International Journal of GEOMATE, Sep., 2025 Vol.29, Issue 133, pp.118-128
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.133.5041
Geotechnique, Construction Materials and Environment

MAPPING EXPANSIVE SOILS BASED ON PHYSICAL PARAMETERS FOR FOUNDATION FAILURE RISK IN KUTA

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*Corresponding Author, Received: 05 May 2025, Revised: 04 July 2025, Accepted: 06 July 2025

ABSTRACT: Kuta Village, located within the Mandalika Special Economic Zone (SEZ), has undergone rapid development, presenting challenges due to the presence of expansive soils. These soils swell and shrink with moisture changes, potentially causing structural damage and foundation failure if not properly managed. This study aims to map and assess the risks associated with expansive soils using physical soil parameters to support early mitigation efforts. Soil samples from 13 locations at depths of 30–50 cm were analyzed in the laboratory. The data were processed using ArcGIS 10.4, and a spatial distribution map was created using the Inverse Distance Weighted (IDW) interpolation method. Key soil parameters including liquid limit, plasticity index, activity, and expansion potential were evaluated. Soil behavior was classified using three established frameworks: the Seed, Chen, and Ladd & Lambe methods. Results indicate the Seed method provides a more conservative classification, while the Chen and Ladd & Lambe methods are more predictive. Despite differences, the classifications are generally consistent across methods. For practical application, the Chen method is recommended for initial screening, followed by Ladd & Lambe for field verification, and the Seed method for final validation and design. The study confirmed consistency in identifying high-risk zones, validating the reliability of spatial analysis in pinpointing areas susceptible to foundation failure. These insights offer a practical tool for guiding infrastructure planning and design to mitigate risks related to expansive soils and prevent structural damage.

Keywords: Kuta Village, expansive soil, foundation failure risk, Mandalika Special Economic Zone (SEZ)

1. INTRODUCTION

Kuta Village, located in Pujut Sub-district, Central Lombok District, West Nusa Tenggara Province, is one of Indonesia's nationally strategic tourism areas that is rapidly developing through the Mandalika Special Economic Zone (SEZ) program. In recent years, the region has experienced significant growth in infrastructure development, including tourism facilities, accommodation, and other supporting amenities. However, amid this rapid development, a geotechnical challenge has emerged that requires serious attention namely the presence of expansive soil [1]. Structures are more susceptible to damage when constructed on expansive soils [2].

Seasonal fluctuations in soil moisture content can induce volumetric and structural transformations in the soil [3]. Expansive soil is a type of soil that has the ability to swell when absorbing water and shrink when drying [4]. This volume change can cause uplift or uneven settlement in foundation structures [5]. As a result, buildings constructed on such soil are at risk of experiencing structural damage such as cracks in walls and floors, cracked asphalt and uneven, wavy road pavement, displacement of buildings, damage to utility networks, and potentially even total foundation failure [6]. The presence of expansive soil that is not identified early can lead to significant economic losses and safety hazards [7]. In the context of Mandalika's massive and sustainable development, early identification of the soil properties in the area, especially its expansive potential, is crucial.

One approach that can be employed is expansive soil mapping based on physical parameters such as liquid limit, plastic limit, plasticity index, activity value, swelling potential, and expansion ratio. With accurate mapping, technical risks due to expansive soil can be minimized through proper foundation planning and soil reinforcement strategies [8].

The index properties liquid limit, plastic limit, plasticity index and shrinkage limit of fine-grained soils are useful for estimating shear strength, compressibility, and swelling potential. These parameters also play a crucial role in understanding the mechanical behavior of soils, which has led to the development of various methods for predicting the degree of soil expansion [9]. Commonly used approaches include methods developed by Seed et al., Chen, and Ladd & Lambe [10-12]. The integration of these different approaches aims to produce more comprehensive and accurate results in mapping expansive soil potential. The information obtained from this mapping is essential as a basis for decision-making in foundation planning and design, particularly in areas with high geotechnical vulnerability, such as Kuta Mandalika [13].

Therefore, this study has been conducted to evaluate and map the expansive soil potential in the Mandalika area using a three-method prediction approach based on physical soil parameters.

The results of this research are expected to support the planning of safe, sustainable infrastructure that is resilient to geotechnical risks posed by expansive soils.

In efforts to mitigate the risk of foundation failure, the characterization of expansive soils represents a critical preliminary step [14]. This study focuses on evaluating the degree of soil expansion based on the analysis of physical soil properties and scientifically recognized predictive approaches. Expansive soils are primarily composed of clay or silty clay. However, not all clays can be classified as expansive soils [15]. Soils with coarse-grained particles, such as cobbles, pebbles, and sands, may also exhibit expansive behavior depending on the proportion and type of clay minerals present in their finer fractions [16].

