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EXPERIMENTAL STUDY OF MATTRESS FOUNDATION ON VERY SOFT CLAY FOR UNPAVED ROAD

*Suyuti Suyuti[1], and Mukhlis Muslimin[2]

[1]Department of Civil Engineering, Universitas Khairun, Indonesia
[2]Department of Mechanical Engineering, Universitas Khairun, Indonesia

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ABSTRACT: Soft clay subgrade contains an undrained strength ranging from 5~25 kN/m^2, which is significantly low and provides inadequate support for road construction. Therefore, this study proposes a mechanical method to increase the bearing capacity within the concrete precast of local stone material used in Ternate Island, also known as a mattress. The experiment was conducted by modelling a mattress with hexapod concretes comprised of granular material, wet soil mixed with gravels, sands, and soils. The obtained component was manually compacted and used as a mattress foundation on the very soft clay for designing an unpaved road. Furthermore, empirical mathematical methods were used to determine the field CBR tests by observing the ultimate stress levels of the mattress foundation. The results showed that the hexapod mattress obtained an average CBR of 7.99% or a quom of 79.9 kN/m2, with more than 6% below the minimum standard. Based on the simulation results, CBR 6.14% and 7.99% can be used to apply static load on axle P at 40.17 kN, with a tire inflation pressure pc of 620 kN/m2, and load distribution angle α0 of 26.5 °. The predictive response of the internal friction of the mattress ϕ at 45 ° ~ 50 °, led to an ultimate minimum stress qum of 61.42 kN/m2, showing that the safety factors F0 of 1.5 to 2.1 provided unpaved h0 design thicknesses of 0.50 meters and 0.60 meters, respectively. In conclusion, very soft clay with CBR 6% and thickness h_0 of 0.30 ~ 1.20m needs to be applied as a mattress foundation on unpaved roads for rill construction.

Keywords: Experimental study, Soft clay, Mattress foundation, Hexapod concrete, Unpaved road

1. INTRODUCTION

Low soil consistency in a subgrade is generally classified under undrained strength c_u of 5~12.5 kN/m^2 and 25 kPa for very soft soil, and soft soil, respectively. It is caused by a lack of significant loading pressures due to the road load bearing capacity of soft soil consistency [1]. In line with the description above, the local government of North Maluku province is focused on erecting basic infrastructure at the capital city of Sofifi, located at coordinates of 0°44'16.08"N latitude, and 127°34'15.33"E longitude. This area is mainly characterized by lowland, including a composite of alluvial soil layers varying from 7.0 meters to 12.0 meters. The difference was shown by susceptibility to liquefaction zone, and categorized within moderate to high levels [2].

The access road erected from Sofifi to the Maba city was characterized by soft ground under saturated conditions. In this regard, subgrade is naturally characterized by low bearing capacity. As a result, the soft ground needed to be improved with innovative materials [3]. The Cone Penetration Test was conducted considering the erection of the runway strip 2,500 meters long, and 45 meters wide for the new airport located on 200 hectares of land, in Tidore archipelago city. Furthermore, the results of soil investigation consisted of conus resistance values q_c, friction ratio R_f, and down depth H_s of 0.25 ~ 0.6 MN/mm^2, 2 ~ 6, and 4.0 ~ 9.5 meters, respectively. These values were obtained in the very soft and soft soil layers of the designated area for the construction of Loleo New Airport [4,5].

The soil consistencies resulted in a bearing capacity problem for supporting loads. Static load distributive values of road infrastructure constructed on soft ground must be equivalent to the horizontal and vertical directions in accordance with the Indonesian national standard (SNI). The loading activities on the bearing capacity, also called the ultimate stress of the foundation, were improved using a mechanical reinforcement, namely a mattress [5]. The recent analysis of the road bank on very soft soils adopted the hardening method. In addition, the simulation process conducted using the finite element method produced a factor of safety Fs of 2.1, and vertical settlement during 90 days. The following values, 0.01 meters and 0.02 meters, were obtained based on the hardening soil method and field observations respectively [6,7]. In this context, field stability of coastal dike was detected by carrying out full scale tests on the soil bags underlying very soft clay c_u of 5 kN/m^2, saturated soil γ_{sat} of 14.3kN/m^3 and internal friction ϕ of 9.5^o. These were reinforced using natural materials, such as short bamboo piles. The reinforcement method was conducted on seven points in line with the California Bearing Ration (CBR), resulting in a value of 4.86% [3].

