Evaluating the Causes of Land Subsidence in Central Jakarta Using 1-Dimensional Consolidation Approach

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Abstrak - Penurunan tanah di Jakarta Pusat, didorong oleh proses geologi alami dan faktor yang disebabkan oleh manusia. Pembangunan industri Jakarta yang pesat dan berkontribusi terhadap masalah penurunan tanah yang sedang berlangsung di kota tersebut. Pemantauan penurunan tanah dengan InSAR di Jakarta Pusat menunjukkan laju rata-rata 1-10 cm/tahun. Penelitian ini bertujuan untuk mengevaluasi kontribusi konsolidasi dan faktor antropogenik terhadap penurunan tanah di Jakarta Pusat. Metode analisis menggunakan teori konsolidasi 1-D diterapkan. Hasil menunjukkan bahwa konsolidasi alami memiliki peran yang signifikan terhadap penurunan tanah, yang diprediksi akan terus berlanjut hingga tahun 2368. Laju penurunan tanah untuk konsolidasi alami berkisar antara 1,5-9,1 cm/tahun. Sementara itu, faktor antropogenik mencapai 3,4-17,4 cm/tahun. Faktor antropogenik ini mempercepat laju penurunan tanah sebesar 1,9-8,3 cm/tahun atau 26,0-47,7%. Berdasarkan analisis, analisis penurunan tanah di Jakarta Pusat menunjukkan bahwa faktor antropogenik dalam lima tahun tidak berpengaruh secara signifikan terhadap penurunan tanah yang terjadi.

Kata Kunci: Penurunan tanah, konsolidasi alami, faktor antropogenik, Jakarta Pusat.

Abstract *– Land subsidence in Central Jakarta, driven by both natural geological processes and human-induced factors. Jakarta's booming industrial development and contributing to the city's ongoing land subsidence problem. Monitoring of land subsidence with InSAR in Central Jakarta shows an average rate of 1-10 cm/year. This study aims to evaluate the contribution of consolidation and anthropogenic factors to land subsidence in Central Jakarta. The analytical method uses 1-D consolidation theory is applied. Results indicate that natural consolidation has a significant role in land subsidence, which is predicted to continue until 2368. The rate of soil subsidence for natural consolidation ranges from 1.5-9.1 cm/year. Meanwhile, anthropogenic factors achieved 3.4-17.4 cm/year. These anthropogenic factors accelerate the rate of land subsidence by 1.9-8.3 cm/year or 26.0-47.7%. Based on analysis, land subsidence analysis in Central Jakarta shows that anthropogenic factors in five years do not significantly affect the subsidence that occurs.*

Keywords*: Land subsidence, natural consolidation, anthropogenic factors, Central Jakarta.*

INTRODUCTION

Jakarta, as the capital city of Indonesia, plays an important role as a center with diversity and dynamics that reflect the progress of the nation. The population of Jakarta in present time reach more than 10 millions people (Statistics Jakarta Province, 2023). The rising population density in urban areas has exacerbated traffic congestion, as the limited road capacity struggles to accommodate the growing number of vehicles. Jakarta is located in a coastal plain zone with a relatively flat morphology and composed of alluvial deposits (Bemmelen, 1949). These deposits typically consist of a mixture of sand, silt, and clay, often with varying proportions depending on the flow characteristics of the water body and the source material. Due to their composition and depositional environment, alluvial deposits are often characterized as soft soils (Figure 1). Soft soils in Jakarta are dominated by high-plasticity clay and silty clay (Permana & Rahardjo, 2022). Clay soils are known for their cohesive properties and low bearing capacity, tend to undergo deformation and volume changes when subjected to loads (Wesley, 2010).

The construction in Central Jakarta will faces geotechnical challenges due to the soft soil conditions in the area. This soft soil condition becoming unstable that prone to land subsidence. According to USGS, land subsidence is a gradual settling or sudden sinking of the Earth's surface due to removal or displacement of subsurface earth materials. Land subsidence can be caused by natural and anthropogenic processes. Natural land subsidence results either from isostatic sediment loading and natural compaction of Holocene deposits or from tectonic and volcanic activities (Raucoules et al., 2007). Anthropogenic land subsidence, the sinking of land caused by human activities, is a growing concern in many parts of the world. Two primary anthropogenic factors driving this phenomenon are excessive groundwater extraction and the increasing weight of urban infrastructure. Excessive extraction of groundwater can lead to the depletion of underground aquifers. The construction of heavy buildings, particularly in urban areas, can also contribute to land subsidence. The weight of these structures places an additional burden on the underlying soil, causing them to compact and sink. Land subsidence can lead to several significant impacts, including the cracking of permanent structures and roadways, tilting and sinking of buildings and houses, alterations in river and drainage systems, expansion of coastal or inland flood zones, and increased intrusion of seawater into inland areas (Abidin et al., 2015).

