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Research Article

A Study of Shallow Foundations on Expansive Soils (A Case Study of Bojonegoro Soil)

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Abstract
Soil plays a vital role as the primary support in structural foundations. However, expansive clay soils often present challenges in construction due to their water-dependent characteristics. When wet, these soils expand; when dry, they shrink, potentially causing cracks in foundations and other structural elements. This study aims to identify the type of soil in the Bojonegoro area and evaluate its impact on stress distribution beneath shallow foundations placed on expansive soils. Laboratory tests were conducted, including plasticity index analysis, Atterberg limits, compaction test, and shear strength test. The focus of the study includes identifying the level of expansion potential, soil activity classification, and analyzing the pattern of vertical and horizontal stress distribution beneath the foundation, particularly in relation to the theoretical 2V:1H approach. Based on the analysis results, the soil in Bojonegoro is classified as highly expansive, with a plasticity index (PI) of 53.92%, a liquid limit (LL) of 84.60%, and a plastic limit (PL) of 30.68%. According to the USCS classification, the soil falls into the CH category (Clay with High Plasticity). Observations on the foundation model showed a settlement of 103.36 mm and an uplift (unloading) of 6.05 mm. The observed stress distribution followed a 6V:3H pattern, which theoretically corresponds to the 2V:1H ratio. These findings are expected to serve as a reference for designing more adaptive and safe foundations in expansive soil conditions.

Keywords: Expansive clay soil, shallow foundation, stress distribution, 2V:1H.

INTRODUCTION

Soil is a fundamental material in the field of construction, as it serves as the supporting medium for any structure. According to Bowles (1981), soil is one of the most economical and readily available construction materials found in nature. It can be used for various purposes such as road embankments, railway beds, levees, and dams. Although soil is easily accessible and cost-effective, its engineering properties must be properly tested before being used as a foundation material to avoid potential structural failures.

Common problems encountered in construction are often related to poor soil characteristics, such as low shear strength, high plasticity, and other undesirable soil behaviors. One of the most problematic soil types is expansive clay soil, characterized by a significant volume change due to variations in moisture content. Expansive soils exhibit swelling when wet and shrinkage when dry. This behavior is heavily influenced by water content and environmental conditions. Expansive soils are well known for causing structural damage such as wall cracking, foundation uplift, and pavement heaving. All clay soils containing expansive minerals tend to undergo significant volume changes with fluctuations in water content. The swelling process in expansive clay soils is affected by environmental factors such as climatic variations, rainfall intensity, drainage systems, and groundwater table fluctuations (Agung and Istri, 2014).

Bojonegoro Regency is one of the regions in Indonesia with expansive soil conditions, meaning that the soil tends to shrink during the dry season and expand during the rainy season due to changes in water volume within the soil. This volume change can compromise the structural integrity of buildings constructed on such soils. Cracked buildings are typical indicators of damage caused by expansive soil movements. When expansive soils dry, they shrink, leading to a reduction in bearing capacity and potentially causing foundation failure or structural deformation.

Shallow foundations are a type of substructure element that transfers loads from the superstructure to the underlying soil strata located relatively close to the ground surface. This type of foundation is commonly used for low-rise buildings or structures with light to moderate loads, where the soil near the surface provides sufficient bearing capacity. Examples of shallow foundations include isolated footings, strip footings, and raft foundations. The selection of the appropriate foundation type depends on factors such as soil conditions, structural load magnitude, and construction efficiency.

In problematic soils like expansive clay, the performance of shallow foundations becomes critical. Expansive soils undergo significant volume changes due to moisture fluctuations—swelling when wet and shrinking when dry. These changes can cause vertical uplift forces acting on the foundation, which may lead to cracking of floors and deformation of upper structural elements. Therefore, designing foundations on expansive soils requires a specialized approach that considers stress distribution and settlement analysis to ensure structural stability.

Previous research by Widoanindyawati et al. (2021) found that uniform load distribution on saturated soft soils exhibits a stress dispersion ratio of 2.25 vertical : 1 horizontal, which is steeper than the commonly assumed 2V:1H ratio. This indicates that stress distribution in soil is not always symmetrical or ideal, particularly under soft or expansive soil conditions. In this study, isolated footing foundations were modeled and subjected to controlled loading to analyze soil response, especially in expansive soil environments. The study examined foundation settlement, stress distribution curve patterns, and validation of actual load dispersion angles observed in the field.

