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Integrated Analysis of Land Subsidence from Alluvium Formation Based on Conventional Deep Pipe Monitoring (CDPM) and Geotechnical Parameters in Pekalongan and Surrounding Areas, Indonesia

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Abstract - Despite being densely populated and economically thriving, the northern coast of Java, specifically Pekalongan, encounters significant challenges to further development, notably land subsidence. Since the late 2000s, these hazards have become increasingly evident, causing infrastructure damage and displacing residents. Alluvial deposits are formations that provide insight into unconsolidated sediment affecting land subsidence. This study integrated land subsidence in alluvial deposits at nine Conventional Deep Pipe Monitoring (CDPM) spread between 2021 and 2025, Standard Penetration Test (SPT) results, geotechnical analysis, including Compressibility Index (Cc), and Activity Ratio (Ac) of undisturbed samples to assess the mechanisms of subsidence and spatial variability. The alluvium formation observation results are separated into three groups: fluvial deposit group 1, marsh-swamp deposit group, and fluvial deposit group 2. The average SPT test was the softest, measuring 8.9 in Wonokerto and 11.1 in Kandang Panjang, for the biggest CDPM decrease of -3.89 cm/year in Wonokerto and -3.24 cm/year in Tirto annually. Wonokerto and Depok have the biggest clay sediment accumulations, measuring 43.3 m and 43 m, respectively. Then, at depths approximately 10 m to 22 m below the surface, laboratory testing revealed that the highest values for (Cc) are 0.1 to 0.7 and (Ac) are 1.3 to 1.5. The study findings show that areas with thick soft clay layers and high compressibility exhibit the highest subsidence rates, exceeding more than -2.5 cm/year in the central northern region of the studied area in Wonokerto, Tirto, and Hoegeng. The average land subsidence is positively correlated with the average SPT and the accumulation of clay sediments. According to Cc, Ac, and SPT values, the marsh-swamp deposit group has the biggest impact on land subsidence with approximately depth range of -10 m to 40 m that categorized as "Very High Potential Risk". In the end, this study offers a more secure framework for building infrastructure in regions vulnerable to land subsidence.

Keywords: land subsidence, CDPM, SPT, Compressibility Index, Activity Ratio

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Introduction

Land subsidence, particularly in coastal areas, has become a critical issue driven by both natural processes and human activities. Studies on land subsidence have been extensively conducted in coastal cities worldwide, particularly in Southeast Asia (Widyasamratri and Karmilah, 2019). A comprehensive analysis of coastal land subsidence in Asian coastal cities, including Tokyo, Manila, Jakarta, and Ho Chi Minh City, has revealed common challenges (Cao *et al*., 2021). Human activities are often the primary drivers of land subsidence, as demonstrated in North Coast of Java and many other regions globally (Sarah and Soebowo, 2018; Andreas *et al*., 2019a; Sarah 2022; Suyono *et al*., 2025).

Numerous studies using various methods, including extensometers, deep pipe, and Geographic Information Systems (GIS), have established a strong correlation between human factors and land subsidence, such as urban development. For instance, research in the coastal area of Texas, USA, analyzed the relationship between land cover types and subsidence rates (Zhong *et al.*, 2022). Human population density, as a proxy for urban development, has also been shown to be closely linked to land subsidence in both local and global studies (Hasan *et al*., 2023; Cigna and Tapete, 2022). Understanding the impact of certain area development factors on the rate of land subsidence could derive urban strategies that are sustainable for planning. Moreover, installing wells to monitor subsidence rates at specific points within soil layers, has been seen in studies at Semarang and Jakarta (Sarah, 2022; Sahu and Rawat, 2023). Moreover, China has employed the direct extensometer and the Column Element Settlement Model (CESM), to analyze subsidence patterns across different soil layers (Chen *et al*., 2019; Cao *et al.*, 2021; Yang *et al*., 2022; Sang *et al*., 2023). Working similarly with the extensometer has been employed to track subsidence rates in regions affected by mining-induced subsidence in Poland *(Murdzek et al.*, 2018). Previous studies on land subsidence in Pekalongan have not provided a clear understanding of land subsidence trend of certain formation layers and correlation with lateral subsidence and land-use development. Land-subsidence evaluation with an approach Conventional Deep Pipe Monitoring (CDPM) was developed to show the trend of vertical land-subsidence on formation layers manually, which was then linked to direct SPT, laboratory test, and sediment accumulation from boreholes. The combined methods have specific findings regarding the sediment layers that have the most significant land subsidence impact provide a more geotechnical basis compared to previous general studies. This can formulate a comprehensive approach to urban development which is essential for coastal areas (Rahayu *et al*., 2018).

Geological/Stratigraphical Settings

Like other countries, Indonesia is also vulnerable to land subsidence, especially in the coastal areas of the northern Java Coast that is relatively tectonically stable (Tubagus, 2014; Andreas *et al*., 2019b). Land subsidence is a slow process that affects large areas that occur primarily in lowland and coastal locations on soft alluvium deposits (Sarah and Soebowo, 2018; Sarah, 2022). Natural and anthropogenic processes are thought to contribute to the land subsidence in this region. According to the geomorphological map of the islands of Java and Madura (Pudjoprajitno, 2011), the studied area consists of alluvial and coastal plain. In addition the region is characterized by alluvial formations based on the Banjarnegara and Pekalongan map sheets (Condon *et al*., 1996), then detailed by Ferdy *et al*. (2022) (Figure 1), explaining the subsurface distribution. It consists of the younger alluvial formation consists of Beach Deposits (Qb) Delta Deposits (Qd), Swamp Deposits (Qs), Channel Deposits (Qch), Flood Plain Deposits (Qlf) above the older Damar Formation.