Several previous studies had been conducted on unpaved roads constructed on soft subgrade soil with geotextile reinforcement loaded by a truck. The contact pressure on the unpaved road was represented in mathematical equations [8,9]. Variation in load intensity was studied and a simulation of flexible pavement [10]. A modified hexapod concrete completely filled with granular materials such as gravel, sand, and clay was used to maintain a satisfactory structure of shallow foundation for unpaved roads.

The foundation's function depended on two reasons: firstly, to investigate the consolidation mechanism of very soft clay under saturated conditions. The water dissipation process was realized through a one-dimensional consolidation. Secondly, to facilitate a layer for distributing and resting unpaved roads [11]. The mechanical mattress reinforcement was used to increase the bearing capacity of the soft subgrades. This criterion of the construction method was adopted to improve the unpaved road [12]. This study focused on producing an innovative fabricated hexapod concrete without bars, rearranged with granular material to improve very soft clay. In addition, wet soil mixed with granular materials and sand was not subjected to chemical stabilization; rather the mixture was layered and compacted within the hexapod [13,14].

Ultimate stress of soft subgrade of unpaved road depends on "soil Young modulus", it can be increased by using mechanical soil improvement methods such as concrete blocks of hexapod filled with granular materials. This method uses the experimental study to observe the bearing capacity performance of field CBR, and it can be applied to soil parameters to compare the result with the empirical method.

2. RESEARCH SIGNIFICANCE

This experimental study should be essential to cover the soft ground of the embankment's road infrastructure in North Maluku. By using this innovation, natural local material of precast concrete of concrete block of hexapod as material for mattress foundation, the local government can easily design soil mechanics stabilization for unpaved roads, and construct based on geotechnical rules. It should follow Indonesia's national standards. Also, this precast concrete can be easily produced by local people and manually without machines, and it can be created in any area in North Maluku. The CBR field test is also a famous method applied by local engineers and the government.

3. FUNDAMENTAL THEORY

3.1 Young's Modulus of Subgrade

Theoretically, constructing a shallow foundation on soft ground leads to improved bearing capacity. This required considering soil subgrade mechanical properties such as undrained shear strength and the effect of overburden pressure. Empirically, the ultimate stress q_u was stated in the following equation [5]:

For strip footing

$$q_u = cN_c + qN_q + 0.5BN_\gamma \quad (1)$$

The application of ultimate stress due to the CBR piston, is stated in the following equation

$$q_u = 1.2cN_c + qN_q + 0.3BN_\gamma \quad (2)$$

where N_γ, N_q and N_c are the bearing capacity factors dependent on the soil friction, B is the width of footing, c is the soil cohesion, and q is the soil overburden pressure.

3.2 Granular on Soft Clay

A granular layer of selected materials on soft clay is also expressed as a mattress foundation. The load spreads through the granular layer at an angle corresponding to two vertical units. However, for every horizontal unit, it is referred to as an alpha α [15].

Building upon the description above, buried circular footing tests were conducted on the sand layer overlying clay. Therefore, assuming the load spreads through an inclination of 2β, which was tested and simulated, then the β parameter depends on the bearing capacity ratio, the granular and clay layers alone. The ultimate stress of mattress foundation, as reported by Jacobsen and Kenny (1997), is stated in the following equation

$$q_u = q_c\left(1+\frac{\beta H}{B}\right)\left(1+\frac{\beta H}{L}\right) + \gamma D \leq q_s \quad (3)$$

where the granular sand layer capacity alone, q_s is

$$q_s = 0.5\gamma BN_\gamma S_\gamma + \gamma DN_q S_q \quad (4)$$

and inclination parameter due to force β is

$$\beta = 0.1125 \pm .0344\left(\frac{q_s}{q_c}\right) \quad (5)$$

Then, qc is the ultimate stress of clay alone, H is the thickness of the mattress, B is the width of the footing, α is the angle of load spreading, D is the depth of the footing within the granular, S_γ and S_q are the capacity factors of foundation types.

