



3D Geospatial Analysis of Soil Unit Weight Using the Radial Basis Function (RBF) and Ordinary Kriging (OK) Methods in Ketahun Sub-district, North Bengkulu

Nafisa Auliya, Lindung Zalbuin Mase*, Khairul Amri, Rahmat Fahrizal, Rena Misliniyati, Hardiansyah

Department of Civil Engineering, Faculty of Engineering, University of Bengkulu

Correspondence email: lmase@unib.ac.id

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ABSTRACT

Ketahun is one of the areas in North Bengkulu Regency, Bengkulu Province, which is affected by seismic activity, with geological conditions dominated by sedimentary from Bintunan Formation, which influence soil characteristics for geotechnical planning. Previous research on three-dimensional (3D) geospatial modeling in Bengkulu region was generally limited to soil technical parameters, while soil unit weight parameters were rarely used. This study aims to make 3D modeling of subsurface structure and soil unit weight distribution (γ_{sat} , γ_b , and γ_d) in Ketahun using geospatial approach. The research utilize data from field investigations at 15 Cone Penetration Test (CPT) points, which were then empirically correlated determine soil unit weight values. The 3D modeling was built using Leapfrog Geo application, through the Implicit Geological Modeling approach based on Radial Basis Function (RBF), while the distribution of bulk density parameters was estimated using Ordinary Kriging (OK). The validation results showed an R^2 (0,95 - 0,96), RMSE (0,48 – 0,55), and MAE (0,34 – 0,46) proving that this 3D model is able to represent the spatial distribution of soil parameters measurably, with consistence parameter relationships, where $\gamma_{\text{sat}} > \gamma_b > \gamma_d$. The average values obtained for γ_{sat} is 19,77 kN/m³, γ_b is 19,67 kN/m³, and γ_d is 15,82 kN/m³. The results of this study are expected to provide insight into the subsurface and distribution of bulk density to further geotechnical analysis for support the planning of earthquake-resistant building structures.

KEYWORDS: Ketahun; 3D modeling subsurface; bulk density; ordinary kriging

INTRODUCTION

Ketahun, a district in North Bengkulu Regency, Bengkulu Province, is influenced by tectonic activity due to its location in the convergence zone of the Indo-Australian and Eurasian plates. This plate interaction leads to crustal deformation and activates significant fault systems, such as the Sumatra and Mentawai Faults, making the region highly susceptible to earthquakes and potential damage (Mase et al., 2024). Hadi et al. (2026) note that the Sumatra Fault, also known as the Sumatran Fault System (SFS), consists of 19 segments,

including the Ketahun segment. Seismic records from Bengkulu reveal that earthquakes with magnitudes of $M_w \geq 5$ have occurred along this segment in the last twenty years, specifically in 2000 with a magnitude of M_w 7.9 and in 2007 with M_w 8.6. These tectonic features are depicted on a seismotectonic map adapted from Mase & Putri (2026), as illustrated in Figure 1.

Geological conditions, alongside tectonic factors, play a role in how soil reacts to seismic activity. Data from Indonesian geological maps indicate that the Ketahun area is primarily composed of the Bintunan Formation, characterized by clay, silt, and sand sediments.

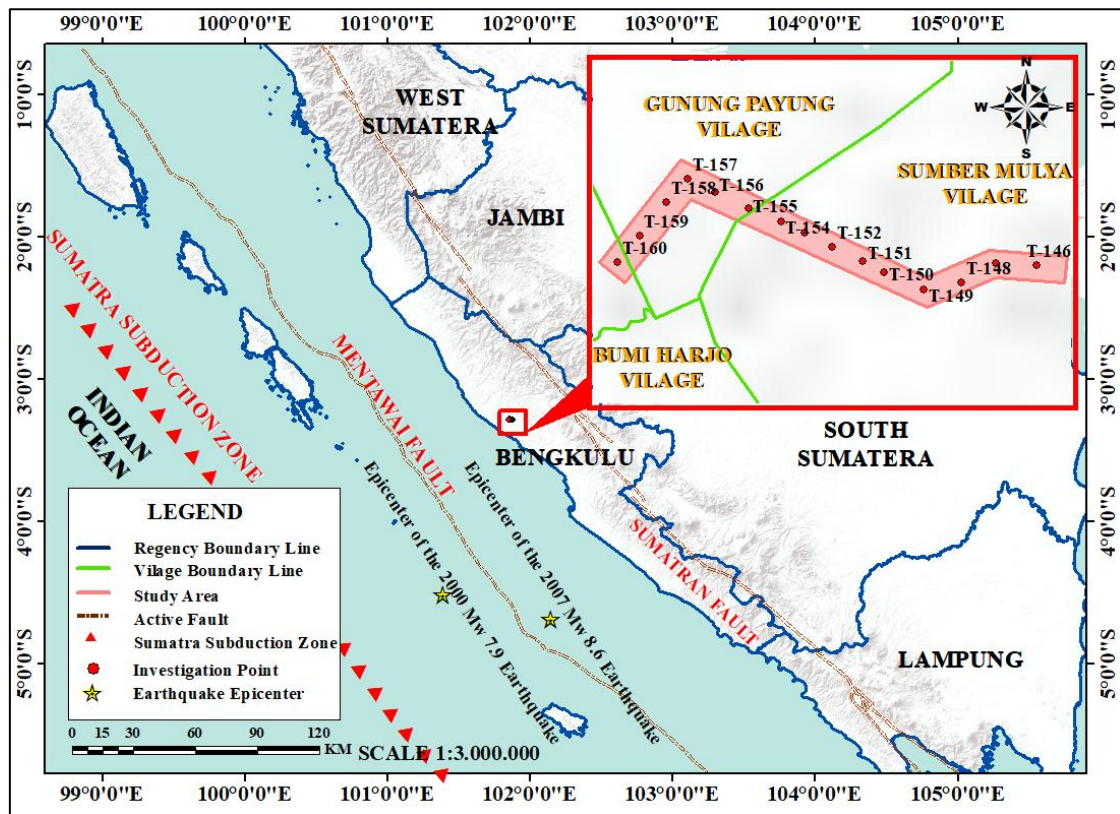


Figure 1. Seismotectonic map of Bengkulu Province (adapted from Mase & Putri (2026))

Considering the tectonic, geological, and morphological conditions present, conducting a geotechnical study is essential to aid in the design of durable and earthquake-resistant infrastructure in this area. Novtrisa et al., (2025) highlight that earthquake-induced building damage is significantly affected not only by the quality of construction but also by the geotechnical properties of the local soil. Additionally, understanding lithology and subsurface geotechnical characteristics is vital for assessing the potential impact of earthquake damage (Suprandani et al., 2026). Among the soil parameters used in geotechnical design, soil unit weight plays a key role in determining soil behavior under load conditions (Dungca & Galupino, 2023). This parameter is crucial for analyzing the effects of local seismic wave amplification. Thus, comprehending the geospatial distribution of soil unit weight is particularly important in regions prone to high seismic activity.

