

Estimation of Ultimate Bearing Capacity of Soil for Shallow Foundation



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Abstract Evaluation of ultimate bearing capacity is a tedious process, as the determination of shear strength parameters within the underlying soil structure is a difficult task. The purpose of current research work was to arrive at an alternative way for calculating ultimate bearing capacity by thoroughly considering soil properties like density, specific gravity and grain size distribution. Soil samples were collected from different construction sites of South Goa at 1.5 m depth from the ground level. Numerous tests like core cutter, moisture content, specific gravity, direct shear, sieve analysis and pipette analysis were conducted to determine the soil properties. Using the results of direct shear test (c and ϕ values), ultimate bearing capacities were calculated as per Terzaghi, Hansen, Meyerhof, Vesic and code IS: 6403-1981 methods for square footing of $2\text{ m} \times 2\text{ m}$. The softwares like SoFA and OptumG2 were also used to calculate ultimate bearing capacities. Various correlation equations were arrived between different soil properties and ultimate bearing capacity using multiple regression technique. The softwares used to arrive at a regression equation were IBM SPSS Statistics 24 and Minitab. Prediction accuracies were evaluated using coefficient of determination, root mean square error and mean error between the measured and the predicted values.

Keywords Ultimate bearing capacity · Shear strength · Multiple regressions · OptumG2 software · Minitab

1 Introduction

Bearing capacity is the strength of the soil, which absorbs the superstructure effort, without undergoing shear failure or excessive settling. While designing the foundation we consider two main factors, namely the ultimate bearing capacity (UBC) of the soil beneath the foundation and the amount of settlement that is allowed with taking

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into consideration that the settlement does not affect the efficiency of soil. The ultimate bearing capacity means the load under the foundation can carry without failing in shear and the settlement consists of approximation of the settlement which is caused by superstructure load [1]. The bearing capacity of foundations depends on some of the mechanical properties of the soil, such as density, shearing strength and deformation characteristics. It also depends on the original stresses and the water conditions inside the ground. The size, shape, depth and roughness are some visible features of the foundation on which bearing capacity depends [2]. Judging of the ultimate bearing capacity is a tough process as it is hard to evaluate the shear strength parameters within the underlying soil structure. To determine the ultimate bearing capacity of soil for shallow foundation, Terzaghi's [3], Meyerhof's [2], Hansen's [4], Vesic's [5], IS 6403: 1981 [6] methods and also softwares such as SoFA [7] and OptumG2 [8] were used. A comparison was made between the values found from methods given by various investigators, SoFA and OptumG2. Manual methods for the estimation of ultimate bearing capacity are based on shear strength parameters. A nonlinear regression is used to model the relationship between bearing capacity and fines contents of soil using square footing [9]. An attempt was made to provide an easier, faster and economical method to determine the ultimate bearing capacity of soil by generating an equation by regression analysis using IBM SPSS Statistics 24 [10] and Minitab [11] softwares. A relationship was derived between ultimate bearing capacity and soil properties such as density, specific gravity and grain size distribution. Based on the coefficient of determination (R^2), the derived equation was validated. The nearer the R^2 is to 1, the accurate is the relationship between the dependent and independent variables [12].

2 Methodology

The present work was carried out for shallow foundation considering a square footing of size $2\text{ m} \times 2\text{ m}$ and depth of foundation as 1.5 m.

2.1 Soil Sampling

The soil samples used in the study were collected from different talukas of Goa. The samples were collected using core cutter method from the base of the foundation which were approximately at 1.5 m depth. The location of some of the sites from where the soil samples were collected is as shown in Table 1.

Table 1 Location of sites

Soil sample	Location	Latitude	Longitude
Site 1	Housing Board, Gogol, Curtorim, Margao	15°16'47.0'' N	73°59'35.4'' E
Site 2	Behind Korgaonkar Petrol Pump, Fatorda, Margao	15°17'29.5'' N	73°58'37.3'' E
Site 3	Panjifond, Margao	15°16'31.3'' N	73°57'46.4'' E
Site 4	Borda, Margao	15°16'47.9'' N	73°58'28.4'' E
Site 5	Near GEC campus, Donshiwadi, priol, Ponda	15°25'11.0'' N	73°58'59.5'' E
Site 6	Ponda Tisk, Ponda	15°23'37.7'' N	74°00'07.9'' E
Site 7	Mhalshewada, Margao-Belgaum By pass Road, Ponda	15°24'16.4'' N	74°01'51.8'' E
Site 8	Near Margao-Quepem Road, Paroda, Quepem	15°13'19.5'' N	74°03'29.7'' E
Site 9	Pontemol, kakoda, Quepem	15°15'05.4'' N	74°07'28.0'' E
Site 10	Margao-Chandor-Curchorem Road, Xelvona, Quepem	15°15'52.5'' N	74°05'02.8'' E
Site 11	Near Sanguem-Calem Road (MDR35), Sanguem	15°14'07.4'' N	74°08'58.2'' E
Site 12	Kharkhate Ghati, Cotarli, Sanguem	15°13'44.5'' N	74°07'60.0'' E
Site 13	Near Tilamol-Rivona-Colomb Road, Rivona, Sanguem	15°09'32.3'' N	74°06'57.1'' E