The developed method supported the model footing test. Several forces acted on the vertical shear planes, such as the Earth's passive and inclined upward pressure at an angle δ to the horizontal. [15]. The development of a laboratory test of shallow footing [16]. The mechanism of foundation is shown in Fig.1.

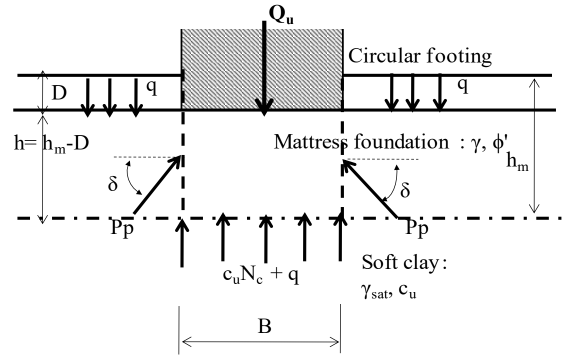


Fig.1 Illustration of ultimate stress for mattress foundation on the soft clay

The capacity of mattress foundation on the soft clay for circular footing area A was defined using the following empirical formular

$$Q_{um}=A\times q_{um} \tag{6}$$

where ultimate stress q_{um} for strip footing

$$q_{um}=c_uN_c+\gamma D+0.5P_p\frac{\tan\partial}{B} \tag{7}$$

and for circular footing of CBR piston

$$q_{um}=1.2c_uN_c+0.3P_p\frac{\tan\partial}{B}+q \tag{8}$$

where the total passive pressure due to mattress confining is stated as follows

$$P_p=0.5\gamma h_m^2\left(1+\frac{2D}{h_m}\right)\left(\frac{K_p}{\cos\phi}\right) \tag{9}$$

angle friction of mattress layer δ = 2/3.

Coefficient of shear punching K_s is,

$$K_s=K_p\left(\frac{\tan\partial}{\tan\phi}\right) \tag{10}$$

and the coefficient of passive pressure K_p = $\tan^2(45^o + \phi/2)$.

The load capacity of mattress foundation on the soft

3.3 Hexapod Concretes as Mattress Foundation

The main concrete material was produced using a crushing machine, with the original stone obtained from Ternate quarry, referred to as "*batu angus*" in local language. The abrasion test was used to detect approximately thirty-eight percent of concrete. As a result, quality hexapod concrete without bar were produced with a maximum compressive strength f'_c of 14.5 MN/m^2. This hexapod was used to produce a volumetric dimension of 150mm for each inner body and six pods.

The wet mixing materials, was spread and compacted to approximately 0.50m from the button level of soft clay to the top or mattress layer. This granular material had a bulk density, and internal friction for supporting and spreading loads from embankment.

3.4 Field CBR Test

An ultimate bearing capacity of mattress foundation on soft clay, was determined using a field CBR test recommended by the National Standard of Indonesia based on the following series of number 1738:2011 [18].

The bearing capacity was reported in mattress application of soil bags underlying very soft clay reinforced bamboo piles [8]. In addition, the bearing capacity in respect to a penetration standard of 2.54mm (0.1 inches), is stated as follows

$$CBR=\frac{p_{measured}}{\frac{0.71kg}{mm2}}\times 100\% \tag{11}$$

For penetration standard of 5.08mm (0.2 inches),

$$CBR=\frac{p_{measured}}{\frac{1.06kg}{mm2}}\times 100\% \tag{12}$$

where $p_{measured}$ is the recorded data from each model test.