Geological modeling is an essential component of earth sciences, significantly contributing to the comprehension of the

layers of features and dynamics (Kamal et al., 2024). The development of three-dimensional (3D) subsurface geological modeling has been extensive, as it offers a more detailed representation of subsurface conditions compared to two-dimensional (2D) models (Benedetta et al., 2023). This advancement in 3D geological modeling improves our grasp of subsurface geotechnical parameters, thus aiding the analysis process. According to (Benedetta et al., 2023), 3D geological modeling is regarded as an effective method for capturing the complexity of subsurface structures within geological contexts.

In the Bengkulu area, significant advancements have been made in the 3D modeling of subsurface geology. Prior investigations, including those by Fikri et al., (2025) and Mase & Putri (2026), have utilized the Interpolation Distance Weighted (IDW) method to mapped the 3D distribution of soil technical parameters. Nonetheless, these studies face methodological challenges. As noted by Ligas et al., (2022), the IDW method falls short as it does not explicitly account for geospatial autocorrelation. Additionally, Z. Li,

(2021) pointed out that the IDW method overlooks the correlation among data points, while previous research has focused on soil technical parameters, there is a lack of studies on soil unit weight in the Bengkulu region.

Unlike the previous method, this research utilizes an Implicit Geological Modeling technique that relies on Radial Basis Functions (RBF) to develop the geometry of the 3D model, while the Ordinary Kriging (OK) method is used to estimate parameter distribution values through the Leapfrog Geo software. The selection of a spatial interpolation technique is vital for ensuring the precision of 3D geological models. Yang et al. (2025) highlight that the RBF approach is beneficial for 3D modeling as it implicitly reconstructs intricate geological contact boundaries, resulting in a smooth surface visualization. Nevertheless, the RBF technique is limited to constructing 3D models and does not estimate parameter distribution values. The OK method was incorporated into the Leapfrog Geo workflow to explicitly estimate parameter distributions within model blocks. As detailed by Li et al. (2022), the OK method is a Best Linear Unbiased Estimation (BLUE) technique that achieves optimal

interpolation of geostatistical data by reducing the variance of the estimates. This method examines the distance and direction of data dispersion through variogram analysis (Fauzi & Hariyadi, 2018). With this methodology, the study seeks to model the subsurface structure and soil unit weight. The findings are anticipated to offer insights into soil characteristics via a 3D distribution of soil parameters, forming a foundation for further geotechnical analysis and planning, and aiding in the design of earthquake-resistant infrastructure.

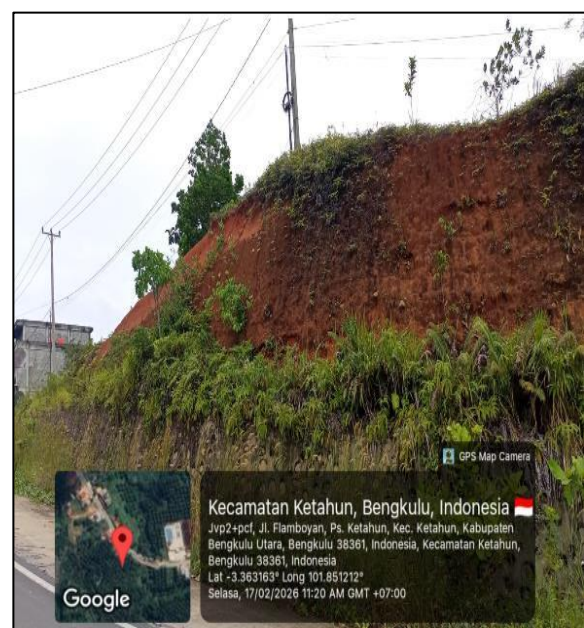
METHODS

Study Area and Data Collection

The research took place in the Ketahun region of North Bengkulu, Bengkulu. The area's morphology is quite diverse, with certain sections characterized by cliffs with relatively steep inclines and varying elevations, as depicted in Figure 2, which portrays the morphological features near the representative point. This particular point was chosen because it is situated on a very steep slope, which might affect the stability of the slope and the properties of the nearby soil, making it a critical aspect to consider.



(a)



(b)

Figure 2. Morphological conditions around the representative point (a) T-148, and (b) T-160

This research employed data from field studies conducted at 15 Cone Penetration Test (CPT) locations, which were part of the planning process for building electricity pylons in the Ketahun region. The cone tip resistance (q_c) and friction ratio (RF) values derived from the CPT tests were subsequently utilized to determine and categorize the soil layers using the Soil Behavior Type (SBT) classification system outlined by Robertson (2009). The soil classifications identified in the study area included Organic soils – clay, Clay – silty clay to clay, Silt mixtures – clayey silt to silty clay, Sand mixtures – silty sand to sandy silt, and Sands – clean sand to sandy silt. Using these soil layers, the q_c value was empirically linked to ascertain the soil saturation values (γ_{sat} , γ_b , and γ_d). This empirical correlation method is commonly used in interpreting CPT data to estimate geotechnical parameters across different soil conditions.

The empirical correlation formulated by Mayne (2010) was employed to determine the value of γ_{sat} . This equation necessitates the shear wave velocity (V_s) as an input parameter. The V_s value is derived from CPT data through the empirical correlations established by Madiati & Simoni (2004), Iyisan & Ansal (1993), and Stokoe & Nazarian (1983), as illustrated in Eq. (1), (2), and (3).

$$V_s = 21(q_c)^{0,23} \quad (1)$$

$$V_s = 45(q_c)^{0,41} \quad (2)$$

$$V_s = 154 + 0,64(q_c) \quad (3)$$

where V_s is the shear wave velocity (m/s) and q_c is the cone tip resistance (MPa).

