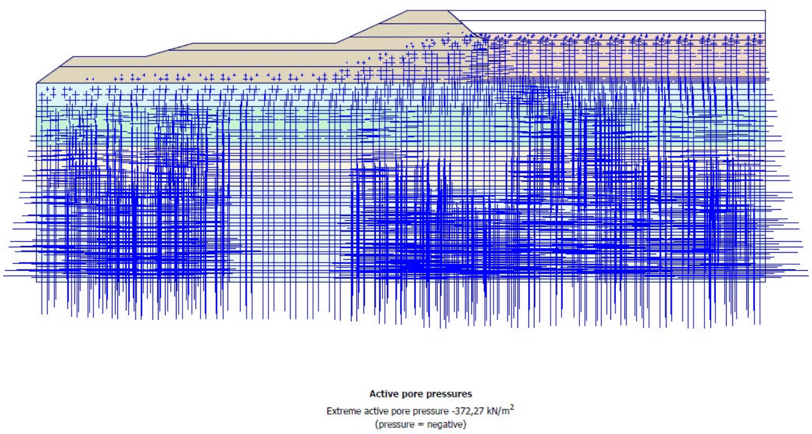


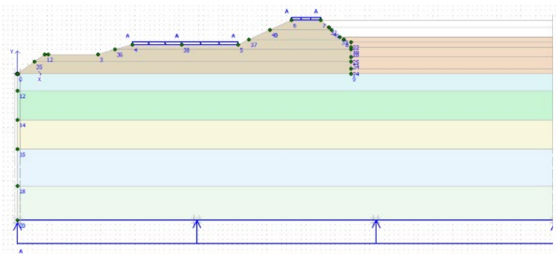
Figure 7. Active Pore Water Pressure Due to Consolidation Process = -372,27 kN/m2

ISSN 2541-223X
Volume 4 2022

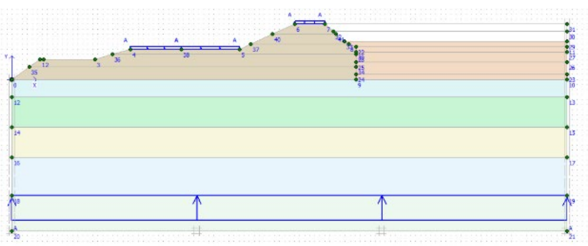
Table 3. Pore Water Pressure Analysis Using CPTu Measurement and Plaxis

Analysis Results	CPTu	Consolidation Analysis (Plaxis)	Difference
Pore Water Pressure (kN/m^2)	-580 kPa	-372 kPa	-208 kPa

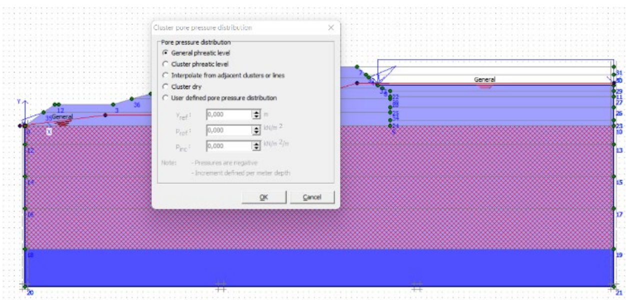
The pore pressure analysis stage then proceeds to the subsurface pressure modeling. It is carried out by using 3 modeling scenarios, namely: first, reduce the soil parameters strength assuming subsurface pressure causing the reduction of soil strength. Second, provide an uplift force on layers 4 and 5 of the embankment subgrade as a form of pressure from the subsurface. Third, provide an increment of the pore water pressure distribution using User Define Pore Pressure (UDPP) that induced by the subsurface pressure. All the modeling scenarios have been obtained using Plaxis and presented in Figure 8. The results show that scenario 1 and 2 have no significant effect on the change of pore water pressure. However, the scenario 3 by using UDPP gives the closest result to the CPTu pore water pressure value (Figure 5) is -579,99 kPa (Figure 9)



(a)



(b)



(c)

