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Article

Finite Element Analysis to Estimate Bearing Capacity of Strip Footing in Coastal Sandy Soils in Bengkulu City, Indonesia

Lindung Zalbuin Mase[1,a,*]**, Jihan Saputra**[1,b]**, Annisa Fitria Edriani**[1,c]**,**
Suraparb Keawsawasvong[2,d]**, and Van Qui Lai**[3,4,e]

1 Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Bengkulu, 38371, Indonesia
2 Department of Civil Engineering, Thammasat School of Engineering, Thammasat University, Khlong Nueng, Pathumthani 12120, Khlong Nueng, Thailand
3 Faculty of Civil Engineering, Ho Chi Minh City University of Technology, (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam
4 Vietnam National University Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
E-mail: [a,*]lmase@unib.ac.id (Corresponding author), [b]saputrajihan27@gmail.com, [c]annisa.fe@unib.ac.id, [d]ksurapar@engr.tu.ac.th, [e]lvqui@hcmut.edu.vn

Abstract. This study presents results of bearing capacity analysis for strip footing in coastal sandy soils. Three sites located at coastal area are investigated. The site investigation and laboratory tests are conducted to obtain soil properties. Variations on depth and width of strip footing are considered. Finite element analysis is conducted to observe failure mechanism and bearing capacity of strip footing. Several results such as relationship between ultimate bearing capacity and foundation dimensions, factor of safety, displacement, and failure mechanism are discussed. The comparison between finite element results and exact solutions is also presented. The results show that variations of dimension tend to influence the bearing capacity and failure mechanism. The results also shows that finite element result is generally consistent with the exact solution. The results states that the footing dimension of 1.1. m embedded at 1.0 m below ground surface as the suitable strip footing in the study area. This study can also benefit local engineers designing strip footing for the coastal sandy soils.

Keywords: Bearing capacity, strip footing, finite element analysis, sandy soils.

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1. Introduction

Bengkulu is the capital city of Bengkulu Province which is located on the west coast of the island of Sumatra, Indonesia. Bengkulu is located in a coastal area directly opposite to the Indian Ocean. Bengkulu has a very long coastline and does not have any area of more than 30 km distance from the coastline [1]. Bengkulu is also known as a developing city that is growing rapidly. Supporting facilities for development in the coastal area of Bengkulu, such as lodging, shopping centers and recreational facilities are also growing rapidly. Based on the research that has been done, buildings in coastal areas are generally designed using only shallow foundations (strip footing, continuous footing) as consideration. Soil investigation activities for foundation construction purposes are also carried out with inadequate limitations [2].

Several studies on soil characteristics in coastal area of Bengkulu City had been conducted by local researchers. Mase *et al.* [3] and Mase [4] stated that the soil in coastal areas is usually dominated by silty sand (SM), poorly graded sand (SP), clayey sand SC), gravelly sand (SG) and well graded sandy (SW). Sandy soil has a low bearing capacity and tends to experience a significant displacement in building foundations [5, 6]. Therefore, it is necessary to carry out an in-depth analysis of the bearing capacity of the soil and the displacement of foundations to avoid the collapse of buildings built in the area around the coast.

One of the methods to analyze bearing capacity of soil is finite element method. Several researchers have presented the use of finite element simulation for analyzing stability problems in geotechnical engineering, such as underground excavation [7], railway embankment [8], spatial variability [9], active trapdoors [10], slope stability at riverbank [11] and three-dimensional stability analysis [12]. These researchers mentioned that the implementation of this method is reliable and appropriate since the results obtained from the analysis is consistent with real cases in geotechnical engineering. It can be concluded that finite element analysis can be the choice to solve the geotechnical engineering problems, especially related to the stability analysis.

In line with the problem of bearing capacity along coastline area of Bengkulu City and the use of numerical analysis to solve the problem in geotechnical engineering, a study on the numerical analysis is conducted. This study presents the results of the analysis of the soil bearing capacity and the failure mechanism based on finite element simulation that is experienced by shallow square footing in the coastal area of Bengkulu. In addition, the use finite element method would also produce the value of the safety factor (SF), the carrying capacity of the maximum settlement that would be experienced by the shallow foundation. The width and depth of the foundations in several locations in the coastal area of Bengkulu were considered. The analysis process is focused on using the finite element method. Several empirical equations to analyze bearing capacity and the selection of suitable shallow foundation dimension are also discussed in this study. In general, this study can provide benefits for civil engineers in designing footing foundations for low-rise buildings in coastal areas.

2. Method

2.1. Study Area

The area that is the center of the research is shown in Fig. 1. This research was conducted in 3 locations in the coastal area of Bengkulu City. The research location is Pasir Putih beach, Taman Berkas beach and Kualo beach. Based on the observations that have been performed, the existence of this location is a very strategic place to support tourism activities and community economic activities. Development activities, such as lodgings and fish auctions, are centralized in this location. In these locations, undisturbed soil samples were collected to obtain soil parameter values and soil types. Soil samples were then subjected to laboratory tests. The results of laboratory tests that have been carried out in 3 locations can be seen in Table 1. Laboratory test conducted in this study includes physical properties test and engineering properties test. Several parameters such as unit weight, water content, specific gravity, grain size, porosity and void ratio are obtained from physical properties test. The main objective of physical properties test is to know the soil classification, whereas engineering properties test is addressed to obtain soil shear strength. In this study, the shear strength parameters are obtained from direct shear test. For engineering properties, several parameters related to shear strength such as soil cohesion and internal friction angle are obtained.

Overall, based on the Unified Soil Classification System (USCS), it was found that the type of soil in the coastal area of Bengkulu City is dominated by poor-graded sand (SP). The values of cohesion (c) and internal friction angle (ϕ) varied from 1.08 kN/m^2 to 1.34 kN/m^2 and 36.10 to 33.86°, respectively.

2.2. Theoretical Background

Foundation is an important element for all civil engineering structures. Every building structure, such as bridge, highway, tunnel, and canal are constructed above the ground and all applied loads are transferred to the ground. The foundation in its application is divided into 2 types, namely shallow foundations and deep foundations [13]. Strip footing is an example of foundation that falls into the shallow foundation category. Strip footing is a type of stand-alone foundation that functions to transmit column loads to the ground [14]. Strip footing is usually used for low to medium-rise buildings [15].

When designing foundations, the bearing capacity of the soil is a major concern in the field of geotechnical engineering. The problem of soil bearing capacity has been one of the earliest discussed issues in the geotechnical field. Various methods have been widely applied [16, 17]. These methods may be carried out analytically or experimentally. The analytical method involves slip line approximation, limit equilibrium analysis, boundary analysis, numerical analysis, and limit analysis in combination with numerical analysis [18, 19]. The use of analytical methods itself has been widely used until now. The most used methods are Terzaghi's method and Meyerhof's method [20, 21, 22]. Ultimate bearing capacity is the maximum load per unit area where the soil can still support the load without collapsing [23, 24]. In this modern era, many geotechnical experts have abandoned the use of classical theory in carrying out soil bearing capacity analysis. Many researchers have switched to using the finite element method. The use of the finite element method in geotechnical engineering is considered more effective in terms of the process [25, 26]. Therefore, the method is preferred for geotechnical problem solving.

The finite element method (FEM) is a numerical method that uses the discretization concept. Solid materials are divided into systems of structure, mass, or solid into smaller elements. This method supports the system to have unlimited degrees of freedom, so it can help the calculation process because each element contributes to the overall result [27, 28]. There are several kinds of soil mechanical properties modeling using the finite solution method. These models include the Mohr-Coulomb Model, Jointed Rock Model, Hardening Soil Model, Soft Soil Creep Model, and Soft Soil Model. Brinkgreve *et al.* [29] also stated that of several existing models, the Mohr-Coulomb failure model is one of the commonly used methods to determine the value of shear failure. In fine-grained soils (cohesive soil) such as clay, the shear strength of the soil (τ) is dependent on soil cohesion (c). In coarse-grained soils (non-cohesive) such as sand, the shear strength due to the presence between soil grains is often called the friction angle in the soil (ϕ). In soils which are a mixture of fine-grained and coarse-grained soils or those with parameters c and ϕ, the shear strength is dependent on the presence of bonds between particles or cohesion and between soil grains or ϕ.