The findings of this research are expected to contribute to a better understanding of soil–structure interaction mechanisms in shallow foundations, particularly under expansive soil conditions commonly found in various regions of Indonesia.

METHOD

Data Collection Method

The data collection methods used in this study are divided into two categories:

1. Primary Data, obtained from laboratory testing conducted at the University of Bojonegoro.
2. Secondary Data, obtained from previous research or journal publications, Indonesian National Standards (SNI) test references, textbooks, and related institutions or agencies.

Data Analysis Method

The data analysis methods employed in this research are as follows:

1. Data Processing Method Using Excel

The data processing method using Microsoft Excel involves using its features and functions to organize, analyze, calculate, and present data effectively. Excel serves as a computational tool to process data, perform calculations, create graphs, and generate reports automatically and efficiently throughout this research process.

2. Analysis of Test Results Using Standard Laboratory Modeling

The analysis of test results through laboratory modeling is an approach used to interpret research findings based on controlled laboratory testing data. This method enables the modeling of physical or mechanical phenomena observed in the field under more measurable and regulated conditions. The modeling process aims to determine specific parameters relevant to the study and to provide a more accurate understanding of soil behavior under testing conditions.

RESULTS AND DISCUSSION

Physical Properties

Soil physical properties are the primary characteristics that influence soil response to loads and environmental changes. These properties include texture, density, water content, specific gravity, and Atterberg limits, reflecting soil behavior under various conditions. Expansive soil, the focus of this study, has the ability to expand and contract significantly due to changes in water content. This type of soil generally has a high clay mineral content, especially montmorillonite, which causes extreme volume changes. Therefore, understanding the physical properties of expansive soil is crucial in civil engineering planning to mitigate negative impacts such as cracks in buildings or highways.

In this laboratory study, several soil physical properties were tested to understand the characteristics of expansive soil before and after the application of vertical sand drains. The main parameters analyzed include natural water content, specific gravity, liquid limit and plastic limit to determine soil plasticity, and grain size distribution to identify the dominance of clay or silt fractions. The results of these physical properties tests will form the basis for analyzing the soil consolidation process using the vertical sand drain method, which aims to accelerate the soil compaction process and reduce the potential for excessive volume expansion.

Water content

The original soil water content test is conducted to determine the amount of water contained in the soil naturally without any disturbance or change. This method is important in geotechnical studies, because the soil water content affects the physical and mechanical properties of the soil. Soil samples were taken at a depth of 50 cm, in July 2025. The results of the water content test were 84.60%. This indicates that the soil is a clay or silt soil that is very saturated with water. Bowles (1997) in Foundation Analysis and Design states that water content > 60% is usually found in soft cohesive soils (soft clay).

Picture 1Water Content Testing

(Source: Research Results, 2025)

Table 1 Water Content Test Results

Uji Kadar Air SNI 1965 : 2008			
No. cawan	1	2	3
Berat cawan (gram)	14.34	14.34	14.56
Berat cawan + Tanah basah (gram)	60.44	48.55	50.3
Berat cawan + Tanah kering (gram)	39.3	32.9	33.9
Berat tanah kering (gram)	24.96	18.56	19.34
Berat air (gram)	21.14	15.65	16.4
Kadar air (%)	84.70	84.32	84.80
Rata-rata Kadar air (%)	84.60		

(Source: Research Results, 2025)

Specific gravity

Specific Gravity is the ratio of the weight of the soil to the weight of the water at a constant temperature. The existence of this test is important because its value is used in every calculation related to air and water/pores as well as solid soil particles. Based on the Specific Gravity test standardized by SNI 1964:2008, it was found that the expansive soil has a value of 2.61. This value of 2.61 is a normal value for mineral soil, especially clay or silt. According to Coduto (2011) Geotechnical Engineering: Principles and Practices, a specific gravity value of around 2.60 in clay soil indicates the mineral content of kaolinite or montmorillonite.