Figure 8. The Modeling of Subsurface Pressure in Plaxis Program: (a) Uplift Force on Layer 5; (b) Uplift Force on Layer 4; (c) Using UDPP to Define The Contribution of Subsurface Pressure

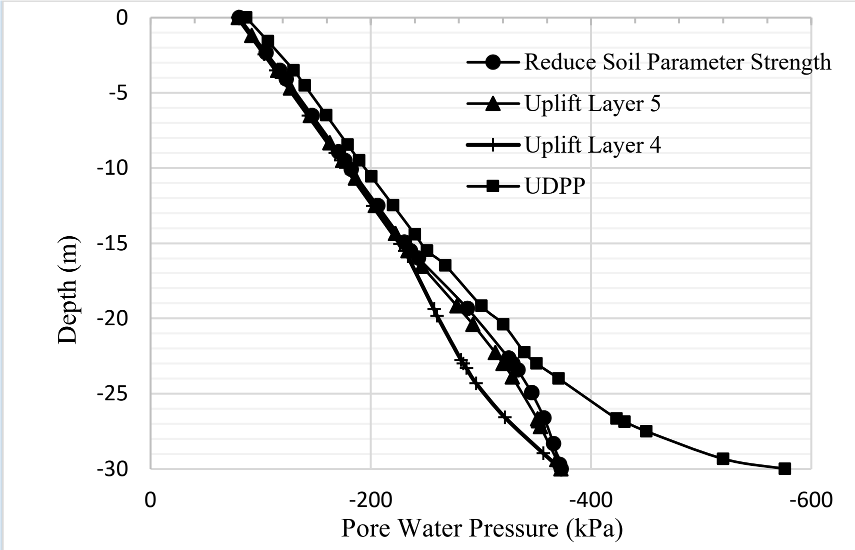


Figure 9. Pore Water Pressure Analysis Results of All Models

4.4. Effective Soil Stress

The analysis of effective soil stress was performed under 2 conditions, ideal conditions where there is no effect from subsurface pressure and with the subsurface contribution conditions. The analysis was obtained using Plaxis program by considering the consolidation process.The analysis results show there is an anomaly to the effective soil stress on the subgrade of the embankment with a decrease in the effective stress from a depth of -13 m to -30 m (Figure 10.b). It begins with the increasing of pore water pressure at that depth due to subsurface pressure with extreme active pore water pressure is -580 kPa at -30 m depth (Figure 10.a). The maximum effective stress on the subgrade of the embankment under ideal conditions is around -333,66 kN/m2, while in conditions where there is subsurface pressure is -253,22 kN/m2. Thus, the reduction of effective soil stress around 6%-56% from the ideal conditions with the largest reduction occurred at a depth of -30 m.

It should be noted that in the consolidation process, the effective soil stress will increase with time where the pore water pressure will be dissipate through the soil pores. Pore water pressure rate are mainly controlled by the permeability of soil .The highest excess pore water pressure occurs in the soft soil with a thickness 15 m which has a very low permeability. Furthermore, the consequence is consolidation process will occur that lasts for a long time due to the low permeability of the soft soils and high pore water pressure due to the subsurface pressure. In consideration the subgrade of mud volcano embankment has a high pore water pressure due to subsurface pressure. So the soil improvement is needed to increase the effective soil stress and the rate of the excess pore pressure dissipation.