2.2 Laboratory Analysis

The different tests on soil samples were conducted in laboratory-like core cutter test to find density and moisture content; direct shear test to find cohesion (c) and angle of friction (ϕ); specific gravity test, wet sieve analysis to find percentage of gravel and sand; and pipette analysis to find percentage of silt and clay.

2.3 Data Analysis

The data obtained from the above test results were used to find ultimate bearing capacity of soil at different sites. Using the values of ultimate bearing capacity, regression analysis was done using IBM SPSS Statistics 24 Regression analysis and Minitab software.

3 Results and Discussion

Tests were carried out on the soil samples to determine different properties of soil. The tests like density of soil according to IS:2720 (1975: Part 29) [13], moisture content according to IS:2720 (1973: Part 2) [14], specific gravity according to IS:2720 (1981: Part 3: Sect. 3) [15], shear strength (cohesion and angle of internal friction) according to IS:2720 (1986: Part 13) [16], wet sieve analysis (% gravel and % sand) and pipette analysis (% clay and % silt) according to IS:2720 (1985: Part 4) [17] were conducted. The test results of different soil samples for the above properties are as shown in Table 2.

The inputs required to find the ultimate bearing capacity of soil are cohesion, unit weight of soil, depth of foundation, width of footing and angle of internal friction. A square footing of size 2 m × 2 m was considered. The ultimate bearing capacity for each soil sample was determined using Terzaghi's analysis, Hansen's analysis, Vesic's analysis and IS 6403: 1981 code and also using softwares such as SoFA and OptumG2. The values of ultimate bearing capacity are shown in Table 3.

In statistical modelling, regression analysis is a set of statistical processes for estimating the relationships among variables. It includes many techniques for modelling and analysing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables (or predictors). More specifically, regression analysis helps one understand how the typical value of the dependent variables changes when any one of the independent variables is varied, while the other independent variables are held fixed. Multiple linear regression analysis was carried out between the values of ultimate bearing capacity and the soil properties (such as density, specific gravity and grain size distribution) to form an equation using IBM SPSS Statistics 24 Regression analysis and Minitab software. After the comparison was made between manual methods and softwares, it was found that IS 6403: 1981 code values and OptumG2 softwares values of ultimate bearing capacity are similar. Hence IS 6403: 1981 code values of ultimate bearing capacity were used for regression analysis. The independent variables used in regression were density (kN/m^3), specific gravity, gravel (%), sand (%), silt (%), clay (%) and water content (%). Using different combination of variables, regression analysis was done and the combination which gives greater value of coefficient of determination was considered as perfect combination which relates variables well. Using combination of dependent variable as ultimate bearing capacity and independent variables as specific gravity, density, gravel (%), sand (%) and silt (%) an equation was obtained which gives greater value of coefficient of determination from all other combination which were used for regression analysis in IBM SPSS Statistics 24 Regression analysis software. To check whether there was any multiple relation between the variables selected the simple correlations, variance increase factors (VIFs), tolerance value and the condition index (CI) were examined. The values of VIF are shown in Table 4.

When the simple correlations are examined, if variance increase factors (VIF) is equal to or greater than 10, then there are multiple relations between variables

Table 2 Soil test results

Soil sample	Dry density (g/cm ³)	Water content (%)	Specific gravity	Cohesion (kN/m ²)	Angle of friction (in degrees)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Site 1	1.45	31.36	2.69	4.807	12.27	6.6	20.0	73.4	0.00
Site 2	1.75	14.99	2.73	12.753	12.13	39.2	39.2	21.6	0.00
Site 3	1.83	14.24	2.57	1.780	17.87	50.0	13.6	36.4	0.00
Site 4	1.64	12.27	2.89	15.696	14.70	36.4	23.4	40.2	0.00
Site 5	1.63	13.44	2.96	10.100	20.68	43.8	38.6	1.4	0.18
Site 6	1.93	15.81	2.69	5.000	13.22	58.4	12.4	28.5	0.71
Site 7	1.57	14.00	2.61	2.330	11.15	15.4	27.6	57.0	0.00
Site 8	1.80	15.51	2.54	5.200	11.86	21.8	29.2	48.4	0.63
Site 9	1.74	9.07	2.67	9.830	10.24	55.4	30.2	14.4	0.00
Site 10	1.50	6.49	2.51	8.400	5.63	0.2	59.2	40.6	0.00
Site 11	1.80	12.76	2.73	13.160	10.26	33.2	30.0	36.8	0.00
Site 12	1.54	9.07	2.55	7.200	7.69	0.4	23.2	76.4	0.00
Site 13	1.77	11.95	2.87	18.400	10.24	18.1	43.9	38.0	0.00

