ANALYSIS OF NATURAL COMPACTION IN MRT TUNNEL CP201, CENTRAL JAKARTA

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Abstract *— This study analyzes the land subsidence caused by natural consolidation in the Thamrin Area, Central Jakarta, along the MRT CP201 tunnel route. Jakarta's soft soils, particularly clay layers, contribute to land subsidence, with 0.2 to 3.6 meters and rate of subsidence is 1,24 cm/years. Rate of subsidence refers to the speed at which the ground surface lowers over a specific period due to many factors . Calculating rate of subsidence is essential for assessing its impact on infrastructure and predicting subsidence predictions. Using both analytical (one-dimensional consolidation) and numerical (finite element) methods, subsidence predictions were made based on geotechnical data from three boreholes which is TS-01,TS-02 and TS-03. Results show positive correlation between the two methods, with numerical approach yielding slightly smaller values due to its consideration of both vertical and horizontal deformations. This analysis highlights unavoidable nature of subsidence due to natural consolidation and emphasizes the need for mitigation and adaptation measures, such as spatial planning and monitoring systems, to minimize impacts on infrastructure.*

Keywords*: Land subsidence, Natural consolidation, One-Dimensional Terzaghi, Finite element*

I. INTRODUCTION

MRT Jakarta has been designed as one of the integrated modes of transportation to overcome the problem of congestion. The current Jakarta MRT development project work program in phase 2 stretches along about 11.8 kilometers from Bundaran HI Station to West Ancol Station. Phase 2 development is a national strategic project based on Presidential Regulation Number 56 of 2018 about Second Amendment to Presidential Regulation Number 3 of 2016 on Accelerating the Implementation of National Strategic Projects [1]. Jakarta MRT Tunnel CP201 construction is an important part of the development of the public transportation system in Central Jakarta with total length of 2.6 km and depth of 17 to 36 meters underground [2]. Jakarta, which is located in land subsidence prone area, has geological conditions dominated by soft soils, such as clay and silt, which can affect the stability of the tunnel. Research shows that the conditions of the soil below the surface are various, with soft soil layers having high plasticity, which has the potential to cause deformation and surface subsidence during and after the tunnel excavation process [3].

Land subsidence is a geological phenomenon that occurs when the soil surface decreases due to various factors, including human activities and geological conditions. Land subsidence are problem of several cities in Indonesia, especially in the coastal area of the North Coast of Java (Pantura), such as Jakarta, Semarang, Pekalongan, and Semarang showed in Figure 1. In addition, Bandung is also an area with the potential for land subsidence. Land subsidence in Jakarta has been going on since 1970 [4]. This subsidence can be caused by various factors, both natural and anthropogenic. In Jakarta, natural factors include natural compaction and tectonic activity, while anthropogenic factors primarily consist of groundwater extraction and structural loads from buildings. [5]. Land subsidence in Jakarta occurs spatially at a rate of 3–10 cm/year [6]. Recent studies analyzing land subsidence in Central Jakarta using InSAR technology have indicated a slower rate, ranging from 0 to 2.5 cm/year [7].

One of the causes of land subsidence in Central Jakarta is natural compaction. Natural sediment compaction is a process where the volume of sediment layers decreases due to the weight of overlying sediments (overburden) [8]. Natural compaction referred to the study is natural consolidation. The assessment of land subsidence due to natural consolidation in Central Jakarta is essential for evaluating necessary mitigation and adaptation measures. This study aims to analyze the rate of land subsidence caused by natural compaction factors using analytical and numerical methods. Geotechnical data are collected

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through secondary sources and laboratory tests to determine the parameters required for the subsidence analysis.