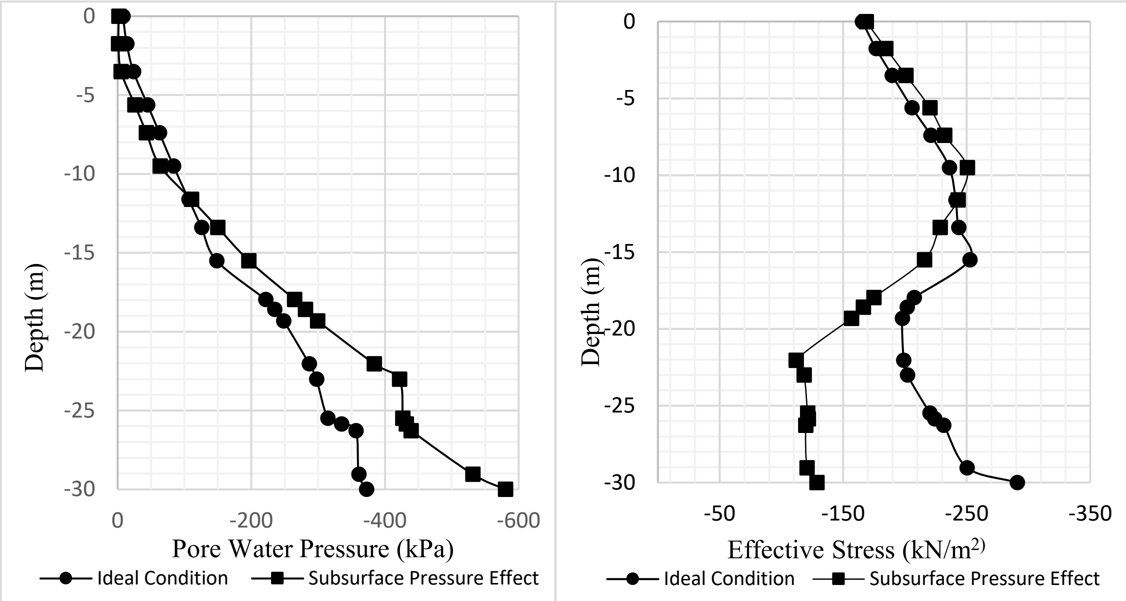


Figure 10. The Comparison of Ideal Condition and Subsurface Effect Conditon: (a) Pore Water Pressure; (b) Effective Stress

5. CONCLUSION

The pore water pressure analysis has been conducted using Plaxis based on CPTu investigation data to determine the contribution of subsurface pressure. The results show high active pore water pressure in these area is around -580 kPa, due to the consolidation process is -372 kPa and the contribution of subsurface pressure is -208 kPa. Unfortunately, this condition lead to the effective soil stress decrease in the subgrade of embankment. The 3 scenarios models have been obtained to estimate the effect of the subsurface pressure to pore water pressure. It can be concluded that modeling by providing an increment to the the distribution of pore water pressure using UDPP give the closest result to the CPTu value.

The analysis of effective soil stress has been obtained under the ideal condition where have no contribution to the subsurface pressure and the subsurface effect condition.The analysis results show there is an anomaly to the effective soil stress on the subgrade of the embankment with a decrease in the effective stress from a depth of -13 m to -30 m. It begins with an increase in pore water pressure at that depth due to subsurface pressure with extreme active pore water pressure is -579,99 kPa at -30 m depth. The maximum effective stress on the subgrade of the embankment under ideal conditions is around -333,66 kN/m2, while in conditions where there is subsurface pressure is -253,22 kN/m2. Thus, the reduction of effective soil stress is around 6%-56% from the ideal conditions with the largest reduction occurred at a depth of -30 m. In consideration of the result, the soil improvement is needed to increase the effective soil stress and the rate of the excess pore pressure dissipation. However, the analysis of subsurface pressure and it’s effect are needed to be observed for further study.

6. ACKNOWLEDGMENTS

We are extremely thankful to the Center For Sidoarjo Mudflow Containtment and Ministry of the Public Works and Housing for the generous support that made this research conducted well.

7. REFERENCES

Mazzini A *et al.*, 2007 Triggering and dynamic evolution of the LUSI mud volcano, Indonesia *Earth Planet. Sci. Lett.* 261, 3–4 p. 375–388.

Tingay M, 2010 Anatomy of the Lusi Mud Eruption, East Java *ASEG Ext. Abstr.* 2010, 1 p.1–6.

Davies R J Swarbrick R E Evans R J and Huuse M, 2007 Birth of a mud volcano: East Java, 29 May 2006 *GSA Today* 17, 2 p. 4–9.

Davies R J Brumm M Manga M Rubiandini R Swarbrick R and Tingay M, 2008 The East Java mud volcano (2006 to present): An earthquake or drilling trigger? *Earth Planet. Sci. Lett.* 272, 3–4 p. 627–638.

