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Geospatial Modeling of Soil Plasticity Index and Water Content Distribution in Coastal Bengkulu: A Basis for Resilient Infrastructure Planning

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ABSTRACT
Bengkulu Province, located along the western coast of Sumatra, is one of Indonesia's most seismically vulnerable regions due to its proximity to major tectonic boundaries. This study aims to enhance earthquake-resilient infrastructure planning by developing a two-dimensional geospatial model of key geotechnical parameters—Plasticity Index (PI) and water content (w)—in the coastal zone. A total of 65 geotechnical observation points served to generate detailed maps by using the Inverse Distance Weighting (IDW) method down to 30 meters depth. The model integrates empirical correlations with statistical and spatial analyses to overcome the challenges of limited data. Results highlight distinct geotechnical variations across different soil layers and administrative regions, revealing zones with high liquefaction potential. The findings provide insight for engineers, urban planners, and disaster risk authorities in designing site-specific construction strategies. This research fills a critical gap in the current literature regarding Inverse Distance Weighting (IDW)-based geospatial modelling in seismically active areas. It offers a replicable framework for other coastal regions with similar geological contexts.

Keywords: *Plasticity Index; Water Content; Geospatial modeling; Inverse Distance Weighting (IDW)*

1. Introduction

Bengkulu Province, Indonesia, has a high earthquake risk due to its location along the western coastline of Sumatra. Bengkulu Province becomes vulnerable to earthquakes because it is found where the Indo-Australian and Eurasian tectonic plates meet. These two tectonic plates produce two active fault systems in Sumatra along with the Semangko fault zone, which creates the possibility of further seismic activity in this area [1], [2]. Bengkulu Province experiences earthquakes due to three dominant seismic sources: the Mentawai Fault, the Sumatra Fault, and the Sumatra Subduction. Several administrative divisions in the coastal region of Bengkulu comprise the regencies of Muko-Muko, North Bengkulu, Central Bengkulu, Bengkulu City, Seluma, South Bengkulu, and Kaur. The area has become an important economic centre due to its booming tourism sector and infrastructure. A range of ground investigation data helps developers plan safe construction in this seismic region.

Along with the rapid development of technology and development in Bengkulu Province, the availability of geological data is critical to support construction planning [3]. To reduce the risk of construction failure due to earthquakes or other natural disasters, earthquake-resistant building planning is required. One of the essential elements in such planning is soil geological data that includes various parameters. In engineering geology, inappropriate geological surveys of specific soil types often trigger geological disasters, which can cause substantial economic losses and loss of life. Therefore, it is essential to understand the technical characteristics of soils and rocks and to identify and evaluate potential engineering geological problems quickly and accurately in every

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engineering activity [4]. A deep understanding of soil characteristics allows designers to choose the right type of foundation and building structure so that buildings can be safer and more resistant to disaster threats. The plasticity index (PI) is a key geotechnical parameter for soil classification, as it indicates the degree of plasticity and helps predict soil behaviour under varying loads. This relationship helps select appropriate construction techniques and materials, ensuring the stability and durability of structures built on the soil. Additionally, soil water content (w) also affects the shear strength and compressibility of the soil, which are essential factors in any construction project [5].

Given the complex and expensive process of soil sampling, as well as the risk of soil disturbance that could affect the accuracy of the data, this study employed data from 65 observation points in the coastal area of Bengkulu Province to map the distribution of soil plasticity index (PI) and water content (w*)*. This methodology provides solutions to speed up and decrease engineering geological survey expenses and solves technical boundaries and environmental restrictions while minimizing data interpretation subjectivity. The coastal area of Bengkulu Province receives mapping and visualization of geological structures through an Inverse Distance Weighting (IDW) method by using plasticity index (PI) and water content (w) data [6], [7]. A modern, innovative depth modelling approach extending to 30 meters is a crucial research element for the coastal zone of Bengkulu Province. The Inverse Distance Weighting (IDW) interpolation method helps produce visible clearings of soil physical distributions like plasticity index (PI) and water content (w), enabling better strategic decisions to develop and manage the region.