Expansive soils are known for their ability to undergo significant volume changes due to fluctuations in moisture content, which can exert considerable pressure on foundation structures [17]. Accordingly, the evaluation was conducted through a series of laboratory tests on key physical parameters, including water content, bulk density, specific gravity, liquid limit, plastic limit, sieve analysis, and hydrometer analysis. The results of these physical tests were further analyzed to determine soil classification, plasticity index, and soil swelling potential. Subsequently, the study proceeds with the classification of the degree of soil expansion and mapping of expansive soil distribution, which are discussed in the following sections.

2. RESEARCH SIGNIFICANCE

This study presents a new approach by integrating laboratory-based soil physical properties with spatial analysis to evaluate foundation failure risks caused by expansive soils in a rapidly developing area. This research compares three established classification methods: Seed, Chen, and Ladd and Lambe. The key contribution lies in combining these methods and applying them in Kuta, part of the Mandalika Special Economic Zone. The results offer a practical and reliable mapping tool to identify high-risk zones, supporting early mitigation and guiding infrastructure design to minimize structural problems linked to expansive soils.

3. CLASSIFICATION METHODS FOR SOIL EXPANSION DEGREE

The degree of soil expansion was evaluated using three classification methods [10–12]. These methods were selected for their consistency in producing coherent classifications across different locations and for their complementary approaches. Seed et al.'s method relies on laboratory data derived from actual swelling percentage [10]. Chen's method is based on the Plasticity Index (PI) which reflects clay mineral activity [11]. Ladd & Lambe's method takes into account the influence of moisture on expansion potential [12]. The combined use of these three methods enhances the reliability of classification by integrating distinct yet mutually reinforcing perspectives [18].

3.1 Method

The Seed et al. method is an empirical approach used to evaluate the expansive potential of soil based on the results of swelling tests conducted on compacted soil samples [10]. The framework of this method is based on the assumption that expansive soil behavior can be directly measured through volume changes that occur as a result of wetting under controlled laboratory conditions. Although it provides more accurate results, this method is sensitive to the initial condition of the samples and test parameters, and generally requires more time and cost compared to index-based methods. The relationship between the Plasticity Index (PI) and the swelling potential, is presented in Eq. (1). The results obtained from Eq. (1) were subsequently classified into expansion categories as presented in Table 1 [19].

$$S = 60K(PI)^{2.44} \quad (1)$$

Where S is swelling potential; K is correlation constant (i.e. 3.6×10^{-5}); and PI is the Plasticity Index.

Table 1. Classification of soil expansion degree based on the Seed et al. method

Swelling Potential, *S* (%)	Classification
0 - 1.5	Low
1.5 - 5	Moderate
5 - 25	High
> 25	Very high

3.2 Chen Method

The Chen method is an empirical approach used to evaluate the expansive potential of clay soils based on parameters such as the Plasticity Index (PI), Liquid Limit (LL), and the content of active clay minerals [11]. The framework of this method is based on the assumption that high PI and LL values reflect a high level of clay mineral activity. Its main advantage lies in its ease of application, as it does not require complex advanced testing. However, the method is indicative in nature and does not provide a quantitative estimate of actual field expansion, making it more suitable for preliminary evaluation stages in geotechnical studies. Data from the liquid limit and plastic limit tests are required to obtain the Plasticity Index (PI) value [20]. The classification according to the Chen method based on the Plasticity Index (PI) is summarized in Table 2.

Table 2. Classification of soil expansion degree based on the Chen method

Plasticity Index, *PI* (%)	Classification
0 - 10	Low
10 - 20	Moderate
20 - 35	High
>35	Very high

3.3 Ladd & Lambe Method

The Ladd & Lambe method evaluates soil expansive potential by combining natural moisture content, Liquid Limit (LL), Plasticity Index (PI), and soil structure [12]. It is based on the assumption that the interaction between moisture content and active minerals influences expansion, emphasizing the importance of field conditions such as moisture and suction. Although this method provides a more representative approach, it involves complex interpretation and requires accurate moisture data. This method, relates the Liquid Limit (LL) to the soil expansion degree. The higher the Liquid Limit (LL) value, the greater the soil's capacity to expand when exposed to water, as shown in Table 3 [21].

Table 3. Classification of soil expansion degree based on the Ladd & Lambe method

Liquid limit (%)	Expansion Degree
20 - 35	Low
35 - 50	Moderate
50 - 70	High
70 - 90	Very high
>90	Extremely High