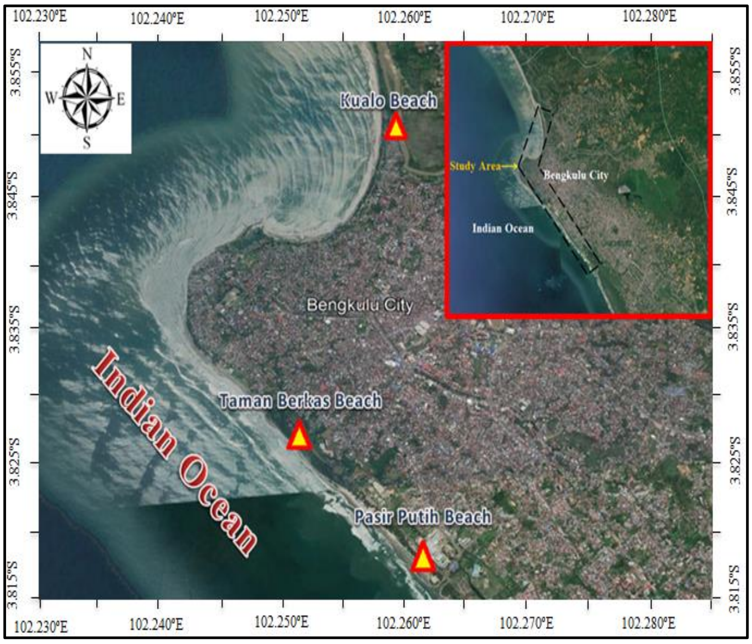

Fig. 1. Layout of study area (modified from Google Earth, 2021 [30]).

Table 1. Soil parameters.

Soil parameters	Symbols	Unit	Locations		
			Kualo Beach	Taman Berkas Beach	Pasir Putih Beach
Water content	w	%	22.23	19.84	18.03
Bulk unit weight	γ_b	kN/m³	20.08	19.51	18.80
Dry unit weight	γ_d	kN/m³	16.43	16.29	16.10
Saturated unit weight	γ_{sat}	kN/m³	20.25	20.18	20.12
Specific gravity	Gs	-	2.65	2.67	2.68
Void ratio	e	-	0.61	0.64	0.66
Porosity	n	-	0.38	0.39	0.41
Grain fraction					
>200	-	%	2.81	2.13	1.34
<200	-	%	97.19	97.87	98.66
C_u	-	-	1.50	1.46	1.58
C_c	-	-	0.94	1.01	0.89
Soil cohesion	c	kN/m²	1.34	1.29	1.08
Internal friction Angle	ϕ	°	33.86	34.94	36.10
Soil classification	-	*USCS*	SP	SP	SP

Several researchers have used the finite element method in carrying out soil bearing capacity analysis for shallow foundations. Keskin and Laman [31], Acharyya and Dey [32], Hamidi and Abbece [33] carried out an analysis of the soil bearing capacity for shallow foundations located at a distance from the slope using the finite element method. The research was conducted by calculating the distance from the foundation to the slope. One of the results of the study obtained a graph of the relationship between ratio on distance and width of foundation and the bearing capacity of the foundation. Salahudeen and Sadeeq [34] conducted an analysis of the bearing capacity of the soil using the finite element method and some classical theories. Salahudeen and Sadeeq [34] also proposed a graph of the relationship between the bearing capacity of the soil from several methods and the width of the foundation. Gupta and Mital [35, 36] performed a comparative analysis of the bearing capacity of the soil for footings using the finite element method with laboratory experimental testing. The test was carried out on sandy soil using soil reinforcement parameters. Iman and Harwadi [37] conducted an analysis of the bearing capacity of shallow foundations on peat soil using the finite element method. The results of the analysis produce a description of the deformation mechanism that occurs in peat soil due to foundation loads. Pusadkar and Bhatkar [38] and Sarma [39] carried out an analysis of shallow raft footings using the finite element method. One of the results of the analysis produces a description of the failure mechanism experienced by the foundation. Other researchers such as Ukritchon *et al.* [40] and Waheed and Ismael [41] also performed strip footing analysis on clay using the finite element method. The results of the analysis provide information in the form of a description of the mechanism of foundation collapse. Ouahab et al [42] conducted an analysis of the bearing capacity of shallow foundations using the finite element method. The analysis was carried out using an inclined load. The results of the analysis provide an overview of total displacement mechanism and several graphs of the relationship between the slope of the load and the inclination factor.

2.3. Research Framework

The research flow chart is shown in Fig. 2. The flow chart provides general information on the stages of research carried out starting from the literature study to the conclusion. The literature study conducted in this research includes matters relating to the geological conditions of Bengkulu City, the characteristics of the coastal soil and the use of the finite element method for the analysis of the carrying capacity of the soil. Qodri [43] and Mase *et al.* [44] mentioned that information on geological condition is important in geotechnical analysis.

The next step is to conduct a soil investigation. Soil investigation was carried out by taking undisturbed soil samples in the area that are tested in the laboratory. Soil samples were then subjected to laboratory tests to obtain soil parameters such as bulk density (γ), cohesion (c) and internal friction angle (ϕ) in the soil. This research was conducted using the Finite Element Method. The material model that is used for the soil in this analysis is the Mohr-Coulomb Model. For the foundation, the concrete is modelled as linear-elastic material model. The soil parameters to be used in this study were obtained from the results of testing soil samples obtained from 3 locations in the coastal area of Bengkulu City

The type of strip footing that is analyzed is square strip footing. Several variations of the dimensions of the width (B) and depth of the foundation (D) are considered in this study. The depth of the foundation to be analyzed varies from 0.00 to 1.50 m. The depth of the foundation was analyzed at the interval depth of 0.50 m. For the dimensions of the width of the foundation, it is adjusted to the depth of the foundation and in accordance with the theory put forward by Terzaghi, where the value of the width of the foundation is less than the same as the depth of the foundation ($D/B \leq 1$). The parameters that have been obtained are used in the finite element analysis. Before inputting, the data that has been obtained is validated. After the validation process is determined whether the data obtained meet or not. If it does not meet, the ground investigation could be carried out again. Then, if it meets the input process, it is then carrying out the analysis process. Soil parameters that are input into the finite element method program can be seen in Table 2. In Table 2, several parameters, such as permeability, elastic modulus, and Poisson's ratio are assumed based on study conducted Carter and Bentley [45] and Bowles [46]. In this study, both vertical and horizontal permeability coefficients are assumed to be the same because the soil type in the study area is generally homogenous. It should be noted that the vertical load applied is 100 kN/m. The reason why the vertical load of 100 kN/m is selected is based on the experience on the structural design in the coastal area in this study. In this study area that is dominated by low-story building, the vertical load of 100 kN/m is commonly applied.

Afterwards, the simulation process is performed. Finite element simulation is initiated by building a model. In this study, the plain-strain finite element model is used. The properties listed in Table 2 is then assigned in plain-strain model. Once the model is built, the meshing element is performed. Each single element is triangular element. Furthermore, initial condition is applied in the model. It should be noted that ground water level is not considered in this study. In the simulation, the step of construction is implemented. First, the model of strip footing is implemented. The next step is vertical load is applied for each model. The final step is to check the factor of safety under the calculation criterion of shear strength reduction. Several important outputs such as total displacement, factor of safety, bearing capacity are obtained. In general, the results of this study could provide benefits for civil engineers in designing footing foundations for low-rise buildings in coastal areas.

3. Results and Discussion

3.1. The Effect of Foundation Dimension Variations

The results of the analysis of the ultimate bearing capacity of the soil and the allowable considering the variation of width of the foundation (B) can be seen in Figs. 3 to 6. One hundred and forty seven (147) foundation models were analysed. Of the 147 models analysed, each location has 49 models. Figure 3 present the relationship of q_{ult} and q_{all} with the width of the foundation (*B*) at a depth (*D*) of 0.00 m. In Fig. 3, for Pasir Putih Beach, the q_{ult} value is in the range of 274.08 to 882.63 kN/m². The q_{all} value is in the range of 91.36 to 294.21 kN/m². In location Taman Berkas Beach, q_{ult} value is in the range of 245.48 to 795.23 kN/m². The q_{all} value is in the range of 81.83 to 265.08 kN/m². For Kualo Beach, q_{ult} values are in the range of 210.76 to 672.91 kN/m². q_{all} values are in the range of 70.25 to 224.30 kN/m². Figure 4 is the relationship of q_{ult} and q_{all} with the width of the foundation (B) at a depth (D) of 0.50 m. In Fig. 4, it can be seen that for location Pasir Putih Beach, the q_{ult} value is in the range of 663.76 to 1272.31 kN/m². The q_{all} value is in the range of 221.25 to 424.10 kN/m². In Taman Berkas Beach, q_{ult} value is in the range of 632.48 to 1182.23 kN/m². The q_{all} value is in the range of 210.83 to 394.08 kN/m². In location Kualo Beach, q_{ult} values are in the range of 598.68 to 1060.83 kN/m². q_{all} values are in the range of 199.56 to 353.61 kN/m². Figure 5 is the relationship of q_{ult} and q_{all} with the width of the foundation (B) at a depth (D) of 1.00 m. In Fig. 5, it can be seen that Pasir Putih Beach, the q_{ult} value is in the range of 1287.20 to 1692.90 kN/m². The q_{all} value is in the range of 429.07 to 564.30 kN/m². In Taman Berkas Beach, q_{ult} value is in the range of 1168.20 to 15.34.70 kN/m². The q_{all} value is in the range of 389.40 to 511.57 kN/m². In Kualo Beach, q_{ult} values are in the range of 1017.20 to 1325.30 kN/m². q_{all} values are in the range of 339.07 to 441.77 kN/m². Figure 6 is the relationship of q_{ult} and q_{all} with the width of the foundation (B) at a depth (D) of 1.50 m. In Fig. 6, it can be seen that for Pasir Putih Beach, the q_{ult} value is in the range of 1927.87 to 2140.72 kN/m². The q_{all} value is in the range of 642.62 to 710.24 kN/m². In Taman Berkas Beach, q_{ult} value is in the range of 1747.20 to 1930.45 kN/m². The q_{all} value is in the range of 582.40 to 643.48 kN/m². In Kualo Beach, q_{ult} values are in the range of 1539.20 to 1693.25 kN/m². q_{all} values are in the range of 513.07 to 564.42 kN/m².