Research in the geology field has progressed rapidly in developing two-dimensional modelling for mapping the distribution of soil parameters. Understandability requires a 2D presentation of the fundamentally three-dimensional geological information [8]-[11]. [12] has also illustrated geological distribution through a two-dimensional representation, which displays various aspects of geological structure and the distribution of soil and rock layers. In this research, the mapping of soil parameters was done using the findings from the study of each soil layer.

Based on this, this research aims to fill this gap by focusing on two-dimensional modelling of the plasticity index (PI) and water content (w) parameters of soils in the coastal areas of Bengkulu Province. Recent research by [13] suggests that an integrated approach combining geophysical methods with seismic vulnerability analysis in the Bengkulu City area can improve the accuracy of assessing the level of earthquake vulnerability while supporting the development of more effective mitigation strategies. Using the Inverse Distance Weighting (IDW) interpolation method [3], the researcher studied how shear wave velocity density values and specific resistance and SPT test results were distributed across Bengkulu City. According to the findings, the Teluk Segara sub-district recorded the maximum shear wave velocity values in the clay layer. The highest cone resistance and penetration test values occurred most frequently within the Kampung Melayu sub-district about the clay layer. On the other hand, [14] conducted a study on seismic response in the north coastal area of Bengkulu Province affected by liquefaction. Their findings revealed that the liquefaction phenomenon has the potential to occur in relatively shallow soil layers, especially those dominated by sand materials.

This research focuses on preparing a two-dimensional distribution map of plasticity index (PI) and water content (w), geological variation analysis, and statistical analysis. The presented analysis of geological variations utilizes statistical methods to evaluate available data and generate histogram graphs for display. Statistical analysis also determined the parameter values at the studied observation points. This research aims to map the distribution of parameters, including PI and w, which have been previously undocumented along the coast of Bengkulu Province. The resulting model is expected to serve as an essential reference in natural resource management, infrastructure development planning, and mitigation efforts against potential geological disasters along the Bengkulu Province coast.

2. Material and Method

2.1. Geological Formation and Subsurface Conditions

The coastal area of Bengkulu Province has diverse and complex geological characteristics, reflecting the region's long history of geotectonic dynamics. Based on an interpretation of recent

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geological maps as shown in Figure 1, the coastal area is dominated by several major geological formations that extend from the north to the south of the province. One of the most extensive and striking formations is the Bintunan Formation (QT), the dominant geological unit along the coast of Muko-Muko Regency, North Bengkulu, and parts of South Bengkulu and Kaur. This formation consists of various rock types, such as polymict conglomerate, breccia, claystone tuff, pumice, reef limestone, and siltstone. Based on [15]. This formation is also identified in several areas directly adjacent to Central Bengkulu and Seluma regencies. This material diversity indicates a complex formation environment, presumably derived from volcanic processes and shallow marine sedimentation.

Another important formation is the Terrace Alluvium Formation (Qat), which is widely distributed in the coastal area of Bengkulu City. This formation is characterized by sand, silt, clay, and gravel deposits, which are commonly found in the lowlands near the coast. [16] revealed that this area is highly vulnerable to liquefaction phenomena, as occurred during the Bengkulu-Mentawai earthquake in 2007. The area also includes various strategic zones, such as tourist destinations and historical sites, requiring special attention in disaster risk mitigation efforts. Further south, the Alluvium Formation (Qa) spreads along the coast of Seluma Regency as well as parts of South Bengkulu and Kaur. This formation consists of young sediments such as gravel, sand, silt, clay and mud, which are generally unconsolidated. These characteristics indicate that the area is prone to deformation, especially under seismic conditions or high rainfall.

Meanwhile, the Simpangaur Formation is found around the coast of Kaur Regency. This formation comprises sandstone, mudstone, limestone, conglomerate, and coal. Its composition reflects a varied formation environment, ranging from marine to deltaic areas, which are full of organic and clastic materials. This shows the potential of geological resources and challenges in terms of civil engineering.