4. METHOD

4.1 Sampling Design and Procedure

Kuta Village consists of 20 hamlets, and based on a visual survey considering topography, population density, and accessibility, 13 hamlets were selected using restricted random sampling as sampling locations. The sampling locations are summarized in Table 4. Soil sampling was conducted on February 6, 2025, during the rainy season in Kuta Village, Central Lombok. The saturated soil conditions during this season increase the potential for soil expansion, so the data obtained represent the maximum expansion conditions. However, since samples were only collected during the rainy season, the study results do not reflect the seasonal behavior of expansive soils and cannot evaluate volume changes due to the annual wet–dry cycle. Undisturbed soil sampling was conducted by excavating the soil to a depth of approximately 40–50 cm. A sampling tube was then carefully inserted vertically into the bottom of the pit and gently pressed to allow the soil to enter and fill the tube without disturbing its natural structure. Once the tube was completely filled, both ends were sealed tightly to prevent exposure to air and to maintain the soil's moisture content and structural integrity [22–23]. The sealed sampling tubes were then stored in a specialized sample box designed to protect them from shocks, direct sunlight, and temperature fluctuations. The samples were subsequently transported by a four-wheeled vehicle to the laboratory for further analysis.

4.2 Soil Properties

To determine the physical characteristics of the soil, the samples were subsequently tested in the laboratory following standard ASTM procedures. The tests conducted included water content (ASTM D2216-98), bulk density (ASTM D7263-21), specific gravity (ASTM D854-02), and Atterberg limits, comprising liquid limit and plastic limit (ASTM D4318-00). Additionally, particle size distribution was analyzed using sieve analysis (ASTM D1140-00) and hydrometer methods (ASTM D422-63). These data are essential for understanding the soil consistency and particle size distribution, which significantly influence its mechanical behavior and expansive potential.

4.3 Mapping

The data used to create the expansive soil zoning map consists of physical soil properties test results. These data were analyzed to determine the soil's plasticity index, soil classification, activity, and expansive soil characteristics classification. The mapping of soil expansion degree distribution based on several physical property parameters in this study was carried out using ArcGIS 10.4. The mapping method used is Inverse Distance Weighted (IDW), a simple deterministic method that considers nearby points. The assumption of this method is that interpolated values are more similar to nearby sample data than to those farther away. In addition to the physical property analysis data, the mapping process also required coordinate data from sampling locations spread across Kuta Village. Several researchers have utilized ArcGIS for mapping purposes, including [24-25].

5. RESULTS

5.1 Physical Characteristics of The Soil

Physical soil property testing was conducted to gain an understanding of the subsurface soil conditions in Kuta Village, which play an important

Table 4. Results of physical properties tests on soil samples

Location	Water content (%)	Bulk density (gr/cm^3)	Spesifik gravity	Liquid limit (%)	Plastic limit (%)
Mong lauk	35.68	1.44	2.34	44.01	33.85
Mong I	32.78	1.22	2.14	68.02	29.74
Merendeng	32.55	1.35	2.06	50.60	29.19
Mengalung	22.38	1.69	2.30	30.10	20.39
Ngolang	32.44	1.37	2.14	51.48	15.60
Rangkap I	24.28	1.69	2.22	38.53	25.79
Lenser	33.38	1.36	2.23	42.06	26.71
Ujung daye	35.62	1.44	2.43	51.10	27.89
Ketapang	18.24	1.66	2.49	38.26	25.03
Rangkap II	25.00	1.55	2.29	40.53	27.89
Ebunut	36.07	1.31	2.17	54.93	35.73
Emate	42.58	1.26	2.15	56.57	38.11
Kuta	20.48	1.57	2.31	31.77	21.61
Mean	30.11	1.45	2.25	45.99	27.50
Standard deviation	7.27	0.16	0.12	10.70	6.23
Standard error	2.02	0.04	0.03	2.97	1.73
Margin of error	3.95	0.09	0.07	5.82	3.38
Confidence interval lower bound	34.07	1.54	2.32	51.81	30.89
Confidence interval upper bound	26.16	1.37	2.18	40.18	24.12
Relative confidence interval width	26.27	12.10	6.00	25.29	24.61
Type of variability	High	Moderate	Low	Moderate	Moderate

role in soil responses to environmental changes, particularly its expansion potential. The results of the physical soil property analysis along with descriptive statistics are presented in Table 4.

Based on the statistical analysis of five soil physical property parameters, namely water content, bulk density, specific gravity, liquid limit, and plastic limit, the mean values indicate that the soils in the study area generally exhibit relatively highwater content (30.11%), moderate bulk density (1.45 g/cm³), and relatively low and uniform specific gravity (2.25), which suggests a homogeneous mineral composition. Meanwhile, the liquid limit (45.99%) and plastic limit (27.50%) reflect a moderate to high level of soil plasticity, indicating a significant presence of active clay minerals.

Standard deviation analysis shows that water content has high variability, indicating heterogeneous moisture conditions likely due to environmental factors during the rainy season. Bulk density, liquid limit, and plastic limit display moderate variability, while specific gravity shows low variability, suggesting consistent soil mineralogy across the sampling locations. Nevertheless, a key limitation of this study is the relatively small number of sampling locations, that is only 13 points, which may affect the spatial representativeness of the data and increase uncertainty in interpreting the results. This limited sample size reduces the reliability of drawing generalized conclusions about the overall soil conditions in the study area, particularly in regions with high geological heterogeneity. Therefore, to improve the reliability and accuracy of the data, it is recommended that future studies include a greater number of sampling points with more evenly distributed sampling locations.