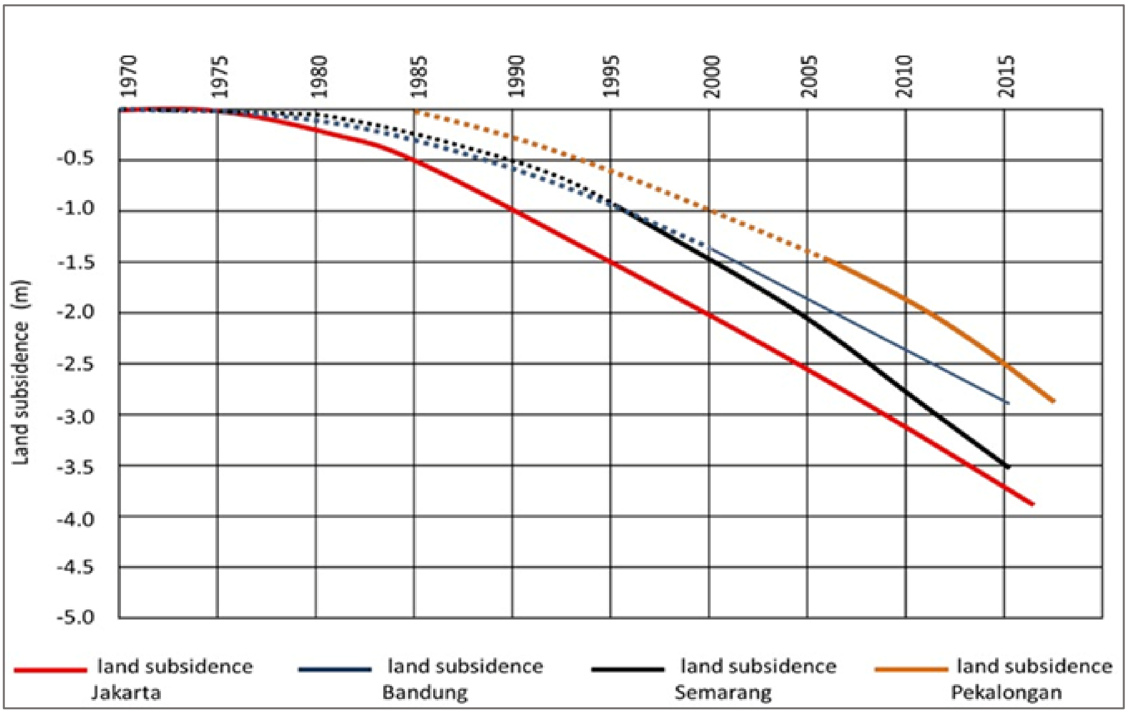

Figure 1. Land subsidence of several city in Indonesia [4]

A. Geology of Study Area

Physiographically, West Java is divided into four zones: Batavia Plain Zone (Jakarta), Bogor Zone, Bandung Zone, and Southern Mountain Zone. The study area is located in Batavia Plain Zone, which extends along the northern coast from Serang to Cirebon. This zone spans approximately 40 km in width and features relatively flat morphology. It is composed primarily of alluvial deposits transported by rivers. [9]. The Jakarta Basin consists of a thick sequence of Quaternary deposits measuring approximately 200-250 meters, which overlay Tertiary basement rocks. The basal contact of these Quaternary layers serves as the lower boundary of the groundwater aquifer system. This sedimentary sequence can be divided into three main stratigraphic units based on their relative ages, arranged from oldest to youngest: (1) Pleistocene marine and non-marine sediments, (2) volcanic fan deposits from the late Pleistocene, and (3) Holocene deposits, including marine and floodplain sediments [10]. Based on the regional geological map, Turkandi et al. (1992) classified the rocks in the study area, ranging from the Early Miocene to the Holocene, into several formations. Regional stratigraphy of the study area, from youngest to oldest, as follows: aluvium (Qa), Coastal Ridge Deposits (Qbr), Alluvial Fan Deposits (Qav), Coral Limestone (Ql), Andesite of Sundamanik Mount (Qvas), Young Volcanic Rock (Qv), Banten Tuff (QTvb), Serpong Formation (Tpas), Genteng Formation (Tpg), Bojongmanik (Tmb), Klapanunggal Formation (Tmk), Jatiluhur Formation (Tmj) and Rengganis Formation (Tmrs).