In general, bearing capacities (*q*) increase with depth. A larger bearing capacity, a deeper depth of foundation (*D*) [40]. A deeper depth means a larger effective stress (σ_v'). Effective stress is a factor that influences bearing capacity. Effective stress also influences soil strength. Therefore, a bearing capacity is also related to the depth of foundation.

3.2. Factor of Safety and Total Displacement

Figure 7 shows a graph of the relationship between the safety factor (SF) with variations in the width of the foundation at a depth (D) of 0.00 m to 1.50 m. In Fig. 7a, the value of the safety factor for location Pasir Putih Beach is 1.13 to 2.29 and for Taman Berkas and Kualo Beach SF values are 1.11 to 2.25 and 1.08 to 2.18. In Fig. 7b, SF values in Pasir Putih Beach is 1.55 to 3.39 while in Taman Berkas and Kualo Beach, SF values are 1.51 to 3.24 and 1.46 to 2.49. In Fig. 7c, SF values for Pasir Putih Beach, Taman Berkas and Kualo Beach are 2.79 to 4.27, 2.69 to 4.04 and 2.49 to 3.71, respectively. In Fig. 7d, SF values in Pasir Putih Beach is 4.27 to 5.38. In Taman Berkas and Kualo Beach, SF values are 4.01 to 5.10 and 3.72 to 4.70. Based on the analysis results obtained, the constructed foundation is classified as safe for low-rise buildings at a depth (D) of 0.50 m where the value of SF values obtained ranges from 1.50 to 3.00. In general, it can be seen that SF values is directly proportional to the width and depth of the foundation. The wider and deeper footing, the greater SF.

Figure 8 shows a graph of the relationship between total displacement and the width of the foundation (B) at a depth (D) of 0.00 m to 1.50 m. Figure 8a shows the total displacement value for location Pasir Putih which is 50.70 to 10.80 mm. The displacement value for Taman Berkas is 44.44 to 8.60 mm and displacement value of Kualo is 49.94 to 9.44 mm. In Fig. 8b, the total displacement value for Pasir Putih is 34.04 to 8.36 mm. For Taman Berkas and Kualo are 28.25 to 7.17 mm and 30.48 to 7.50 mm, respectively. Figure 8c shows that the total displacement value for Pasir Putih is 7.24 to 16.47 mm. Total displacement value for Taman Berkas and Kualo are 5.95 to 13.28 mm and 6.34 to 14.16 mm, respectively. In Fig. 8d, the total displacement value for in location Pasir Putih is 6.21 to 9.04 mm. For Taman Berkas and Kualo are 5.31 to 7.25 mm and 5.56 to 7.53 mm, respectively. Also, in Fig. 8, it can be generally seen that the width of the foundation can affect the total displacement that occurs. Meyerhof [47] suggested that a maximum settlement of 1 inch is required for shallow foundation settlement. In line with the suggestion, the displacement generally occurred during the loading is relatively small, i.e., less than 1 inch. Therefore, it can be roughly concluded that soil properties are relatively suitable for strip footing construction.

3.3. Failure Mechanism

To present the failure mechanism, in this study the representative results are presented. Figures 9 to 12 provide information about the deformation that occurs in foundation with B of 1.50 at the location of Pasir Putih, Taman Berkas and Kualo due to the working point load. Figures 9 to 12 present mesh deformation that occurs in the foundation width (B) 1.50 which is at the depths of (D) 0.00 m; 0.50 m; 1.00 m; and 1.50 m, respectively. In general, it can be seen that the tendency of mesh deformation for the foundation subjected to the load is relatively similar for all models.

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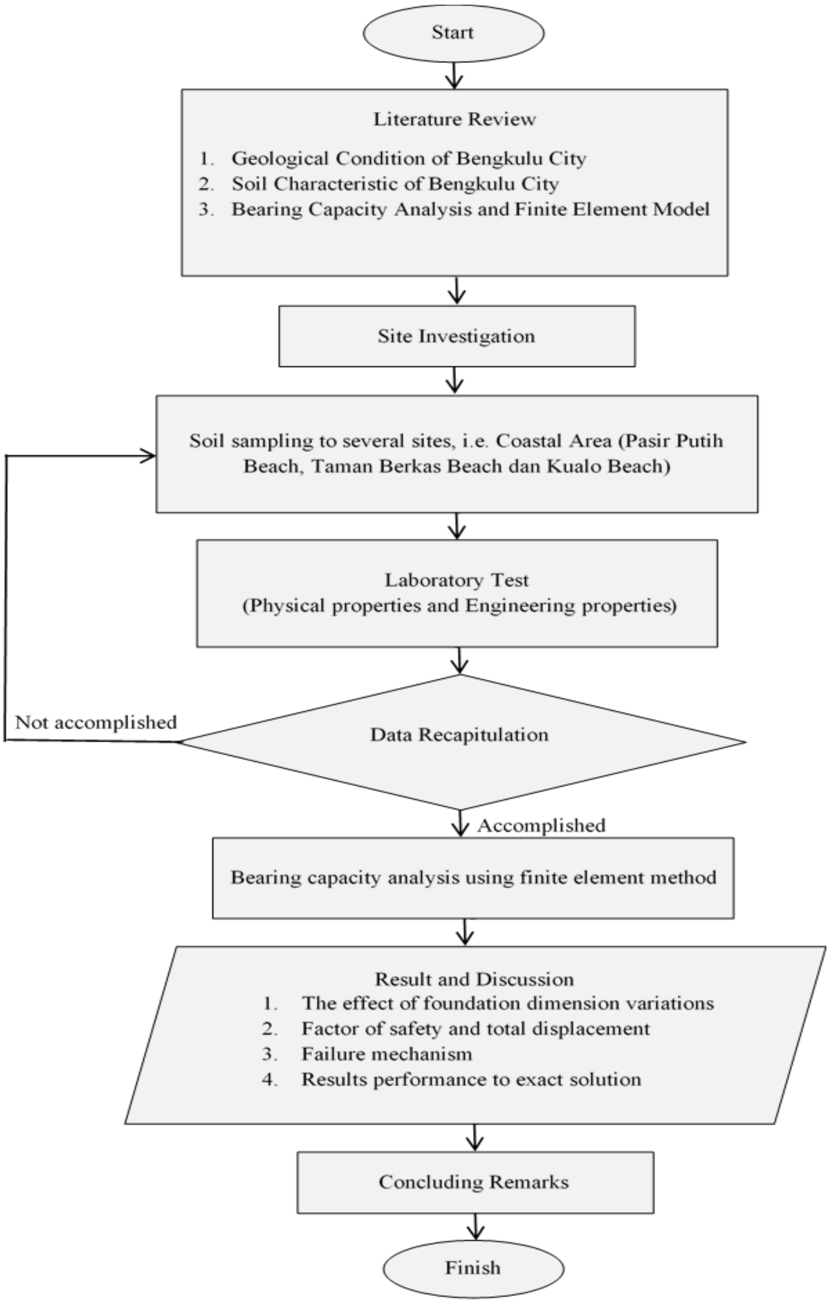
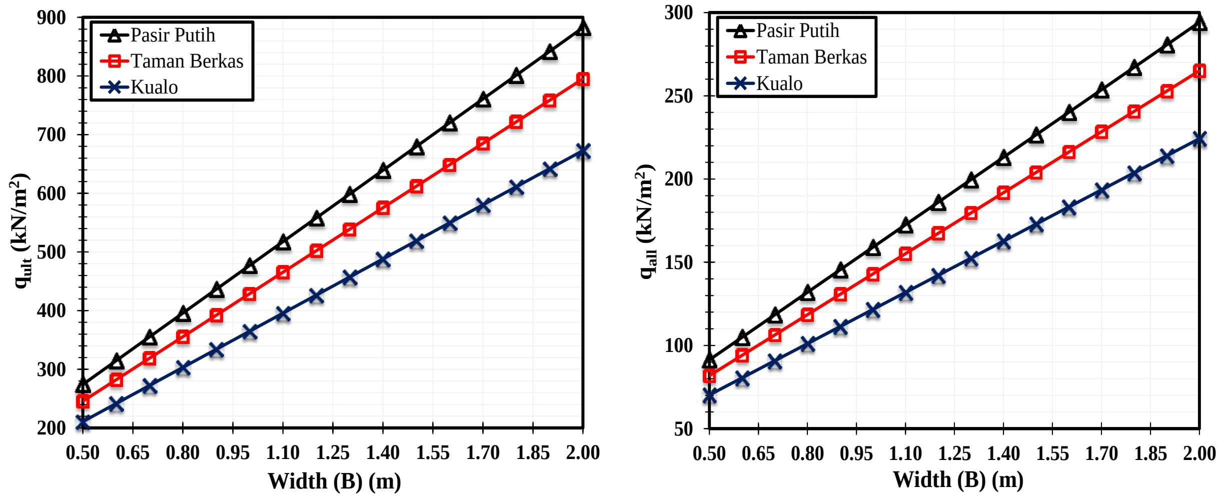


Fig. 2. Research framework.