Methods and Materials

Materials

The researched areas consist of the CDPM. Geotechnical data were obtained from boreholes including SPT-N values, laboratory consolida-

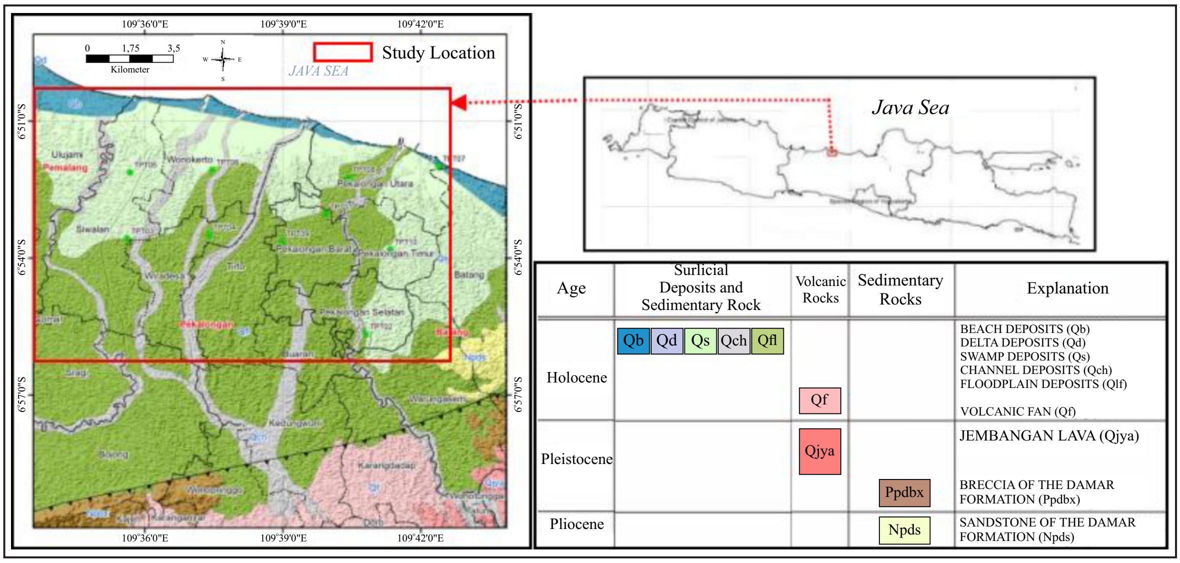

Figure 1. Geological map of Pekalongan and surrounding area (Ferdy *et al*., 2022).

tion tests for determining compression index (Cc), and Activity Ratio (Ac), focused on nine points around Pekalongan City and Pekalongan Regency (7°1'10"S, 109°49'47"E) (7°1'10"S and 109°29'4"E) (Figure 1). Then, based on the sediment identification, the baseline of the CDPM, which is the alluvial (Figure 2.) This land subsidence evaluation integrates analysis of land subsidence trend to SPT and laboratory test to investigate land subsidence and recommend development approaches within the area.

Methods

The CDPM installation is expected to provide more information on land subsidence, as well as vertical and subsurface. The CDPM locations are

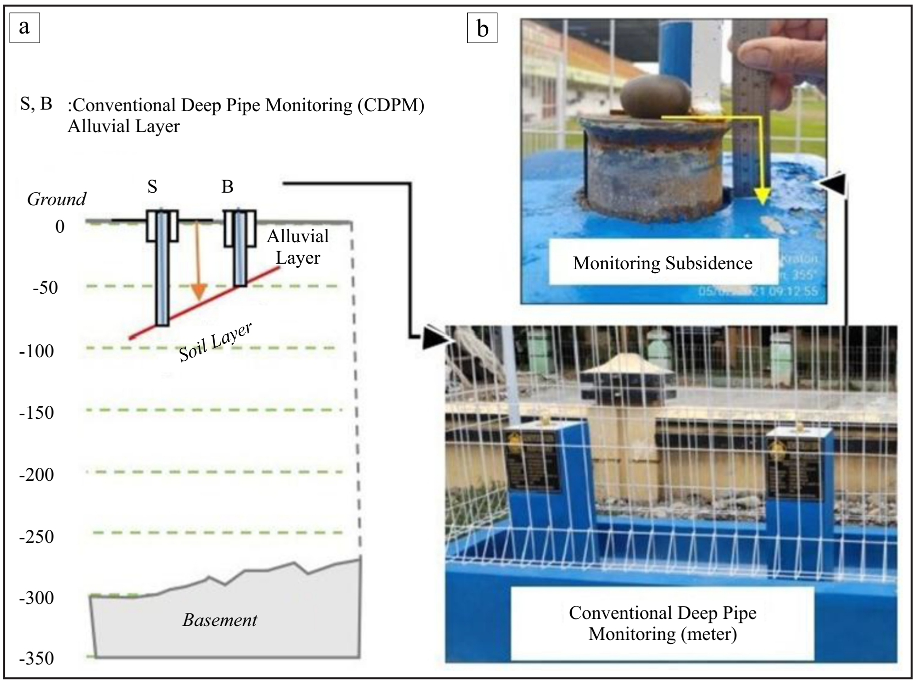

Figure 2. a. Conventional deep pipe installation model (modified Chen *et al*, 2019); b. Aplication of the Conventional deep pipe monitoring in Pekalongan.

illustrated in two profiles: Profile 1 (S 05), (S 07), (S 01), (S 02), and Profile 2 (S 06), (S 08), (S 03), (B 01), (S 04) (Figure 3). B 01 was observed from March 2020 to March 2024 every month, while another point were observed from January 2022 to March 2024. CDPM was installed with depth variations of alluvial between -45 m to -92 m.

Then, to determine the softness level of the deposits, SPT tests were conducted at each location to a depth of 50 m with 5 m intervals. Subsequently, borehole (core) and undisturbed samples were taken for physical and strength testing of the soil in selected clay and silt layers, with a total of forty-eight samples from nine borehole locations.

Land-Subsidence Trend, Sediment Accumulation and SPT

An overview of ground subsidence in alluvial deposits will be given by CDPM, highlighting variations at each site. In the meantime, soft layers at particular depths can be identified through direct testing using SPT by Terzaghi *et al.* (1996) (Table 1). CDPM boreholes demonstrate differences of soil type in alluvium sediment formation. These sediments have various layer thicknesses and intervals. Based on Ferdy *et al.* (2022), alluvium is a mixture of gravel, sand, silt, and clay found in river and marsh deposits. These deposits are of Holocene age. For this study, the sediment deposits and sediment accumulation were simplified based on their dominant materials, which are clay, silt, sand, and in some locations, fill material.

Table 1. N SPT Classification based on Terzaghi *et al.* (1996)

N SPT	Consistency
<2	Very soft
2-4	Soft
4-8	Medium
8-15	Stiff
15-30	Very Stiff
>30	Hard

Index Compressibility (Cc) and Activity Ratio (Ac)

The compression index value (Cc) provides information on the behaviour of cohesive soil under compression when effective stress changes. The probability of land subsidence increases with the value of Cc. The soil compressibility index value based on Bell Classification (Bell, 2007) is divided into four classes as shown in Table 2.