Ultimate stress of mattress foundation on very soft clay q_{um} is stated as follows [19]

$$q_{um}=10CBR \tag{13}$$

where CBR is measured in unit percent, and q_{um} in unit kN/m^2.

3.5 Loading Pressure of Loads

The unpaved materials were composited by the selected gravel, with the contact pressure area due to load of truck and mattress thickness were considered.

However, the acting load pressure of a single tire p' at the hexapod mattress surface, was determined using the following equation.

$$p'=\frac{P}{A_c}+\gamma_0 h_0 \tag{14}$$

Contact area A_c,

$$A_c=(B_0+2h_0\tan\alpha_0)\times(L_0+2h_0\tan\alpha_0) \tag{15}$$

where P is the axle load, B_0 and L_0 are the width and length of contact pressure $B_0 = \sqrt{(P/p_c)}$ and $L_0 = B_0/2$, h_0 is the unpaved thickness, and α_0 the angle of spread load distribution.

The effect of reinforced method using mechanical procedures was observed by load-settlement. In this regard, the ultimate bearing capacity of soft soil subgrades was expressed in dimensionless quantity, namely Bearing Capacity Ratio (BCR).

The mechanism of allowable pressure and deformation under foundation should be presented by considering elasticity and plasticity under load intensities on the soft subgrades [20] . The ultimate stress condition in respect to the loading pressure intensity, was due to load pressure distribution through mattress layer. Therefore, the ultimate safety F_0 is defined as

$$F_0=\frac{q_{um}}{p'} \tag{16}$$

4. METHODOLOGY

4.1 Scheme of Study

The impact of the bearing capacity of the mattress foundation on the very soft clay is shown in the following flow chart. The fill down soft soil is an assembly of a soft ground model. Furthermore, the soft soil materials were obtained from the alluvial lowland at Gambesi in Ternate Island.

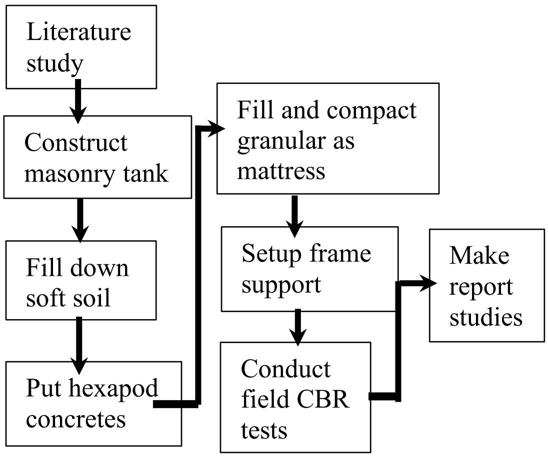


Fig.2 Flow chart of the methodology

4.2 Tank of Soft Ground

The tank, placed underneath the soil surface, was made from masonry, and the sides of the walls were lined with porcelain ceramics from top to bottom as shown in Fig.3.

4.2.1 Construct a soft soil tank

It was treated daily to ensure that very soft soil was saturated within the tank. The preparation process consisted of collecting samples for laboratory testing. This aimed to determine the following soil parameters: cohesion, internal friction, and bulk density.

4.2.2 Material: very soft soil

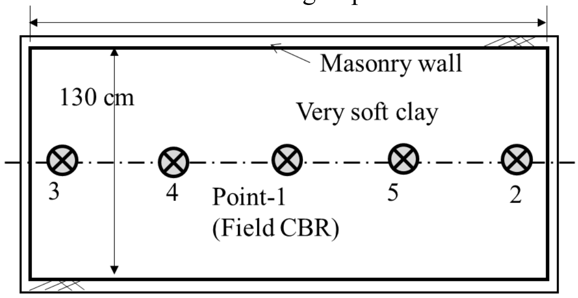
The regular maintenance of very soft ground models was conducted to retain water. In line with this result, the following soil properties and mechanical parameters, plasticity index PI, unit weight γ_s, cohesion c_u, and internal friction ϕ_s were determined to have values of 7%, 14.3 kN/m^3, 5 kN/m^2 and 9.5°, respectively [3].