Table 3 Comparison of ultimate bearing capacity using manual method, SoFA and OptumG2

Soil sample	Theory (kN/m ²)				Software (kN/m ²)			
	Tetzaghi				SoFA			
	Meyerhof	Hansen	Vesic	IS code	Meyerhof	Hansen	OptumG2	
1	111.85	169.98	185.98	193.29	99.96	165.50	178.64	80.55
2	212.75	303.78	329.36	341.53	174.90	297.81	321.87	184.95
3	138.19	281.02	298.98	319.07	148.52	272.18	292.41	144.74
4	272.62	412.82	438.71	467.81	217.05	413.36	445.48	256.56
5	284.48	570.31	567.94	636.72	244.11	565.17	592.52	314.31
6	140.94	224.04	245.92	250.70	130.55	219.38	237.01	124.27
7	81.81	128.91	138.72	143.39	80.47	122.34	131.36	48.72
8	127.37	192.43	210.53	219.87	116.27	186.76	201.38	100.65
9	161.13	217.95	238.54	246.28	136.72	216.67	233.39	126.16
10	110.64	130.59	150.56	143.13	90.18	118.83	135.61	55.99
11	198.27	263.60	288.43	306.07	163.37	262.93	283.65	163.07
12	112.28	143.07	160.81	158.93	93.09	125.08	148.24	64.42
13	245.39	314.62	344.76	365.24	193.75	290.69	338.42	203.98

Table 4 Multiple relations coefficients

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.	Correlations			Collinearity statistics		
	B	Std. Error				Beta	Zero-order	Partial	Part	Tolerance	VIF
	1	Specific Gravity	260.176	59.272	4.746	4.390	0.003	0.961	0.856	0.199	0.002
	Density (kN/m ³)	5.690	7.205	0.658	0.790	0.456	0.956	0.286	0.036	0.003	336.478
	Sand (%)	-6.092	2.152	-1.373	-2.831	0.025	0.900	-0.731	-0.129	0.009	114.140
	Gravel (%)	-6.450	2.413	-1.533	-2.673	0.032	0.871	-0.711	-0.121	0.006	159.367
	Silt (%)	-6.944	1.989	-2.130	-3.492	0.010	0.766	-0.797	-0.159	0.006	180.449

[12] and from Table 4, it can be seen that VIF values for all are greater than 10. In addition to these, if tolerance values are greater than 0.10, no multiple relations between variables are decided [12]. It can be seen from Table 4 that all tolerance values are less than 0.10. The absolute value β (beta) in Table 4 indicates the order of importance of the independent variables. The variable with the highest β value is relatively the most important variable. The CI values are shown in Table 5.

In cases where the CI value is greater than 30, it is regarded that there are multiple relations between variables [12]. Yet, as it is clear from Table 5, the CI values calculated are greater than 30. Thus, it can be concluded that there were multiple relations between the variables. The summary of the model according to ANOVA statistics is shown in Table 6.

In consequence of the standard regression analysis, the model's degree of predicting dependent variable, that is, correlation coefficient was found to be $R = 0.993$. The model's degree of explaining the variance in the dependent variable, that is, coefficient of determination was found to be $R^2 = 0.986$. Hence, the model predicts the dependent variable very well. Based on the regression analysis result, the regression equation was obtained as shown in Eq. 1:

$$\text{UBC} = 260.176X_1 + 5.690X_2 - 6.092X_3 - 6.450X_4 - 6.944X_5 \quad (1)$$

where UBC = ultimate bearing capacity, X_1 = specific gravity, X_2 = density (kN/m^3), X_3 = sand (%), X_4 = gravel (%), X_5 = silt (%).

Values used for regression analysis (observed UBC, that is, values obtained from IS 6403: 1981 code) and values obtained from Eq. 1 of regression analysis (predicated UBC) are tabulated in Table 7 and graph of observed UBC versus predicated UBC is shown in Fig. 1.

To verify the results obtained using IBM SPSS Statistics 24 software, Minitab was used. The test results which were used as input for regression analysis in IBM SPSS Statistics 24 software were used in Minitab software. The result of regression analysis obtained using Minitab software is shown in Table 8.