5.2 Mapping of Soil Expansion Degree

Mapping of soil expansion degree is essential to identify the spatial variability of expansive soil hazards within the study area. The presence of expansive soils may cause severe damage to civil structures due to their shrink–swell behavior. Therefore, a comprehensive spatial analysis was conducted to determine the degree of soil expansion in Kuta Village, Central Lombok Regency.

The location of the study area is illustrated in Fig. 1, which shows the administrative map of Lombok Island with the position of Kuta Village highlighted. Based on field investigations and soil sampling, a series of expansion degree maps were generated using different empirical methods widely referenced in geotechnical engineering studies.

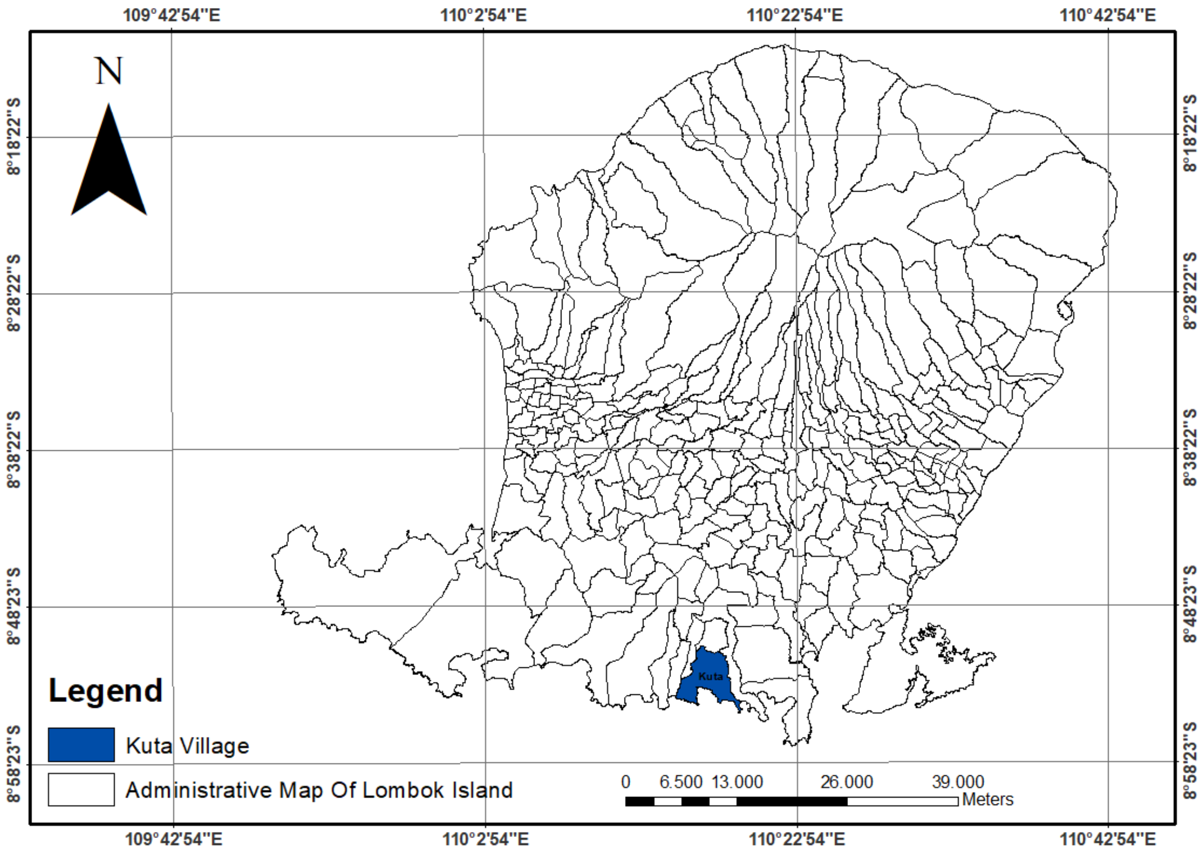

Fig. 1 Administrative map of Lombok Island indicating the study area in Kuta Village

This section presents the results of soil expansion mapping conducted using three established methods: those proposed by Seed et al., Chen, and Ladd and Lambe. Each method uses different soil parameters and classification criteria to determine the degree of expansiveness, which is visualized through thematic maps to support comparative analysis.

5.2.1 Mapping of Soil Expansion Degree Using The Seed et al. Method

The mapping of soil expansion degree was carried out based on the method developed by Seed et al., which utilizes the plasticity index as the primary parameter for estimating soil expansion potential. The data obtained from liquid limit and plastic limit tests, as presented in Table 4, were used to calculate the plasticity index. This index was then used to determine the expansion potential through Equation (1). The results of these calculations, along with the classification of soil expansion degrees, are summarized in Table 5. The mapping results using this method are shown in Fig. 2.