The mean value of V_s is subsequently utilized as an input parameter for determining γ_{sat} . This determination is performed using the correlation suggested by Mayne (2010), which is illustrated in Eq. (4).

$$\gamma_{sat} = 8,32 \log(V_s) - 1,61 \log(z) \quad (4)$$

where γ_{sat} is the saturated unit weight (kN/m^3) and z denotes the thickness of the soil layer (m).

The values of γ_b and γ_d are calculated using the empirical correlations developed by Mayne (2007), as shown in Eq. (5) and (6).

$$\gamma_b = 2,6 \log(f_s) + 15 \log(G_s) - 26,5 \quad (5)$$

$$\gamma_d = \gamma_b - \left(\frac{\gamma_{sat} - \gamma_b}{G_s - 1} \right) \quad (6)$$

where γ_b is the wet unit weight (kN/m^3), γ_d is the dry unit weight (kN/m^3), f_s is the CPT friction resistance (MPa), and G_s is the specific gravity of the soil. The specific gravity (G_s) is taken to be 2.65, a standard value frequently applied in geotechnical studies (Amoozegar et al., 2023). This assumption might lead to uncertainty when dealing with soil layers that have varying mineral properties. The soil unit weight parameters derived from empirical correlations at the 15 CPT test locations were then utilized as input for 3D modeling. Given that the correlation is based on empirical data, the results are inherently estimative. These correlation outcomes can be affected by differences in lithology, geological settings, and local soil features. The parameters derived serve as an approximation to depict the regional subsurface conditions within the study area. Figure 3 provides a summary of the soil profile and unit weight parameters at representative points.

Data Processing

The research adhered to the procedure outlined in Figure 4. Initially, data were gathered from field investigations employing the Cone Penetration Test (CPT), which included soil profiles and unit weight parameters. This information was then compiled to act as the main input for further processing. After compilation, the data entered a pre-processing phase that involved compounding and transformation. The Ordinary Kriging (OK) interpolation method

was used to analyze the distribution of soil unit weight data. This method consists of three integrated stages: variogram fitting (spherical), kriging estimation, and validation.

A three-dimensional (3D) mesh was created using an Implicit Geological Modelling approach based on Radial Basis Functions (RBF).

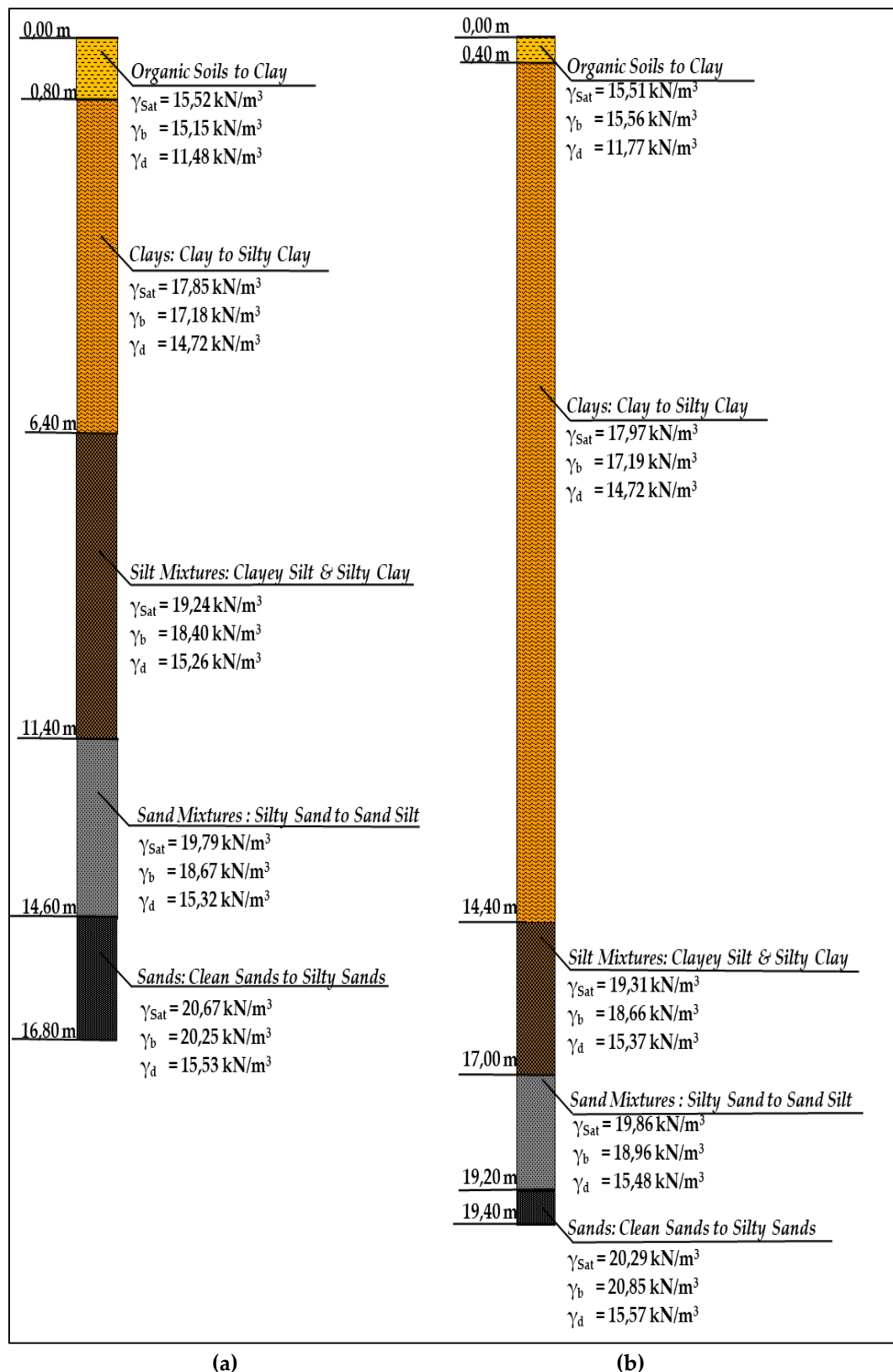


Figure 3. Soil profiles and parameters at representative points (a) T-148, and (b) T-160