One kind of soil that exists based on structural changes is expansive soil, which undergoes volume changes as a result of variations in soil moisture content. Environmental factors may in-

Table 2. Compressibility Index based on Bell (2007)

Soil Type	Cc Volume	Description
Soft Clay	>0.3	Very High
Clay	0.15 - 0.3	High
Silt	0.75 - 0.15	Medium
Sandy Clay	<0.75	Low

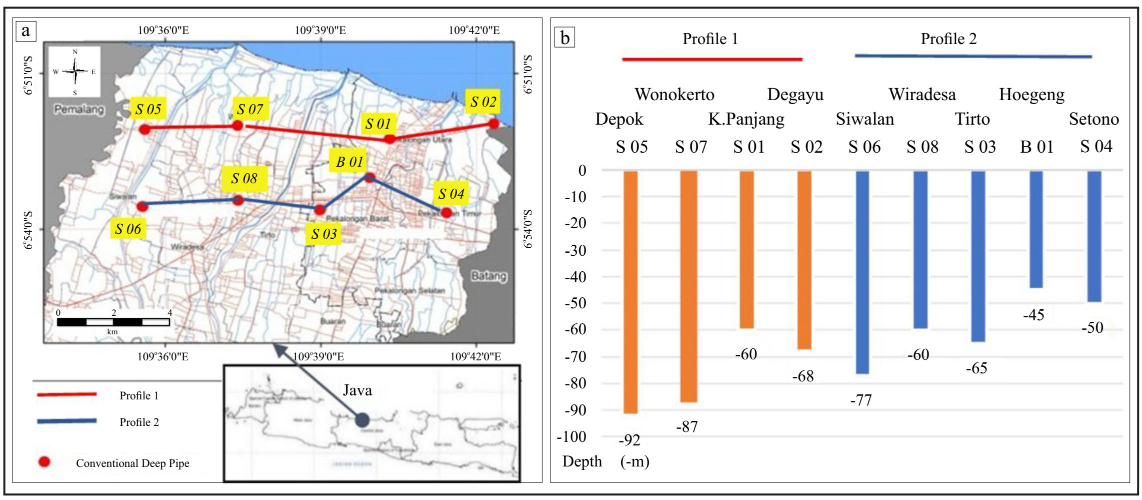

Figure 3. a. CDPM location, B 01 (observed March 2020 to March 2024), S code 05, 07, 01, 02, 06, 08, 03, and 04 (observed January 2022 to March 2024). b. Depth alluvium of well monitoring locations as shown in Figure 3a.

fluence changes in the content of the soil, as well as soil parameters that relate to the expansive or shrinking-swelling characteristics (Nelson and Miller, 1992, in Mitchell and Soga, 2025). One could argue that the primary cause is the minerals found in the soil (Table 3). The magnitude of the activity (Ac), which is determined using the following equation put forth by Skempton (1984), yields this swelling potential:

$$Ac = \frac{PI}{\%\ Clay\ Fraction} \quad (1)$$

Ac = Activity Ratio
PI = Plasticity Index
% Clay Fraction < 0.001

Table 3. Activity (Ac) classification based on Skempton (1984)

Activity (Ac)	Description
Ac> 1.25	Active and responsive
0.75<Ac<1.25	Normal
Ac<0.75	Non- Active

Result and Analysis

Results

CDPM Subsidence Trend

The recorded land subsidence from all CDPM shows an annual average is -2.41 cm. Based on the location, the highest is -3.89 cm in (S 07) Wonokerto, and the lowest is -0.86 cm in (S 06) Siwalan. The difference in soil settlement as shown in Figure 4 indicates the variability of subsurface deposit conditions, which vary in both thickness and sediment type.

Sediment Accumulation

The sediment profile shows a correlation from the alluvium formation to the upper boundary of Damar Formation (Figure 5). Laterally, it appears interfingering at a depth of approximately -30 m. Profile 1 is dominated by thick clay, while Profile 2 at the same depth has a thinner clay layer interspersed with silt and sand, indicating a change in the depositional environment. The depositional environment has changed over geological time, with deposition shifting from one fluvial system (Fluvial deposits group 2) to a swamp-marsh environment (swamp-marsh deposits group), and back to a fluvial system (fluvial deposits group 1), indicating that this area was a dynamic terrestrial depositional environment such as a delta system or alluvial plain, where rivers frequently shifted their course (meandered), and left behind varying deposits. The alluvium formation has an unconformable relationship above The Damar Formation, indicating a geological time gap or significant erosion before the youngest alluvium deposits accumulated.

Standard Penetration Test

Nearly all locations have very low SPT values 0 to about 10 at shallow depths about 2 to 20 m, according to the SPT results (Figure 6). This suggests the existence of a loose clay or silt-dominated soft alluvial soil layer. A shift to denser soil layers is indicated by SPT values below 20 m, which typically rise with depth. There are notable variations in the inner layers consistency laterally, such as in S 05 and S 07, where a soft layer extends down to a depth of about 30 m. On the other hand, the soft layer up to about 25 m at S 06, S 08, and B 01 suggests a shallower dense layer there.

Index Compressibility (Cc) and Activity Ratio (Ac)

Almost all locations show relatively high values of Cc (above 0.3) at depths of 0 to 20 m, indicating the presence of a thick layer of soft alluvial deposits throughout the studied area (Figure 7). Until the decrease in the value of Cc at greater depths (above 40 m), indicating a transition to denser and more consolidated material. At S05 and S07, the depth ranging of 20 m to 40 m in the swamp-marsh deposits showing the highest values of Cc at the top and bottom layers approaching 0,6 and 0,9 at S07. This confirms that these organic swamp clay deposits are highly compressible. Regionally, Profile 2 tends to show slightly lower values of Cc or a faster decrease in Cc values with depth compared to Profile 1, indicating that the soil in the Profile 2 area may