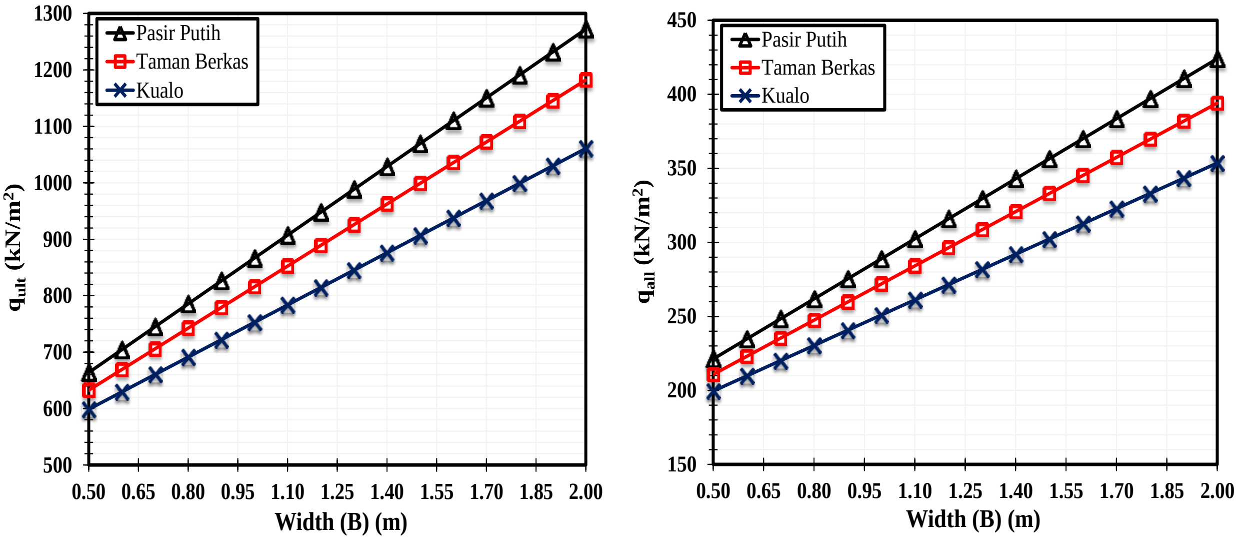
Table 2. Input parameters.

Soil Parameters	Symbols	Unit	Locations			Concrete
			Kualo Beach	Taman Berkas Beach	Pasir Putih Beach	
Material Model	-	-	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Linier-Elastic
Material Type	-	-	Drained	Drained	Drained	Non-Porous
Dry Density	γ_d	kN/m³	16.43	16.29	16.1	24
Saturated Density	γ_{sat}	kN/m³	20.25	20.18	20.12	24
Water Content	w	%	22.23	19.84	18.03	-
Vertical Permeability	k_x	m/day	1	1	1	-
Horizontal Permeability	k_y	m/day	1	1	1	-
Cohesion	c	kN/m²	1.34	1.29	1.08	-
Internal Friction Angle	φ	°	33.86	34.94	36.1	-
Elastic Modulus	E	kN/m²	1.46×10^4	1.46×10^4	1.15×10^4	2.35×10^7
Poisson's Ratio	v	-	0.3	0.3	0.3	0.15
Vertical Load	-	kN/m	100	100	100	-



(a) (b)

Fig. 3. Relationship for bearing capacity (q) and foundation width (B) at 3 locations with D = 0.00 m. (a) q_{ult} and width of foundation (B) (b) q_{all} and width of foundation (B).



(a) (b)

Fig. 4. Relationship for bearing capacity (q) and foundation width (B) at 3 locations with D = 0.50 m. (a) q_{ult} and width of foundation (B) (b) q_{all} and width of foundation (B).

Figures 13 to 16 present the criteria for failure of the foundation with a width of (B) 1.50 m at the location of Pasir Putih, Taman Berkas and kualo due to applied point load. Similar to Figs. 9 to 12, the presentation in Figs. 13 to 16 is also provided for B of 1.5 m and D of 0.00 m; 0.50 m; 1.00 m; and 1.50 m, respectively. Based on Figs. 13 to 16, it shows that tendency of the failure mechanism is relatively similar. Larger dimensions tend to result in larger failure sides. This is because the stress distribution due to the applied load increases with the width of the foundation.

It should be noted that normally the failure mechanisms of strip footings are symmetric and laterally extend from the center of footings as log-spiral curves in both sides of footings. The issue on the non-symmetrical failure mechanism shape is generally due to the patterns of element distribution. In this study, the used mesh type is very fine mesh. The selection of mesh criteria could affect failure mechanism. Therefore, it should be considered the fine to very fine meshing to result in the appropriate patterns.

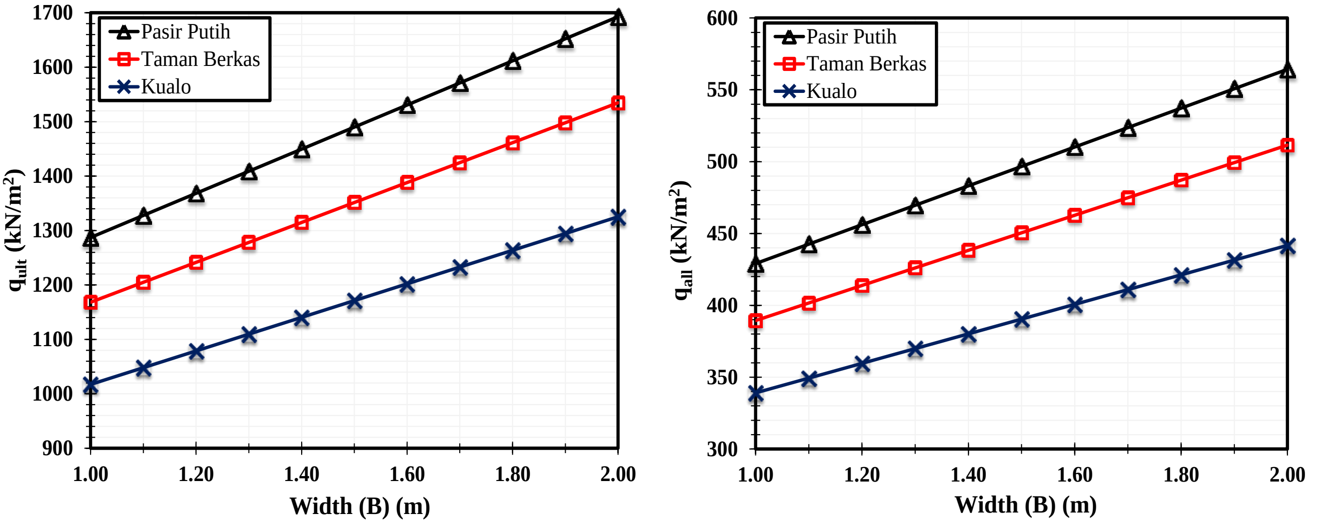
3.4. The Correlation of Bearing Capacity Between Finite Element Analysis and Classical Theories

The results of the analysis that have been carried out using the finite element method are compared to the results of classical methods as shown in Fig. 17 and 18. The classical methods employed in this study are Terzaghi's and Meyerhof methods. Figure 17 shows the comparison between finite element result and solution from Terzaghi's method. It can be seen that the exact solution from Terzaghi's method tends to be more conservative that finite element results. However, the plotted points are generally forming a linear correlation.