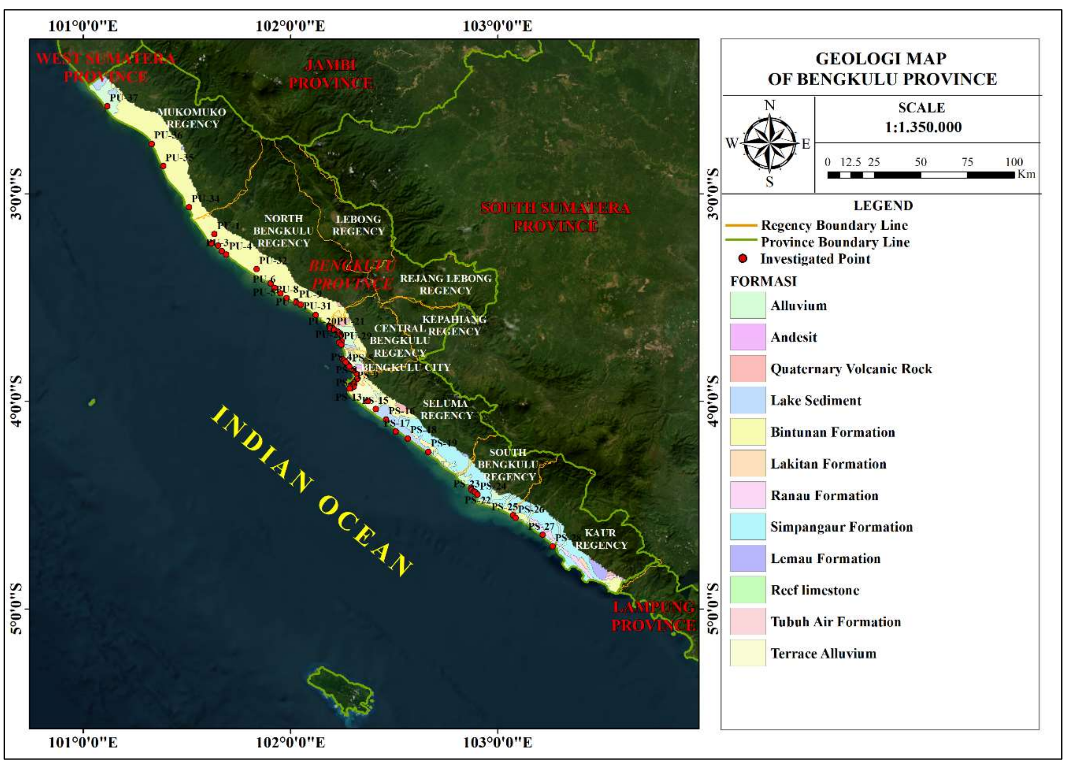

Figure 1. The Geological Map of Coastal Bengkulu Province
Source: Modified from Mase [17]

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2.2. Methodological Framework for Geospatial and Geotechnical Analysis

This research framework was developed to show the systematic steps taken in achieving the study's primary objective: to create a two-dimensional model that illustrates the distribution of PI and w of soils in the coastal areas of Bengkulu Province. Figure 2 shows the processes undertaken, from the conceptual stage to spatial visualisation. The initial stage began with a literature review examining previous studies related to two-dimensional geological modelling, shear wave velocity, plasticity index and water content characteristics. This stage is the theoretical and methodological foundation for designing the appropriate approach. The next step was collecting and processing field data, including shear wave velocity (V_s) data at 65 observation points scattered along the coastal area.