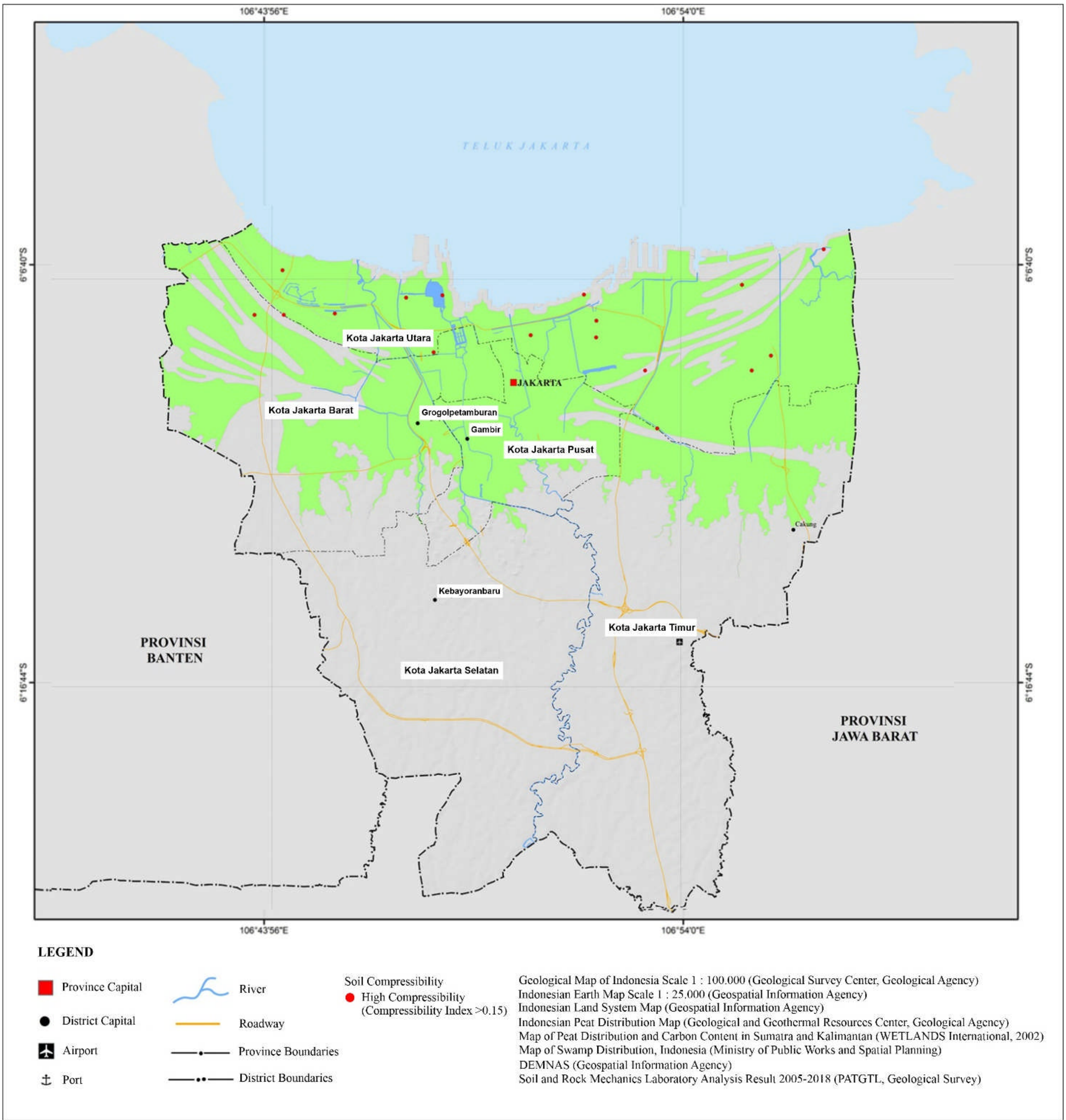

Figure 1. Map of soft soil distribution in Jakarta (modification Ministry of Energy and Mineral Resources, 2019).

Land subsidence in Jakarta has occurred since 1974 (Abidin dkk., 2015). There are four factors of land subsidence that can occur in Jakarta basin, subsidence caused by groundwater extraction, construction loads (e.g., subsidence of highly compressible soil), natural consolidation of alluvial soil, and subsidence resulting from geotectonic processes (Murdohardono dan Sudarsono, 1998). Based on previous study, land subsidence in Jakarta affected by anthropogenic

DOI: https://doi.org/10.31315/jigp.v11i2.13643
p-ISSN 2356-024X
e-ISSN 2987-100X

factors is bigger than natural process, such as groundwater exploitation and building loads. Land subsidence in Jakarta has spatial and temporal variations with a typical rate of about 3-10 cm/year (Figure 2).

