

Research on improvement of Terzaghi's bearing capacity equation for coral sand foundation

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Received 7 August 2021; received in revised form 30 October 2021; accepted 10 November 2021

DOI <https://doi.org/10.21595/jve.2021.22170>



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Abstract. The mechanical characteristics of coral reef sandy soil is significantly different from the sand and clay soils. Currently, Terzaghi's bearing capacity equation is still commonly applied to evaluate the bearing capacity of coral reef, while the calculation result is not consistent with the actual condition. Based on a port project in east Africa, plate loading test of the coral reef sandy soil has been conducted and the P-S curves are obtained, and the bearing capacity values obtained from the plate loading test results are compared with the calculated results based on the Terzaghi's bearing capacity equation. According to multiple linear regression and the optimal regression equation selected by the significance test, the modified Terzaghi foundation equation of bearing capacity in coral reef sandy soil area is proposed, and the modified Terzaghi foundation equation has important reference value for the calculating of the bearing capacity of the coral reef sandy soil foundations.

Keywords: coral reef sandy soil, bearing capacity of foundation, Terzaghi's bearing capacity equation, plate loading test, regression analysis.

1. Introduction

Coral reef sandy soil is a special natural geological body mainly formed by coral reefs and their associated microorganisms after a series of biochemical processes under different natural geological conditions. It primarily features friable particles in irregular shapes, high content of calcium carbonate, and a high void ratio, which allows it to have special engineering mechanical properties compared with general soil bodies. According to the classical theory of soil mechanics, solid particles are incompressible and unbreakable. However, coral reef particles are easily broken due to various types of intragranular pores and have high friction angles and high compressibility. It is believed that particle breakage is the major factor affecting deformation and strength [1], making coral sand differ significantly from terrigenous sand formed in continental deposits in terms of engineering mechanical properties [2]-[4]. Coral reef sandy soil has so far not been listed as a category in the Code for Investigation of Geotechnical Engineering in China, and with respect to the bearing capacity of the coral reef sandy soil foundation [5], relatively few experimental studies have been conducted by domestic and foreign scholars. Zhu [6] et al. analyzed the bearing capacity characteristics of the coral sand foundation through field tests and pointed out that the deformation modulus of the foundation soil is positively correlated with the blow count N₁₀ of the light dynamic penetration test. The test results of Wang [7] et al. showed that the bearing capacity and deformation modulus of artificially filled coral soil foundations were significantly higher than those of naturally formed reef flat facies and sandbank foundations and that the resilient modulus of coral soil increased with the increase of the degree of compaction; Yang et al. [8] using the least square method proved the correlativity between the eigenvalue of foundation bearing capacity and the blow count N of standard penetration test (SPT) and the blow count

N63.5 of heavy dynamic penetration test with modified eigenvalue of foundation bearing capacity; Li et al. [9] conducted a plate loading model test study on coral sand foundation and found that the settlement of coral sand was 50 % to 67 % of the value calculated with the empirical equation. Huang et al. [10] pointed out that the effective overlying stress increases with the increasing of the buried depth of the soil layer and groundwater level. On the whole, few studies on the ultimate bearing capacity of the coral reef sandy soil foundation have been conducted at home and abroad. The conventional Terzaghi's bearing capacity equation is still employed to calculate the bearing capacity of the coral reef sandy soil foundation, however, the calculation result is usually inconsistent with what is actually measured and cannot meet the actual engineering needs.

2. Field plate loading test

2.1. Test program

Based on a container terminal project in East Africa, the strata disclosed at the site of geotechnical investigation are mainly coral reef limestone and its debris formed by biochemical sedimentation, as shown in Fig. 1. According to the geological survey and SPT, the SPT blow count of the surface coral reef backfill is about 8 to 12; the second stratum, consisting of 2 to 8 m thick undisturbed coral reef limestone residual soil, has an SPT blow count of about 18, and a local SPT blow count of less than 8. The stratum downward is strongly weathered coral reef limestone, with an SPT blow count of about 30. The coral reef backfill is bulky and powdery granular soil. The foundation composed of such type of soil is generally treated through vibration rolling, dynamic compaction, etc.