In Fig. 17, it is also observed the linear equation can be proposed as q_{ult}(Terzaghi) = 1.1020 (q_{ult}(FEM)) with coefficient of determination (R^2) of 0.9976. Figure 18 shows the comparison between finite element result and exact solution from Meyerhof Method. In general, it can be also observed that the classical method from Meyerhof is relatively more conservative that finite element results. The proposed equation is q_{ult}(Meyerhof) = 1.5785 (q_{ult}(FEM)) with R^2 of 0.996. Based on the analysis, it can be observed that R^2 is closed to 1. It means that both parameters are strongly correlated. Therefore, it is reliable to estimate bearing capacity results for the study area by using these correlations. This is also strong indication that the calculation using the finite element method can be used for foundation design in the study area. For practical use, finite element method is also more effective and efficient because its work is relatively fast and does not take a long time.

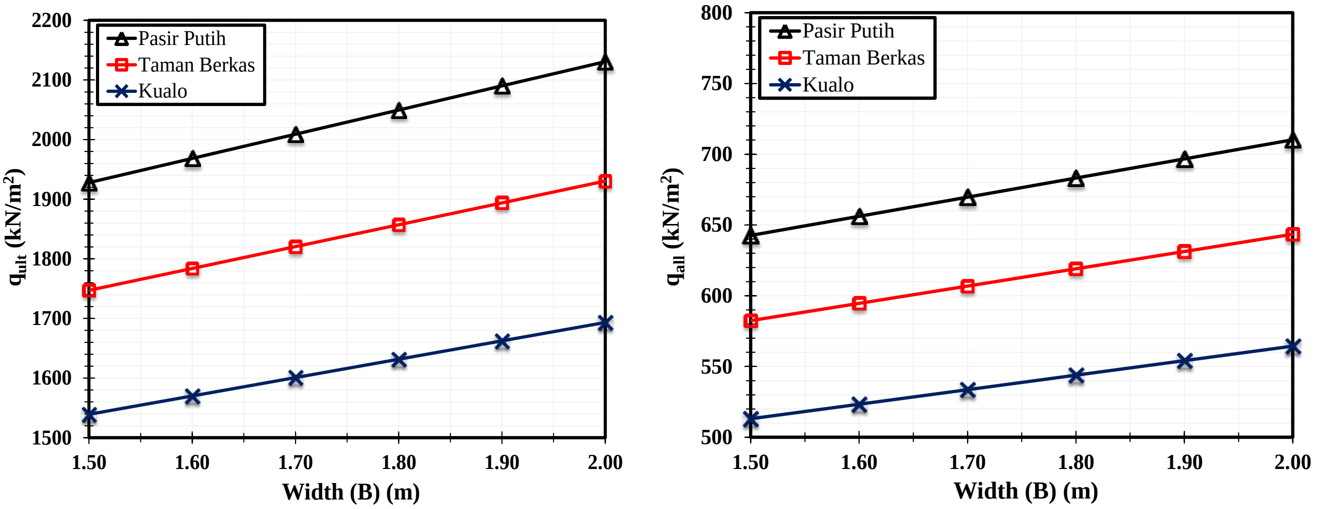
3.5. Recommended Allowable Bearing Capacities

To estimate recommended dimension of strip footing for allowable bearing capacity, the plotting analysis as suggested by Mase *et al.* [48] is used. In this analysis, the ultimate bearing capacity is then analysis by considering the recommended factor of safety, i.e., 2.5 to 3. Upper boundary means allowable bearing capacity considering safety factor of 2.5, whereas lower boundary means allowable bearing capacity considering safety factor of 3.0. Furthermore, the allowable bearing capacity from the numerical analysis is then plotted corresponding to strip footing dimension. The recommended dimension is defined as the dimension lied between both boundaries.



(a) (b)

Fig. 5. Relationship for bearing capacity (q) and foundation width (B) at 3 locations with D = 1.00 m. (a) q_{ult} and width of foundation (B) (b) q_{all} and width of foundation (B).



(a) (b)

Fig. 6. Relationship for bearing capacity (q) and foundation width (B) at 3 locations with D = 1.50 m. (a) q_{ult} and width of foundation (B) (b) q_{all} and width of foundation (B).

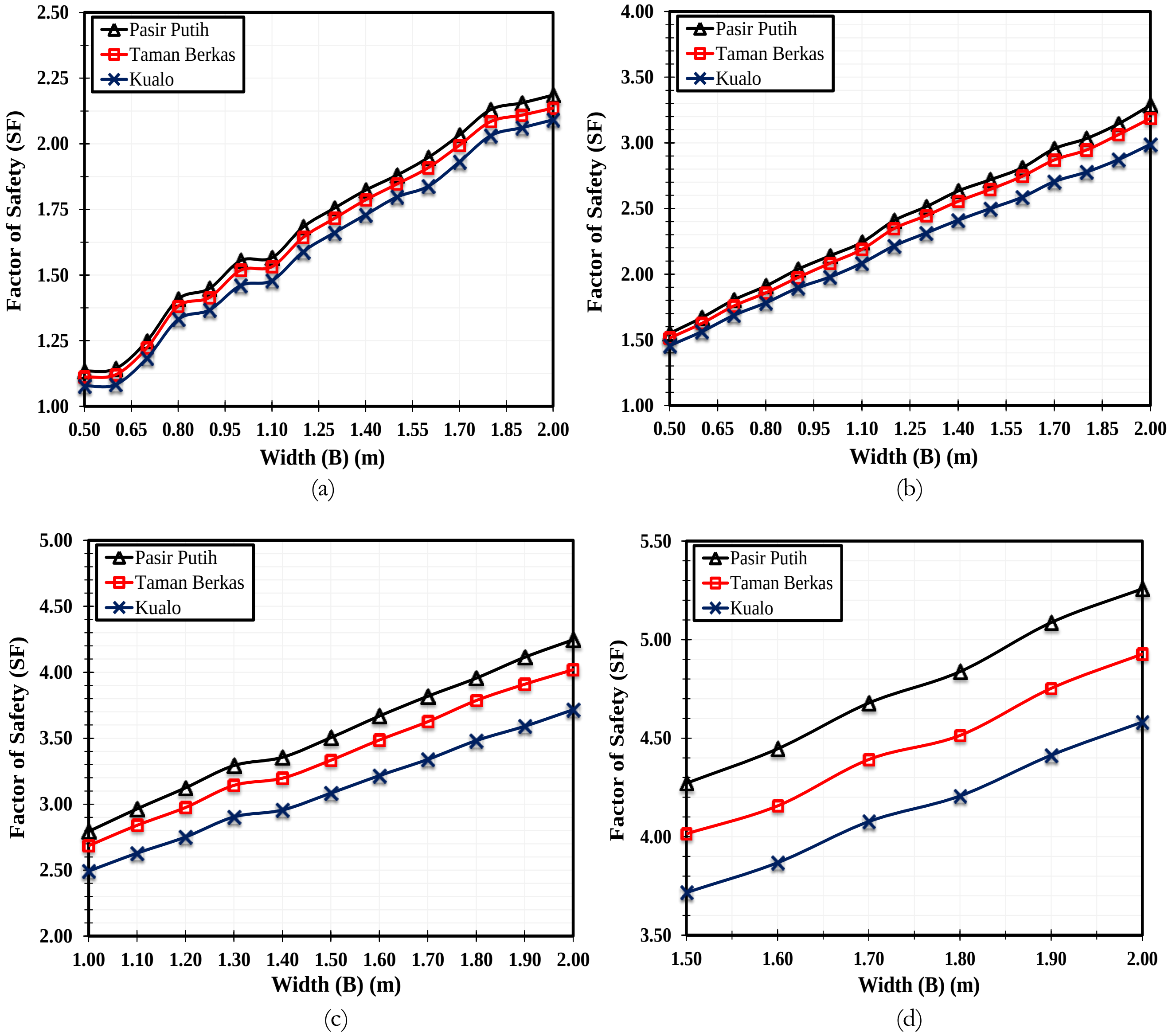


Fig. 7. Factor of safety (FS) vs width of the foundation (B) for depths of (a) D = 0.00 m (b) D = 0.50 m (c) D = 1.00 m (d) D = 1.50 m.

Figure 18 presents chart of allowable bearing capacity and strip footing dimension, for surficial strip and embedded footing. It should be noted that the use of chart is addressed for strip footing design for maximum vertical load of 100 kN/m. The reason why the vertical load of 100 kN/m is selected is based on the experience on the structural design in the coastal area. In this study area that is dominated by low-story building, the vertical load of 100 kN/m is common implemented in the study area. Figure 18a presents the chart for allowable bearing capacity and strip footing dimension for surficial strip footing. It is observed that all analyzed dimensions do not meet the criteria of recommended dimension. This is because all allowable bearing capacity values do not fall into between both boundaries. Figure 18b presents chart presenting the relation between allowable bearing capacity and strip footing dimension for strip footing embedded at 0.5 m depth below ground surface. In Fig. 18b, it is observed that for all investigated sites, The dimensions of strip footing of 1.5 to 1.7 m falls into between both boundaries. Therefore, the recommended strip footing dimension is 1.6 m for better safety. Similar to other Figures 18, the interpretation for embedded strip footing at 1.0 m is presented in Fig. 18c. In Fig. 18c, the dimensions of strip footing of 1.0 to 1.2 m falls into between both boundaries. For a better safety reason, the strip footing dimension of 1.0 m is recommended. For Fig. 18d, it can be seen that there is no dimension that falls between boundaries. It can be concluded that the use of strip footing embedded at 1.5 m depth is not recommended in the study area.