The research location is in Central Jakarta, with geographic coordinates ranging from 106°48’44“-106°49'58.61“ East longitude and 6°9'35.72“-6°11'27.60“ South latitude. Figure 2 shows that the geology at the research area alluvium fan deposits [11]. This deposit consists of fine-grained layered tuff, sandy tuff, interspersed with conglomeratic tuff. The formation process of this deposit originates from the young volcanic rocks in the highlands of Bogor, which were deposited in a terrestrial environment, forming a fan morphology. These deposits are estimated to be of Pleistocene age. The soil conditions in Central Jakarta, particularly in the Menteng subdistrict, are dominated by soft to very soft clay layers.

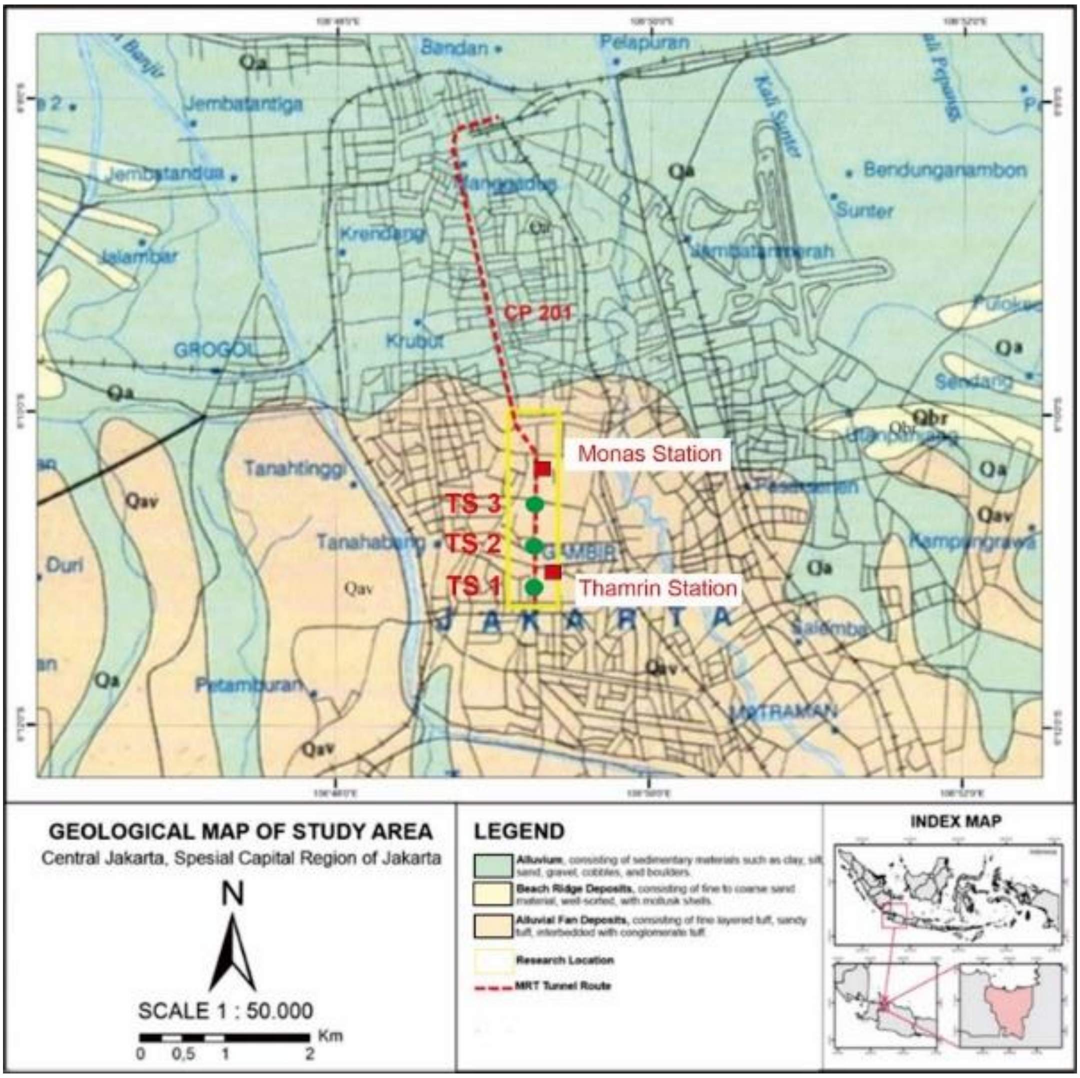

Figure 2. Modification geological map of study area [11]