An empirical correlation analysis was used together with data estimation methods to determine PI and w parameter values because direct data was unavailable. Using the collected data, we compared it with V_s to estimate PI and w. This study used an approach that connects PI values to an equation developed by [18]. On the other hand, w was estimated using a formula derivative introduced in reference [19]. Not every V_s value from the data was used for the correlation; only those associated with the related soil parameters were included in the study. After all the data were collected, statistical analyses were conducted to evaluate each parameter value's distribution pattern and spread. Visualisation in histogram graphs was used to illustrate the trend and concentration of data, which plays a vital role in identifying geotechnical characteristics at each site. The final stage of the framework was two-dimensional spatial modelling using the IDW interpolation method. This technique allows the preparation of spatial distribution maps for each soil parameter. The final results of this research are two-dimensional maps of the PI and w of the soil, which can serve as a reference for the technical analysis of soils, the preparation of geological disaster mitigation strategies, and support for safe and sustainable infrastructure planning along the Bengkulu Province coast.

2.3. Inverse Distance Weighting (IDW)

This research uses the Inverse Distance Weighting (IDW) spatial interpolation method, which is a deterministic approach based on the principle that values that are nearby tend to have higher similarity than values that are far apart [20]-[25] . In practice, IDW gives greater weight to data points closer to the point to be predicted, allowing for a more precise estimation of values at locations that have not been directly measured [26]. An Interpolation is designed to estimate the value of $f_{(x)}$ for an x between the points x_0, x_1, … … … , x_n, for which you have the value of $f_{(x)}$. You may obtain the values from a mathematical function, or they may be modelled using empirical formulas based on data and observations (1)

$$f_0 = f\left(x_0\right), f\left(x_1\right), \ldots, f_n = f\left(x_n\right) \tag{1}$$

This method was chosen because it can describe the spatial distribution of soil engineering parameters despite the limited data available. In the geotechnical field, IDW has proven effective for mapping important soil parameters such as PI and w, especially in the coastal areas of Bengkulu Province. The distribution and proximity between observation points strongly influence the accuracy of the IDW method. Therefore, 65 data points were used in this study, which have been analysed and correlated empirically.

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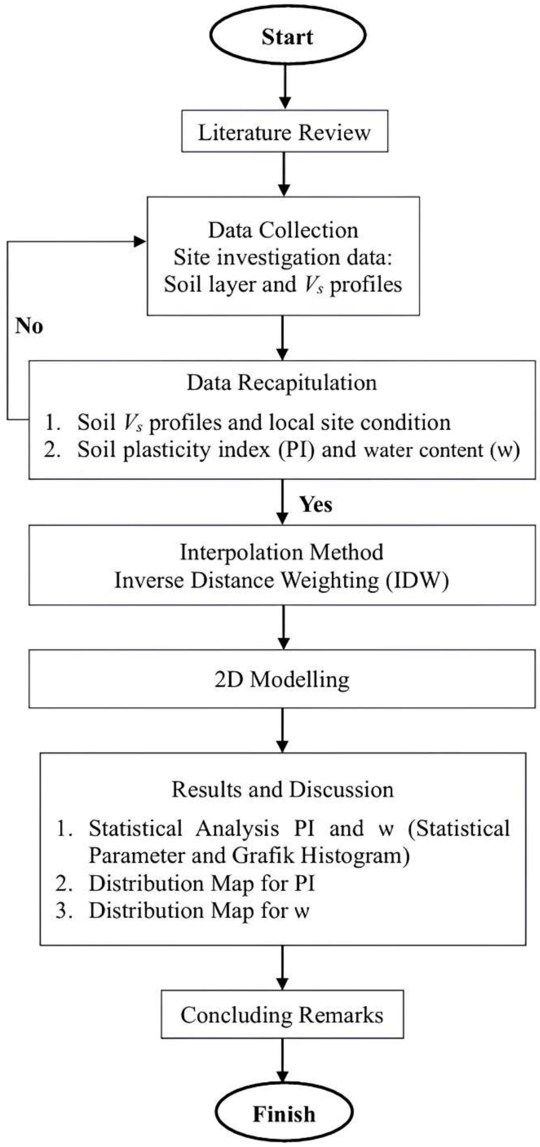

