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Jl. Letjen S. Parman No. 1, Jakarta Barat 11440
P: 021 - 5695 8744 (Humas)
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Road settlement analysis on improved peat soil in Pekanbaru

Aniek Prihatiningsih[1*] and *Jonathan Wansons* Khohara[1]

[1]Undergraduate Program of Civil Engineering, Universitas Tarumanagara, Jl. Letjen S. Parman No. 1, Jakarta, Indonesia

Abstract. Indonesia is one of the countries that has the largest area of peat soil. Construction on peat soil may cause problems to the structure due to poor physical properties of peat soil such as having low bearing capacity. There have been several cases where roads built on peat experience damages, like uneven road due to settlement. This research presents a study in peat soil with soil improvement where the peatland was used as a location for road construction, which the bearing capacity, settlement and time required for settlement to take place is predicted. The analysis was conducted in a condition where the pavement is placed from the elevation of 0,0 m to -0,88 m, and the pavement is considered as a reinforcement layer. This research presents the bearing capacity, amount of settlement occurred, and the time needed for consolidation of roads on improved peat soil.

1 Introduction

Indonesia is one of the countries in the world that has the largest peat area, where the country has around 14,9 million hectares [1]. Peat soil is known for its low bearing capacity, which is caused by their poor physical properties, which make it difficult to be used in construction. Generally, peat soil is an organic substance which is formed naturally which has plant matter as its main component [2]. With the growth and economic development, peat land must be utilized to be used in construction therefor construction on peat lands can no longer be avoided.

One of the infrastructures needed in this time is structures that support the flow of transportation, such as road. However, construction of roads on peat soil results in some problems caused by its poor physical properties which may lead to road settlements and uneven surfaces. Construction on peat soil usually is done with soil improvement to increase the physical properties and bearing capacity of the soil, however with this the cost needed for construction increases as well. This research analyses the settlement of improved peat soil which is used for road construction.

1.1 Peat soil

Peat soil can be defined as a soil substance which have a high organic content that comes from plant material. Peat soil is formed when the organic material accumulates faster and then the rate of decaying [3]. According to Pd T-06-2004-B also known as the Department of Settlements and Regional Infrastructure, peat soil is a type of soft soil which has plant remains that undergo decay as its main component. Generally, peat soil has a high compressibility and low undrained shear strength, and high permeability. A soil is classified as peat soil when their organic content is > 75%. Peat soil bearing capacity is low, and it has a fibrous texture which makes the soil to have a high permeability Not parallel. Therefore, it can be concluded that peat soil is not great when used for construction, and if it is going to be used in construction soil improvement is needed to increase bearing capacity of the soil [4]. Peat soil also has the characteristics like a sponge which make the soil particles to be very loose [5].

1.1.1 Physical properties of peat soil

Peat soil has a relatively low unit weight, where peat soil usually has a unit weight in the range of 8,3 – 11,5 kN/m^3. Peat soil is a highly compressive soil, which made the soil to have quite a high void ratio. Void ratio of peat soil can be around 5 – 15 and for fibrous peat can reach to 25 [6].

1.2 Shallow foundation

Shallow foundations are foundation structures that are placed on the ground with the depth that is not larger than its width. Shallow foundation consists of pad foundation, strip foundation and raft foundations [7]. The bearing capacity of shallow foundation can be calculated using theories such as Terzaghi (1943), Meyerhof (1963), Hansen (1970) and Vesić (1973, 1975).

1.3 Effective stress

Effective stress is stress that is carried by the particles in the soil. Assume a saturated soil element which is applied with normal stress (σ) from Equation 1, which is applied on a horizontal boundary as shown in Fig. 1.