Fig. 1. Core sample of coral reef sandy soil foundation

The coral reef backfill was treated by dynamic compaction and vibration rolling of different energy levels, and shallow plate loading tests were conducted on the coral reef sandy soil before and after reinforcement, as shown in Fig. 2 and Fig. 3.



Fig. 2. Field plate loading test



Fig. 3. Plate Size 0.5×0.5 m

The tests were conducted according to the requirements, procedures and machinery of the loading test as specified in the 2018 edition of Code for Investigation of Geotechnical Engineering [11]. The test site was divided into four test zones, i.e. vibration rolling zone, and 500 kJ, 1000 kJ and 3000 kJ dynamic compaction zones and in each zone, eight points were selected. For further determination of the effect of reinforcement, the plate loading tests were conducted in the test zones respectively before and after the reinforcement. During the test, the measuring points were arranged in the center of the vibration rolling zone and between the rammers in the dynamic compaction test zones. The deformation modulus was calculated by using Eq. (1) as follows:

$$E_0 = \frac{I_0(1 - \mu^2)Pd}{s}, \tag{1}$$

where E_0 is the deformation modulus (MPa); I_0 is the shape factor of the loading plate (0.886 for a square loading plate); P is the total load (kPa); s is the settlement (mm) under the effect of total load P imposed on the plate; d is the side length of the plate (0.50 m here); μ is the Poisson's ratio (0.27 for gravelly soil and 0.30 for sandy soil).

The 0.5 m×0.5 m plate used in the field loading test was loaded in levels according to the actual situation, and a load of 100 kPa was added at each level. It was decided to end the test (that is, to stop loading) when the soil body extruded significantly around the loading plate or the soil body around the loading plate presented obvious uplift or radial crack propagation. The P-S value was summarized and the P-S curve as shown in Fig. 4 was drawn to evaluate the reinforcement effect of the backfilled foundation.