Figure 2. Research Flow Chart

3. Result and Discussion

3.1. Statistical Analysis

From the results of data recapitulation, three types of soil layers, such as sand, clay and soft rock, were obtained at the 30m deep research point. The available data values for PI 14.40 to 47.58% appear in Table 1. Similarly, Table 2 displays the w statistical analysis data 0.10 to 21.16%. Figure 3 depicts PI data through a histogram graph, demonstrating the PI values found in the clay layer. The clay layer PI parameter contains frequency data (n) of 16 within the 31 - 41% range. w data has been displayed in Figure 4a-c; however, the sand layer demonstrates the highest frequency values (n) of 27 alongside a data range of 9-13%. These combined analysis results deliver extensive data about PI and water content w distribution in Bengkulu Province coastal regions.

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Table 1. Estimation Statistical Value of Plasticity Index (PI) (%)

Statistical Parameters	Clay
Mean	29.20
Mode	-
Median	30.59
Min	14.40
Max	47.58
Standard Deviation	8.74
Variance	74.72
Coeff of Variation	29.95
Standar Error	1.32
the 95th Percentile	39.28

Table 2. Estimation Statistical Value of Water Content (w) (%)

Statistical Parameters	Sand	Clay	Soft Rock
Mean	10.31	15.50	7.91
Mode	13.30	-	7.94
Median	9.57	14.34	7.87
Min	0.26	0.10	5.71
Max	21.16	46.27	11.15
Standard Deviation	3.37	8.12	1.03
Variance	11.17	64.50	1.03
Coeff of Variation	32.70	52.41	12.97
Standar Error	0.44	1.22	0.15
the 95th Percentile	16.19	28.62	9.84