4.3 Construction Step

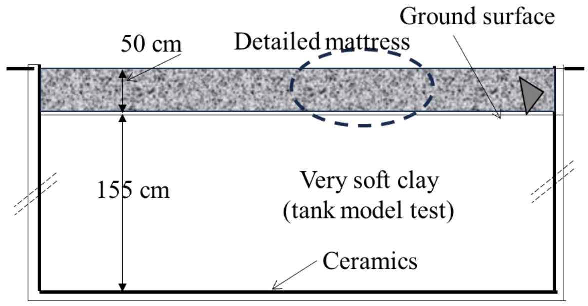
Gravel and sand materials used for hexapod concrete are produced in the quarry at Ternate Island, known for its deposition of *igneous* stones. These were processed by adhering to the following steps 1) Preparing construction tank, 2) Making construction wall and plate bad, 3) Filling down soft soil, 4) Producing, and 5) Putting hexapod concretes, 6) Spreading compact granular materials within the hexapod voids, and 7) Conducting field CBR.

4.4 Observe Bearing Capacity

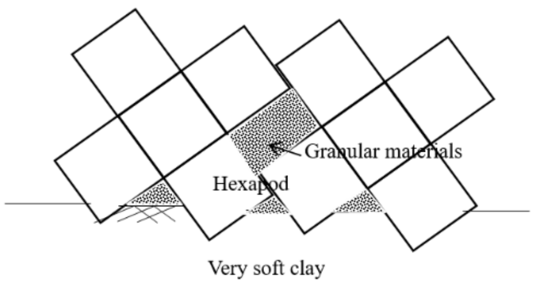
The bearing capacity of the hexapod mattress on very soft ground was observed using a full-scale test. method such as the field CBR. This method focused on the relationship between the penetration intensity and deformation of each loading steps.



a) Layout experimental setup



b) Long section of soft soil tank



c) Detailed mattress foundation

d) Hexapod dimension: 15cm×15cm×15cm

Fig.3 Schematics of the experimental setup of the mattress foundation

5. RESULTS AND DISCUSSIONS

An ultimate bearing capacity was investigated based on two perspectives. This includes preparing and observing load penetration and deformation conducted using the field CBR method.

5.1 Experimental Setup

The experimental setup related to constructing a mattress with wet granular material mixing on the very soft clay is shown in Fig.4. The following steps i.e: a) The very soft clay is prepared under saturated conditions by ensuring the water level is equivalent to the dimension of the soil tank.

a) Preparation of very soft clay with tank model

b) Placement view of hexapod concretes

c) Construction model of mattress foundation

Fig.4 Construction process of experimental study

b) The hexapod concretes were placed with approximately 12 pieces unreinforced with concrete quality f'c of 14.5kN/m^2, embedded into a soft clay layer. This procedure ensured the rearrangement was not altered under loads. After the installation, the tank's surface water was used to fill the granular materials.

c) Spreading compact granular materials, gravel, coarse sand, and clay as mattresses. These were mixed in the following composition: 2 parts of gravel, two parts of sand, 1,5 and 0.5 parts of soil. Furthermore, the granular material was spread and compacted manually using a wooden beam. This method was performed 3~4 times every three days to increase the flexural soil strength [20].

5.2 Experimental field CBR

Data was obtained using the field CBR method. Additionally, five points were placed at the line of symmetry on the mattress foundation surface as shown in Fig.5