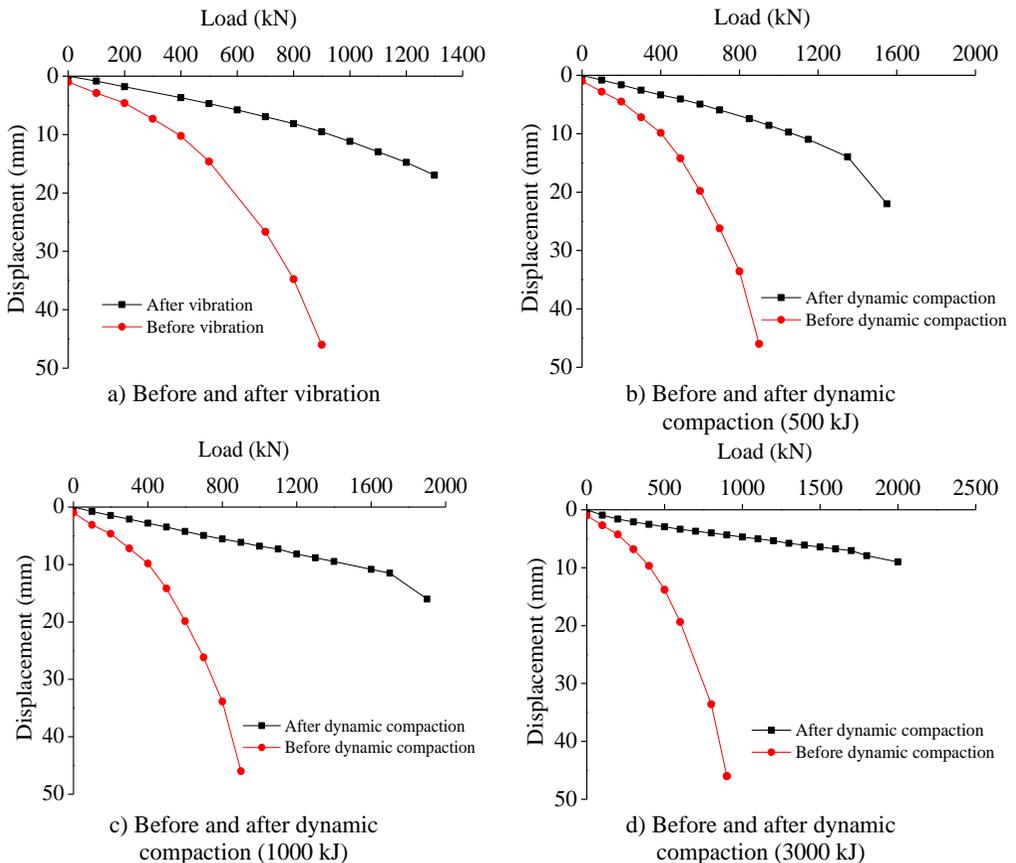


Fig. 4. P-S Curve of loading test before and after reinforcement of test zone

As can be seen from the above figures, the P-S curve of coral reef backfill gradually drops and nearly becomes a straight line, lacking the three typical and obvious stages of the typical P-S curve and making it difficult to acquire the proportional limit.

2.2. Determination of bearing capacity

The bearing capacity of coral reef foundation soil can be determined according to the relevant specifications on coral reef geology in the Code for Investigation of Geotechnical Engineering [11] and the Code for Geotechnical Investigation on Port and Waterway Engineering [12], that is, for the relatively flat section of the P-S curve, the stress corresponding to a relative settlement of not greater than 0.02 is taken as the allowable bearing capacity; if the ultimate load P_u is smaller than twice the $P_{s/b=0.02}$, $P_u/2$ is taken as the allowable bearing capacity. Considering the high compressibility of coral sand, $P_u = \min(P_{s/b} = 0.02, 1/2P_u)$ for general clay or soft soil is taken as the eigenvalue of bearing capacity f_a . Then, the ultimate bearing capacities obtained from the plate loading test on the foundation soil before and after reinforcement are shown in the Table 1 and Table 2.

Table 1. Results of plate loading test on foundation soil before reinforcement

Test No.	Depth (m)	Diameter of loading plate (m)	Ultimate bearing capacity (KN)
SY-1	0.5	0.5	410
SY-2	0.5	0.5	410
SY-3	0.5	0.5	430
SY-4	0.5	0.5	430
SY-5	0.5	0.5	420
SY-6	0.5	0.5	420
SY-7	0.5	0.5	430
SY-8	0.5	0.5	430

Table 2. Results of plate loading test on foundation soil after reinforcement

Test No.	Reinforcing method	Depth (m)	Diameter of loading plate (m)	Ultimate bearing capacity (KN)
SY-1	Vibration rolling	0.5	0.5	650
SY-2	Vibration rolling	0.5	0.5	650
SY-3	500 kJ dynamic compaction	0.5	0.5	775
SY-4	500 kJ dynamic compaction	0.5	0.5	775
SY-5	1000 kJ dynamic compaction	0.5	0.5	950
SY-6	1000 kJ dynamic compaction	0.5	0.5	950
SY-7	3000 kJ dynamic compaction	0.5	0.5	1000
SY-8	3000 kJ dynamic compaction	0.5	0.5	1000