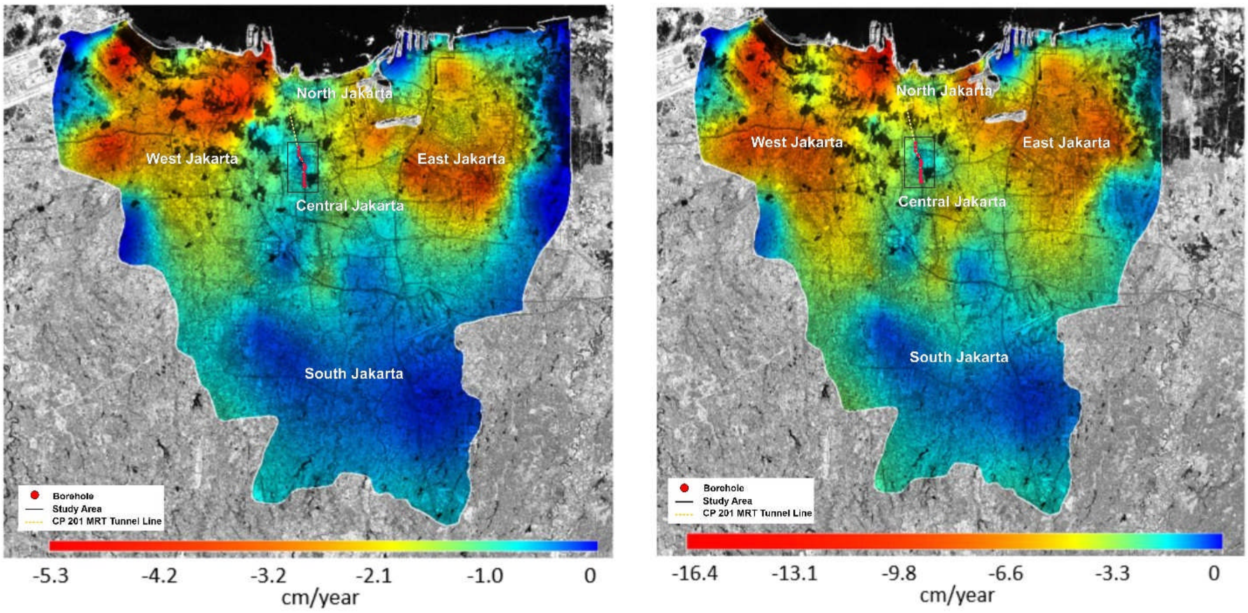

Figure 2. Rate of land subsidence in Jakarta during the period of 1974-2010 (Irwan Gumilar in Abidin, 2015)

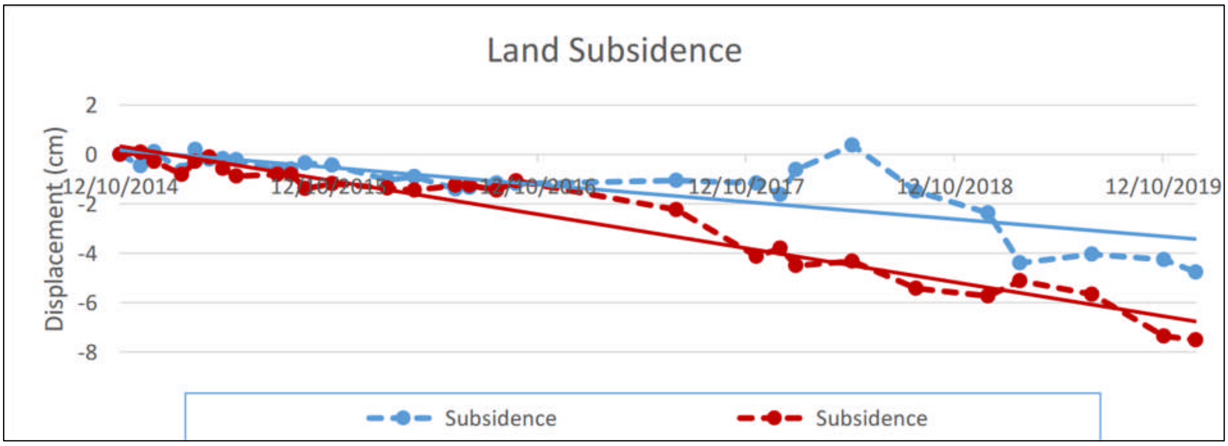

Figure 3. Subsidence time-series in Jakarta during period of 2014-2019 (Bernike dkk., 2020).