3.6. Estimation of q_{ult} from Dimensionless Factor (B/D)

The use of finite element model could provide the solution for the reliable design. As elaborated in previous section, the study areas are now becoming the prospective zones for developing in Bengkulu City. Therefore, the construction will be significantly increased in the future. For engineering practice, it is important to present how to estimate bearing capacity in the study area based on dimensionless factor.

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In this study, the recommendation chart to estimate bearing capacity is presented in Fig. 19. In Fig. 19, the ultimate bearing capacity (q_{ult}) is estimated based on dimensionless factor (B/D). In Fig. 19, it can be observed bearing capacity at Pasar Putih Site is larger than other sites. In Figs. 3 to 6, it can be observed that a larger dimension means a larger bearing capacity. Site investigation data showed that geological condition is relatively homogenous. Therefore, for this case the shear strength increases with depth and the shear strength is also influenced by effective stress. Generally, a larger depth means a large effective stress. This factor can influence the bearing capacity. Therefore, based on B/D ratio, the larger B/D ratio means the larger bearing capacity.

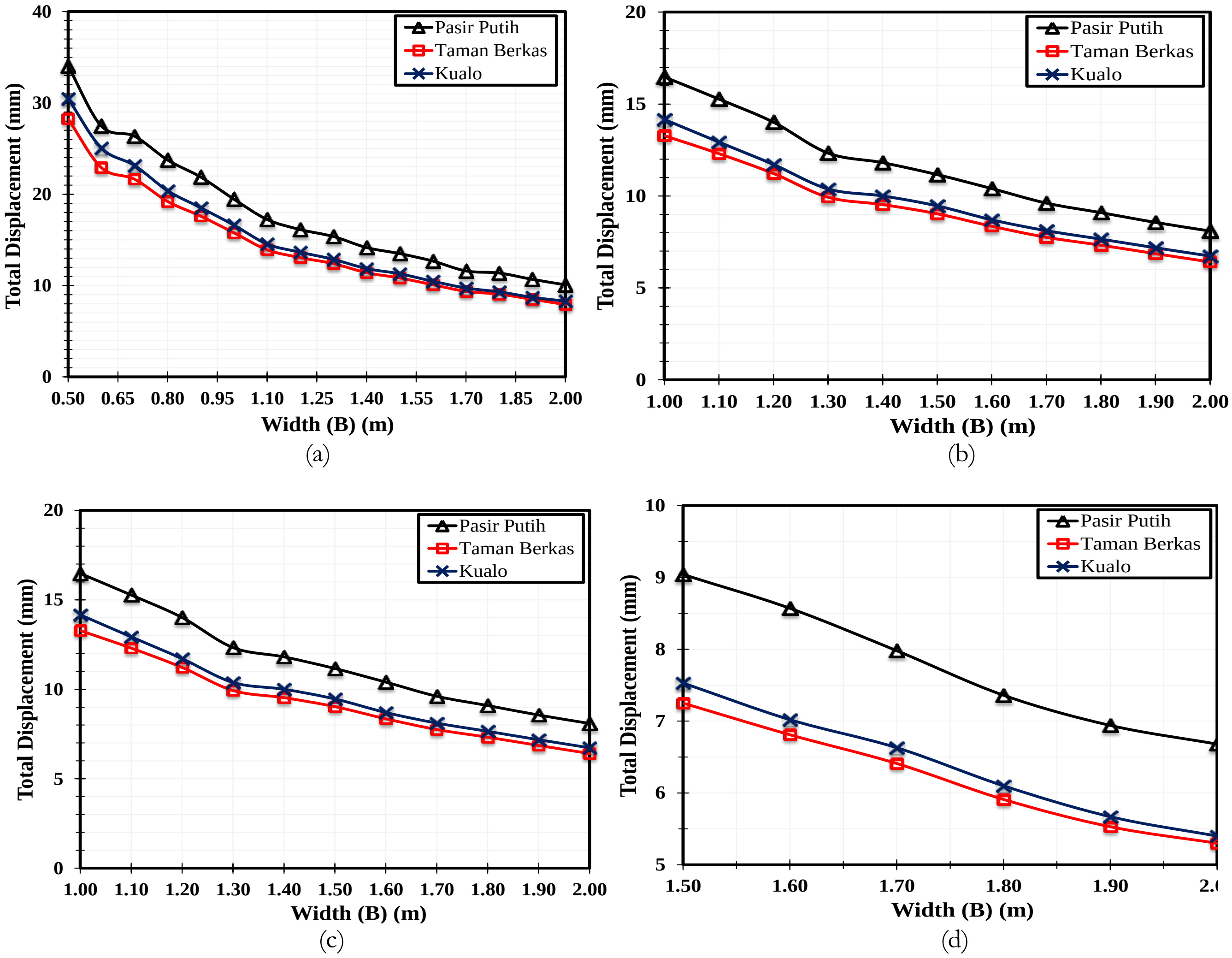
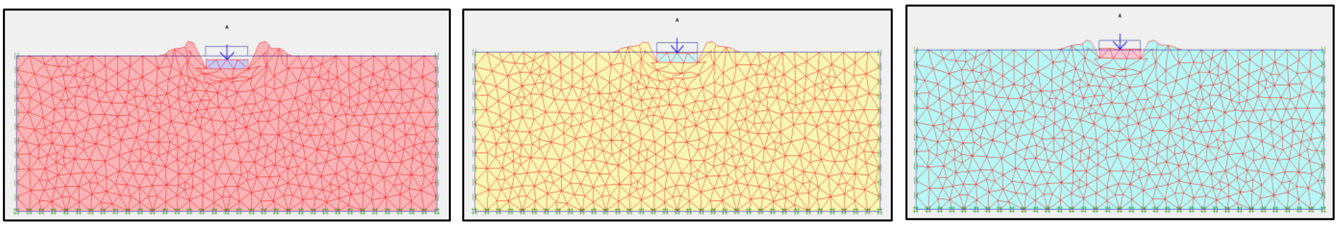
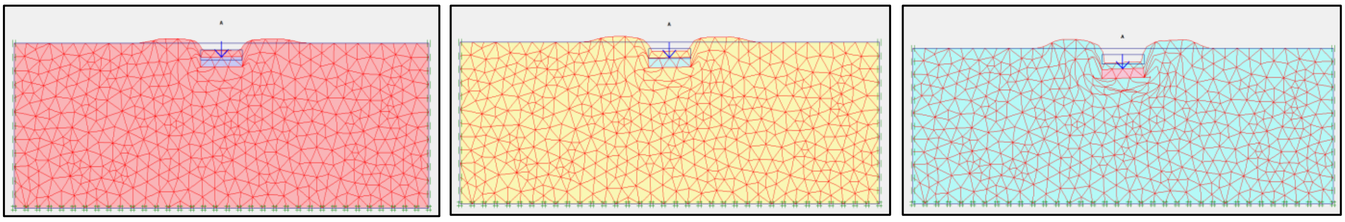


Fig. 8. Total displacement vs the width of the foundation (B) for depths of (a) D = 0.00 m (b) D = 0.50 m (c) D = 1.00 m (d) D = 1.50 m.