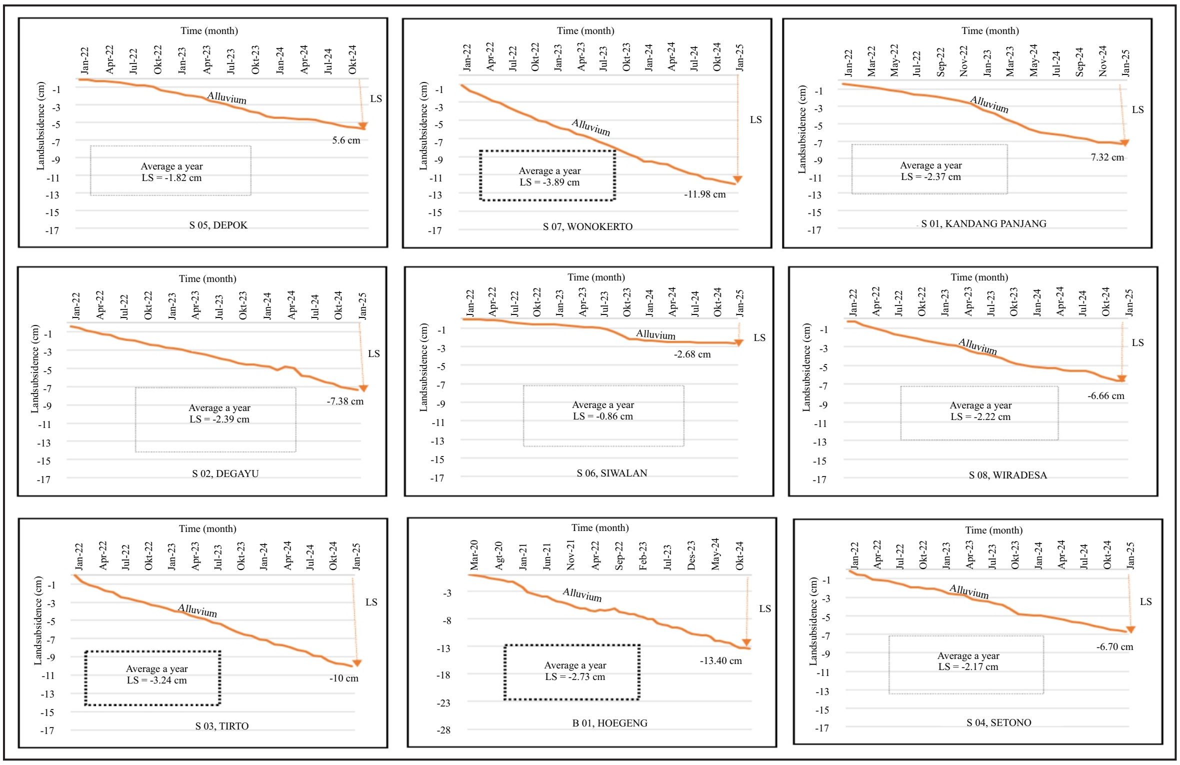

Figure 4. Land subsidence trend through CDPM.

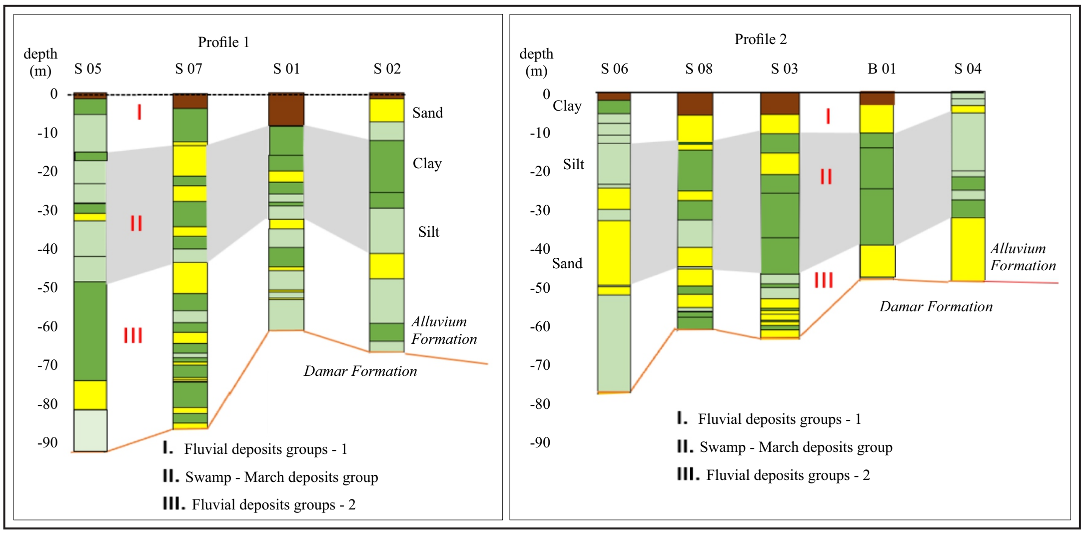

Figure 5. Cross-sections of sediment boreholes Profiles 1 and 2.

be slightly more consolidated or contain a higher proportion of silt and sand.

The Activity Ratio (Ac) value changes at each different soil layer with a significant difference in (Ac) values observed between Profiles 1 and 2, indicating highly heterogeneous geological conditions along the two different cross-sectional paths (Figure 8). At some points, especially in Profile 2, the (Ac) value reached or even exceeded 2.25. This figure is far above the "active and responsive" limit (1.25), indicating the presence of highly expansive clay soil at that depth. Highly active soil requires special attention in foundation design to avoid structural damage due to significant soil volume changes when water content changes, such as during dry and rainy