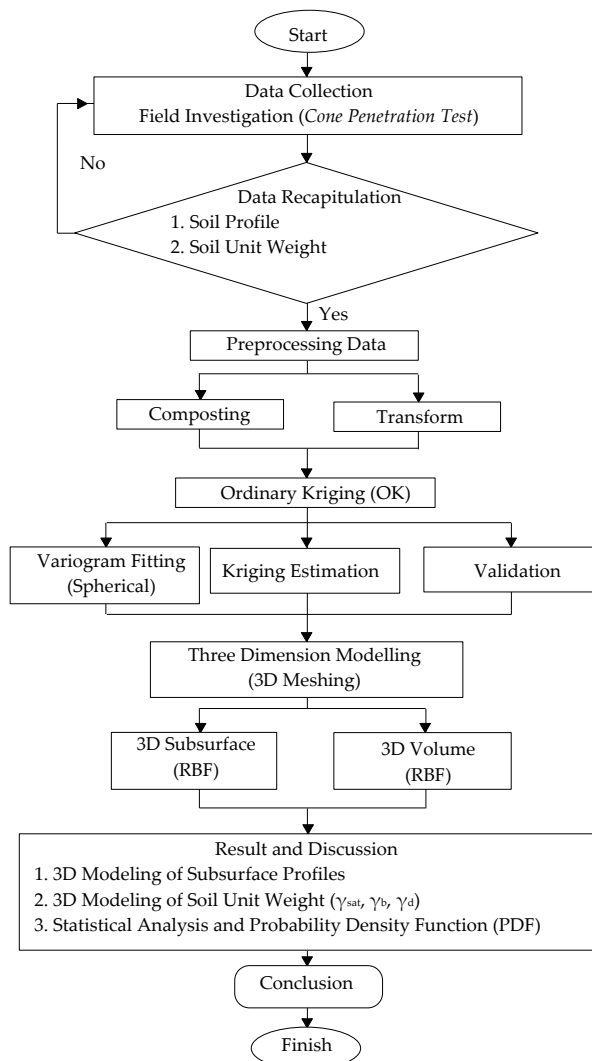


Figure 4. Research Framework

Ordinary Kriging (OK) ranks among the most frequently employed methods for geospatial estimation (Atalay, 2024). Additionally, it offers the Best Linear Unbiased Estimate (BLUE) with the least variance among deterministic approaches (Chauke, 2026). The method also quantifies uncertainty through the kriging variance (Lindi et al., 2024). Nonetheless, a limitation of this method is its tendency to overlook regions with high gradation and to smooth out the data (Mahdy & Salim, 2022). The formulation of estimated values using the OK method is presented in Eq. (7) below (Chauke, 2026).

$$Z^*(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (7)$$

where $Z^*(x_0)$ is the estimated (krigged) value at point x_0 . Meanwhile, n represents the count of data points utilized for the estimation. Each observed value is assigned a kriging weight, denoted as λ_i . The observed value of the variable at a specific location is represented by $Z(x_i)$.

The kriging weights were derived through an isotropic experimental semivariogram analysis conducted with the Leapfrog Geo application. The process involved fitting the data to a Spherical model to determine the Nugget (C_0), Sill (C_1), Total Sill, and Range (A) parameters. The model's reliability was quantitatively assessed using the Goodness of Fit (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) metrics.

The 3D geological model was developed using the Leapfrog Geo application, which applies the concept of Implicit Geological Modeling. This technique reconstructs geological structures as isosurfaces estimated through the Radial Basis Function (RBF) method. This method allows for efficient data integration, converting values into equipotential values to create a smooth surface (Yang et al., 2025). Utilizing the Leapfrog Geo application in 3D geological modeling enhances the depiction of geological structures, resulting in models that are more credible and align with observational data (Åberg et al., 2021).

RESULTS AND DISCUSSION

3D Modeling of Subsurface Geology

A 3D geological model of the subsurface was developed using soil profile data from the research location, as depicted in Figure 5. The model was created with an average offset of 200 meters from the investigation sites. This geological model is represented in the Universal Transverse Metric (UTM) coordinate system. Figure 6 illustrates a 3D slice of the soil profile, while Figure 7 presents cross-sections along the lines A-A', B-B', and C-C'.