Table 5. Degree of expansion categories of soil samples using the Seed et. al. method

Location	Swelling potential (%)	Degree of expansion
Mong lauk	0.62	Low
Mong I	15.73	High
Merendeng	3.81	Moderate
Mengalung	0.55	Low
Ngolang	1.76	Moderate
Rangkap I	1.08	Low
Lenser	1.69	Moderate
Ujung daye	4.64	Moderate
Ketapang	1.18	Low
Rangkap II	1.05	Low
Ebunut	2.92	Moderate
Emate	2.65	Moderate
Kuta	0.62	Low

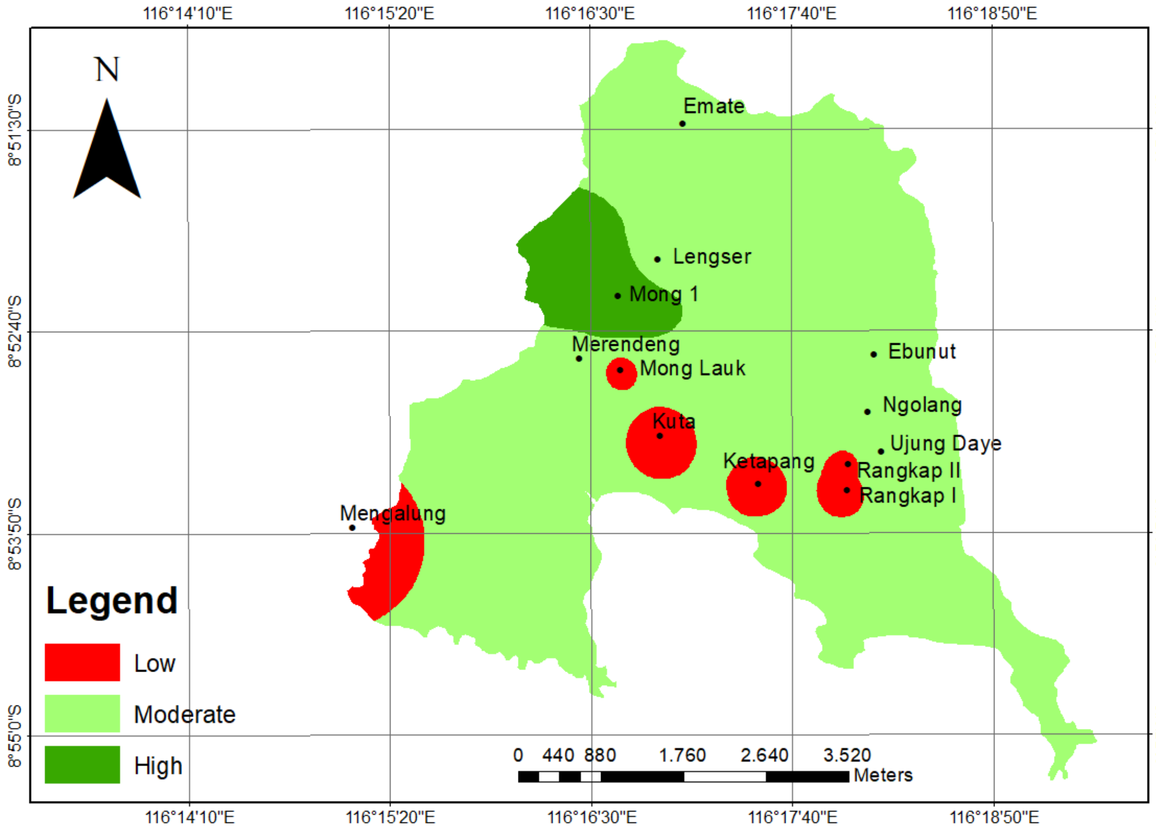

Fig. 2 Mapping of expansive soils using the Seed et al. method

5.2.2 Mapping of Soil Expansion Degree Using Chen Method

The mapping of soil expansion degree was conducted based on the method developed by Chen, which utilizes the plasticity index as the primary parameter for classifying the degree of soil expansion. The data obtained from liquid limit and plastic limit tests, as presented in Table 4, were used to calculate the plasticity index. This value was then used to determine the expansion classification. The calculated plasticity index values and the corresponding expansion classifications are presented in Table 6. The mapping results using this method are shown in Fig. 3. The "low" category does not appear on the Chen map because the plasticity values between sample points in this method are relatively uniform and close to the minimum value, resulting in a narrow and less varied Inverse Distance Weighted (IDW) interpolation. Distant points like Mengalung and Emate also do not show significant differences due to their relatively flat values. This contrasts with the Seed and Ladd & Lambe methods, which have greater value variation, allowing their maps to display categories with clearer contrast.