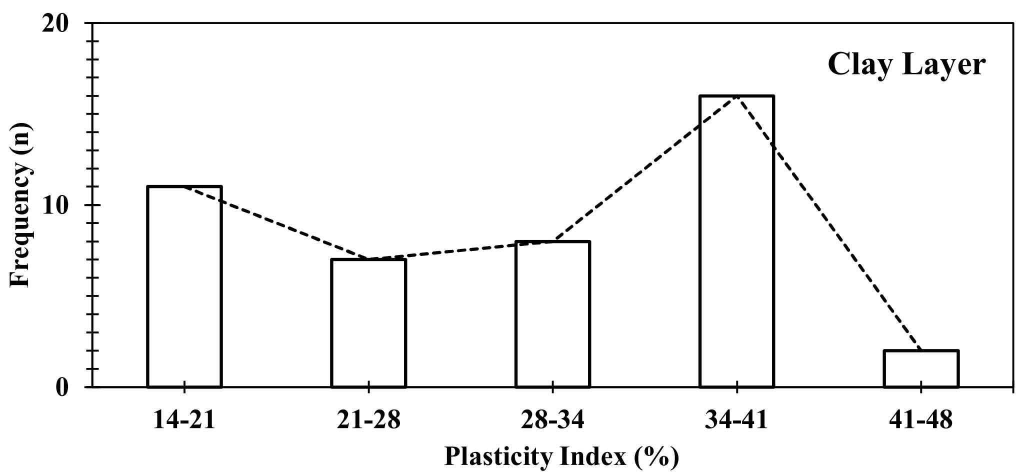

Figure 3. Histogram of geological variation parameter PI

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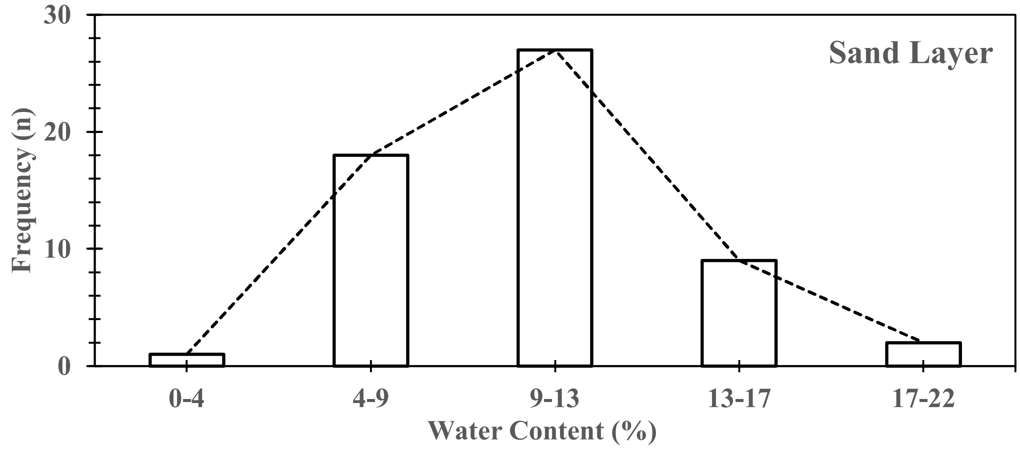
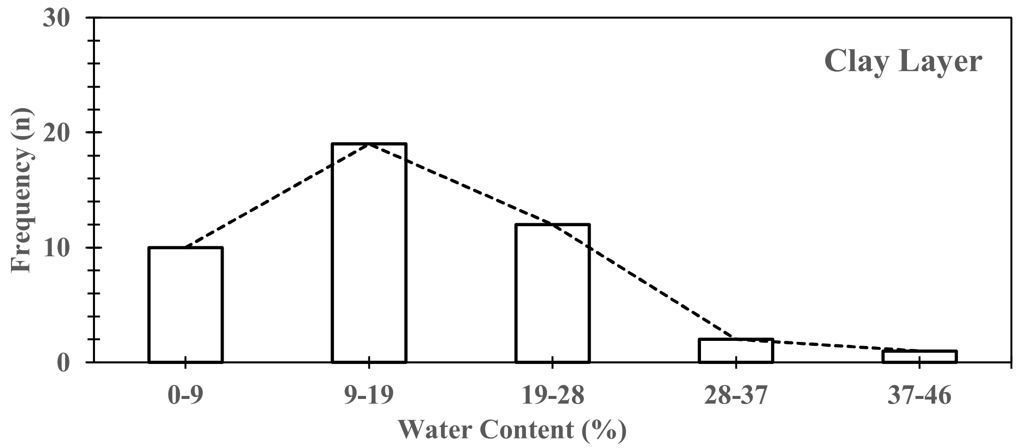


(a)



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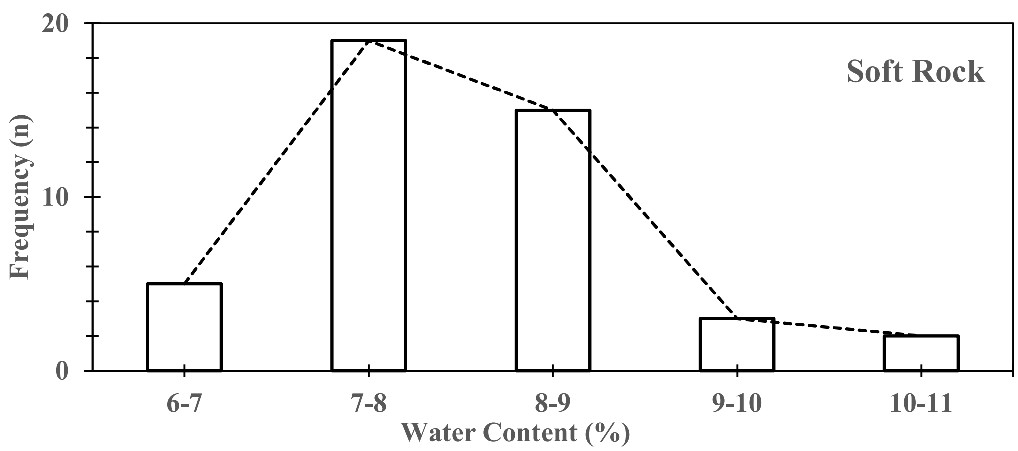