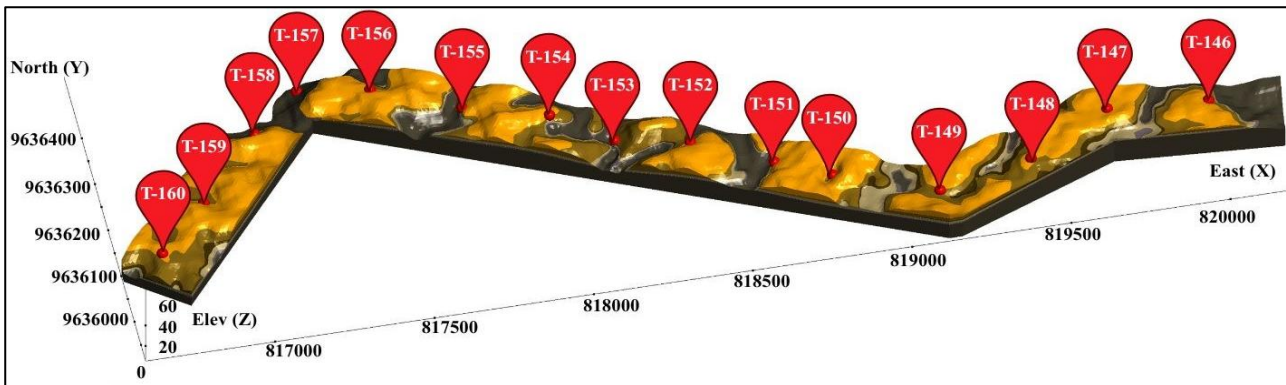


Figure 5. 3D modeling of subsurface lithology in the study area

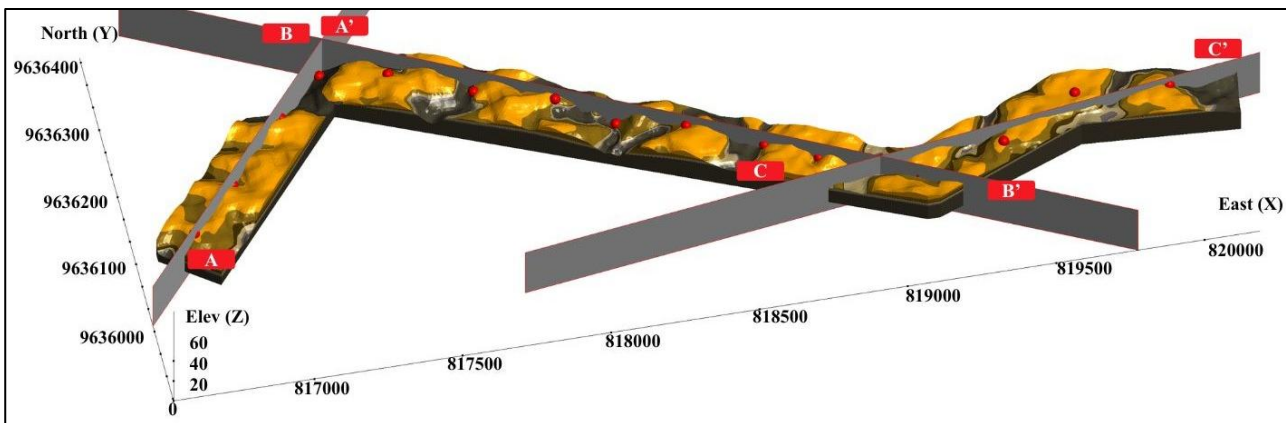


Figure 6. 3D subsurface cross-section modeling

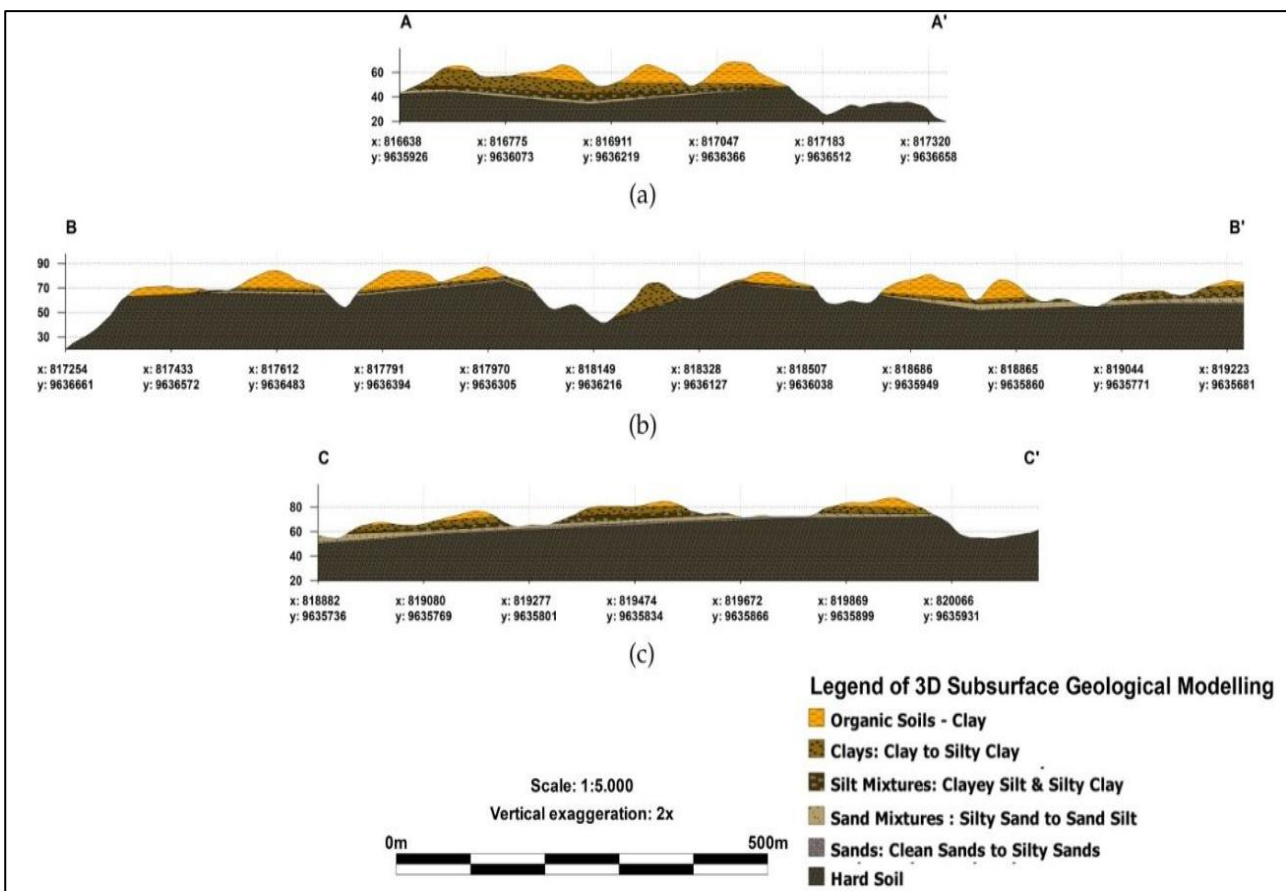


Figure 7. 2D cross-section (slice) (a)A-A', (b)B-B', and (c) C-C'

The visualisation of this model employs a horizontal scale (X-axis) of 1:5000. Additionally, a vertical exaggeration factor, or Z-scale, of 2x is applied to better define the stratigraphic boundaries, as a 1x vertical exaggeration would not sufficiently emphasize the variations in thickness and contrast between layers. The use of distinct horizontal and vertical scales is intended to improve visualisation without altering the model's geometry, actual thicknesses, or volume calculations, as all computations are based on the model's original coordinates. This approach aligns with Seequent's official documentation, which clarifies that the vertical exaggeration setting in Leapfrog Geo influences only the graphical display, leaving the numerical data and computational model results unchanged. In the model, the hardsoil layer is interpreted as dense sand, derived from interpretative assumptions and conceptual extrapolation based on the trend of increasing parameter values at the CPT tip depth. This hardsoil layer is included in the model purely for visualisation purposes, ensuring the continuity of the soil profile in the 3D subsurface visualisation without impacting the original data.