Table 2 Specific Gravity Test Results

Uji Berat Jenis Tanah (Gs) SNI 1964 : 2008			
Nomor Percobaan	Satuan	147	234
Berat piknometer, W1	gram	50.3	48.6
Berat piknometer + air, W2	gram	148.15	149.85
Berat piknometer + air + tanah, W3	gram	163.55	165.3
Berat tanah kering, Ws	gram	25	25
Temperatur, 27°C	°C	27	27
Faktor koreksi, a = gr/g20		0.998	
Berat Jenis Spesifik, Gs	gram/cm³	2.60	2.61
Berat jenis rata-rata, Gs	gram/cm³	2.61	

(Source: Research Results, 2025)

Picture 2 Soil Specific Gravity Testing

(Source: Research Results, 2025)

Grain Size Analysis

In this analysis system, soil is classified according to its particle size. For coarse-grained soil, the particle size division can be done using Sieve Analysis/sieving, while for fine-grained soil, the particle division can be done using the settling rate method or settling in water, also known as the mechanical method. The results of the sieve analysis test can be seen below:

Table 3 Sieve Analysis Test Results

Sieve Analisis					
Nomor Saringan	Diameter lubang saringan (mm)	Berat tanah yang tertahan saringan	% berat tanah tertahan saringan	% kumulatif dari tanah yang tertahan	% tanah yang lolos saringan
4	4.75	8	10.59	10.59	89.41
10	2	11.5	15.22	25.81	74.19
20	0.85	21.4	28.33	54.14	45.86
40	0.425	13.5	17.87	72.01	27.99
60	0.25	4.05	5.36	77.37	22.63
140	0.106	8	10.59	87.95	12.05
200	0.075	9	11.91	99.87	0.13
PAN	-	0	0.00	99.87	0.13
Berat Total W1		75.45			

(Source: Research Results, 2025)

Picture 3 Sieve Analysis Testing

(Source: Research Results, 2025)

In the analysis of soil grain classification, the Hydrometer method is used, because this soil is relatively small in size, namely passing through 200 mesh. The Hydrometer method itself is a sedimentation analysis method where the experimental reading is obtained from the relationship between the concentration of sample grains which can be read on the Hydrometer Tower.

Mechanical Properties

The mechanical properties of expansive soil encompass various parameters that determine its response to loads and environmental changes. One key mechanical property is the soil's bearing capacity, which indicates the soil's ability to withstand loads without excessive deformation. Expansive soils tend to have low bearing capacities due to significant volume changes during wet and dry cycles. Furthermore, these soils exhibit cohesion and internal friction angles that can vary depending on their water content. High cohesion values under dry conditions can decrease drastically as the soil absorbs water, leading to decreased shear strength and potentially leading to landslides. Therefore, studying the mechanical properties of expansive soils is crucial for understanding how these soils behave under real-world conditions.

In this study, the mechanical properties of expansive soil were tested to evaluate settlement and determine stress distribution. With a deeper understanding of soil mechanical properties, it is hoped that this research will provide better solutions for addressing expansive soil problems in field construction.

Standard Proctor

The Light Density Test, or Proctor Standard, is a process of mechanically compacting soil particles, resulting in a reduction in air and water volume. Soil compaction aims to determine the maximum density of the soil by impact, namely by understanding the relationship between water content and soil density. The water content that produces maximum dry weight is called the Optimum Moisture Content (OMC). The results of the light density test can be seen in the following table:

Table 4 Light Density Test Results

SNI 1742 : 2008																
Penentuan Kepadatan Basah (Wet Density Determination)																
No.Mould	-	1			2			3			4			5		
Massa Mould	gram	3535			3535			3535			3535			3535		
Massa Tanah Basah + Mould	gram	4755			4910			5030			5260			5110		
Massa Tanah Basah, Wwet	gram	1220			1375			1495			1725			1575		
Volume Mould	cm³	939.493			939.493			939.493			939.493			939.493		
Kepadatan Basah	gr/cm³	1.299			1.464			1.591			1.836			1.676		
Kadar Air (Water Content Determination)																
No. Container	-	44	54	57	63	40	11	27	41	1	2	4	55	74	34	14
Massa Tanah Basah + Container	gram	44.2	54.5	56.5	70.34	65.54	69.54	62.5	79.3	71.1	58.02	53	52.1	52.3	49	40
Massa Tanah Kering + Container	gram	43.2	53.25	55.15	64.9	60.5	64.12	55	69	62.5	49.2	44.9	44.6	43.2	40.4	33.9
Massa air	gram	1	1.25	1.35	5.44	5.04	5.42	7.5	10.3	8.6	8.82	8.1	7.5	9.1	8.6	6.1
Massa Container	gram	14.54	14.65	14.9	14.30	14.57	14.44	14.29	14.76	14.38	14.09	14.20	14.9	14.32	14.54	14.78
Massa Tanah Kering	gram	28.66	38.6	40.25	50.60	45.93	49.68	40.71	54.24	48.12	35.11	30.70	29.7	28.88	25.86	19.12
Kadar Air	%	3.49	3.24	3.35	10.75	10.97	10.91	18.42	18.99	17.87	25.12	26.38	25.25	31.51	33.26	31.90
Kadar Air Rata-rata	%	3.36			10.88			18.43			25.59			32.22		
Penentuan Kepadatan (Density Determination																
Massa tanah basah, W_{wet}	gram	1220			1375			1495			1725			1575		
Kadar air rata-rata	%	3.36			10.88			18.43			25.59			32.22		
Massa tanah kering $Wdry = \frac{Wwet}{1+\left(\frac{W}{100}\right)}$	gram	1180.335			1240.102			1262.368			1373.561			1191.168		
Volume mold	cm³	939.493			939.493			939.493			939.493			939.493		
Kepadatan kering $\gamma\ dry = \frac{W\ dry}{V\ mould}$	gram/cm³	1.256			1.320			1.344			1.462			1.268		
γw = Gs/((1+(w/100) . Gs)	gram/cm³	2.397			2.031			1.761			1.564			1.417		