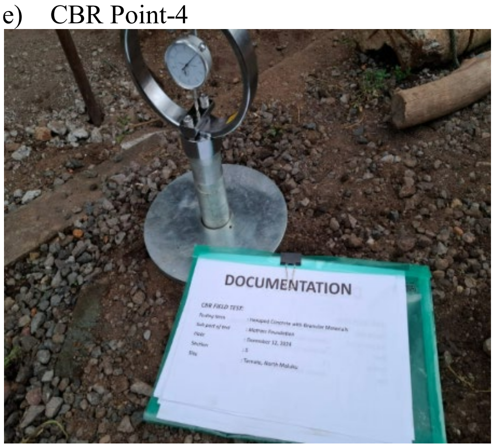
a) Placed still frame

b) CBR Point-1

c) CBR Point-2

d) CBR point-3

e) CBR Point-4



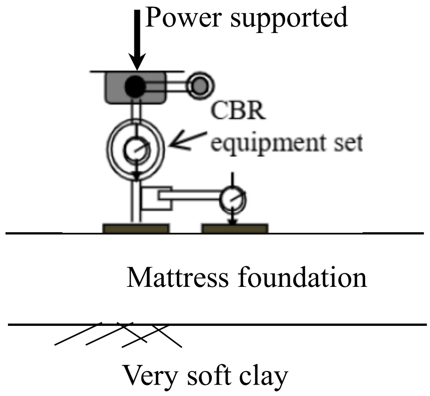
f) CBR Point-5

Fig.5 Placing points of field CBR on the mattress foundation

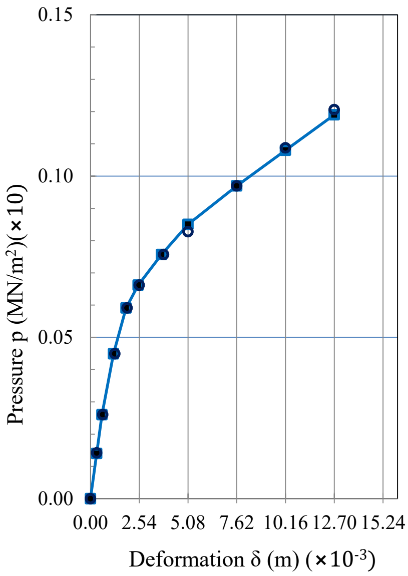
In Fig.5, the compacting process was manually aided in determining the maximum dry density of the mattress foundation. Following the discussion, no bleeding problem. Data was obtained using the field CBR method. Additionally, five points were placed at the line of symmetry on the mattress foundation surface.

5.3 Field CBR and Empirical Results

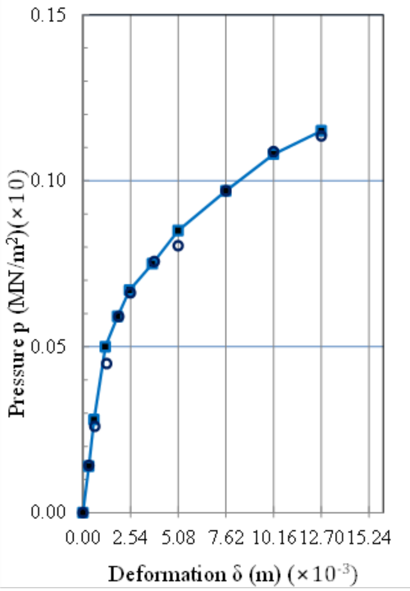
Field CBR was used to obtain the ultimate bearing capacity of mattress foundation for five points as shown in Fig.6. The experiment was conducted from December 10 to 12, 2024, as shown in Table 1.