Tingay M, 2015 Abnormal pore pressure and associated environmental and geohazards Initial pore pressures under the Lusi mud volcano , Indonesia *Interpret. Vol. 3, No. 1 (February 2015); p. SE33–SE49, 5* 3, 1.

Tanikawa W Sakaguchi M Wibowo H T Shimamoto T and Tadai O, 2010 Fluid transport properties and estimation of overpressure at the Lusi mud volcano, East Java Basin *Eng. Geol.* 116, 1–2 p. 73–85.

Rempe M Di Toro G Mitchell T M Smith S A F Hirose T and Renner J, 2020 Influence of Effective Stress and Pore Fluid Pressure on Fault Strength and Slip Localization in Carbonate Slip Zones *J. Geophys. Res. Solid Earth* 125, 11.

Andreas H Abidin H Z and Kusuma M A, After Four Years of Ground Displacements Following LUSI Mud Volcano Eruption ; Sign of its Ending Eruption After Four Years of Ground Displacements Following LUSI Mud Volcano Eruption ; Sign of its Ending Eruption May 2011 p. 18–22.

Abidin H Z Davies R J Kusuma M A Andreas H and Deguchi T, 2009 Subsidence and uplift of Sidoarjo (East Java) due to the eruption of the Lusi mud volcano (2006-present) *Environ. Geol.* 57, 4 p. 833–844.

Chaussard E Amelung F Abidin H and Hong S H, 2013 Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction *Remote Sens. Environ.* 128 p. 150–161.

PPLS, 2021, Laporan Akhir Paket Pekerjaan Penilaian Kinerja Sarana dan Prasarana Pengendalian Lumpur (PT Aditya Engineering Consultant), Surabaya.

Handoko L Rifa'i A Yasufuku N and Ishikura R, 2015 Physical properties and mineral content of Sidoarjo mud volcano *Procedia Eng.* 125, December p. 324–330.

Agustawijaya D and Sukandi, 2012 The Stability Analysis of the Lusi Mud Volcano Embankment Dams using FEM with a Special Reference to the Dam Point P10.D *Civ. Eng. Dimens.* 14, 2 p. 100–109.

Sungkono Husein A Prasetyo H Bahri A S Monteiro Santos F A and Santosa B J, 2014

The VLF-EM imaging of potential collapse on the LUSI embankment *J. Appl. Geophys.* 109 p. 218–232.

Agustawijaya D and Sukandi, 2017 The Displacement Models of The Lusi Mud Volcano Embankment November 2013.

Hakim, Abdul., Gunawan A, 2020 Evaluation of Sidoarjo mud volcano embankment *AIP Conf. Proc.* 2251, August.

Verruijt A, 2001 *Soil Mechanics, Open courseware* Technical University Delft.

Hardiyatmo H C, 2012 *Mekanika Tanah I* Ke enam Yogyakarta: Gadjah Mada University Press.

Hardiyatmo H C, 2019 *Mekanika Tanah II* Sixth Yogyakarta: Gadjah Mada University Press.

Washington State Department of Transportation, 2022 *Geotechnical Design Manual M46-03.08* October .

Climent G H, 2017 Pore Water Pressure Behaviour and Evolution in Clays and Its Influence in The Consolidation Process p. 86.

Handoko L Yasufuku N Ishikura R and Rifa'i A, 2016 Comparison of consolidation curves for remolded mud volcano of Sidoarjo, Indonesia *Int. J. GEOMATE* 10, 4 p. 1978–1982.

Fox P J, 2003, Chapter 19: Consolidation and Settlement Analysis, (CRC Press LLC), p. 1–15.

Brinkgreve R B J, 2007 *Plaxis 2D.V8* Delft University of Technology&PLAXIS b.v. Yhe Netherlands.

PPLS, 2019, Laporan Review Design Supervisi Peningkatan Tanggul, Embung, Sistem Drainase dan Embung di Kawasan Lumpur Sidoarjo (PT Tri exnas Consultant & Management Engineering KSO PT Atlantik Bina Persada Konsultan Teknik dan Supervisi), Surabaya.