(Source: Research Results, 2025)

Figure 4 Standard Proctor Test

(Source: Research Results, 2025)

The standard Proctor graph illustrates the relationship between water content and maximum soil density. The results of the test show an OMC value of 24.75%, which is very suitable for very fine and plastic clay soil. Then, the maximum density value of 1.468 gr/cm³ is low. Because the clay soil is very fine and plastic, this value is very suitable because the soil cannot be compacted too tightly due to its plastic clay properties. According to Das (2010), clay soil with high plasticity will show a high

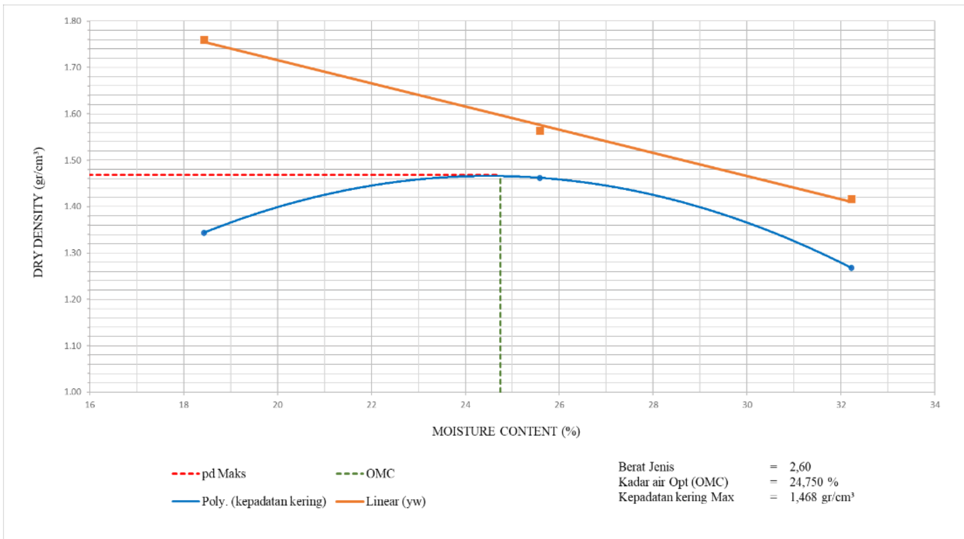


Figure 5.OMC Relationship Graph with Dry Density
(Source: Research Results, 2025)

OMC value and low γd max in the Proctor test, the general range of OMC is 18–28% for CH.

California Bearing Ratio(CBR)

CBR (California Bearing Ratio) is a test to determine the bearing capacity of the soil, a comparison between the test load and the standard load and expressed as a percentage. The CBR value is calculated from the comparison between the pressure required to penetrate the soil specimen at a certain depth (usually 2.54 mm and 5.08 mm), with the standard pressure required to penetrate the reference material (crushed stone) at the same depth. In laboratory CBR testing there are 2 methods, namely without immersion (Unsoaked) and immersion (Soaked). For immersion CBR, the soil sample is soaked for 4 days before penetration, to simulate field conditions when the soil is saturated with water.

The results of the California Bearing Ratio (CBR) Unsoaked test with 10 impacts per layer, at a penetration of 2.54 mm, obtained a value of 3.76% and at a penetration of 5.08, obtained a value of 3.51%.