The subsidence rate along the coastal zone of Jakarta is higher in the central and western parts compared to other areas (Figure 2). This subsidence is based on levelling, GPS and InSAR survey methods (Abidin et al., 2001, 2008a, 2010a, 2011, 2015). Recent InSAR monitoring show in Figure 3 (Bernike dkk., 2020) indicates land subsidence in Central Jakarta shows the smallest rate of -0.6 cm/year and the highest rate of -7.3 cm/year. Blue dan red line show subsidence in South Jakarta (i,e CP104-CP 105 MRT Tunnel line) and Central Jakarta (i.e CP 106 MRT Tunnel line) respectively. Geodetic studies excel at providing a broad picture of land subsidence. They can accurately measure the current rate of subsidence across a large area. However, these techniques have limitations in identifying the specific causes and precisely quantifying the contribution of each factor (Sarah et al., 2021). In order to accurately assess the individual contributions of soil layers to land subsidence, this study employs the one-dimensional consolidation theory, a simplified model that offers greater precision than geodetic methods. The primary objective of this paper is to evaluate the relative contributions of consolidation and anthropogenic factors to land subsidence in Central Jakarta. Employing analytical approaches, this research quantifies the extent to which anthropogenic factors influence the observed subsidence rates.

Geological Area

The study site is located 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 4). Jakarta basin is comprised of a substantial sequence (200-250 meters) of Quaternary deposits overlying Tertiary basement rocks. The basal contact of the Quaternary sequence is considered the lower boundary of the groundwater aquifer. Furthermore, this younger sedimentary succession can be differentiated into three primary units with increasing age from bottom to top. These units include: (1) a sequence of Pleistocene marine and non-marine sediments, (2) a late Pleistocene volcanic fan deposit, and (3) Holocene marine and floodplain deposits (Yong et al, 1995).

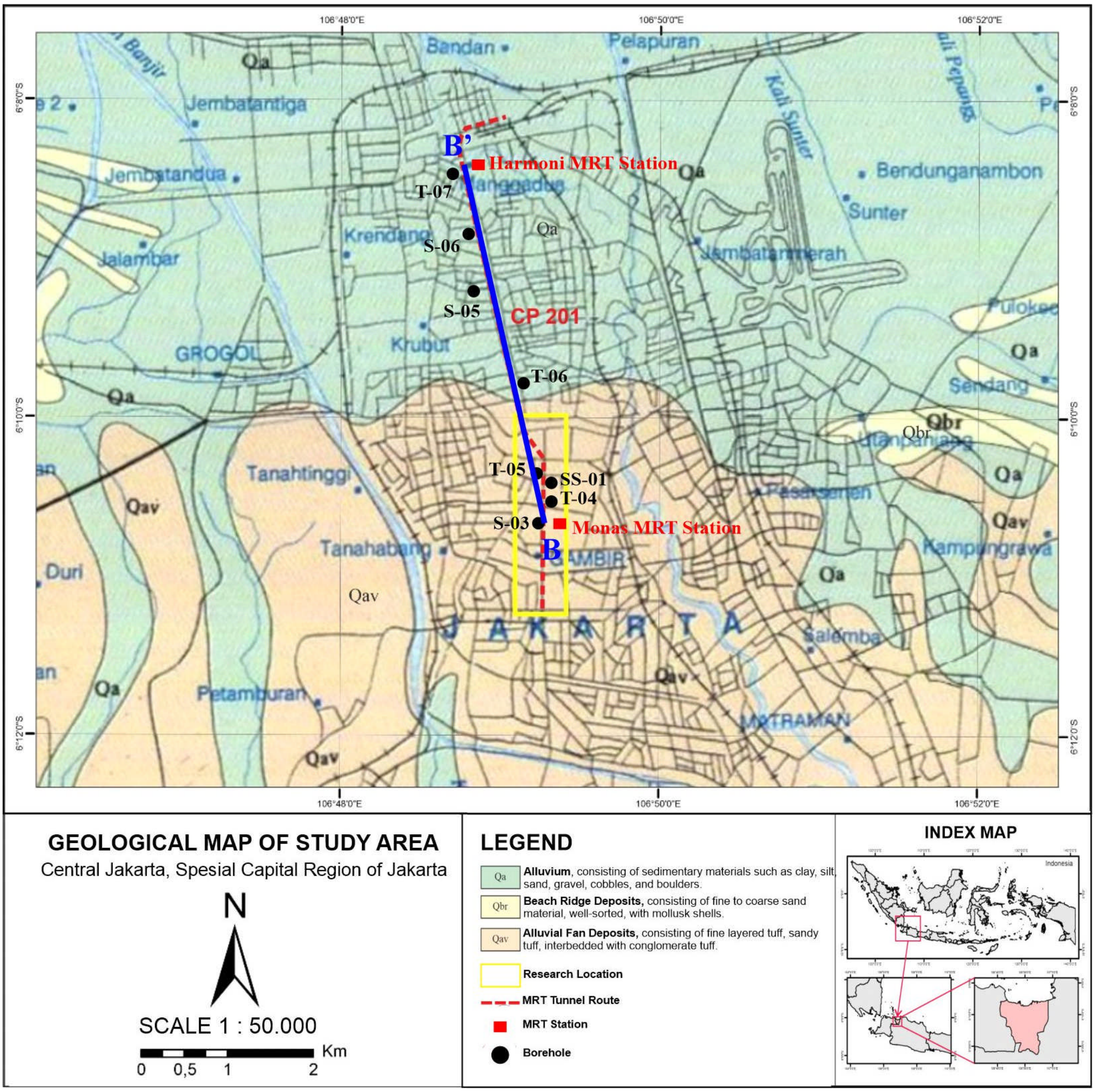

Figure 4. Geological map of Jakarta Area.