3. Modification of Terzaghi's bearing capacity equation

Regarding the bearing characteristics of the foundation, Terzaghi proposed a theoretical equation for the calculation of the ultimate bearing capacity considering the foundation dead load as early as 1940. Over the years, although many scholars have modified the equation according to different construction conditions, the form of the equation for the ultimate bearing capacity of the foundation has not changed, and only the bearing capacity coefficient has been adjusted according to different engineering geological conditions. Moreover, the mechanical properties of coral reef calcareous soil are different from those of common sandy soil and clay foundations. Considering that derivation is to be conducted for the backfilled foundation, the original Terzaghi's bearing capacity equation for a shallow foundation is therefore listed for further derivation. In 1943, scholars first proposed an equation for calculating the bottom bearing capacity of a shallow foundation based on the failure mechanism of the shallow foundation:

$$P_u = 1.3cN_c + \gamma_1LN_q + 0.3\gamma dN_r, \tag{2}$$

$$P_u = 1.3cN_c + \gamma_1LN_q + 0.3\gamma dN_r, \tag{3}$$

where, γ_1 is the equivalent volumetric weight of the soil body above the foundation in kN.m^{-3} ; d is the diameter of the pile foundation in m; γ is the volumetric weight of the foundation soil in kN/m^3 ; c is the cohesion of the foundation soil. N_c , N_q and N_r are the foundation bearing capacity coefficients, and the equations are as shown from Eq. (4) to Eq. (6):

$$N_c = (N_q - 1)\cot\varphi, \tag{4}$$

$$N_q = e^{\pi\tan\varphi}\tan^2\left(45 + \frac{\varphi}{2}\right), \tag{5}$$

$$N_r = 1.8(N_q - 1)\tan\varphi, \tag{6}$$

where, φ is the internal friction angle of the foundation soil in deg.

Although the ultimate bearing capacity equation proposed by Terzaghi for circular foundations is widely used, it is relatively simple and is not applicable to specific geological stratum. Therefore, the ultimate bearing capacity results obtained from the field plate loading test are used as the reference to verify the calculation results of the original equation. The deformation modulus is calculated for the foundation soil under each level of load applied in the plate loading test and the results are summarized in Table 3. For the calculation with the Terzaghi's bearing capacity equation, the natural volumetric weight of coral reef sandy soil is taken as 17.2 kN.m^{-3} , the cohesion of coral reef sandy soil is almost 0 and the internal friction angle varies within the range of $40\text{-}42^\circ$.

Table 3. Calculation results of unmodified Terzaghi's bearing capacity equation for foundation before reinforcement

Test No.	Depth (m)	Diameter of loading plate (m)	Cohesion (kPa)	Internal friction angle ($^\circ$)	Deformation modulus (kPa)	Ultimate bearing capacity (kN)
SY-1	0.5	0.5	0	41.11	11.22	1016.3716
SY-2	0.5	0.5	0	41.06	11.02	1008.7585
SY-3	0.5	0.5	0	40.49	8.74	926.4538
SY-4	0.5	0.5	0	40.4	8.4	914.1885
SY-5	0.5	0.5	0	40.97	10.69	995.2185
SY-6	0.5	0.5	0	42.02	14.89	1167.5714
SY-7	0.5	0.5	0	40.59	9.16	940.3092
SY-8	0.5	0.5	0	40.39	8.37	912.8324

Note: The internal friction angle and deformation modulus in the Table are obtained by regression analysis of the SPT blow count

According to Table 3, the values calculated with unmodified Terzaghi's bearing capacity equation for the foundation before reinforcement deviate significantly from the measured ones, about twice greater. As a result, the original Terzaghi's bearing capacity equation is not applicable to the coral reef sandy soil foundation and cannot be directly used in engineering design.