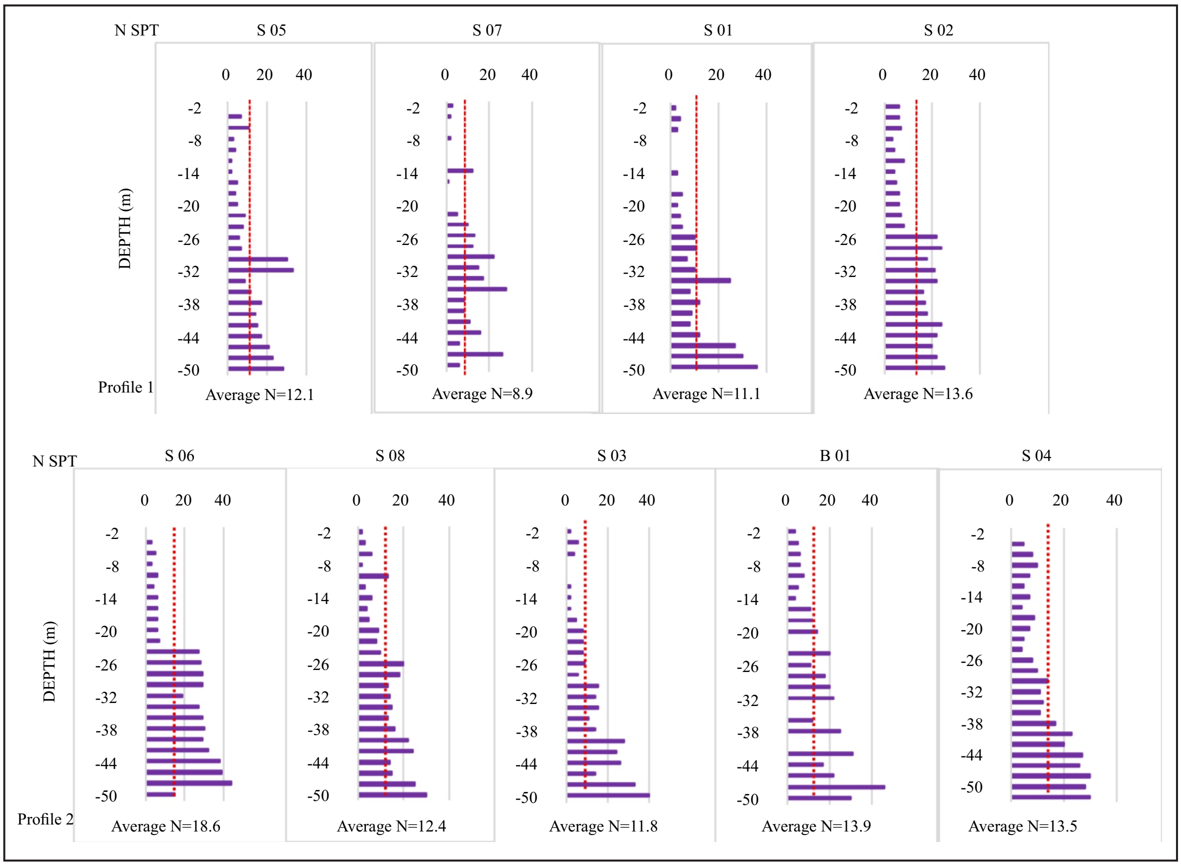

Figure 6. SPT *vs*. Depth in Profiles 1 and 2.

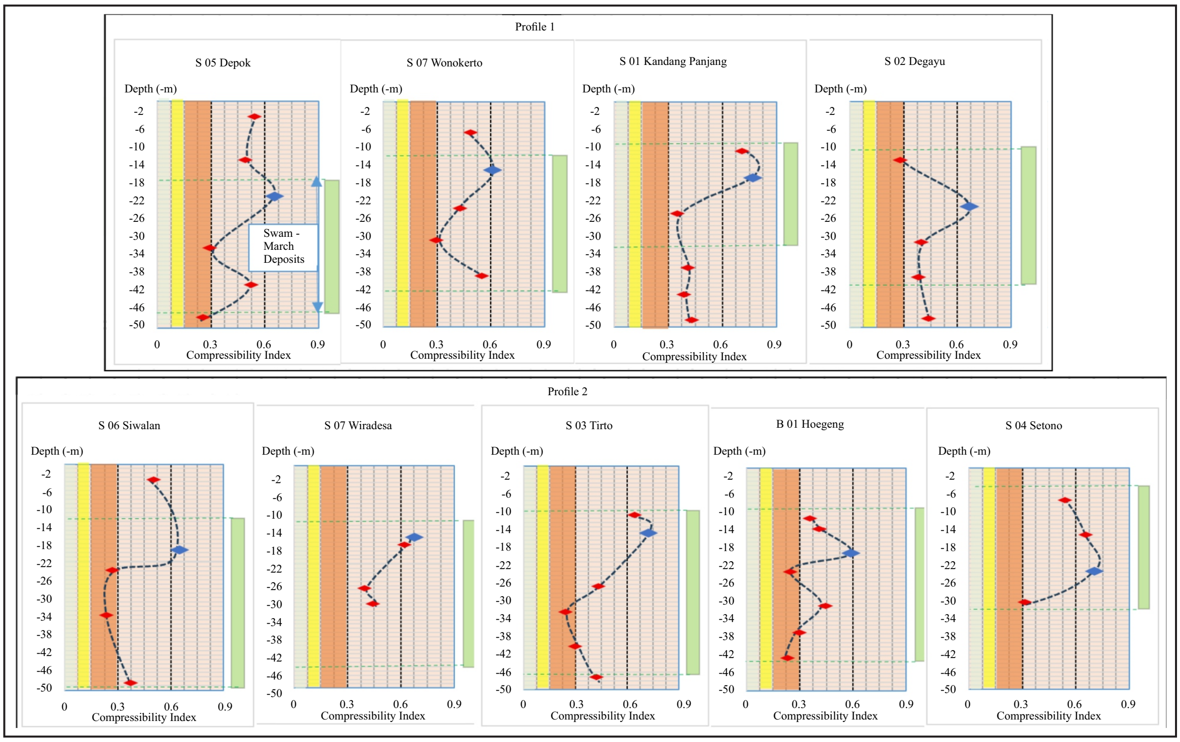

Figure 7. Compressibility Indec (Cc) *vs*. Depth in Profiles 1 and 2.

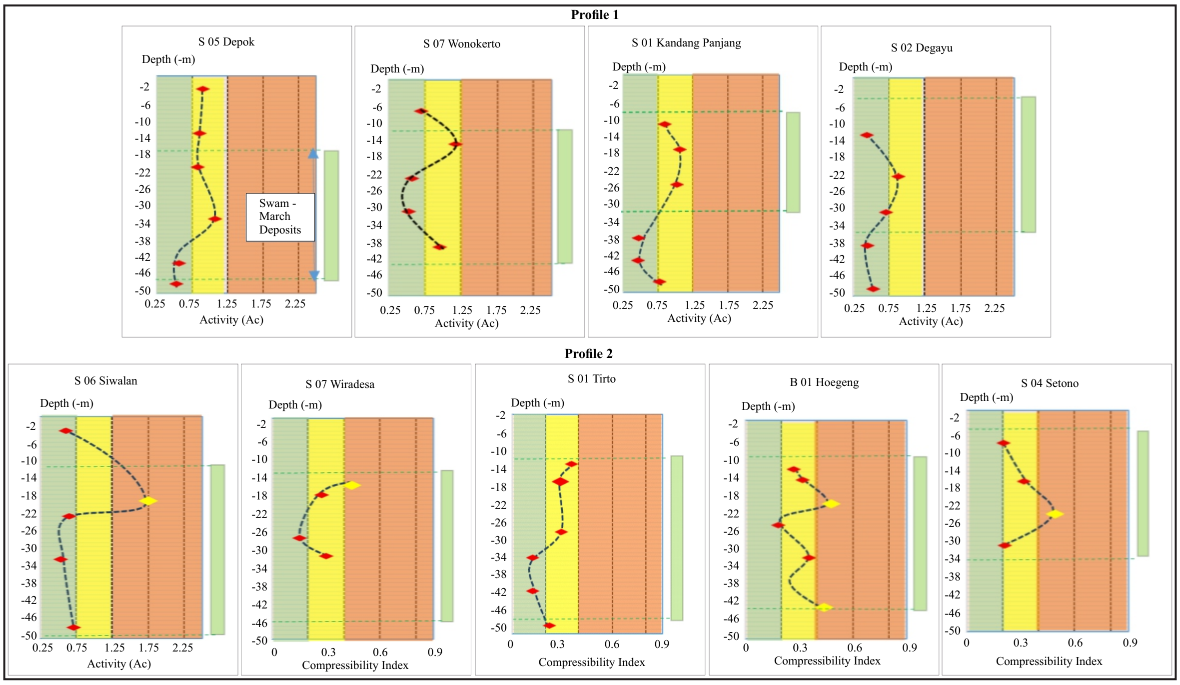

Figure 8. Activity Ratio (Ac) *vs*. Depth in Profiles 1 and 2.

seasons. The swamp-marsh deposit layers visible in Profile 1 tend to show varying (Ac) values, but still within a manageable range compared to some extreme peaks in Profile 2.