*Corresponding author: jonathan.325190003@stu.untar.ac.id

The stress s is called the total stress. The resistance to σ is provided by a combination of the stresses from solids, called effective stress (σ'), and porewater pressure (u) from the water in the pores [8].

$$\sigma = \sigma' + u \tag{1}$$

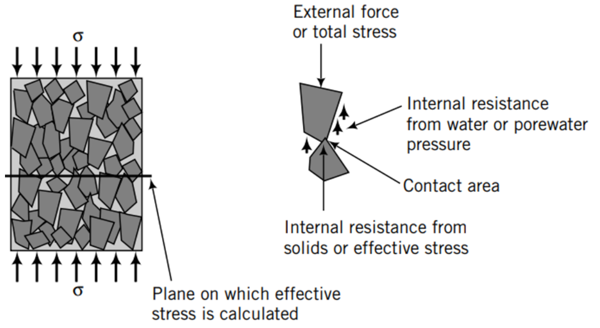

Fig. 1. Effective stress [8].

1.4 Vertical stress

Vertical stress due to a concentrated load can be calculated with Boussinesq method, which use the following Equation 2.

$$\Delta\sigma = \frac{3P}{2\pi z^2\left(1+\left(\frac{r}{z}\right)^2\right)^{\frac{5}{2}}} \tag{2}$$

where Δσ: increase in stress in the depth of z (kN/m^2), P: load (kN), r: perpendicular distance from the load (m), and z: depth (m).

Vertical stress on soil due to strip load can be calculated using correlation table $\Delta\sigma/q_o$ with 2z/B and 2x/B which can be seen in Das & Sivakugan (2017).

1.5 Elastic settlement

Elastic settlement is caused by the elastic deformation of dry, wet and saturated soil without the change of water content. Elastic settlement happen immediately after the construction of a structure or load is applied [7].

Elastic settlement of shallow foundation proposed by Janbu et al (1956) on saturated soil with the poisson ratio of the soil $\mu_s = 0{,}5$. With A_1 and A_2 graph proposed bry Christian and Carrier (1978) which can be seen in Fig. 2 [7].

Equation 3, elastic settlement proposed by Janbu et al (1956) with μ_0 and μ_1 values which can be obtain from Fig. 3.

$$S_e = \frac{\mu_o \mu_1 q_o B}{E_s} \tag{3}$$

where Se: elastic settlement (m), A_1: f (H / B, L / B), A_2: f (D_f / B), L: foundation length (m), B: foundation width (m), D_f: depth of foundation (m), H: soil thickness (m), q_o: applied stress (kN/m^2), and Es = elasticity modulus of soil (kN/m^2).

Elastic settlement on granular soil can be calculated corresponding to the theory of elasticity (Equations 4-16).

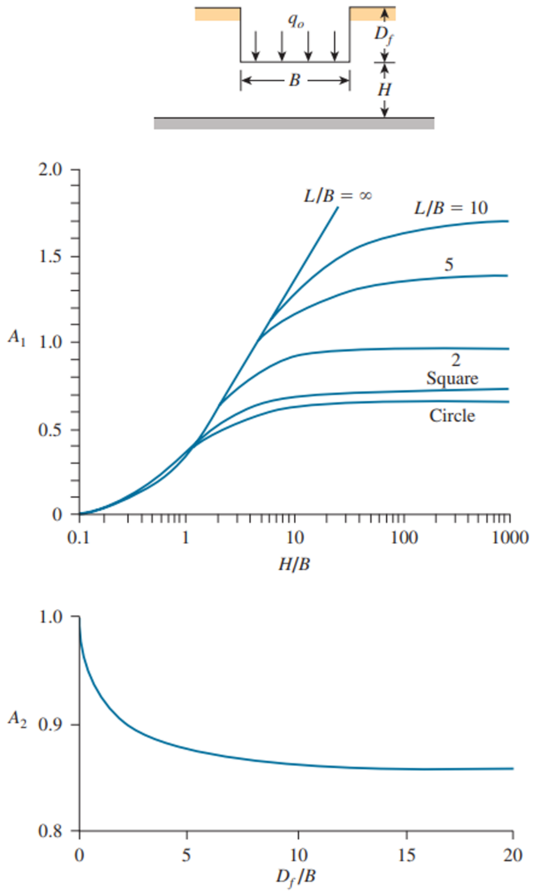

Fig. 2. A_1 and A_2 values for elastic settlement calculation [7].