3D Modeling of Soil Unit Weight Distribution (γ_{sat} , γ_b , and γ_d)

This 3D model of soil density distribution was developed to examine the spatial variation in soil characteristics, aiming to offer a more precise depiction of subsurface conditions and aid in geotechnical evaluations. The geospatial analysis employed a spherical semivariogram model to illustrate the distribution of soil unit weight. A very low Nugget value (C_0) relative to the Total Sill suggests that the data have strong spatial dependence with minimal random measurement error. The ellipsoid geometry was consistently configured with a maximum major axis Range (A) of 1,300 m to restrict spatial correlation, maintaining the standard orientation (Dip 0, Azimuth 0). Table 1

presents all operational components of the modeling.

Table 1. Semivariogram parameters resulting from the statistical analysis of the soil unit weight distribution (γ_{sat} , γ_b , and γ_d)

Parameter <i>Semivariogram</i>	γ_{sat}	γ_b	γ_d
<i>Nugget (C_0)</i>	0.21	0.25	0.18
<i>Sill (C_1)</i>	3.9	4.83	3.35
<i>Total Sill ($C_0 + C_1$)</i>	4.11	5.08	3.53
<i>Range (A)(Major)</i>	1300	1300	1300

The interpolation model of reliability is illustrated by the graph in Figure 8 which depicts the correlation between actual (measured) and predicted values derived from cross-validation results. The R^2 values, which are 0.96 for γ_{sat} and 0.95 for both γ_b and γ_d , reflect a high degree of accuracy. A low root mean square error (RMSE) is evidenced by values of 0.48 for γ_{sat} and 0.55 for γ_b and γ_d . Additionally, the mean absolute error (MAE) is represented by values of 0.34 for γ_{sat} and 0.46 for γ_b and γ_d .

Soil unit weight variations are depicted using a color scale, with values spanning from 10 to 22 kN/m³. As illustrated in Figure 9 the γ_{sat} model displays a distribution with relatively high values compared to other parameters. Conversely, the γ_b model, shown in Figure 10, presents a distribution nearly identical to γ_{sat} but with slightly reduced values. On the other hand, the γ_d model, depicted in Figure 11, reveals a distribution with lower values.

Generally, these three parameters maintain a consistent relationship, where γ_{sat} has the highest values, followed by γ_b , and γ_d with the lowest ($\gamma_{\text{sat}} > \gamma_b > \gamma_d$). Although the geospatial distribution patterns of all three are quite similar, the differences in value ranges suggest that soil material and structural conditions primarily influence these variations. From a geotechnical standpoint, this distribution offers crucial insights for analyzing bearing capacity, assessing slope stability, and estimating overburden pressure.

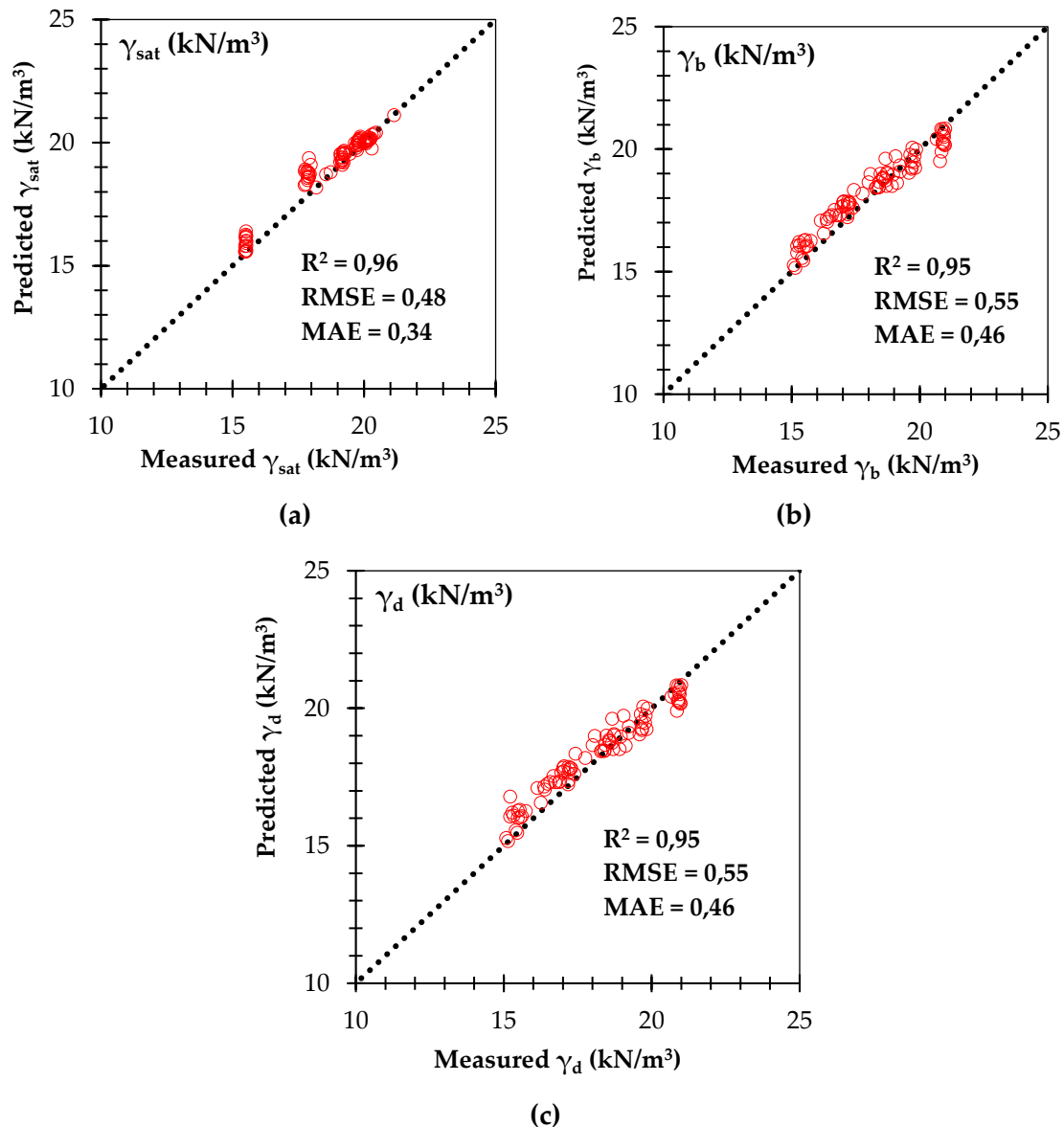


Figure 8. Graph of measured and predicted values from parameter cross-validation (a) γ_{sat} , (b) γ_b , and (c) γ_d