3.1. Modification of Terzaghi's bearing capacity equation for foundation before reinforcement

The theoretical equation is mainly modified with the mathematical statistics method. The coefficients in the original equation are modified based on the mathematical statistics analysis for the plate loading test. According to previous research results, there is a nonlinear relationship between the bearing properties of the foundation soil and the mechanical parameters of the soil body including cohesion and internal friction angle. Therefore, the power function fitting is used to modify the bearing capacity parameter, as shown in Eq. (7) and Eq. (8):

$$P_{u_1} = m_1 L^\alpha, \tag{7}$$

$$P_{u_2} = m_2 d^\beta. \tag{8}$$

The power law constants α and β vary in the range of 0.5 to 1.0. For P_u , the acting forms of cohesion and internal friction angle remain unchanged. N_c , N_q , N_r are calculated using Eqs. (4), (5) and (6). After the relationship between P_u and the two variables is analyzed, Terzaghi's ultimate bearing capacity equation is kept unchanged for comparison with the theoretical equation. The variables are included in a trinomial equation to acquire the hypothetical regression equation, as shown in Eq. (9):

$$P_u = b_1 c N_c + b_2 L^\alpha N_q + b_3 \gamma^\beta N_r, \tag{9}$$

where, b_1 , b_2 , and b_3 are regression coefficients, and other parameters have the same meanings as defined above. Regression analysis is conducted based on the eight bearing capacity test values in the Table in combination with mathematical statistics.

To simplify the analysis steps, the following assumptions are made: $x_1 = c N_c$, $x_2 = \gamma_1 L^\alpha N_q$, $x_3 = \gamma d^\beta N_r$. Then the above equation can be transformed into the Eq. (10):

$$P_u = b_1 x_1 + b_2 x_2 + b_3 x_3. \tag{10}$$

The above equation is a multivariate linear equation. With different values assumed for α and β , the corresponding regression coefficients b_1 , b_2 and b_3 are solved according to the linear regression equation. Then the significance test is conducted to select the optimal regression equation. It is assumed that the ultimate bearing capacity value is a dependent variable and x_1 , x_2 and x_3 are independent variables that vary with the variation of the internal friction angle ψ . Thus, the internal friction angle ψ is defined as the variable factor of the multivariate linear equation. Considering that all three independent variables are selected through the correlation coefficient method, the screening step is not considered during the regression analysis.

"INPUT" is selected as the regression method for full regression analysis. By comparing the linear correlation coefficient, likelihood ratio, regression equation fitting information and its significance level, and the significance level of the linear coefficient standard value, it is found that when $\alpha = 0.6$ and $\beta = 1.0$, the regression equation has the highest significance level and the best goodness of fit; the coefficient of multiple determination R^2 is 0.981; the linear regression coefficients are as follows: $b_1 = 0$, $b_2 = 2.203$, $b_3 = 0.029$. Thus, the regression equation is shown in Eq. (11):

$$P_u = 2.203x_2 + 0.029x_3. \tag{11}$$

The multiple linear regression model passes the F-test and the significance level of the linear regression equation is found to be very high according to the residual statistics. In addition, the standardized predicted value based on regression analysis also passes the T-test and presents a high significance level. Through the T-test with a 90 % confidence level, it is determined that the significance levels of regression coefficients b_1 , b_2 and b_3 meet the requirements.

Table 4. Fitting information of bearing capacity regression equation

Variable name	Standardized coefficient	Significance	Tolerance	T-test	VIF
x_1	0	0.919	0.27	0.536	3.70
x_2	2.203	0.943	0.34	0.518	2.94
x_3	0.029	0.908	0.34	0.684	2.94

Based on the above analysis results, Terzaghi's bearing capacity equation for foundation before reinforcement is shown in Eq. (12):

$$P_u = 2.203L^{0.6}\gamma_1N_q + 0.029\gamma^{1.0}N_r, \quad (12)$$

where γ_1 is the equivalent volumetric weight of the soil body above the foundation in kN.m^{-3} ; d is the diameter of the pile foundation in m; γ is the volumetric weight of the foundation soil in kN/m^3 ; c is the cohesion of the foundation soil.

Terzaghi's ultimate bearing capacity coefficients remain unchanged as N_c , N_q , N_γ , and their values can be calculated with Eqs. (4), (5) and (6) respectively. The internal friction angle and cohesion are put into the fitting equation of the bearing capacity for foundation before reinforcement, and the calculated results are compared with the actual measured values. It can be seen from Fig. 5 that the calculated values are different from the actual measured values. Most results of the modified Terzaghi's theoretical bearing capacity equation is larger than the measured values, but the values differ from each other generally within a small range, not exceeding 10 %.