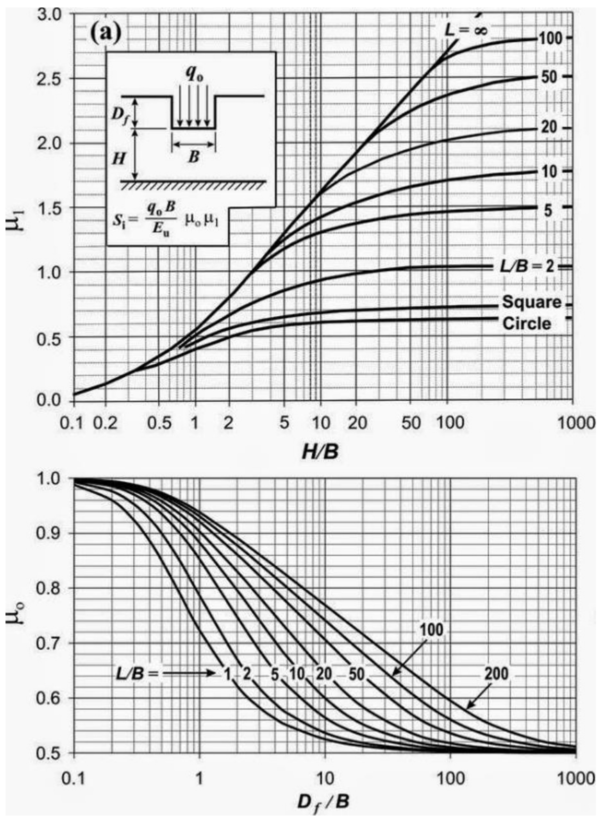

Fig. 3. μ_1 to H/B and μ_0 to D/B correlation graph [9].

$$S_e = q_o(\alpha B')\frac{1-\mu_s^2}{E_s}I_s I_f \quad (4)$$

$$I_s = F_1 + \frac{1-2\mu_s}{1-\mu_s}F_2 \quad (5)$$

$$F_1 = \frac{1}{\pi}(A_0 + A_1) \quad (6)$$

$$F_2 = \frac{n'}{2\pi}tan^{-1}A_2 \quad (7)$$

$$A_0 = \mathrm{m'ln}\frac{\left(1+\sqrt{m'^2+1}\right)\sqrt{m'^2+n'^2}}{m'\left(1+\sqrt{m'^2+n'^2+1}\right)} \quad (8)$$

$$A_1 = \ln\frac{\left(m'+\sqrt{m'^2+1}\right)\sqrt{1+n'^2}}{m'+\sqrt{m'^2+n'^2+1}} \quad (9)$$

$$A_2 = \frac{m'}{n'\sqrt{m'^2+n'^2+1}} \quad (10)$$

Calculation on the middle of the foundation.

$$\alpha = 4 \quad (11)$$

$$m' = \frac{L}{B} \quad (12)$$

$$n' = \frac{H}{\left(\frac{B}{2}\right)} \quad (13)$$

Calculation on the corner of the foundation.

$$\alpha = 1 \quad (14)$$

$$m' = \frac{L}{B} \quad (15)$$

$$n' = \frac{H}{\left(\frac{B}{2}\right)} \quad (16)$$

where α: settlement location factor in foundation, B': B/2 for center of foundation, and B for corner of foundation, I_s: shape factor, and I_f: depth factor (Table 1-2).

Table 1. I_f variation with L/B and D_f/B [10].