The Bintunan Formation, comprising clay, silt, and sand, predominates in the study area. Lower specific gravity in soil correlates with reduced density and increased porosity. Additionally, this region is affected by an active seismotectonic zone, which means that the low soil unit weight characteristics can enhance seismic wave amplification effects. Areas where infrastructure is planned above this zone necessitate specialized geotechnical measures, such as soil improvement or deep foundation use, to ensure earthquake-resistant infrastructure design.

Statistical Analysis and Probability Density Function (PDF)

The results of the statistical analysis from this study are presented in Table 2, which shows that the average values for the saturated unit weight (γ_{sat}) are 19.77 kN/m^3 , the wet unit weight (γ_b) are 19.67 kN/m^3 , and the dry unit weight (γ_d) are 15.82 kN/m^3 . These suggest that the soil unit weight in the study area is moderately dense, necessitating specific geotechnical strategies for designing earthquake-resistant structures.

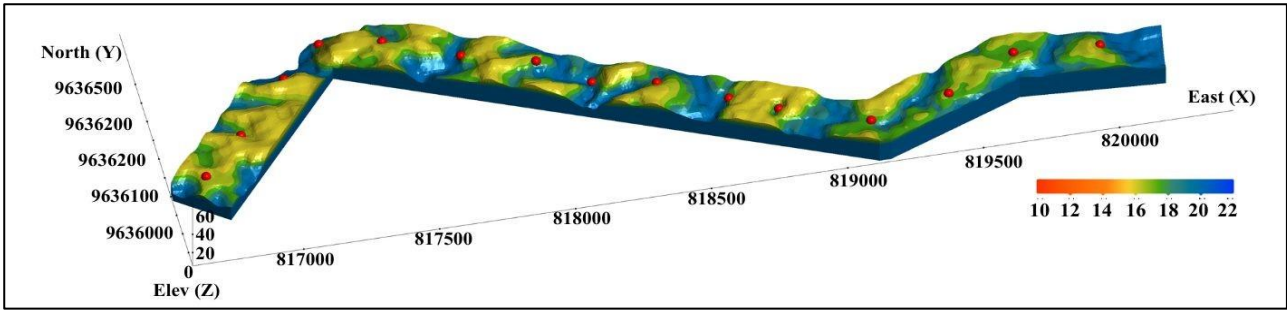


Figure 9. 3D profile of soil unit weight distribution in the study area for γ_{sat} (kN/m³)

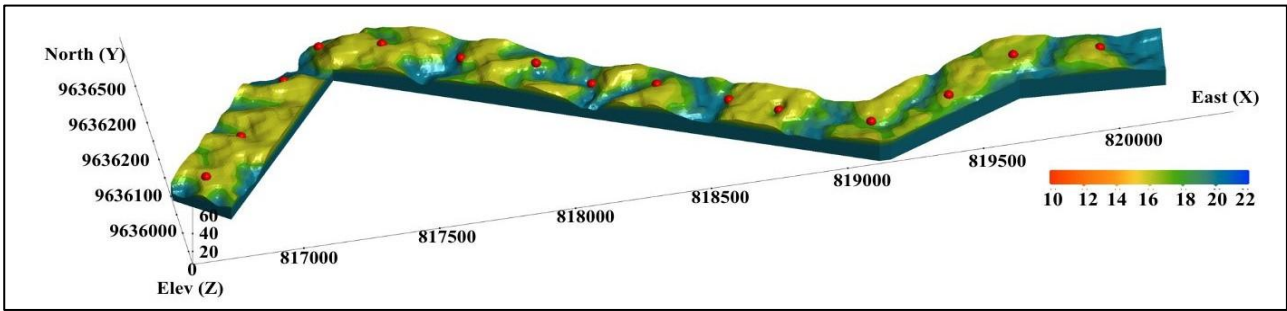


Figure 10. 3D profile of soil unit weight distribution in the study area for γ_b (kN/m³)

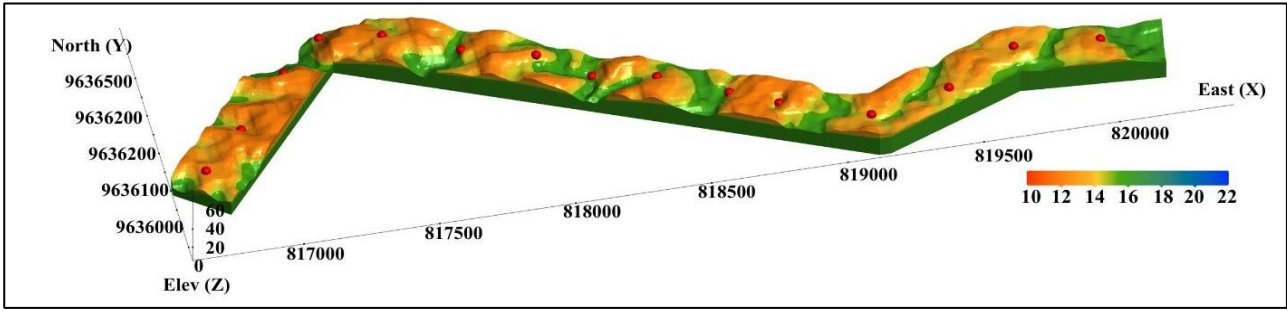


Figure 11. 3D profile of soil unit weight distribution in the study area for γ_d (kN/m³)

The observed range of values shows variability, with γ_{sat} spanning from 15.47 to 22.21 kN/m³, γ_b from 15.09 to 21.73 kN/m³, and γ_d from 11.43 to 17.56 kN/m³. This shows the heterogeneity in soil composition, yet it remains within acceptable bounds for the region geological.