Discussion

Relation Land Subsidence and Sediment Accumulation of Alluvium Formation

Areas with thicker clay sediment accumulation show more significant land-subsidence rates (Figure 9). Alluvial sediments are quite new and not yet totally compacted. (Moechtar *et al*., 2009; Liu *et al*., 2021; Sarah *et al*., 2021). Land subsidence in Pekalongan is highly influenced by the presence of sediment deposits dominated by clay soil that have not been fully consolidated. The thicker the accumulation of clay layers, the greater the potential and rate of settlement. In detail, Profile 1 in the northern part of this area is dominated by very thick clay layers, reaching 43.3 m at S 07 Wonokerto. This indicates a relatively higher settlement, reaching approximately 2 to 3 cm at some points. This indicates that the young alluvial soil in the north is highly susceptible to compaction. Meanwhile, in Profile 2 in the southern, the sand and silt layers are more dominant, and the clay thickness tends to be thinner compared to the ones in the north. Once the land subsidence showed lower rates around 1 to 2 cm in B01 and S04 compared to the north. However, the pattern of land subsidence varies depending on the thickness of the clay at each site. For instance, although the clay thickness at location S 01 is lower than that in location S 02, both exhibit nearly identical subsidence rates of about -2.5 cm. If the accumulation of clay thickness is the sole determining factor, then S01 should theoretically experience less subsidence. In general, the highest land-subsidence value corresponds with the thickness of compressible materials, but not always, relates to the highest thickness (Carla *et al*., 2023). The relationship between land subsidence and sediment accumulation conditions varies.

Spatially, the land subsidence contours simultaneously depict the thickness of the unconsolidated soft soil. The lowest subsidence area is -1 m to -1.5 m located in the southern part. This indicates that the rate of land subsidence in the alluvium formation is higher in the north compared to the one in south (Figure 10), which is characterized by the presence of sea-

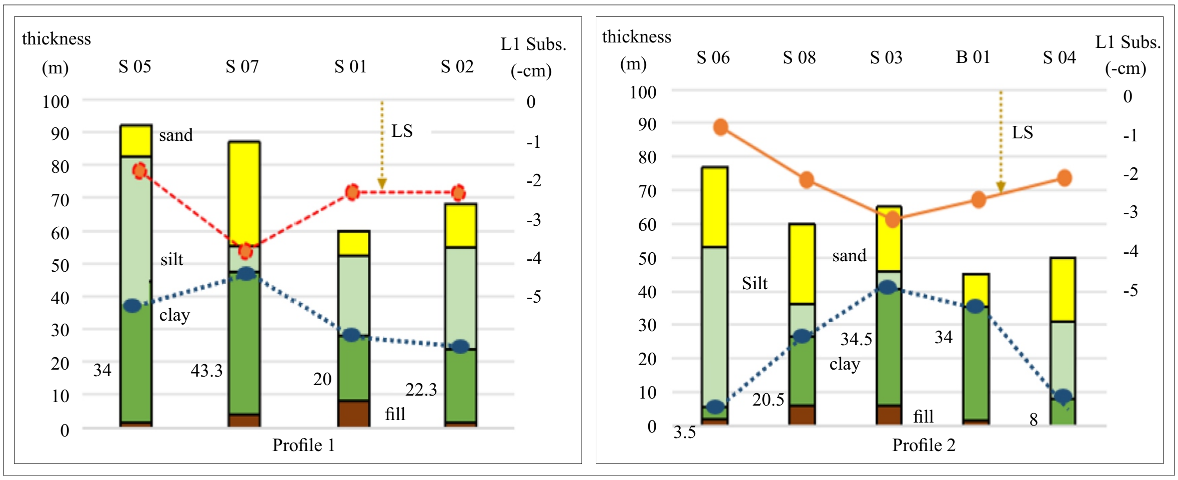

Figure 9. Sediment accumulation vs land subsidence in Profile 1 and Profile 2.

water inundation and floods as the land subsides, even making some land lower than the sea or river water level nearby. The highest subsidence area is approximately -2 m to -3.5 m located in Wonokerto, Tirto, Hoegeng, the northern part of coastal areas, and the central part of studied area. There are parallels with Wiyono *et al.* (2022), and the soft soil layer in Pekalongan and the surrounding areas generally thickens toward the north and northwest.

Relation Land Subsidence, SPT, Compressibility Index (Cc), and ActivitymRatio (Ac)

Low SPT values such as 8.9 at S0 7 and 11.1 at S 01 indicate soft or loose soil, typically clay or silt that have not been well consolidated. This type of soil is very easily compressible, causing significant subsidence. Conversely, higher SPT values such as 18.6 at S 06 and 13.9 at B 01 indicate denser soil, resulting in a relatively lower rate of subsidence. Therefore, the higher the SPT value, the more stable the soil and the lower its potential for subsidence. Profile 1 shows a lower average SPT value compared to Profile 2 (Figure 11). This is directly correlated with a high rate of soil degradation, reaching approximately -3.89 cm at S 07 Wonokerto. The northern region has thick deposits of clay alluvium. However, specifically, there is a note that despite having a very low SPT value of 8.9 at S 07, this indicates very soft and vulnerable soil. The indicated rate of subsidence of -3.89 cm is not drastically higher than S 05 with a subsidence of -1.82 cm and an SPT of 12.1. Then, S 08 shows a relatively high SPT of 12.4, but experiences a subsidence of -2.22 cm, which is lower than B 01 with a subsidence of -2.73 cm and a slightly higher SPT of 13.9. The cause is that the soil characteristics vary greatly in thickness, lateral, and vertical layering, and the limited depth of SPT measurements is only up to 50 m. While some CDPMs are more than 50 m deep, leaving some layers unmeasured by SPT.

To describe land subsidence potential, the Compressibility Index (Cc) and Activity Ratio (Ac) must be incorporated into the Subsidence Potential Criteria (Table 4). The activity ratio determines resistance to time-dependent deformation, whereas the compression index determines the extent of primary consolidation. In contrast to soils with low Cc or low Ac, which show limited and transient subsidence, severe land subsidence only happens when high compressibility is accompanied by increased clay activity. The spatial and vertical variability of land subsidence can be explained by this combined method.