Figure 4 shows that the distribution of soft clay in research location generally occupies tidal plains and alluvial plains of rivers, with deposits in the form of clay, silt and sand. The soft soil has a very soft to soft consistency, high compatibility (0.36-1.16) and relatively low carrying capacity (Ministry of Energy and Mineral Resources, 2019). Monas area is situated on alluvial plains predominantly composed of young sedimentary deposits, including clay, silt, and sand. The top layer of the soil is dominated by soft to intermediate clay from a depth of 1-10 meters. In the middle layer, with a depth of 10-20 meters, it is dominated by clay and silt with medium to rigid stiffness. At a depth of about 16-22 meters, there are

DOI: https://doi.org/10.31315/jigp.v11i2.13643 *e-ISSN 2987-100X*

medium to dense sand lenses following the lower layer is dominated by clay and silt materials that are stiff to very rigid (Figure 5).

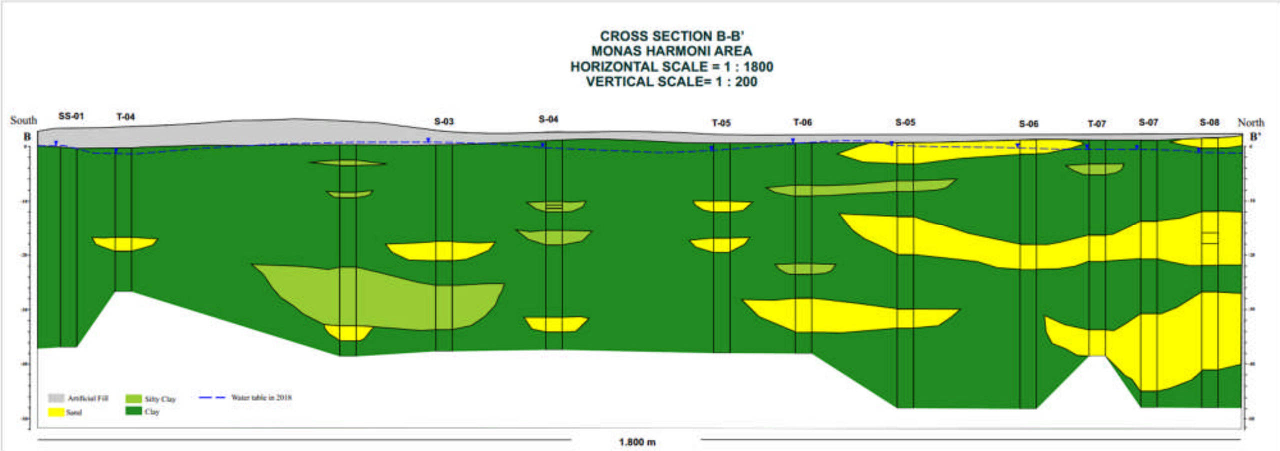

Figure 5. Cross-section B-B' Monas Area.

METHOD

This research used analytical methods approach based on soil properties. We use boreholes and CPTu to create a section in Central Jakarta. Total of nine boreholes core samples were described each to determine the value of soil properties. Selected cross-section B-B' determine in Central Jakarta which is from MRT Monas Station – Harmoni Station (Figure 5). The model's parameters were derived from laboratory measurements conducted on undisturbed soil samples retrieved from boreholes T-04, SS-01,S-03,S-04,T-05,T-06,S-05,S-06,T-07 (Figure 5). We assumed the clay at the study site was homogeneous at the same layer. Details of these measurements are presented in Table 1 and show geotechnical properties employed in the analysis. The input for consolidation analysis used Poisson's ratio (μ) is assumed from literatures values, ranging 0.15 – 0.5 for clay and 0.2 – 0.45 for sand.