Table 6. Degree of expansion caatergories of soil samples using the Chen method

Location	Plasticity Index (%)	Degree of Expantion
Mong lauk	10.16	Moderate
Mong I	38.28	Very High
Merendeng	21.41	High
Mengalung	9.70	Low
Ngolang	35.88	Very high
Rangkap I	12.75	Moderate
Lenser	15.35	Moderate
Ujung daye	23.20	High
Ketapang	13.22	Moderate
Rangkap II	12.64	Moderate
Ebunut	19.20	Moderate
Emate	18.45	Moderate
Kuta	10.15	Moderate

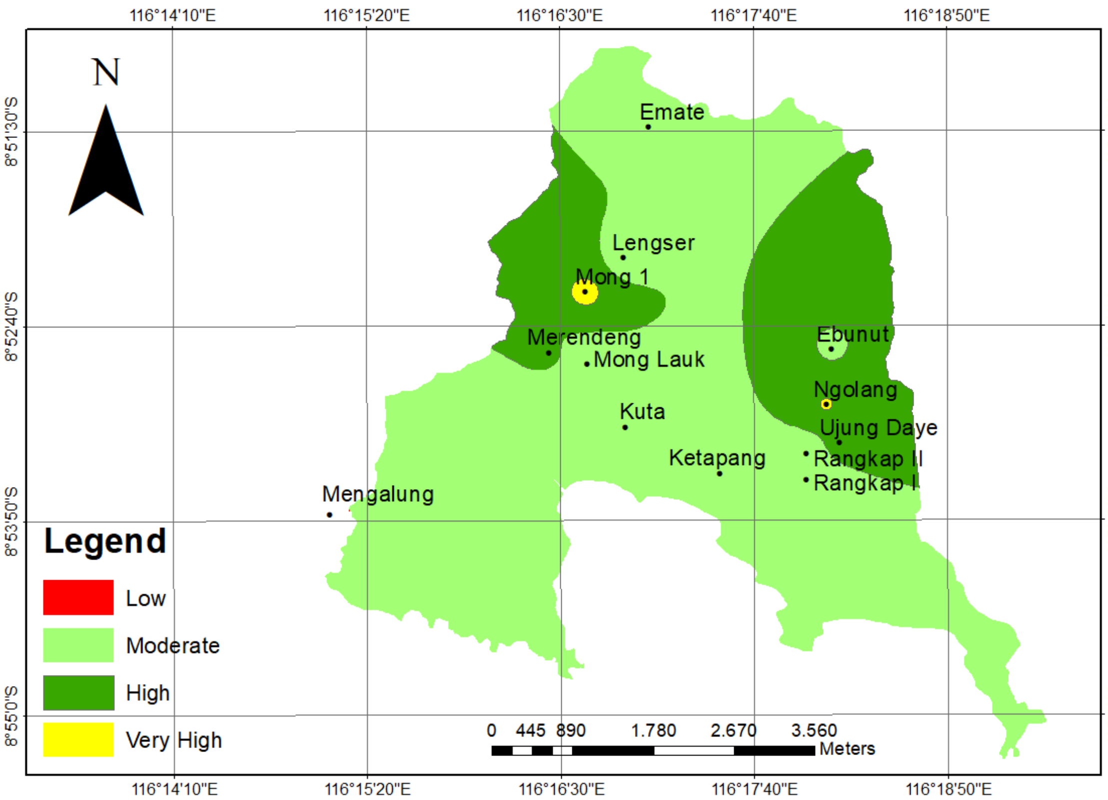

Fig. 3 Mapping of expansive soils using the Chen Method

Additionally, IDW is limited to the range of original sample values and heavily depends on the distance between points; therefore, if sample values are nearly uniform, the interpolated map will appear homogeneous, making the "low" category difficult to detect. For future research, it is recommended to increase the number of sample points, especially in distant areas, explore other interpolation methods such as Kriging, adjust category ranges based on data distribution, conduct multimethod analysis for validation, investigate the influence of IDW parameters, and integrate additional geotechnical data to achieve more accurate and applicable results.

5.2.3 Mapping of Soil Expansion Degree Using The Ladd and Lambe Method

The mapping of soil expansion degree was carried out based on the method developed by Ladd & Lamb, which utilizes the liquid limit as the primary parameter for determining the expansion classification. The liquid limit test data, as presented in Table 7, served as the basis for the classification process. The mapping results obtained using this method are shown in Fig. 4.