II. METHODS

This research used analytical methods and numerical approach based on soil properties. We use boreholes on the track of the CP201 MRT tunnel to describe soil and soil parameter for analysis subsidence. Total of three boreholes core samples were described each to determine the value of soil properties. The model's parameters were derived from laboratory measurements conducted on undisturbed soil samples retrieved from boreholes TS-1, TS-2, and TS-3 in Thamrin-Monas Area. TS-1 and TS-2 are located in Menteng Subdistrict, whereas TS-3 is located is Gambir Subdistrict. Clay at the study area assumed homogeneous at the same layer. Table 1 shows details measurements for land subsidence analysis.

Table 1: Engineering properties of Thamrin-Monas Area Section.

Section	Litology	Saturated unit weight (Kn/m³)	Unsaturated unit weight (Kn/m³)	Void ratio	Coefficient of compression (c_c)	Coefficient of consolidation (c_v) (m²/year)	Swelling Index	Cohesion (kPa)	Internal friction (°)	Modulus young (kPa)	Permeability (m/s)
Thamrin-Monas	Silty Clay	4.5-12.9	12.2-17.8	0.9-3.8	0.2-0.5	1.4-1.9	0.2-0.4	10.0-22.0	26.0-32.0	$2.5x10^3$ to $11.5x10^3$	$5.1x10^{-8}$
	Sand	12.1-13.1	16.7-19.2	0.8-1.0				15.0-18.4	20.0-32.0	$1.6x10^4$ to $4.4x10^4$	$2.1x10^{-4}$
	Clay	5.1-10.5	12.8-16.6	1.1-4.3	0.3-1.6	1.0-2.3	0.2-0.4	8.0-29.8	12.5-29.0	$2.1x10^3$ to $8.0x10^3$	$5.1x10^{-8}$

Figure 3 shows research flow diagram. The research stage starts from the preliminary stage as literature study, then continue data collection stage, the analysis stage, and the conclusion. This analysis carried out was to calculate the amount of land subsidence that occurred at the research area. Idenfitication of consolidation parameters used for land subsidence calculation to produce a comparison of analytical and numerical methods.