Table 1: Engineering properties of boreholes in Central Jakarta

Area	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)
Central Jakarta	Silty Clay	14.1-16.6	8.9-9.7	0.9-1.8	0.2-0.6	1.7-2.1	0.2-0.4	19.2-22.8	22.0-23.0	$2.5x10^3$ to $11.5x10^3$	$5.1x10^{-8}$
	Sand	15.7-21.1	12.7-16.4	0.8-1.0				17.0-19.5	20.0-25.0	$1.6x10^4$ to $4.4x10^4$	$2.1x10^{-4}$
	Clay	14.0-19.1	6.4-14.2	0.9-3.0	0.2-1.2	1.3-2.4	0.2-0.4	11.0-29.9	12.1-26.7	$2.1x10^3$ to $8.0x10^3$	$5.1x10^{-8}$

The increase in groundwater exploitation has caused groundwater level decrease in several parts of the world (Klove et al., 2014). The subsidence of groundwater in the clay and silt layers will result in consolidation so that there is a subsidence in the soil layer. This is due to a decrease in pore pressure which results from increase in effective voltage proportional to the decrease in groundwater level (Aysen, 2002). Jakarta's excessive groundwater pumping is drying up its aquifers, threatening the city with land subsidence. The overexploitation of groundwater resources has been attributed to the rapid population growth and urbanization in Jakarta, coupled with the increasing demand for water for domestic, industrial, and commercial purposes.

Figure 6. Groundwater levels monitoring using piezometer from 2018-2023.

Groundwater monitoring was conducted using observation wells situated from 2018 to 2023 (Figure 6) using piezometer. The calculation is emphasized solely within the scope of stratigraphy from the investigation boreholes. While groundwater extraction is often cited as the main cause, the impact of building load cannot be ignored. The calculation of the additional building load was carried out from 2018-2023, before and after loads are not calculated. The Indonesian Ministry of Public Works' SKBI 1.3.53.1987 (Guidelines for Housing and Buildings Loads) was used to determine the dynamic and static loads of buildings. The prescribed loads assumed four-story office building 85 kN/m² (Sarah et al., 2021) and basic residential housing 15 kN/m² (Sarah et al., 2011) were distributed loads.

The calculation for analytical method used refers to the Simplified Terzaghi one-dimensional consolidation method. Increased stress on saturated soil raises pore pressure. In highly permeable sand, water quickly drains, causing immediate settlement and consolidation together. Conversely, clay's low permeability leads to a slow pore pressure rise followed by much larger and slower consolidation, resulting in significantly more settlement compared to sand. The process of water slowly seeping out of the soil pores, because of additional load, accompanied by the transfer of excess pore water pressure (u) to effective stress (σ') will cause a settlement (Das, 2010), as represented in Equation 1:

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

Where are:
$\Delta\sigma'$ − increase in the effective stress
Δu − increase in the pore water pressure

An equation governing the rate of consolidation has been derived by Terzaghi based on assumptions compression of the soil and flow of pore water occur only in vertical direction, the soil is homogeous and total and effective stress is always uniform on any horizontal plane (Wesley, 2010). One-dimensional consolidation settlement prediction is based on oedometer test results using representative clay soil samples. Primary consolidation calculations can be performed using Equation 2. Secondary consolidation, which occurs after pore water pressure has been fully dissipated, can be calculated using Equation 3 (Das, 2010)

Here is described calculation given in Equations 2 and 3 as follows:

$$Sp = \frac{C_c H}{1+e_0} log\ log\ \left(\frac{p_0+\Delta p}{p_0}\right) \qquad (2)$$

Where are:
Sp = settlement due to primary consolidation

p_0 = effective stress
Δp = vertical stress
C_c = compression index
H = thickness of layer
e_0 = void ratio

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

Where are:
Ss = settlement due to secondary consolidation
C'_α = $C_\alpha / (1 + e_p)$
p_0 = effective stress
Δp = vertical stress
H = thickness of layer

In 1925, Terzaghi introduced the theory of one-dimensional consolidation for water-saturated clay soils. To determine the time required for settlement, the degree of consolidation is used, which relates the amount of settlement to a specific time. The consolidation settlement would continue until 90% of consolidation is achieved. The relationship between the degree of consolidation (U) and the time factor (Tv) is used to calculate the consolidation time as represented in Equation 4 and Equation 5 (Wesley, 2010).

Here is described calculation given in Equations 4 and 5 as follows:

$$U = \frac{\text{settlement at time t}}{\text{total eventual settlement}} \quad (4)$$

Where are:
U = degree of consolidation
T = time

$$T_v = \frac{C_v t}{{H_t}^2} \quad (5)$$

Where are:
T_v = time factor
C_v = coefficient of consolidation
T = time
H_t = thickness of layer

The calculation of soil subsidence using the finite element method is based on Biot's consolidation theory (Biot, 1956) with coupled consolidation equations. These equations are used to simultaneously calculate excess pore pressure and deformation in a porous medium over time (Equation 6). Several assumptions are made in this model: the soil is saturated, uniform, and homogeneous; fluid flow follows Darcy's law; and a small strain poroelastic model is applied.

$$\underline{s} = \underline{s}' + \underline{m}\,(p_{steady} + p_{excess}) \quad (6)$$

Where are:
$\underline{S}$ = total stress vector
$\underline{s}'$ = 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

RESULT AND DISCUSSION

Land subsidence in Central Jakarta is a critical issue that requires thorough analysis. Analysis is focused in Monas Area. The scenario created is land subsidence due to natural consolidation and anthropogenic factors (groundwater level decrease and building loads). We assume that the building load and groundwater level decrease are only calculated for the years 2018-2023. Expenses before and after the year are not considered. Overall, the results of the analysis show that the maximum time of consolidation will occur until the years 2138-2368 (Figure 7).