L/B	D_f/B	I_f		
		$\mu_s = 0.3$	$\mu_s = 0.4$	$\mu_s = 0.5$
1	0.5	0.77	0.82	0.85
	0.75	0.69	0.74	0.77
	1	0.65	0.69	0.72
2	0.5	0.82	0.86	0.89
	0.75	0.75	0.79	0.83
	1	0.71	0.75	0.79
5	0.5	0.87	0.91	0.93
	0.75	0.81	0.86	0.89
	1	0.78	0.82	0.85

Table 2. Various poisson ratio according to type of soils [10].

Soil type	Rasio poisson (μs)
Loose sand	0,2 – 0,4
Medium sand	0,25 – 0,4
Dense sand	0,3 – 0,45
Silty sand	0,2 – 0,4
Soft clay	0,15 – 0,25
Medium clay	0,2 – 0,5

1.6 Consolidation settlement

Consolidation is a time-dependent settlement of soils resulting from the expulsion of water from the pores which are contained within the soil [8]. Consolidation settlement usually occurs in one direction which is vertical from top to bottom, this is due to the soil around could hold the force or weight that is received horizontally which is usually called (one dimensional consolidation) [11]. Consolidation settlement usually occurs in two phases, primary consolidation, and secondary consolidation. In this research will only conduct a calculation in primary consolidation. The following Equations 17-19 are used for calculating primary consolidation settlement:

For normally consolidated soil ($\sigma_o' = \sigma_c'$):

$$S_c = \frac{C_c H_c}{1+e_o}log\frac{\sigma_o' + \Delta\sigma'}{\sigma_o'} \quad (17)$$

For over consolidated soil:

$$\sigma_o' + \Delta\sigma' \le \sigma_c' \rightarrow S_c = \frac{C_s H_c}{1+e_o}log\frac{\sigma_o'+\Delta\sigma'}{\sigma_o'} \quad (18)$$

$$\sigma_o' + \Delta\sigma' > \sigma_c' \rightarrow S_c = \frac{C_s H_c}{1+e_o}log\frac{\sigma_c'}{\sigma_o'} + \frac{C_c H_c}{1+e_o}log\frac{\sigma_o'+\Delta\sigma'}{\sigma_c'} \quad (19)$$

where Sc: primary consolidation (m), C_c: compression index, C_s: swelling index, e_o; initial soil void ratio, H_c: soil thickness (m), Δσ': change of stress (kN/m^2), σ_o': overburden effective stress (kN/m^2), and σ_c' : preconsolidation pressure (kN/m^2).

1.7 Time rate of consolidation

Equations 20-23 are for time factor.

$$T_v = \frac{C_v t}{H_{dr}^2} \quad (20)$$

For U = 0 – 60%

$$T_v = \frac{\pi}{4}\left(\frac{U\%}{100}\right)^2 \quad (21)$$

For U = >60%

$$T_v = 1{,}781 - 0{,}933\log(100 - U\%) \quad (22)$$

Time rate of consolidation

$$t = \frac{T_v H_{dr}^2}{C_v} \quad (23)$$

where Tv: time factor, Cvcoeffiecient of consolidation (mm^2/min), Hdr: maximum drainage length (m). U: degree of consolidation (%), and t: time needed for consolidation.

The allowed settlement in this research is taken from Bina Marga, for road pavement which is 100 mm [12].

1.8 Soil compaction

Soil compaction is one of the oldest and simplest method of soil improvement. The soil is compacted with force applied from rollers or other equipment [7].

Another compaction can be in the form of dynamic compaction where this method uses a heavy tamper which is lifted and dropped repeatedly with various height and compacts the soil. After very phase of compaction, the resulting crater will be even out with a dozer or filled with granular materials before the next phase of compaction. A lighter tamper with low drop height will result in an improvement to the depth of 3 – 4.6 m, for heavier tamper with higher drop height can result an improvement to the depth of 6.1 – 9.1 m [13].

CBR values of soil can also affect the characteristics of soils. Where with CBR value of soil, SPT values of the soil can also be determined with the following Equation 24 proposed by Livneh [14].

$$\log CBR = -5{,}13 + 6{,}55(\log SPT)^{-0{,}26} \quad (24)$$

with CBR: soil CBR value (%), and SPT: SPT value (hit).