(c)

Figure 4. Histogram of Geological Variation Parameter Water Content (Ꞷ). (A) Sand (B) Clay (C) Soft Rock

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In general, the subsoil in this area consists mainly of loose sand, which allows the soil to dampen earthquake waves. Water-saturated sandy soils, as the dominant type, can increase their susceptibility to liquefaction in coastal areas [27] . This research is consistent with the findings of [28], who stated that liquefaction potential is higher in sandy and clayey soils with low resistance, which can increase the risk of disturbance to soil stability. These findings provide an essential foundation for developing infrastructure planning models that comprehensively and accurately consider local soil conditions.

3.2. Map of Distribution

Figure 5 displays a map illustrating the distribution of plasticity index (PI) values per cent in the study area. Based on observations, PI values in this area vary between. This distribution pattern of PI values can be visually observed and classified into five colour groups: 14 to 20% is marked in blue, 20 to 77% in green, 27 to 34% in yellow, 34 to 41% in orange, and 41 to 48% in red. [29] suggested three areas, and Zone A represents soils with a PI < 12% that are potentially liquefaction. Susceptibility to liquefaction for cohesive soils relates best to their plasticity index, where PI > 18% quickly shows very low strength, but isn't a liquefaction risk [30]. The highest PI values were found in several locations in Muko – Muko, North Bengkulu, Central Bengkulu and Bengkulu City regencies. In contrast, the lowest values were recorded in Seluma, South Bengkulu and Kaur regencies. This contributes to environmental safety and the stability of building structures. [31] described that soils with PI ≥ 30% tend to have a significant volume change potential, which risks compromising construction stability.

Meanwhile, Figure 6 shows the distribution map of soil water content (w*)*. At the study site, the w values show variations between 0 and 46%. The distribution of water content can be observed visually on the map, which groups w into three categories of colours: 0 to 9% is marked in blue, 9 to 18% in green, 18 to 27% in yellow, 27 to 36% in orange, and 36 to 46% in red. The points with the highest moisture content were found in several locations in the North Bengkulu and Seluma Regency. In contrast, the lowest points were spread across the North Bengkulu, Central Bengkulu, South Bengkulu, Kaur Regencies and Bengkulu City. According to [5], the moisture content in clay soil layers is generally around 21%. Monitoring the moisture content is essential to ensure that the soil can be optimally compacted, directly impacting the stability of the building structure above it.