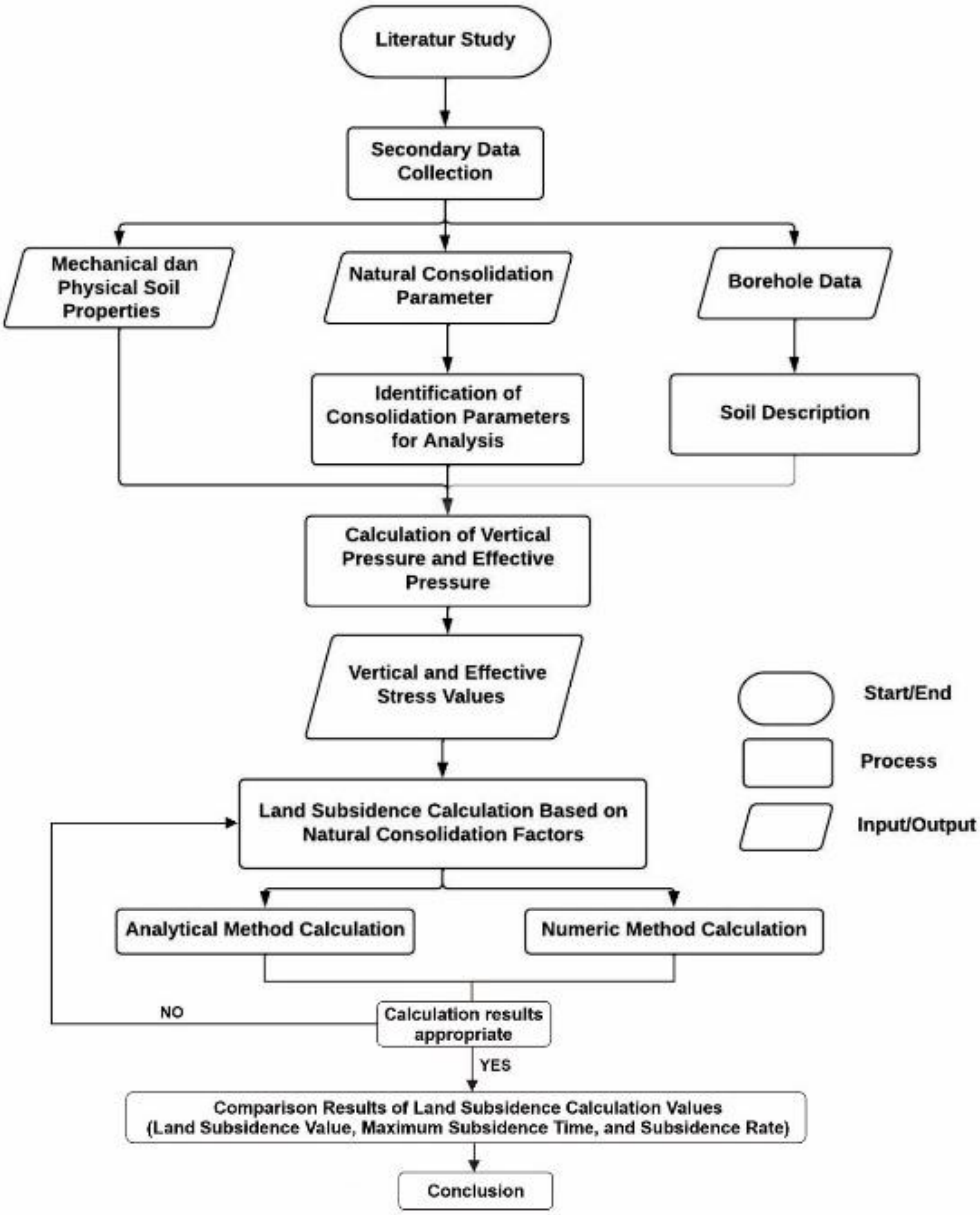

Figure 3. Research flow diagram.

A. LAND SUBSIDENCE ANALYSIS

Land subsidence analysis using one-dimensional consolidation and numerical method using finite element. Borehole used for analysis are TS-1, TS-2, and TS-3. The three boreholes were analyzed at each point. When stress increases in saturated soil, it generates pore water pressure. In highly permeable sand, water drains rapidly, resulting in both immediate settlement and consolidation occurring simultaneously. Soils with lower permeability, such as clay, water disipated gradually under the applied load, causing a slow transfer of excess pore water pressure (u) to effective stress (σ'), as represented in Eq. (1):

$$\Delta\sigma = \Delta\sigma' + \Delta u \quad (1)$$

Where are:

$\Delta\sigma'$ – increase in the effective stress

Δu – increase in the pore water pressure

Rate of consolidation is governed by an equation derived by Terzaghi, based on assumptions that soil compression and pore water flow occur solely in the vertical direction, the soil is homogeneous, and both total and effective stress are uniform on any horizontal plane [12]. Predictions of one-dimensional consolidation settlement are typically made using results from oedometer tests on representative clay soil samples. Primary consolidation can be calculated using Equation 2, while secondary consolidation, which occurs after the pore water pressure has fully dissipated, can be estimated with Equation 3 [13]:

$$\text{Sp} = \frac{C_c H}{1+e_0} log\ log\ (\frac{p_0 + \Delta p}{p_0}) \quad (2)$$

$$\text{Ss} = C'_\alpha H\ log\ (\frac{p_0 + \Delta p}{p_0}) \quad (3)$$

Where are:

Sp = settlement due to primary consolidation
Ss = settlement due to secondary consolidation
C'_α = $C_\alpha/(1 + e_p)$
p_0 = effective stress
Δp = vertical stress
C_c = compression index
H = thickness of layer
e_0 = void ratio

The finite element method for calculating soil subsidence is based on Biot's consolidation theory [14] which employs coupled consolidation equations. These equations enable the simultaneous calculation of excess pore pressure and deformation in a porous medium over time. In this model, several assumptions are made: the soil is homogeneous, uniform, and saturated; fluid flow adheres to Darcy's law; and a small strain poroelastic model is applied.

$$\underline{s} = \underline{s}' + \underline{m}\ (p_{steady} + p_{excess}) \quad (4)$$

Where are:

s = total stress vector
s' = effective stress vector
$\underline{m}$ = unit vector for stress components
p_{steady} = pressure determined as the end of consolidation
p_{excess} = excess pore water pressure

III. RESULTS AND DISCUSSION

A. Analytical Method

Land subsidence is assumed to have started in 2018, with a subsidence value of 0.058 meters. The analysis shows that the maximum subsidence will occur at point TS-02, reaching 3.60 meters, with a maximum time of 242 years. Rate of subsidennce at this point is 1.24 cm/year. The vertical and effective stress, representing the overburden are calculated for each clay layer, with an effective pressure of 486.6 kN and a vertical stress of 398.9 kN. At point TS-02, the depth to the maximum groundwater level is 3.1 meters, and the clay layer thickness is 36 meters (Table 2). Higher the compression index value, the higher coefficient of consolidation value. This will affect the consolidation process which can occur faster. Result of the primary decrease at this point is 3.51 m, while the secondary decrease value is 0.09 m. Relationship between the degree of consolidation (U) and the time factor (Tv) is used to determine the maximum descent time.

Table 2: Primary and secondary subsidence due to natural consolidation.

Code	H (m)	σ'	σv	Sc (m)	S_S (m)	S_{tot} (m)	S_{max} (years)
TS-01	42,6	477	211	1,3	0,07	1,77	1983
TS-02	16,9	487,6	398,9	3,51	0,09	3,6	290
TS-03	16	322,2	230,7	2,19	0,07	2,26	220

The slowest land subsidence in Thamrin-Monas Area is the TS-01 borehole with a sinking value of 1.77 m until 4001. (Table 2). The sinking rate on the TS-01 reaches 0.09 cm/year. This indicates that the thicker the clay, the slower the time required for consolidation [15]. This happens because clay is impermeable that can hold water, while the permeable layer at all drill depths is not described. Previous studies, consolidation process in clay is time-dependent, with the dissipation of excess pore water pressure occurring gradually, especially in soils with low permeability like clay. These studies highlight how water retention and slow dissipation contribute to prolonged settlement and consolidation time in clays [16].

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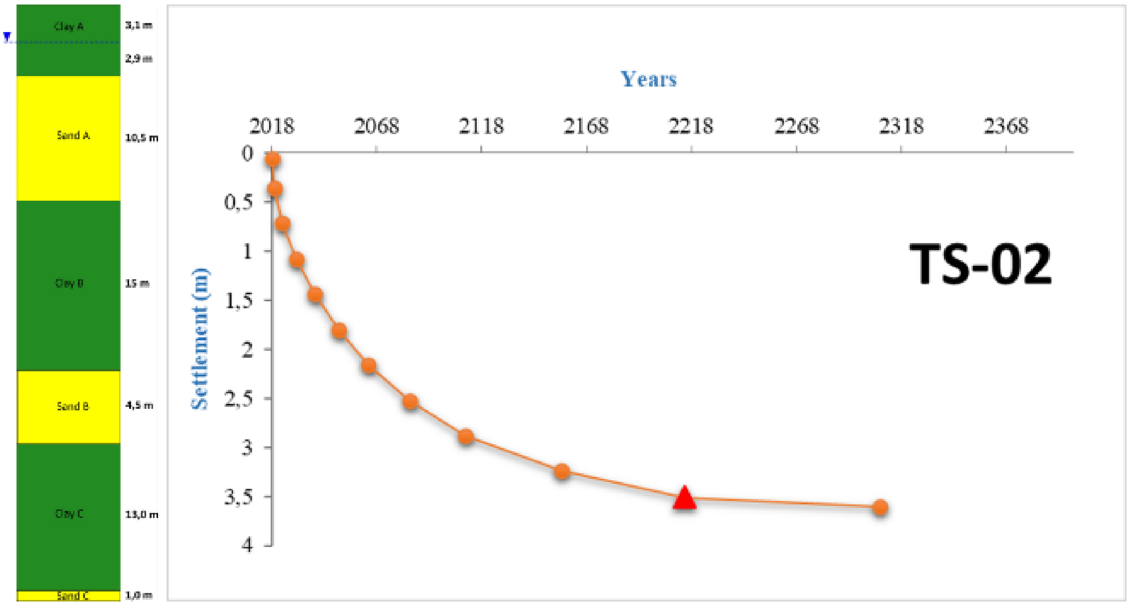