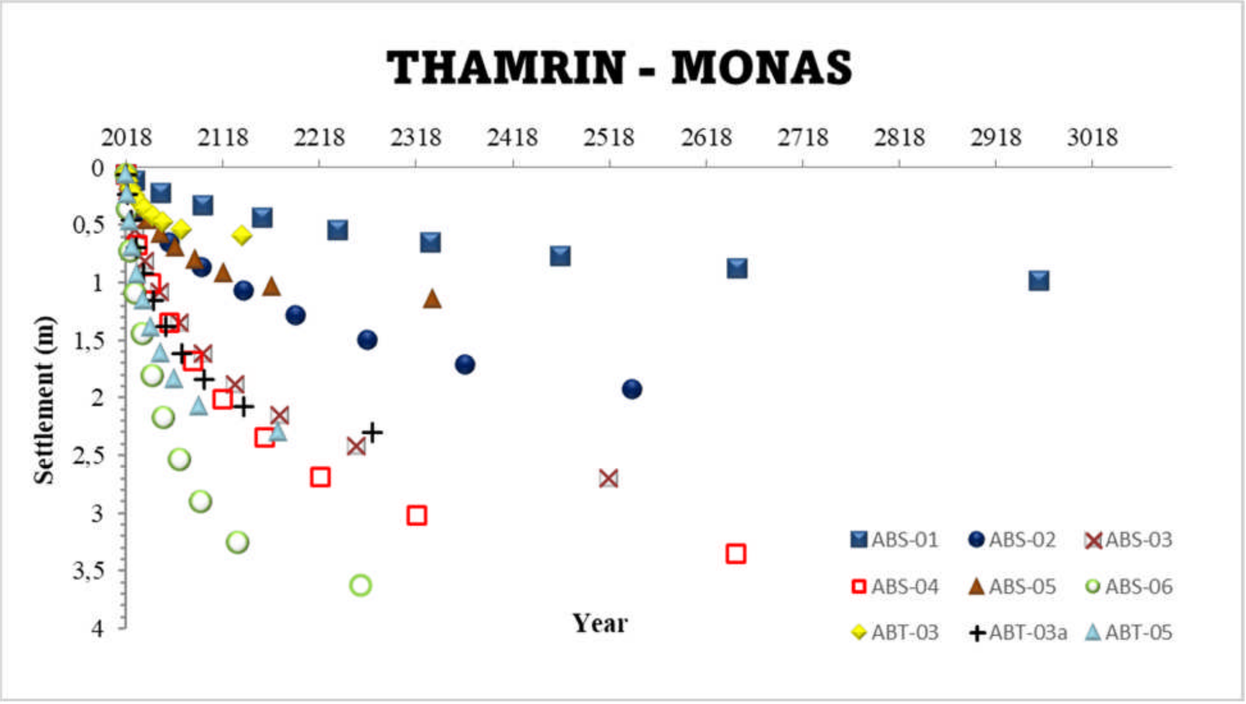

Figure 7. Results of subsidence in Monas Area due to natural consolidation.

Land subsidence that occurred in Central Jakarta assumed started since 2018, with an initial subsidence value of 0.058 m and the boreholes used for analysis are nine boreholes. The results of the analysis show that the maximum land subsidence that will occur is at S-06 with 2.24 m and maximum time of 337 years due to natural consolidation. The rate of subsidence in S-06 reaches 0.66 cm/year. Thickness of clay layer in S-06 is thicker than at other points, with a thickness up to 45 m. The value of the consolidation coefficient and the high compressibility index affect the speed and magnitude of subsidence that occurs with values of 2.3 m²/year and 0.6, respectively. However, the influence of these two values also depends on the thickness of the clay in influencing the time when the subsidence occurs. According to S-06 (Figure 5), the thickness of the clay affects the rate of subsidence and becomes slower.