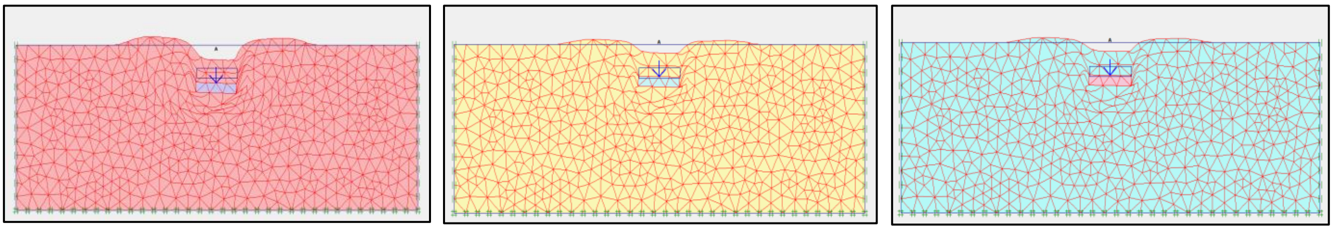
(a) (b) (c)

Fig. 9. Deformation mesh description at 3 locations B = 1.50 m; D = 0.00 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



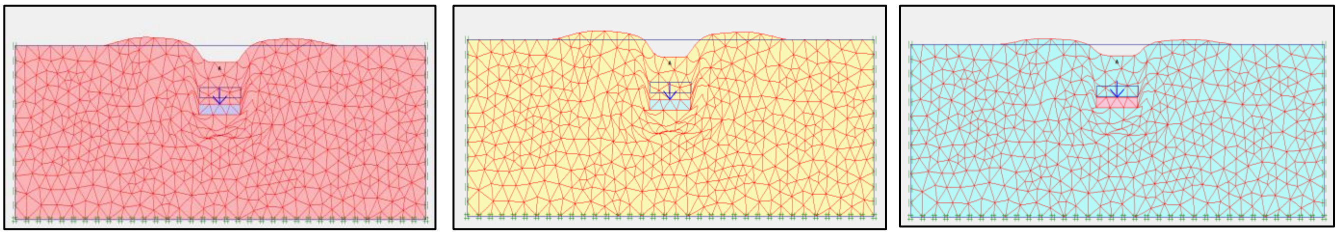
(a) (b) (c)

Fig. 10. Deformation mesh description at 3 locations B = 1.50 m; D = 0.50 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



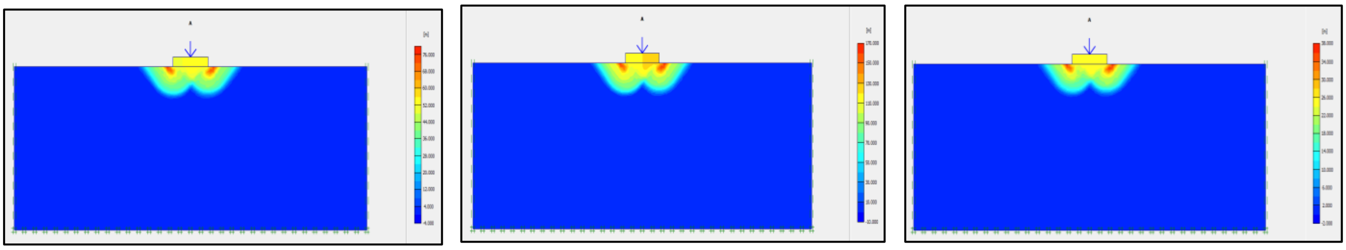
(a) (b) (c)

Fig. 11. Deformation mesh description at 3 locations B = 1.50 m; D = 1.00 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



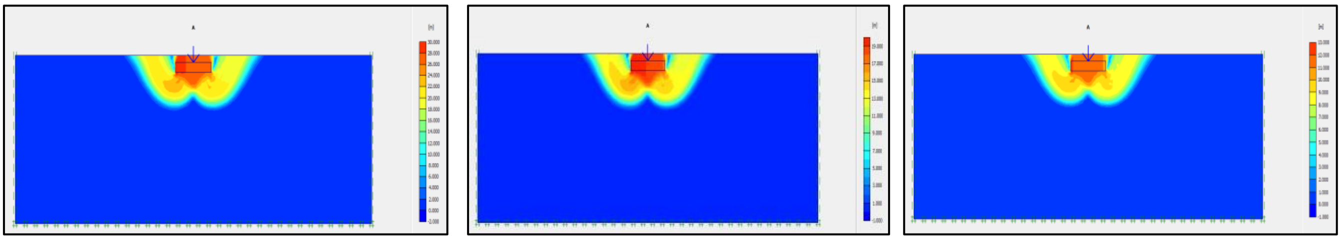
(a) (b) (c)

Fig. 12. Deformation mesh description at 3 locations B = 1.50 m; D = 1.50 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



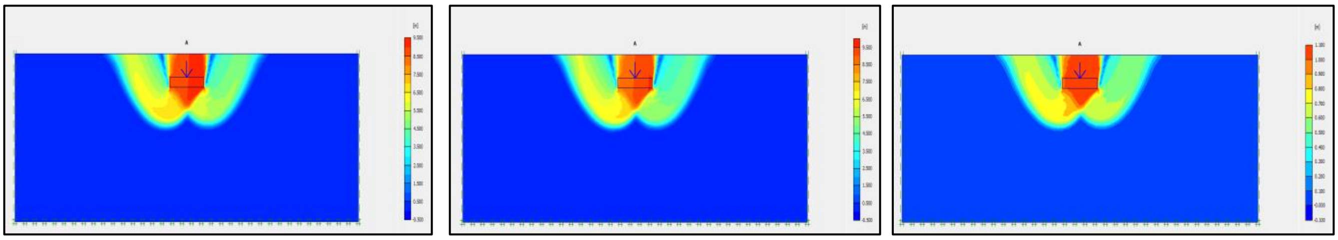
(a) (b) (c)

Fig. 13. Failure side pattern from finite element simulation at 3 locations B = 1.50 m; D = 0.00 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



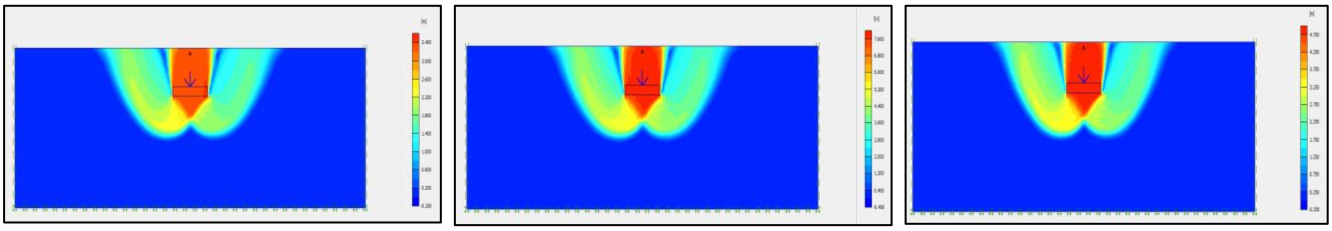
(a) (b) (c)

Fig. 14. Failure side pattern from finite element simulation at 3 locations B = 1.50 m; D = 0.50 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



(a) (b) (c)

Fig. 15. Failure side pattern from finite element simulation at 3 locations B = 1.50 m; D = 1.00 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.



(a) (b) (c)

Fig. 16. Failure side arrow from finite element simulation at 3 locations B = 1.50 m; D = 1.50 m. (a) Kualo (b) Taman Berkas (c) Pasir Putih.

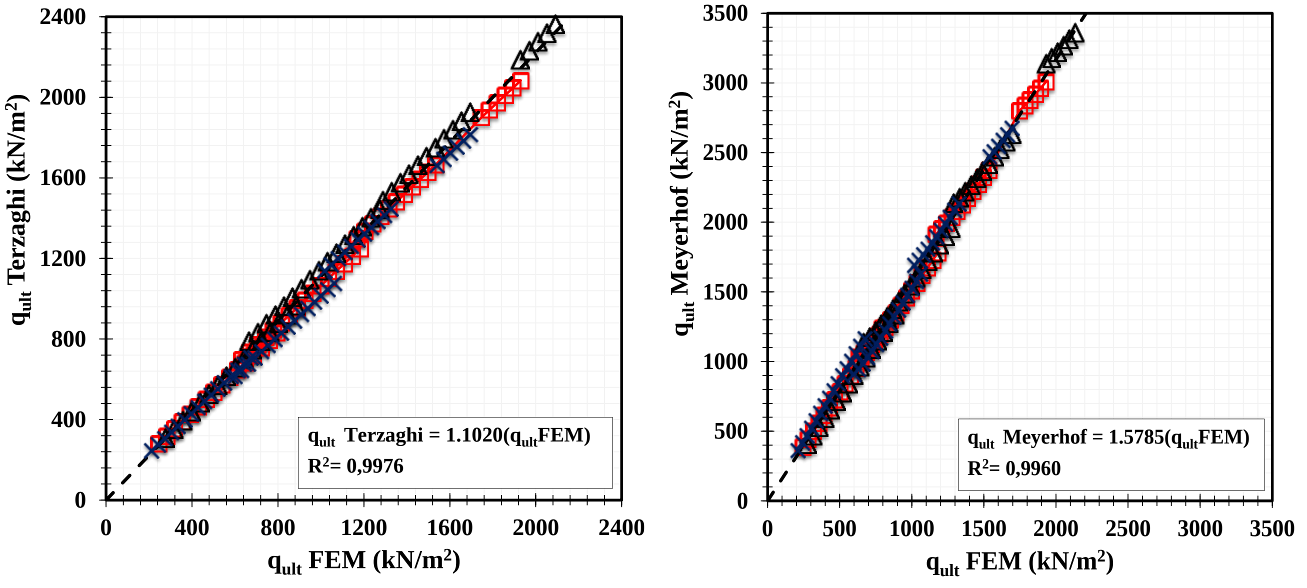


Fig. 17. The correlations of bearing capacity between finite element method and (a) Terzaghi theory and (b) Meyerhof theory.