Figure 4. Land subsidence graph TS-02.

Maximum subsidence time during the consolidation process can be very slow, making it impractical for construction purposes. The subsidence after 90% consolidation is insignificant, thus resulting in minimal impact. Table 3 shows the land subsidence until the 90% consolidation process. The slowest maximum subsidence occurs at TS-01, with a rate of 0.17 cm/year and a maximum subsidence time of up to 944 years. On the other hand, TS-02 experiences the largest maximum subsidence of 3.25 meters in 138 years, with a subsidence rate of 2.82 cm/year. The consolidation process at 90% for point TS-02 will continue until the year 2156.

Table 2: Primary and secondary subsidence due to natural consolidation.

Code	Subsidence (m)	Rate of Subsidence (cm/tahun)	Time Subsidence (years)	Years Subsidence
TS-01	1,6	0,17	944	2962
TS-02	3,24	2,35	138	2156
TS-03	2,04	1,94	105	2123

B. Numerical Method

Numerical method analysis using finite element with Plaxis 2D Software. Figure 5 shows the model and element mesh used for analysis by the finite element method at point TS-02, as the largest subsidence. The loads used for the analysis are based on the respective loads on the soil layer. Based on the model, land subsidence that occurred due to natural consolidation was 3.25 m. The value of the land subsidence occurs until the consolidation process is completed.

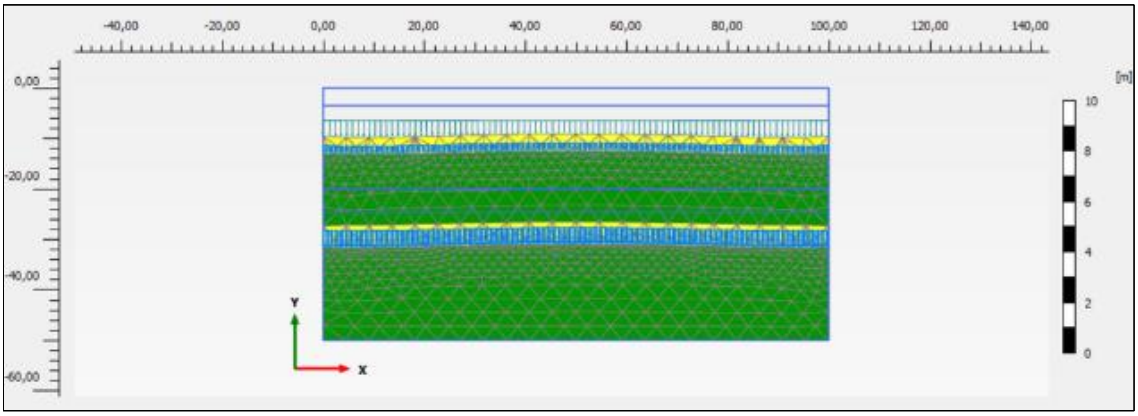

Figure 5. Land subsidence graph TS-02.