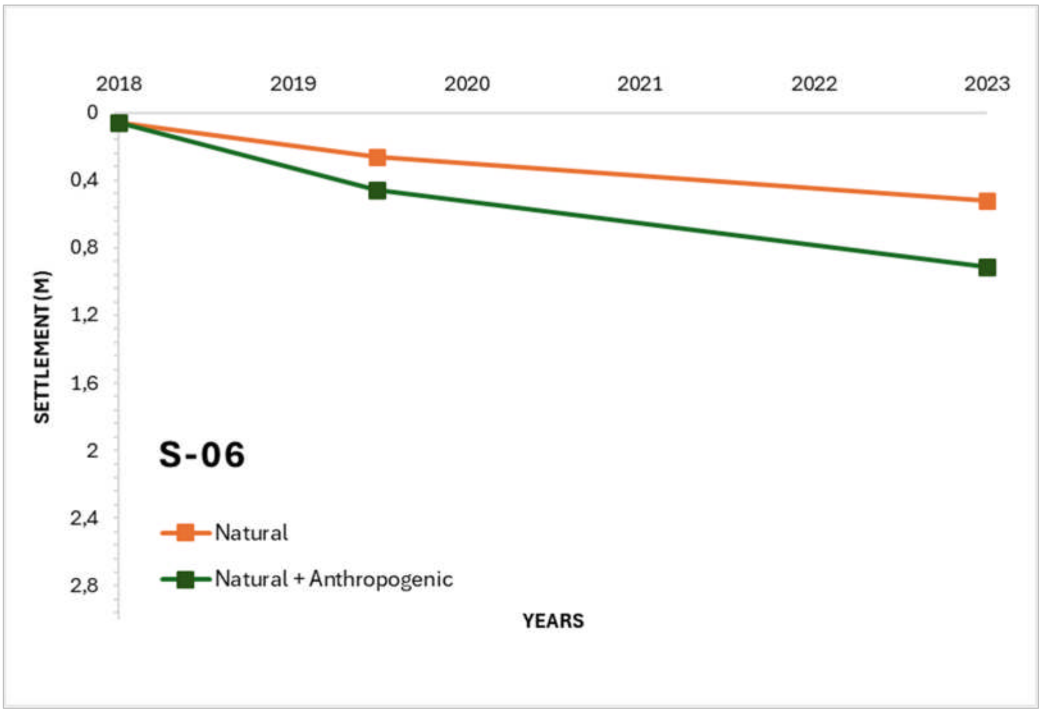

Figure 8. Sample result of subsidence due to natural and anthropogenic factors in Central Jakarta.

Figure 8 show sample result of comparation between settlement due to natural and anthropogenic factors. Groundwater level decrease can trigger land subsidence as a result of a decrease in pore pressure in soil. When the groundwater level decreases, the hydrostatic pressure on the soil will decrease, causing soil stability to be disturbed. Industrial development (additional building load) in Central Jakarta has resulted disturbances groundwater condition and effect potential for land subsidence. The value of land subsidence due to groundwater level decrease is 0.09-0.18 m. Moreover, the addition of building load have impact with 0.06-0.20 m. This is because the addition of building loads in this section is not much, and groundwater extraction is still relevant. Nevertheless, these anthropogenic factors still affect the magnitude of the subsidence and rate of subsidence that occurs.

Table 2: Contribution of anthropogenic factors to land subsidence.

Boreholes Code	Percentage (%)			Rate of Subsidence (cm/tahun)	
	Natural	Groundwater level decrease	Additional buidling load	Natural	Natural + anthropogenic
T-04	68,1	31,9	-	6,1	9,0
SS-01	43,5	56,5	-	1,5	3,4
S-03	71,7	28,3	-	7,9	10,1
S-04	70,3	29,7	-	4,5	6,6
T-05	33,9	66,1	-	5,4	7,3
T-06	30,6	41,7	27,7	1,9	6,1
S-05	59,3	29,9	10,5	6,7	11,3
S-06	54,7	19,7	25,6	9,1	17,4
T-07	35,2	38,2	26,6	3,1	8,7

Table 2 shows that anthropogenic factors affect land subsidence on the Monas Area. Borehole S-06 has the greatest influence on the magnitude and rate of land subsidence with 0.35 m. The contribution of the additional building load factor is greater than the subsidence of the groundwater level, with land subsidence reaching 0.20 m. The percentage of each factor is also calculated, with the rate of subsidence due to the addition of anthropogenic factors to natural consolidation. Based on analysis, factors of increasing building load contributed 12.2 - 66.1% and groundwater level contributed 10.5-63.7%.

CONCLUSIONS

Anthropogenic factors are affecting the magnitude of the subsidence in the Central Jakarta. During the period 2018–2023, these anthropogenic factors contributed variated with averages 24.02%. The rate of soil subsidence for natural consolidation in Central Jakarta ranges from 1.5-9.1 cm/year. Meanwhile, there are anthropogenic factors such as groundwater level decrease and increase of building load achieved 3.4-17.4 cm/year. These anthropogenic factors accelerate the rate of soil subsidence by 1.9-8.3 cm/year or equivalent to 26.0-47.7%. Based on analysis, land subsidence analysis in Central Jakarta shows that increase in building load and groundwater level decrease does not significantly affect the subsidence that occurs. The impact of anthropogenic factors on land subsidence in Central Jakarta still must be considered and the need for comprehensive management strategies. Data clearly indicate that human activities, particularly anthropogenic factors, substantially accelerate the rate of subsidence beyond natural consolidation processes during the period 2018–2023. Therefore, it is essential to stronger groundwater usage rules and use construction techniques that reduce additional building load in order to lessen these effects.

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