Table 2. Results of the statistical analysis of the soil unit weight distribution (γ_{sat} , γ_b , and γ_d)

Statistical Parameter	γ_{sat}	γ_b	γ_d
Min	15,47	15,09	11,43
Max	21,21	21,13	17,56
Mean	19,77	19,67	15,82
Median	19,75	19,66	15,81
Standard Deviation	1,08	0,94	0,83
Coeff. of Variation	5,47	4,77	5,23
Skewness	-0,26	-0,27	-0,21

The statistical analysis in Table 2 shows that the mean and median values are not significantly different, indicating that the data distribution tends to follow a normal distribution. The low standard deviation and coefficient of variation suggest that the soil weight distribution exhibits minimal dispersion. Although the skewness is negative, it remains near zero, pointing to a slightly left-skewed distribution that lacks statistical significance.

To validate the statistical analysis of soil unit weight distribution (γ_{sat} , γ_b , and γ_d), this study examined the Probability Density Function (PDF) depicted in the histogram in Figure 12. The soil unit weight values in this research display a pattern that nearly mirrors

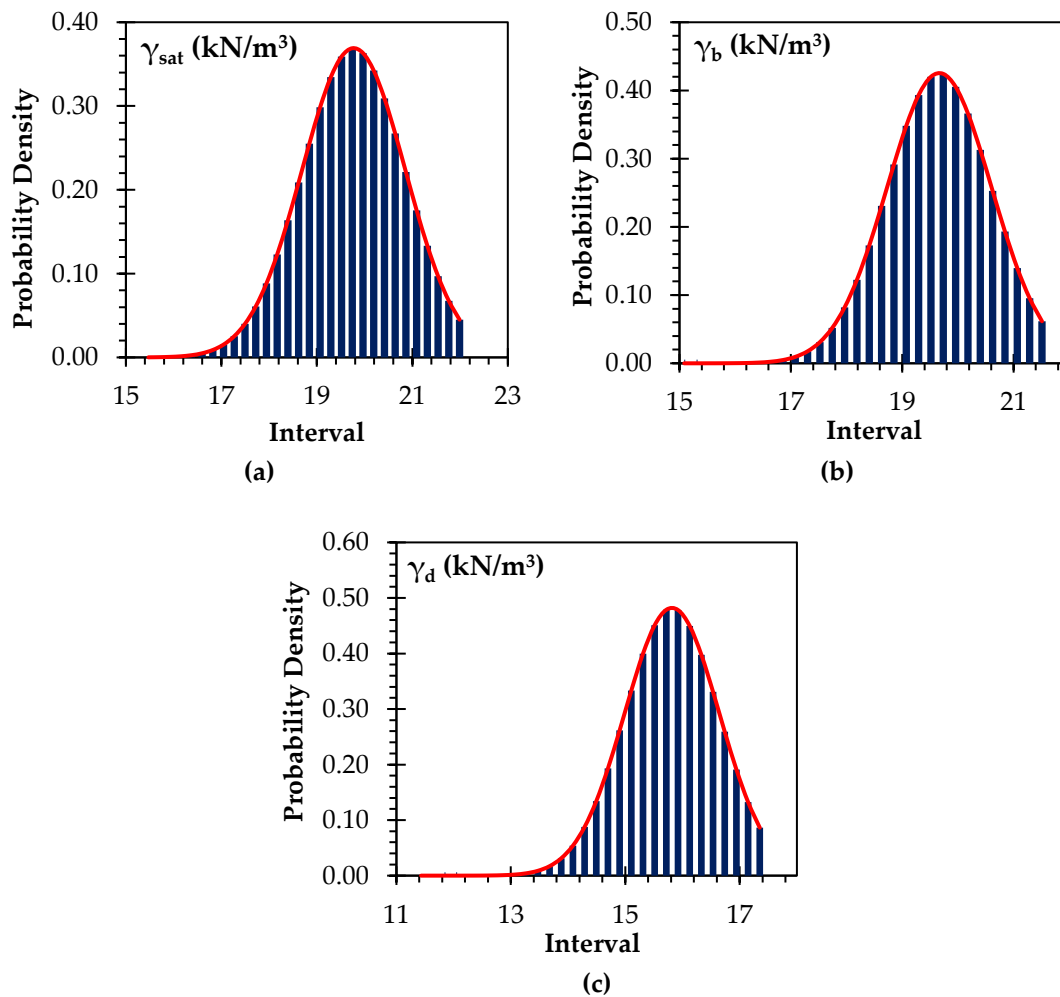


Figure 12. Probability Density Function (PDF) graph of the soil unit weight parameter distribution (a) γ_{sat} , (b) γ_b , dan (c) γ_d

a normal distribution, characterized by a bell-shaped curve that is relatively symmetrical and centered around the mean. This curve signifies a strong fit, as demonstrated by the proximity of the mean and median values and a skewness value nearing zero. Together, these analyses confirm that the data employed in this modeling are of sufficient quality and are representative.

CONCLUSION

In this study, the subsurface conditions and soil density distribution (γ_{sat} , γ_b , and γ_d) in the Ketahun area were effectively mapped in three dimensions using geospatial data, the Leapfrog Geo software, and the Ordinary Kriging technique. The validation results, with R^2 values ranging from 0.95 to 0.96, RMSE between 0.48 and 0.55, and MAE from 0.34

to 0.46, indicate that the 3D model accurately depicts the spatial distribution of soil parameters. The order of soil unit weight values is consistent, with γ_{sat} having the highest average value of 19.77 kN/m³, followed by γ_b at 19.67 kN/m³, and γ_d with the lowest average of 15.82 kN/m³ ($\gamma_{sat} > \gamma_b > \gamma_d$). Statistical analysis and the Probability Density Function (PDF) confirm that the data utilized in this research are of adequate quality and representativeness to support geotechnical planning, including soil strength and slope stability analyses, which are crucial for design earthquake-resistant infrastructure. For future research, it is recommended to increase the number of test points in data-scarce areas and conduct deeper investigations to enhance 3D subsurface modeling.

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