To explain the relationship between SPT, Cc, and Ac, it can be illustrated in a correlation graph (Figure 12). The moderate R^2 value reflects the heterogeneity of natural soil and the fact that each parameter represents a different control mechanism. The weak to moderate correlation

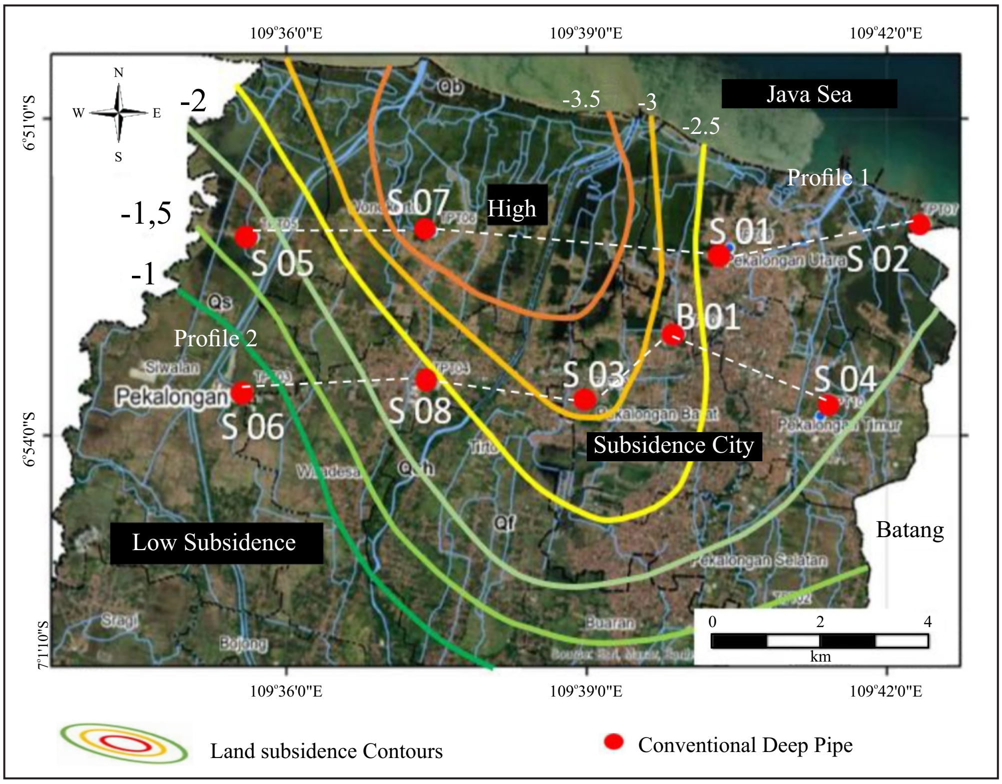

Figure 10. Land subsidence of CDPM contour map.

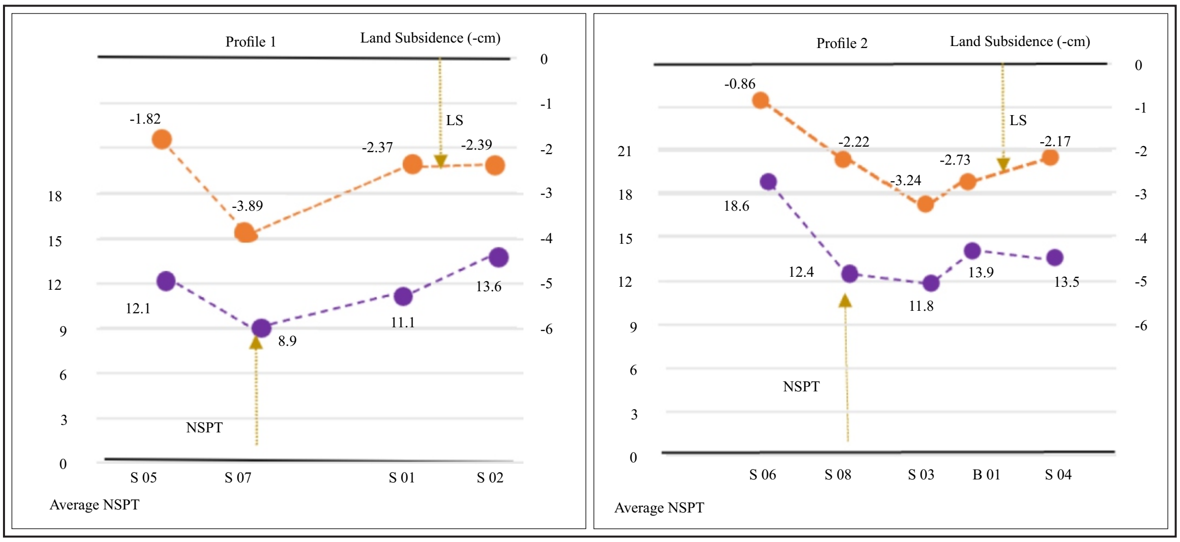

Figure 11. Land subsidence *vs*. SPT in Profiles 1 and 2.

Table 4. Subsidence Potential Combined Cc and Ac Criteria

Subsidance Potential	Criteria Cc and Ac
Very High	Cc ≥ 0.65 and Ac ≥ 1.25
High	0.64 ≥ Cc ≥ 0.45 and 1.25 ≥ Ac ≥ 1.00
Medium	0.45 ≥ Cc ≥ 0.30
Low	0.30 ≥ Cc

does not indicate a limitation of the correlation model, but rather confirms that land subsidence is influenced by interacting processes. Correlation analysis provides insight into soil subsidence, which is controlled by the combined effects of soil stiffness, compressibility, and clay activity. The compression index shows a moderately posi-