Table 7. Degree of expansion categories of soil samples using the Ladd and Lambe method

Location	Liquid limit (%)	Degree of Expantion
Mong lauk	44.01	Moderate
Mong I	68.02	High
Merendeng	50.60	High
Mengalung	30.10	Low
Ngolang	51.48	High
Rangkap I	38.53	Moderate
Lenser	42.06	Moderate
Ujung daye	51.10	High
Ketapang	38.26	Moderate
Rangkap II	40.53	Moderate
Ebunut	54.93	High
Emate	56.57	High
Kuta	31.77	Low

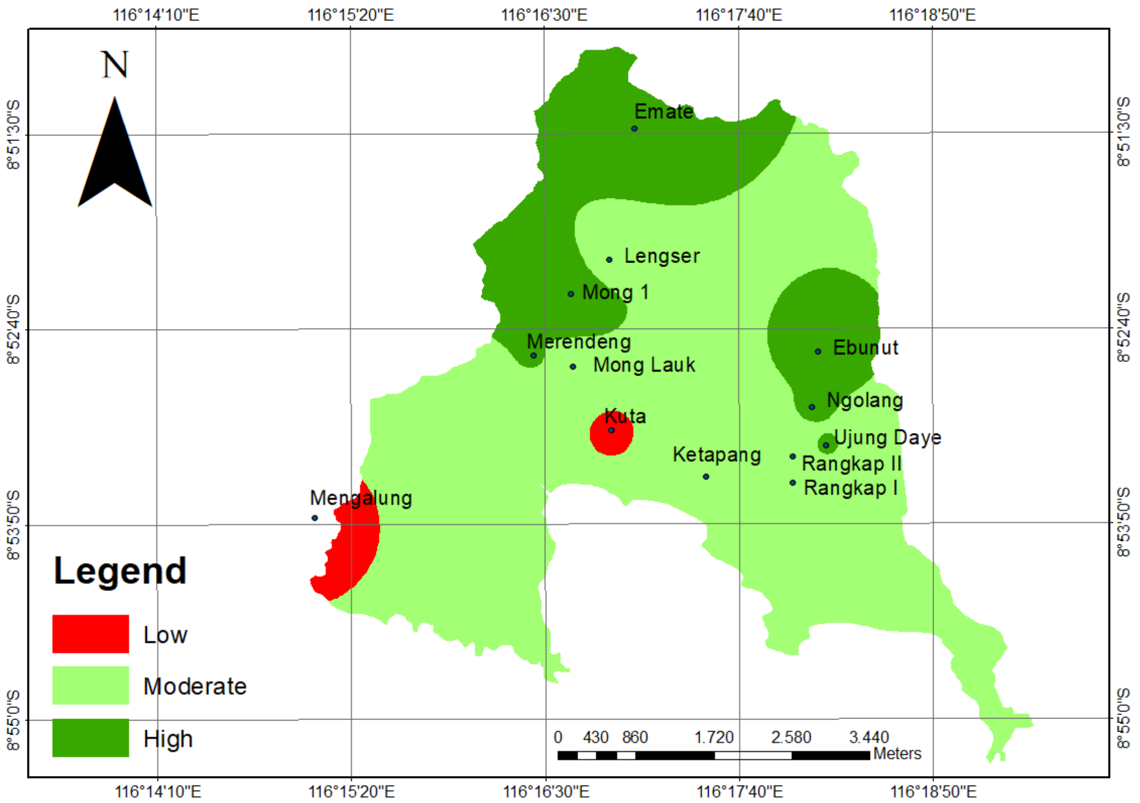

Fig. 4 Mapping of expansive soils using the Ladd and Lambe method

6. DISCUSSION

6.1 Comparative Analysis of Expansive Soil Classification Methods

To gain a more comprehensive understanding of expansive soil behavior, this study compares the results of three widely recognized classification methods: the Seed method, the Chen method, and the Ladd & Lambe method. Each method applies different criteria and thresholds in evaluating soil expansion potential, resulting in varying classifications across locations. By analyzing the results side by side, this section aims to identify patterns, highlight differences, and determine the most conservative classification for each location. This comparison serves as a basis for selecting appropriate design considerations in areas with expansive soil potential. As a result of the comparative analysis, Table 8 summarizes the soil classifications at 13 sampling locations based on the three methods used.

Table 8 shows significant differences in classification outcomes among the methods, particularly between the Seed method, which provides more conservative assessments, whereas the Chen and Ladd & Lambe methods tend to yield more predictive results. Despite these differences, the overall classification trends remain largely consistent, especially at locations with extreme soil characteristics such as Mong I and Mengalung.For preliminary assessments or regional-scale studies, the Chen method is considered more efficient because it relies solely on the plasticity index (PI). In contrast, the Seed method is more suitable for detailed engineering design and high-risk zone delineation, as it is based on laboratory data that reflect actual soil expansion. The Ladd & Lambe method serves as a complementary tool, particularly in areas with significant moisture fluctuations. As a practical approach, it is recommended to apply the three methods in sequence: the Chen method for initial screening, followed by the Ladd & Lambe method for field verification, and the Seed method for final validation and engineering planning.