C. Comparison of Analytical and Numerical Methods

Results of land subsidence analysis using both analytical and numerical approaches show varying differences. These discrepancies arise from the parameters used in the analysis as well as the stress considered in each method. The deformation assumed in the Terzaghi method approach occurs in only one direction, whereas the finite element method assumes deformation in two directions, vertical and horizontal. The percentage difference is calculated to assess the similarity of the results between the two methods. At this point, there is a difference in the results between the analytical and numerical methods. The comparison of subsidence calculations using these two methods show positive correlation across all borehole points, with subsidence difference due to natural consolidation at TS-01 being 0.45 meters. The comparison of subsidence calculations due to natural consolidation using the Terzaghi one dimentional analytical method also yields a positive correlation, with a difference of less than 15%.

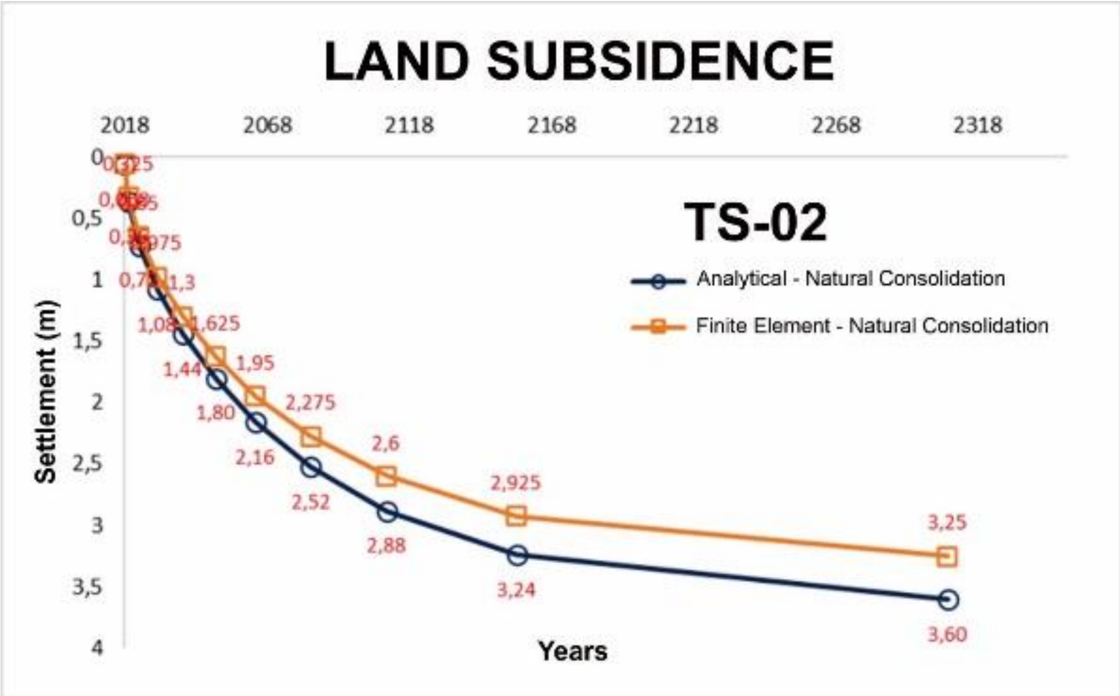

Figure 5. Land subsidence graph TS-02.

IV. Conclusion

Soil condition in MRT CP201 Tunnel especially in Thamrin Area is predominantly composed of soft to very soft clay layers. Loose to very loose sand lenses are trapped in the upper layers, while sand lenses are also found in the lower layers with the soil consistency becomes stiff to very stiff, dominated by clay and silt materials. Discrepancies in interpretation based on the regional geological map and borehole sample descriptions need further examination. These interpretations influence the formation present at the research location. The presence of clay layers beneath the surface contributes to natural consolidation. Overall, natural consolidation has impact on land subsidence ranging from 0.2 to 3.6 meters with rate of subsidence reach 2.35/year. Land subsidence in Central Jakarta due to natural consolidation is unavoidable. Adaptation measures are necessary to minimize the potential impacts, such as spatial planning, early warning systems, and monitoring rate of land subsidence.

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