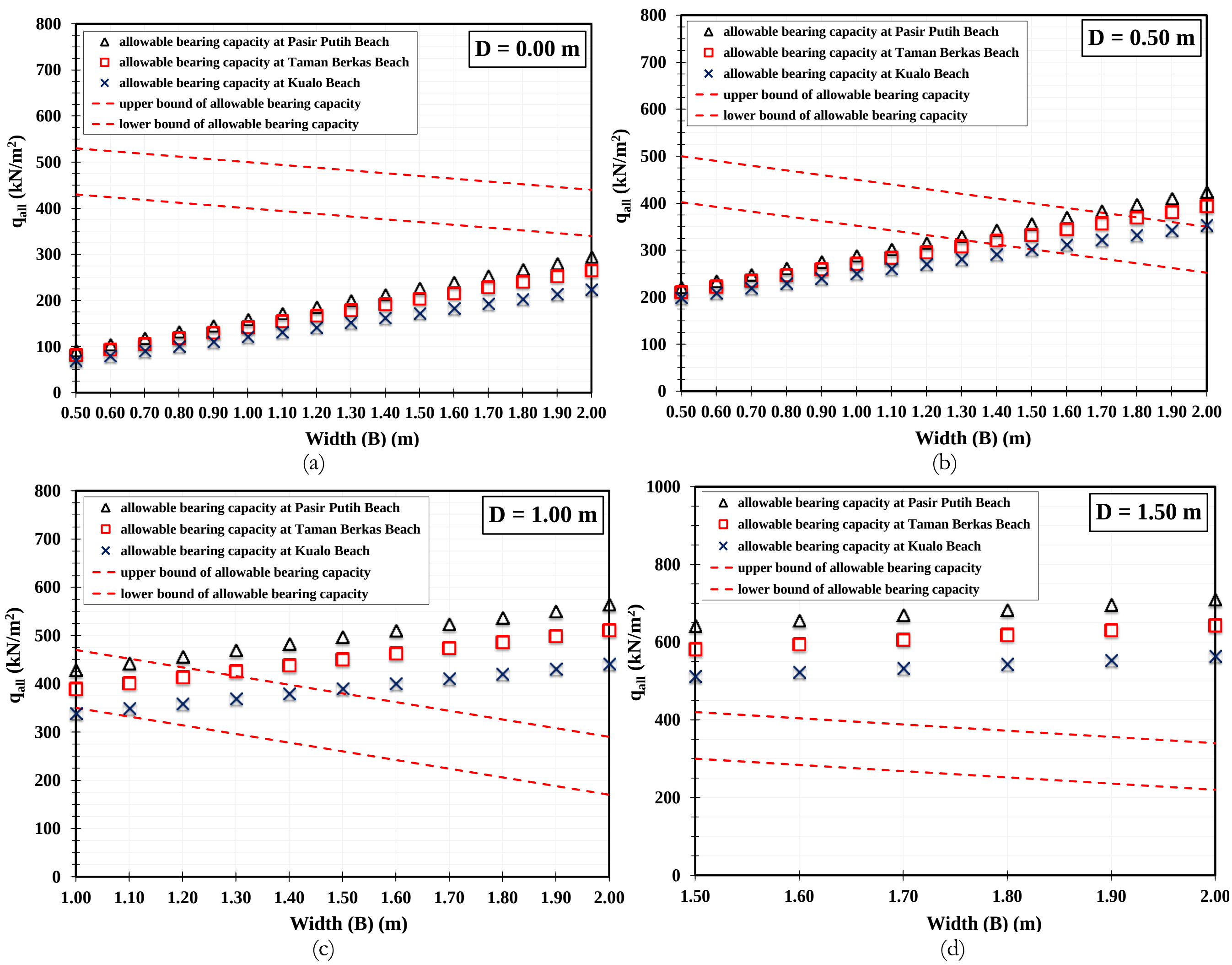


Fig. 18. Comparison between existing and recommended allowable bearing capacities. (a) D = 0.00 m (b) D = 0.50 m (c) D = 1.00 m (d) D=1.50 m.

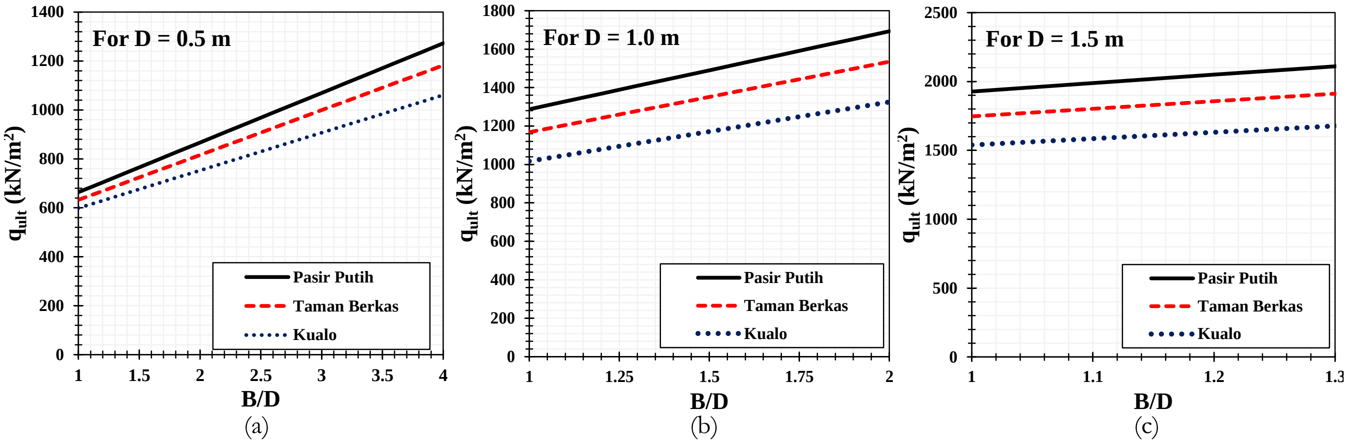


Fig. 19. Recommendation chart to estimate ultimate bearing capacity based on dimensionless factor (B/D) for (a) D =0.5 m, (b) D = 1.0 m, and (c) D = 1.5 m.

4. Concluding Remarks

This study focuses on the analysis of the bearing capacity of the soil for footing foundations located on coastal sandy soil. The analysis was carried out by considering variations in the dimensions of the width and depth of the foundation as well as the research location. The location of the research is focused on the coastal area of Bengkulu. Those locations are Pasir Putih Beach, Taman Berkas Beach and Kualo Beach. Several concluding remarks can be drawn:

1. The location selection was based on the strategic location of the area to support tourism and economic activities for the people of Bengkulu. Pasir Putih, Taman Berkas, and Kualo, are coastal area that are predicted as prospective area in the future. These areas will be more established in the future. Therefore, it is important to study the estimation of bearing capacity in the effort of structural enhancement in these areas. The analysis process is carried out using the finite element method simulation. The input parameters used were obtained from the results of testing the soil properties taken at the location and tested in the laboratory. The results of the analysis that have been carried out using the finite element method show that the highest soil carrying capacity value of the three locations in the coastal area is Pasir Putih Beach. For the lowest carrying capacity is Kualo Beach.
2. The results of the study also provide information on the value of the safety factor (SF) and total displacement for each location. Based on the results of the analysis carried out, each location has an adequate carrying capacity value, but not all dimensions of the width and depth of the foundation meet the requirements for the safety factor and settlement. For foundations located at ground level, each location does not meet the allowable SF, where the safety factor value is less than 3. For low-rise structural buildings built in coastal areas, the placement of the foundation must be placed at a depth of soil to meet the allowable safety factor and total displacement.
3. The proposed equations to correlate the empirical estimation between classical methods and finite element results are appropriate to use for engineering practice. The equations can help local engineer to roughly estimate allowable and ultimate bearing capacity for structural building design in the study area. Finally, the framework implemented in this study could be adopted to solve similar problem in other areas.
4. The plotting analysis has been conducted to select the recommended strip footing for the study area. The analysis is reliable to select the strip footing. Considering the sites condition, the strip footing dimension of 1.1 m embedded at 1.0 m depth can be roughly justified as the most suitable strip footing in the study area. However, the application of this recommended dimension should be followed by adequate site investigation and optimization analysis. Analysis on the selection of an efficient and economical foundation's dimension will be presented in further study. In general, the results could help the implementation for engineering practice in the study area, especially for the selection of strip footing dimension in coastal sandy soils, in Bengkulu City, Indonesia.

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