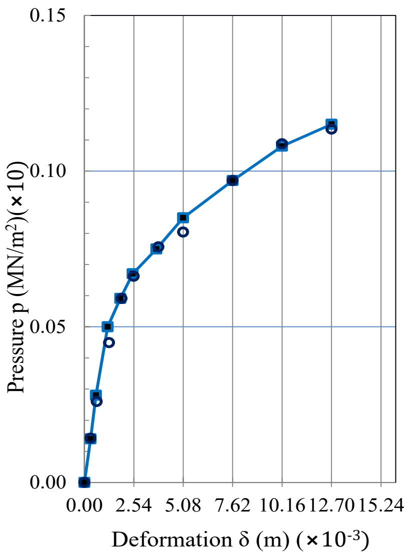
a) Placed field CBR



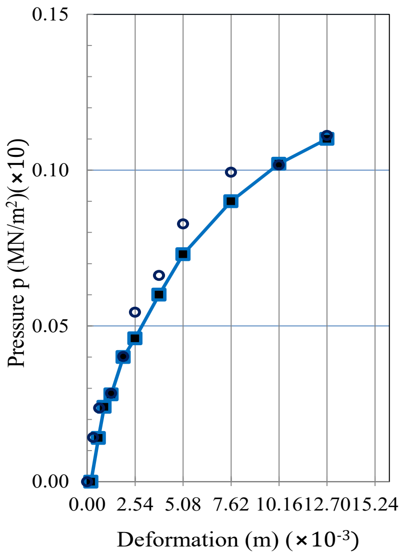
b) Field CBR test at point-1



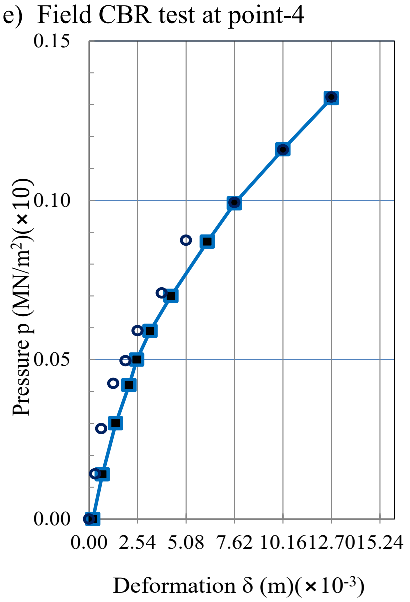
c) Field CBR test at point 2



d) Field CBR test at point-3



e) Field CBR test at point-4



f) Field CBR test at point-5

Fig.6 Field CBR test results of five points

Table 1. Field CBR test results

CBR Point	Pressure p (kg/mm^2)		Field CBR (%) Used Penetration Pistone D = 50.8mm, rut = 60mm		
	0.1″	0.2″	0.1″	0.2″	Average
1	0.060	0.082	7.04	7.92	7.48
2	0.063	0.084	8.87	7.92	8.40
3	0.056	0.076	7.89	7.17	7.53
4	0.060	0.085	8.45	8.02	8.23
5	0.062	0.084	8.73	7.92	8.33

Table 1 shows that the load pressure intensities and deformation on both CBR points on the uniformity mattress layer, had values based on Indonesian Manual standard [17]. These were calculated in respect to the ring capacity of 2.000 lbf based on the calibration certificate series no. 1055/820-1/VII/24, July 18, 2024.

These methods presented a bearing capacity overlying very soft clay, by comparing the results from empirical calculations and field CBR test.

The ultimate stress of very soft clay alone q_c was in line with the soil consistency and empirical methods. In soft clay alone, several mathematical equations were used to obtain factors of 0.67 to 1.0 for $q_c = c_u N_c$ [16]. This included the use of cohesion c_u =5 kN/m^2 and bearing factor N_c = 5.14. Therefore, the ultimate stress of soft clay had minimum q_c = 17.2 kN/m^2 and maximum q_c = 25.7 kN/m^2.

By using the following parameters, soil cohesion c_u of 5 kN/m^2 bulk density γ of 20.5 kN/m^3, diameter piston B of 50.8mm, rut depth D about of 60mm, the ultimate stresses of mattress q_{hm} obtained q_{hm} of 61.42 kN/m^2, and 79.68 kN/m^2 for internal friction ϕ of 45^o ~ 50^o respectively. The subsoil- structural interaction with mattress due to cyclic load was not considered in this study.

Based on field CBR average of 7.99% equivalent to 79.9 kN/m^2, the estimated results of mathematical method applied an internal friction ϕ of 45^o ~ 50^o for mattress foundation.

5.4 Applied Loading Pressures

The comparison of loading pressure at the rear of wheel load with finite element, showed several areas of contact pressures A_c for two tyre inflation pressures p_c of 770 kN/m^2, and 350 kN/m^2 respectively [9,21,22].