2 Research method

First, gathering every reference and theory needed such as journals, books, and articles is crucial. Then undergoing analyses to the characteristics of peat soil, bearing capacity of foundation, type of settlements, as well as bearing capacity and settlement equations.

Gathering data and parameters needed for peat soil parameters and searching as well as selecting the type of class of roads for the research. The next stage is designing the load that is used in accordance with the class of the road then calculating the bearing capacity, elastic settlement and primary consolidation settlement that might occur as well as the time needed for consolidation to take place. Compiling summaries and suggestion based on the results of the research is the last stage in this research.

3 Results and discussion

This research uses soil parameter data from Pekanbaru which is in the form of boring log data. The pavement layer that is used in this research comes from a road in Pekanbaru. The soil parameters used in this research can be seen in Table 3. The pavement is placed on the elevation of 0.0 m to the depth of -0.88 m as seen in Fig. 4. the pavement layer will be considered as a reinforcement layer with the soil beneath it is compacted with a CBR of 15. The pavement layer used in this research comes from the existing road in the location as seen in Fig. 5.

Load calculation can be seen in Table 4. Vertical stress due to concentrated load (vehicle) can be seen in Table 5.

Table 3. Soil parameter.

Depth (m)	Soil type	Konsistensi	γ_{sat} (kN/m^3)	eo	Cc	Cs	φ (°)	Su (kN/m2)	C' (kN/m2)	σ'c (kN/m2)	Es (MPa)	Cv (cm2/s)
0 – 1	Clay	Stiff	18	0,5	0,1	0,07	30	50	10	455	15	0,00085
1 – 4	Organic	Stiff	11	10	3,9	1,5	27	50	10	380	15	0,0007
4 – 8	Organic	Very Soft	8,3	15	5,9	2,26	25	8	1.5	40	2	0,0005
8 – 11	Silt	Very Soft	18	0,65	0,16	0,09	30	24	5	80	7	0,00085
11 – 18	Clay	Medium	16,5	0,7	0,2	0,11	30	30	6	115	9	0,00085
18 – 24	Sand	Medium Dense	18	0,5	0,1	0,08	36	-	-	-	27	-
24 – 28	Sand	Dense	18	0,5	0,1	0,08	37	-	-	-	24	-
28 – 31	Silt	Stiff	18	0,45	0,1	0,07	30	72	16	260	23	0,00085
31 – 40	Sand	Very Dense	18	0,45	0,1	0,07	39	-	-	-	32	-

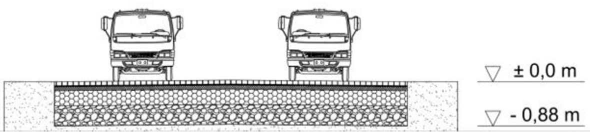

Fig. 4. Pavement layer placement.

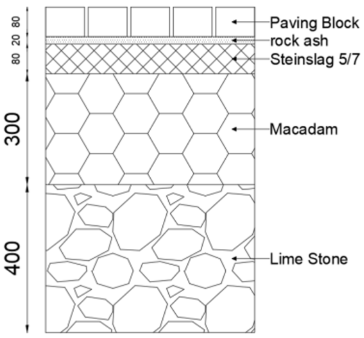

Fig. 5. Pavement layer detail.

3.1 Bearing capacity

The bearing capacity of shallow foundation will be calculated with various method which are Terzaghi, Meyerhof, Hansen and Vesić where the results can be seen in Table 6.

3.2 Elastic settlement

The elastic settlement will be calculated with various methods and equation where its results can be seen in Table 7.

3.3 Primary consolidation

Primary consolidation will be calculated in every layer, where the settlement in every layer can be seen in Table 8. And for the time needed for consolidation can be seen in Table 9.

Table 4. Load calculation.