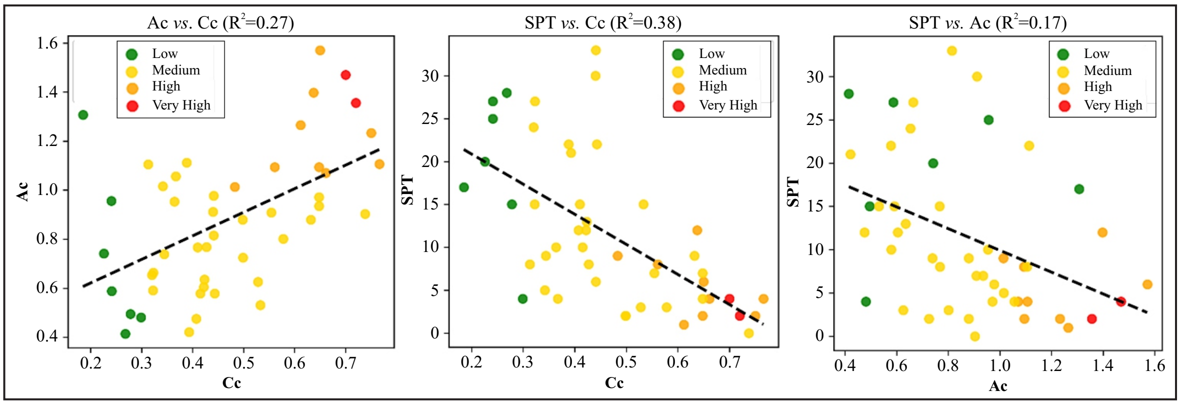

Figure 12. Correlation of Cc, Ac, and SPT, along with subsidence class.

tive relationship with the activity ratio, indicating that highly compressible soils tend to exhibit greater mineralogical activity. Meanwhile, the SPT shows a stronger inverse relationship with the compression index, reflecting its sensitivity to soil stiffness and primary consolidation potential. Conversely, the weak correlation between SPT and the activity ratio confirms that penetration resistance is not related to mineralogical control.

When combined with depth information, the depth cross-section profile indicates a risk of land subsidence with critical areas "Very High Subsidence Potential" at 10 to 25 m, where the Compressibility Index (Cc) values are high to very high, supported by active and responsive Activity Ratio (Ac) (Figure 13). Greater and more progressive subsidence is typically observed in soil with a higher Cc value. The activity ratio (Ac) measures the activity of clay minerals that have higher value active clay minerals or organic soil that is prone to creep and long term deformation. The intermediate layers, which range from 2 m to 10 m to 25 m to 50 m, have "High Settlement Potential" and a high Cc value, but their Ac is inactive and unresponsive.

The strong correlation between the classification of land subsidence risk and the actual land subsidence from CDPM confirms that land subsidence in Pekalongan is primarily caused by the combined effects of soil compressibility and clay activity as describe in Table 5. Locations classified as very high risk consistently show the highest rates of subsidence, while low-risk

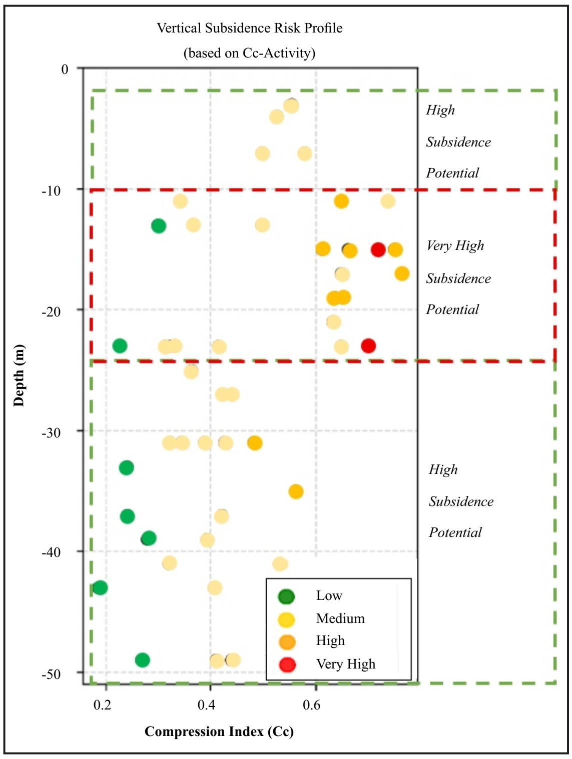

Figure 13. Vertical Subsidence Potential (Depth *vs*. Cc).

locations exhibit low ground deformation. Minor deviations between the subsidence risk for decline and the CDPM values reflect local stratigraphic variability and parameters that are not included in this study, such as hydrogeology, building loads, and local tectonics, rather than inconsistencies in the classification framework. Additionally, locally, factors such as the thickness of the clay layer, drainage conditions, and spatial stress variations can either strengthen or weaken the locally measured land subsidence.

Table 5. Resume of Locations Analysis and Discussion

Location	Dominant Depth (m)	Dominant Soil Type	Average SPT	Dominant (Cc)	Dominant (Ac)	Potential Subsidence Risk (Cc)+(Ac)	Land subsidence CDPM (cm)
Profile 1							
S 05	0-30	Soft Clay	12.1	0.35-0.55	0.9-1.1	Medium-High	-1.82
S 07	0-35	Soft Clay - Active	8.9	0.45-0.70	1.1-1.4	Very High	-3.89
S 01	0-30	Soft Clay	11.1	0.40-0.60	1.0-1.2	High	-2.37
S 02	0-35	Clay - Silt	13.6	0.35-0.55	0.9-1.1	Medium-High	-2.39
Profile 2							
S 06	0-30	Medium Clay	18.6	0.25-0.40	0.7-0.9	Low-Medium	-0.86
S 08	0-35	Soft Clay	12.4	0.40-0.60	1.0-1.2	High	-2.22
S 03	0-40	Clay - Active	11.8	0.45-0.65	1.0-1.3	High-Very High	-3.24
B 01	0-40	Thick Clay	13.9	0.40-0.65	1.0-1.3	High	-2.73
S 04	0-35	Soft Clay	13.5	0.35-0.55	0.9-1.1	Medium-High	-2.17

The findings of the Pekalongan land-subsidence study can be utilized to develop policies governing constructed land use, including adaptation and mitigation (Rahmat *et al.,* 2019*;* Cao *et al.*, 2021; Netzer *et al.*, 2024). that layer. This integrated vulnerability mapping has proven to be in line with physical monitoring data in the field (CDPM), thus providing a strong reference basis for disaster mitigation in this areas.

Conclusions

The results of this study indicate that land subsidence in the alluvium formation is structural and long-term, primarily controlled by the presence of soft clay and active clay layers of marsh-swamp deposits. The land subsidence factor in the region is controlled by the thickness of unconsolidated young clay deposits, soil stiffness level characterized by a low SPT value. The northern region (such as Wonokerto, Tirto, and Hoegeng) experiences the highest land subsidence rates, reaching -2 to -3.5 cm/year, due to being dominated by very thick clay sediment layers (over 43 meters deep).

Geotechnically, the Very High Subsidence Potential is identified at a depth of 10 to 25 meters below the surface. This critical zone occurs due to the combination of a very high Compressibility Index (Cc) value (>0.65) and an active Activity Ratio (Ac) (>1.25), indicating that long-term deformation is controlled by the high compressibility and mineral activity of clay in

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