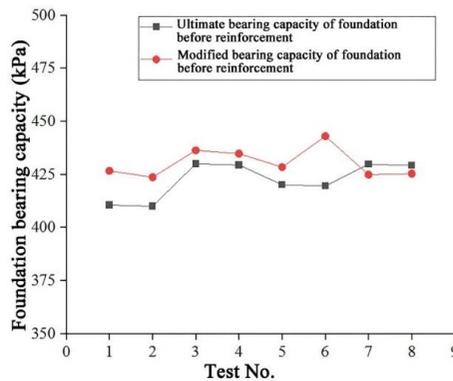


Fig. 5. Comparison between modified value and measured value curves before reinforcement

3.2. Modification of Terzaghi's bearing capacity equation for foundation before reinforcement

The field loading test values of the bearing capacity for the foundation after reinforcement are summarized as shown in Table 5. It can be found that after vibration rolling and dynamic compaction, the cohesion of the soil body has increased compared with that before reinforcement, but limited to a small scale, and its value is taken within the range of 0-1; the internal friction angle has increased significantly compared with that before reinforcement, indicating that the strength of the soil body has been further improved, and the ultimate bearing capacity of the foundation has increased significantly. Now Terzaghi's bearing capacity equation for foundation is modified, mainly by the same steps as stated above.

It can be seen from Table 5 that the calculation results of the bearing capacity are rather large by using the original Terzaghi's bearing capacity equation for coral reef sandy soil foundation after reinforcement. They deviate largely from the measured data and are about 2 times larger, and some 3 times larger. The calculation results of the unmodified Terzaghi's bearing capacity equation for coral reef sandy soil present large errors and are inconsistent with the actual engineering conditions.

The assumed regression equation is the same as Eq. (11). When different values are assumed for α and β , the corresponding regression coefficients b_1 , b_2 and b_3 are solved according to the linear regression equation, and then the significance testing is conducted to select the optimal regression equation. It is assumed that the ultimate bearing capacity value is the dependent variable and x_1 , x_2 and x_3 are independent variables and vary with the variation of the internal friction angle ψ , so the internal friction angle ψ is defined as the variable factor of the multivariate linear equation. Considering that all three independent variables are selected through the

correlation coefficient method, the screening step is not considered during the regression analysis. Inputs are selected in the regression method for full regression analysis. By comparing the indicators including linear correlation coefficient, likelihood ratio, regression equation fitting information and its significance level, and the significance level of the linear coefficient standard value, it is found that when $\alpha = 0.6$, $\beta = 1.0$, the regression equation is at the highest significance level. At this time, the fitting of the equation is optimal. The coefficient of multiple determination R^2 is 0.827, and the linear regression coefficients are as follows: $b_1 = 18.799$, $b_2 = 0.0816$, $b_3 = 0.735$, then the modified Terzaghi's foundation bearing capacity equation after reinforcement are shown in Eq. (13) and Eq. (14):

$$P_u = 15.799cN_c + 0.0816L^{0.6}N_q + 0.435\gamma N_r, \tag{13}$$

$$P_u = 15.799cN_c + 0.0816L^{0.6}N_q + 0.435\gamma N_r, \tag{14}$$

where γ_1 is the equivalent volumetric weight of the soil body above the foundation in $\text{kN}\cdot\text{m}^{-3}$; d is the diameter of the pile foundation in m; γ is the volumetric weight of the foundation soil in kN/m^3 ; c is the cohesion of the foundation soil.