In this context, the angle load spread and distribution α_0 was defined as tan^{-1} (0.5) (2 vertical:1 horizontal) or α_0 of 26.5^o, applied when calculating the thickness of unpaved h_0 of 0.40m. However, the truck on the unpaved construction, had rear axle applied load P of 40.17 kN for two of the tires as shown in Fig.7 [23].

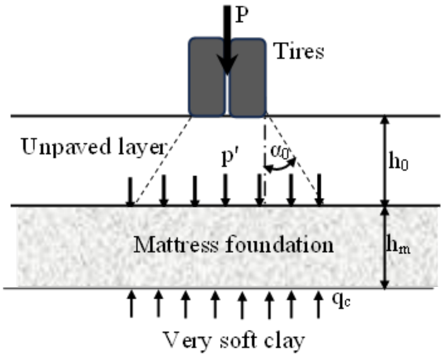


Fig.7 Schematic load pressure on foundation

Based on the axle load P, the simulations of loading pressure p' on the unpaved road were calculated as shown in Table 2.

Table 2. Load simulation for safety factor

Thickness Unpaved (m)	Calculation safety factor with ultimate stress of q_{um}= 61.42 kN/m^2		
	Contact area, B0' × L0' (m^2)	Pressure p' (kN/m^2)	Factor F_0
0.40	1.05 × 0.93	49.87	1.2
0.50	1.26 × 1.13	37.26	1.6
0.60	1.46 × 1.33	29.70	2.1

According to the table, the mattress foundation thickness is fixed at h0 = 0.50m, pc = 620 kN/m2, contact area at the unpaved surface with valuable dimensions of width B0 = 25.5cm, length L0 = 12.7cm, and α0 = 26.5 °.

The varying vehicle load P of 80 kN and 150 kN caused the factors of safety F_0 to decrease from 1.70 to 1.40 for applying unpaved h_0 of 0.40 ~ 0.60m and 0.45 ~ 0.70m, respectively [24]

The bearing capacity of unpaved roads reported a factor of safety of 1.0 and 2.5 for thicknesses 0.30 ~ 0.60m and 0.80 ~ 1.20m, respectively. In addition, the used tire pressure p_c was 150 ~ 350 kN/m^2.

6. CONCLUSIONS

In conclusion, the results of the field CBR test carried out at five points, as shown in Figure 8 and Table 1, significantly increased the ultimate bearing capacity of the mattress foundation overlying very soft clay.

The average value of the field CBR test for a mattress foundation with a thickness of 50 centimeters on the very soft clay was an ultimate stress of 79.9 kN/m^2. However, this value was only considered in a static load of axle P.

By estimating maximum load pressure intensity and variation of unpaved road, the safety factor F0 obtained was greater than 1.5 for a thickness h_0 of 0.50 meters. The experimental data results showed that the mattress's internal friction was significantly affected. This increased the bearing capacity of the soil elastic modulus of the mattress foundation for unpaved, very soft clay [25]. Based on the Indonesian guidelines' minimum standard of soil subgrades, the field CBR test results on bearing capacities exhibited overpowering behavior beneath road load pressure. The bearing capacity of the mattress increased more than three times compared to soft clay alone. Additionally, these were applied before the construction of unpaved roads.

This mechanical soft ground reinforcement model was suitable for the innovative structure of local material. Moreover, the life cycle of hexapod concrete was more durable than geo-synthetics under soft ground.[26]. It may also conduct an experimental study on the monotonic loading of a vehicle truck model [27].

The experimental study focused on the stability of the ultimate stress of mattress foundation performance. However, the study did not discuss its settlement, and it may be considered a two-layer subgrade. Finally, this experimental model was only applied using the CBR field method. Future studies on dynamic load and developed response of hexapod concrete block should focus on the long-term durability performance of the mattress foundation on rill road construction [28].

7. ACKNOWLEDGMENTS

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