6.2 Implications for Foundation Design

The analysis reveals significant variation in the soil expansion potential across the study area, which directly influences the selection of appropriate foundation types. In zones with highly expansive soils, such as Mong I, Merendeng, Ngolang, Ujung Daye, Ebunut, and Emate, the use of deep foundations like driven piles or bored piles is recommended due to the high risk of soil heave caused by moisture fluctuations. These foundations are designed to penetrate expansive soil layers and reach more stable, load-bearing strata, typically located at depths of 3 to

Table 8. Summary of Expansive Soil Classification Results Based on Three Methods

Location	Seed Classification	Chen Classification	Ladd & Lambe Classification	Final Classification Conclusion
Mong Lauk	Low	Low	Moderate	Moderate
Mong I	High	Very High	High	Very High
Merendeng	Moderate	High	High	High
Mengalung	Low	Low	Low	Low
Ngolang	Moderate	Moderate	High	High
Rangkap I	Moderate	Moderate	Moderate	Moderate
Lenser	Moderate	Moderate	Moderate	Moderate
Ujung Daye	Moderate	High	High	High
Ketapang	Low	Moderate	Moderate	Moderate
Rangkap II	Low	Moderate	Moderate	Moderate
Ebunut	Moderate	Moderate	High	High
Emate	Moderate	Moderate	High	High
Kuta	Low	Low	Low	Low

5 meters, based on local borehole data and geotechnical studies conducted in Central Lombok.

The recommended pile materials include reinforced concrete or galvanized steel, with the selection depending on material availability and environmental conditions, such as the potential for corrosion. As an illustration, the estimated cost for deep foundations (bored piles with a diameter of 40 cm and a depth of 5 meters at 16 points) is approximately IDR 41,250,000. In contrast, for a building of similar scale utilizing shallow foundations (footplate and tie beam), the estimated cost is around IDR 24,000,000. This difference indicates that deep foundations may incur approximately 72% higher initial costs. However, cost–benefit analysis suggests that deep foundations offer significantly greater structural resistance to damage caused by soil expansion and contraction, thereby reducing the frequency of repairs and long-term maintenance costs. Consequently, this approach is considered more economical and reliable over the building's life cycle.

In areas with moderate expansion potential, such as Mong Lauk, Rangkap I, Lenser, and Ketapang, more flexible solutions are required. Raft foundations combined with soil stabilization methods, and effective drainage systems are appropriate for controlling soil movement and ensuring structural stability. In areas with low expansion potential, such as Mengalung and Kuta, the use of shallow foundations remains feasible, provided they are supported by additional measures, such as the installation of granular layers to prevent lateral soil movement.

Continuous monitoring of groundwater levels and soil moisture content is essential to ensure long-term structural stability. These findings underscore the importance of implementing an integrated geotechnical design approach, which includes comprehensive soil classification, appropriately designed drainage systems, long-term monitoring, and landscape planning tailored to the specific conditions of each site. The success of foundation performance in expansive soil environments depends greatly on a thorough understanding of soil behavior and the application of engineering solutions aligned with the level of risk.

7. CONCLUSION

There are significant differences in the classification of expansive soil potential among the methods proposed by Chen, Seed, and Ladd & Lambe. The Chen method is considered efficient for preliminary, regional-scale assessments as it relies solely on the plasticity index, whereas the Seed method is more suitable for detailed engineering design and delineation of high-risk zones due to its use of laboratory data that reflect actual expansive behavior. The Ladd & Lambe method serves as a complementary approach, particularly in areas with significant moisture fluctuations. A sequential application of these three methods is recommended to achieve more accurate and practical classification results.

Spatial variations in soil expansion potential have a direct influence on the selection of appropriate foundation systems: deep foundations are recommended for high-expansion zones, raft foundations combined with soil stabilization and drainage systems are appropriate for moderate zones, and shallow foundations with added protection such as granular layers are still viable in low-expansion areas. Regular monitoring of groundwater levels and soil moisture is essential to maintain long-term structural performance. Therefore, an integrated geotechnical design approach that includes comprehensive soil classification, effective drainage systems, continuous monitoring, and site-specific landscape planning is essential to ensure structural reliability in expansive soil environments.

8. ACKNOWLEDGMENTS

The authors express their gratitude to the Higher Education, Research, and Development Council of the Muhammadiyah Central Board and Universitas Muhammadiyah Mataram through the Institute for Research and Community Service (LPPM) for their financial support under the Applied Research Program (Announcement No. 2120/I.3/D/2024 and Agreement No. 0258.064/I.3/D/2025) for the research titled "Risk Analysis of Foundation Failure on Expansive Soils in the Kuta Mandalika Tourism Area, Central Lombok Regency." The authors also thank the Civil Engineering Study Program, Faculty of Engineering, Universitas Muhammadiyah Mataram, for their support and access to laboratory facilities during the research.

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