Description	Material	Unit weight (kN/m3)	Width (m)	Thickness (m)	q (kN/m)	P (kN)
Pavement	Paving Block	22	7	0,08	1,76	12,32
	Rock Ash	18	7	0,02	0,36	2,52
	Steinslag 5/7	14,5	7	0,08	1,16	8,12
	Macadam	15	7	0,3	4,5	31,5
	Limestone	23,87	7	0,4	9,548	66,836
Vehicle Load (MST = 8 Ton)						313,92
Total Load (kN)						435,216

Table 5. Vertical stress due to vehicle load.

Layer (m)	z (m)	Δσz (kN/m2)	
		P1	P2
0 - 1	0.94	8.2454	0.6179
	1	8.7486	0.7108
1 - 4	2.5	7.3271	2.5038
	4	3.8191	2.2523
4 - 8	6	1.8973	1.4639
	8	1.1110	0.9548
8 - 11	9.5	0.7999	0.7173
	11	0.6023	0.5548
11 - 18	14.5	0.3507	0.3344
	18	0.2289	0.2219
18 - 24	21	0.1686	0.1648
	24	0.1293	0.1271
24 - 28	26	0.1103	0.1087
	28	0.0952	0.0940
28 - 31	29.5	0.0858	0.0848
	31	0.0777	0.0769
31 - 40	35.5	0.0593	0.0588
	40	0.0467	0.0464

Calculation example for primary consolidation in layer 1 – 4 m:

$\Delta\sigma' = 9.8309$ kN/m^2

$\sigma'_o = (\gamma_1 \times H_1) + (\gamma_2 \times H_2) + (\gamma_2 \times H_2)$
$= (17 \times 0.85) + ((18 - 9.81) \times 0.15) + ((11 - 9.81) \times 1.5)$
$= 17.4635$ kN/m^2

$\sigma'_c = 380$ kN/m^2

Check $\sigma'_o + \Delta\sigma' \leq \sigma'_c$

$\sigma'_o + \Delta\sigma' = 17.4635 + 9.8309 = 27.2944$ kN/m$^2 \leq \sigma'_c = 380$ kN/m^2

$C_s = 1.5$

$C_c = 3.9$

$H_c = 3$ m

$e_o = 10$

$$S_{c(p)} = \frac{C_s H_c}{1+e_o} log \frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}$$
$$= \frac{1{,}5 \times 3}{1+10} log \frac{17{,}4635+9{,}8309}{17{,}4635}$$
$$= 0{,}0793 \text{ m}$$

Time needed for consolidation with U = 70%

$$T_v = 1{,}781 - 0{,}933 \log(100 - U\%)$$
$$= 1{,}781 - 0{,}933 \log(100 - 70\%)$$
$$= 0{,}4028$$

$Cv = 7 \times 10^{-8}$ m^2/s

$$t = \frac{T_v H_{dr}^2}{C_v} = \frac{0{,}4028 \times 3^2}{7 \times 10^{-8}}$$
$= 51794469$ s = 599 hari = 1,6424 years

Table 6. Bearing capacity summary.

Bearing Capacity (kN/m2)	Theory			
	Terzaghi (1943)	Meyerhof (1963)	Hansen (1970)	Vesić (1973, 1975)
qall	422.4513	359.7380	346.9074	415.2116

Table 7. Elastic settlement summary.

Layer (m)	Es (kN/m2)	H (m)	Elastic Settlement (m)			Largest Settlement (m)
			Saturated Clay	Janbu et al (1956)	Hooke's law	
0,88 – 1	15000	0.12	4.0501×10^{-5}	2.0624×10^{-4}	-	2.0624×10^{-4}
1 – 4	15000	3	6.8794×10^{-4}	1.4547×10^{-3}	-	1.4547×10^{-3}
4 – 8	2000	4	2.2654×10^{-3}	4.6224×10^{-3}	-	4.6224×10^{-3}
8 – 11	7000	3	1.8277×10^{-4}	4.1917×10^{-4}	-	4.1917×10^{-4}
11 – 18	9000	7	1.9449×10^{-4}	3.3452×10^{-4}	-	3.3452×10^{-4}
18 – 24	27000	6	-	-	2.9199×10^{-5}	2.9199×10^{-5}
24 – 28	24000	4	-	-	2.1393×10^{-5}	2.1393×10^{-5}
28 – 31	23000	3	1.4476×10^{-6}	1.2959×10^{-5}	-	1.2959×10^{-5}
31 – 40	32000	9	-	-	1.4620×10^{-5}	1.4620×10^{-5}