Table 5. Calculation results of original Terzaghi's bearing capacity equation for foundation before reinforcement

Test No.	Reinforcing method	Depth	Diameter of loading plate	Cohesion	Internal friction angle	Deformation modulus	Ultimate bearing capacity
SY-1	Vibration rolling	0.5	0.5	0~10	48.65	41.38	1378.2393
SY-2	Vibration rolling	0.5	0.5	0~10	48	38.81	1228.0331
SY-3	500 kJ dynamic compaction	0.5	0.5	0~10	47.16	35.42	1061.7567
SY-4	500 kJ dynamic compaction	0.5	0.5	0~10	47.23	35.73	1074.5639
SY-5	1000 kJ dynamic compaction	0.5	0.5	0~10	50.03	46.92	1776.1019
SY-6	1000 kJ dynamic compaction	0.5	0.5	0~10	50.27	47.87	1858.5464
SY-7	3000 kJ dynamic compaction	0.5	0.5	0~10	52.17	55.48	2700.6564
SY-8	3000 kJ dynamic compaction	0.5	0.5	0~10	53.21	59.63	3352.9516

Note: The internal friction angle and deformation modulus in the Table are obtained by regression analysis of the SPT blow count

The multiple linear regression model passes the F-test and the significance level of the linear regression equation is found to be very high according to the residual statistics. In addition, the normal expected value of regression analysis also passes the T-test and presents a high significance level. Through the T-test with the confidence level at 90 %, it is determined that the significance levels of regression coefficients b_1 , b_2 and b_3 meet the requirements.

Table 6. Fitting information of bearing capacity regression equation

Variable name	Standardized coefficient	Significance	Tolerance	T-test	VIF
x_1	15.799	0.961	0.32	0.52	3.12
x_2	0.0816	0.832	0.38	0.639	2.63
x_3	0.435	0.826	0.41	0.672	2.42

Terzaghi's ultimate bearing capacity coefficients remain unchanged as N_c , N_q , N_r . After calculation, the internal friction angle and cohesion are put into the fitting equation of the foundation bearing capacity after reinforcement, and the calculated results are compared with the

measured values. It can be seen from Fig. 6 that the calculated values are different from the measured values. Most results of Terzaghi's theoretical bearing capacity equation are smaller than the field measured values. Among them, the modified value of bearing capacity after 500 kJ dynamic compaction differs from the test value largely, nearly 10%. The modified values after other reinforcement measures are basically consistent with the test values, generally with a small deviation. This modified equation can provide a feasible method for calculating the bearing capacity of the coral reef sandy soil or calcareous soil foundation after reinforcement.

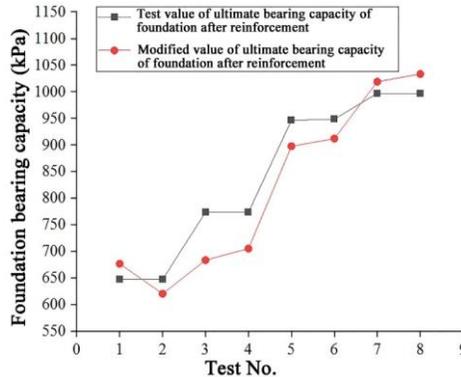


Fig. 6. Comparison between modification value and measured value curves after reinforcement

4. Conclusions

Based on the field plate loading test data and the multiple linear regression model, the optimal regression equation is selected out through the significance testing and Terzaghi's bearing capacity equation is modified. The modified bearing capacity equations suitable for foundations in the coral reef sandy soil area are proposed, which are Terzaghi's bearing capacity equations for coral reef sandy soil foundation before and after reinforcement, and these two equations provide a simple and practical method for determining the bearing capacity of coral reef sandy soil foundations in the Red Sea Area and provide a certain reference for engineering construction in similar areas.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (Grant No. 51708516), the National Natural Science Foundation of China (Grant No. 51708516), China Postdoctoral Science Foundation (2021M691391), the Open Foundation of the United Laboratory of Numerical Earthquake Forecasting (Grant No. 2021LNEF04).

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