Table 5*CBR Unsoaked*10 Collisions

CALIFORNIA BEARING RATIO (CBR)

SNI 1774 : 2012

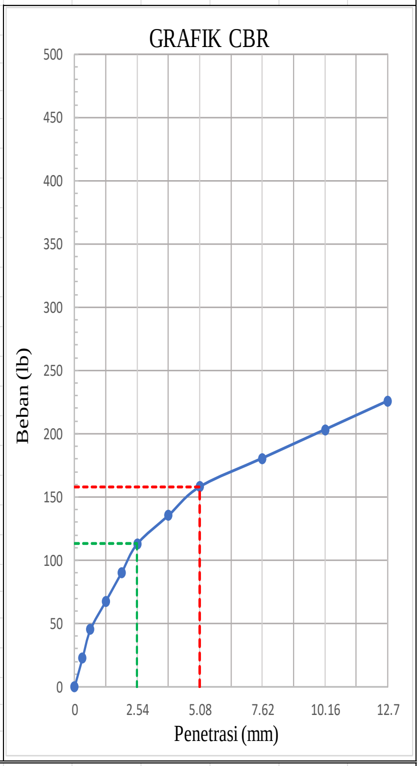
Kadar Air		**Densitas, No Cetakan**	
Massa Tanah Basah + Cawan, g	45.4	Massa Benda Uji + Cetakan, g	11214
Massa Tanah Kering + Cawan, g	39.93	Massa Cetakan, g	7459
Massa air, g	5.47	Massa Benda Uji basah, g	3755
Massa Cawan, g	18.14	Isi Cetakan, cm3	2122
Massa Tanah Kering, g	21.79	Densitas basah (ρ), g/cm3	1.77
Kadar air (w), %	25.10	Densitas Kering (ρd), g/cm3	1.41

Kalibrasi Poving Ring, K= 0.20082 kn = (45.147 lb)

Waktu (menit)	Penetrasi		Pembacaan Arloji Ukur Beban	Bahan Penetrasi = Pembacaan Arloji ukur beban x k	
	mm	in	Devisi	Kn	lb
0	0	0	0	0.000	0.0
`1/4	0.32	0.0125	0.5	0.100	22.6
`1/2	0.64	0.025	1	0.201	45.1
1	1.27	0.050	1.5	0.301	67.7
1 1/2	1.91	0.075	2	0.402	90.3
2	2.54	0.10	2.5	0.502	112.9
3	3.81	0.15	3	0.602	135.4
4	5.08	0.20	3.5	0.703	158.0
6	7.62	0.30	4	0.803	180.6
8	10.16	0.40	4.5	0.904	203.2
10	12.7	0.50	5	1.004	225.7

NILAI CBR, %

2,54 mm	**0,10 in**
$\frac{112.9}{13.5}$ x 100	$\frac{112.9}{3000}$ x 100
= 836.056	= 3.76
5,08 mm	**0,20 in**
$\frac{158.0}{20.02}$ x 100	$\frac{158.0}{4500}$ x 100
= 789.283	= 3.51



Catatan, Jumlah tumbukan per lapis = 10

(Source: Research Results, 2025)

The results of the California Bearing Ratio (CBR) Unsoaked test with 30 impacts per layer, at a penetration of 2.54 mm, obtained a value of 4.51% and at a penetration of 5.08, obtained a value of 4.01%.

CONCLUSION

The results of this study show that the expansive clay soil found in Bojonegoro has very high plasticity and swelling potential, as indicated by a liquid limit (LL) of 84.60%, a plastic limit (PL) of 30.68%, and a plasticity index (PI) of 53.92%. According to the Unified Soil Classification System (USCS), this soil belongs to the CH (Clay with High Plasticity) category. Laboratory testing revealed that the soil exhibits significant shrink–swell behavior and relatively low bearing capacity, characteristics that pose challenges for shallow foundation performance. The observed settlement of 103.36 mm and uplift of 6.05 mm in the foundation model demonstrates the high degree of soil movement caused by moisture variation, directly influencing the stress distribution beneath the foundation.

Furthermore, the analysis of stress distribution patterns revealed a 6V:3H dispersion ratio, which aligns closely with the theoretical 2V:1H assumption but indicates a more concentrated vertical stress propagation. This finding emphasizes the need for specific design considerations when constructing on expansive soils, including improvement techniques such as soil stabilization or the use of vertical sand drains to control swelling and settlement. Overall, this research provides valuable insight into the interaction between expansive soils and shallow foundations, offering a scientific reference for developing safer and more adaptive foundation designs in regions with similar geotechnical conditions.

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