Table 8. Primary consolidation summary.

Layer (m)	σ'o (kN/m2)	Δσ' (kN/m2)	σ'c (kN/m2)	Cs	Cc	Hc	eo	Settlement (m)
0.88 – 1	15.1871	8.8634	455	0.07	0.1	0.12	0.5	0.0011
1 – 4	17.4635	9.8309	380	1.5	3.9	3	10	0.0793
4 – 8	16.2285	3.3612	40	2.26	5.9	4	15	0.0462
8 – 11	25.4935	1.5172	80	0.09	0.16	3	0.65	0.0041
11 – 18	61.1935	0.6851	115	0.11	0.2	7	0.7	0.0022
28 – 31	178.7935	0.1706	260	0.07	0.1	3	0.45	0.0001
Total								0.1330

Table 9. Time needed for consolidation summary.

Layer (m)	H (m)	Cv (m^2/s)	t (years)
0,88 – 1	0,12	$8{,}5 \times 10^{-8}$	0,0022
1 – 4	3	7×10^{-8}	1,6424
4 – 8	4	5×10^{-8}	4,0877
8 – 11	3	$8{,}5 \times 10^{-8}$	1,3526
11 – 18	7	$8{,}5 \times 10^{-8}$	7,3639
28 – 31	3	$8{,}5 \times 10^{-8}$	1,3526
Total			15,8013

For settlement in every year can be seen in Fig. 6.

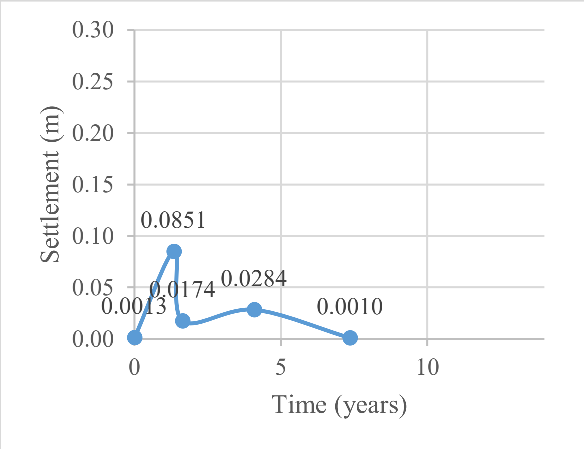

Fig. 6. Consolidation settlement/ time graph.

4 Summary and suggestions

Summary:

1. The total settlement occur is 14.01 cm where the allowed settlement according to Bina Marga to occur is still not fulfilled.
2. The elastic settlement that occurred is 0.71 cm.
3. The primary consolidation that occurred is 13.30 cm.
4. The time needed for consolidation if summed is 15.8013 years with the longest time is 7.3639 years.
5. The largest bearing capacity is from Terzaghi's method which is 422.4513 kN/m^2.

Suggestions:

1. To reduce the settlement occurred in peat soil, it is better to perform soil improvement so that the settlement of roads in peat soil is smaller.
2. To improve peat soil, a specific or better method of soil improvement must be used such as compaction or filling the soil pores with grouting.
3. Due to the characteristics of peat soil which have high percentage of organic substance, there are a lot of uncertainty in predicting the settlement that occurred accurately. Therefore, it is suggested to undergo laboratory testing to predict the settlement that occurred in peat soil.

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