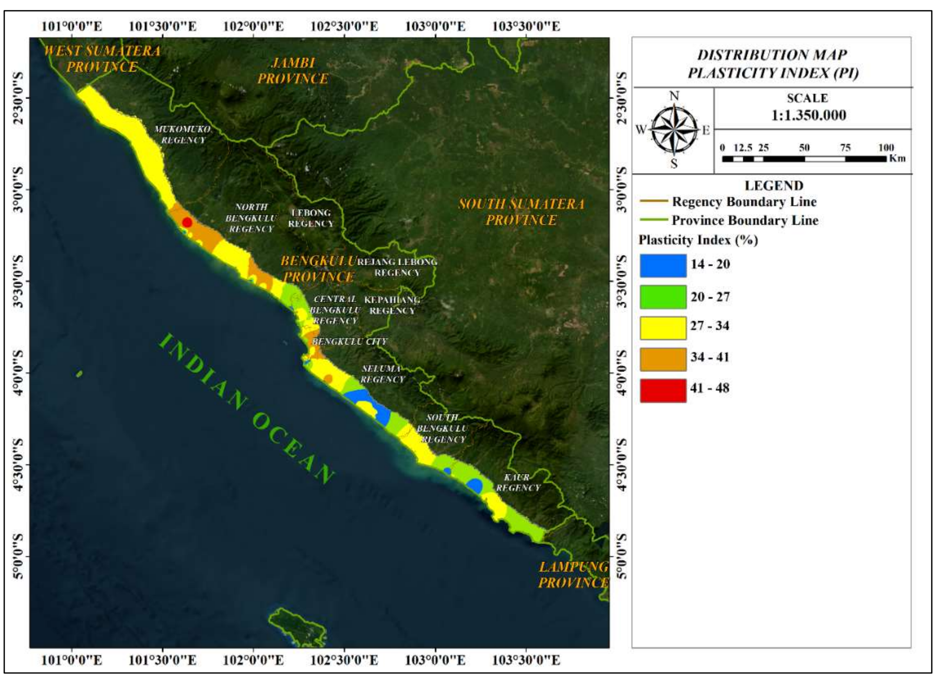

Figure 5. Map of Plasticity Index (PI) Distribution at a depth of 30 meters

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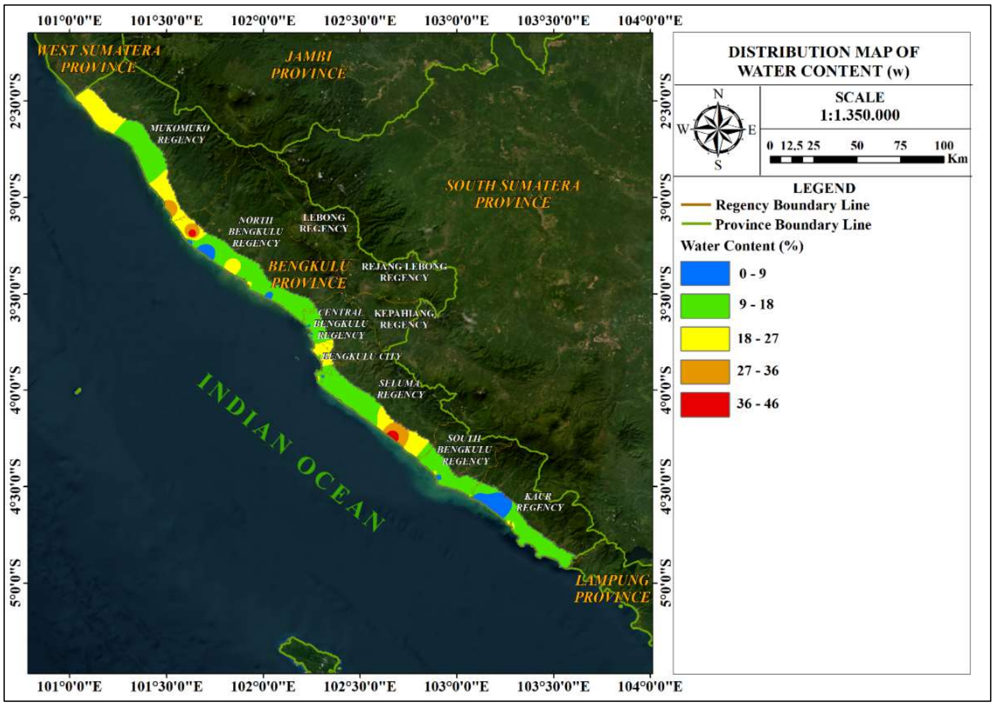

Figure 6. Map of Water Content (w) Distribution at a depth of 30 meters

4. Conclusion

The conclusion of this research is as follows. This study makes an essential contribution to the development of engineering geology through two-dimensional geospatial modelling of soil physical characteristics, namely PI and w, in the Bengkulu Province coast, which is known to have a high level of seismic vulnerability. This study makes a significant contribution to supporting decision-making related to managing disaster-prone coastal areas.

This study's results are highly relevant to disaster mitigation strategies, especially in coastal areas vulnerable to earthquakes and liquefaction. The resulting soil parameter distribution map can be used as a technical reference in designing infrastructure that is resilient to seismic shaking. Furthermore, using the two-dimensional distribution model, PI, and w model provides the scientific basis for resilient infrastructure. It encourages sustainable development by integrating geotechnical considerations into early-stage planning decision-making. The method can be adapted, extended to regions with similar geological characteristics and

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