When the correlations were examined with Minitab software, from Table 8, it can be seen that VIF values for all terms are greater than 10 (Gulden et al. 2013). The result of regression analysis obtained using Minitab software is shown in Table 9.

From Table 9, the coefficient of determination was found to be $R^2 = 98.56\%$. The regression equation was obtained as it is shown in Eq. 2:

$$\begin{aligned} \text{UBC}(\text{kN/m}^2) = & 5.69 \text{ Density } (\text{kN/m}^3) + 260.2 \text{ Specific Gravity} \\ & - 6.45 \text{ Gravel } (\%) - 6.09 \text{ Sand } (\%) - 6.94 \text{ silt } (\%) \end{aligned} \quad (2)$$

The regression equations obtained from IBM SPSS Statistics 24 software and Minitab software are the same.

Table 5 Multiple relations between CI values

Model	Dimension	Eigenvalue	Condition index	Variance proportions					
				Density (kN/m ³)	Specific gravity	Gravel (%)	Sand (%)	Silt (%)	
1	1	4.336	1.000	0.00	0.00	0.00	0.00	0.00	
	2	0.474	3.025	0.00	0.00	0.01	0.00	0.00	
	3	0.186	4.826	0.00	0.00	0.00	0.03	0.01	
	4	0.003	39.024	0.68	0.19	0.05	0.01	0.02	
	5	0.001	65.793	0.32	0.81	0.94	0.96	0.97	

Table 6 Model summary

Model	R	R square	Adjusted R square	Std. Error of the estimate
1	0.993	0.986	0.975	23.11

Table 7 Observed and predicated values of ultimate bearing capacity

S. No	Observed UBC (kN/m ²)	Predicted UBC (kN/m ²)	Error
1	99.96	108.28	-8.32
2	174.90	168.22	6.68
3	148.52	114.67	33.86
4	217.05	188.74	28.31
5	244.11	224.24	19.87
6	130.55	159.64	-29.09
7	80.47	105.12	-24.65
8	116.27	108.89	7.38
9	136.72	152.37	-15.65
10	90.18	94.53	-4.35
11	163.37	160.26	3.11
12	93.09	76.64	16.45
13	193.75	199.38	-5.63

Fig. 1 Graph of observed UBC versus predicated UBC

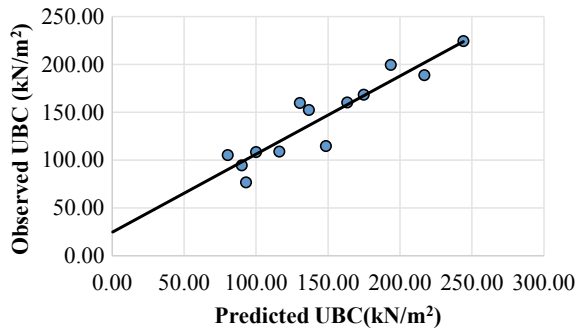


Table 8 Multiple relations coefficients

Term	Coefficients	SE coefficients	T-value	P-value	VIF
Density (kN/m ³)	5.69	7.20	0.79	0.456	336.48
Specific gravity	260.2	59.3	4.39	0.003	566.79
Gravel (%)	-6.45	2.41	-2.67	0.032	159.37
Sand (%)	-6.09	2.15	-2.83	0.025	114.14
Silt (%)	-6.94	1.99	-3.49	0.010	180.45

Table 9 Model summary

Std. error of the estimate	<i>R</i> -square	<i>R</i> -square adjusted	<i>R</i> -square predicted
23.1117	98.56%	97.53%	95.63%

4 Conclusion

The ultimate bearing capacity of selected soil samples were determined using Terzaghi, Hansen, Meyerhof, Vesic and IS: 6403-1981 code methods and were compared with OptumG2 and SoFA softwares. The IS 6403:1981 code comparatively matched the software results. The relationship between the soil properties and ultimate bearing capacity of square footing was determined. The regression analysis was performed using values of ultimate bearing capacity obtained using IS 6403: 1981 code and soil properties (specific gravity, density, gravel (%), sand (%) and silt (%)). Regression analysis was done using IBM SPSS Statistics 24 software and was verified using Minitab software. The variance increase factor (VIF) values for all the variables were greater than 10, and also the tolerance values were less than 0.10. The condition index (CI) values obtained were greater than 30. The values of variance increase factor (VIF), tolerance and condition index (CI) state that there are multiple relations between dependent variables and independent variables. The correlation coefficient was found to be $R = 0.993$ and the coefficient of determination was found to be $R^2 = 0.986$. Hence, the model predicts the dependent variable very well. The results obtained from Minitab software and the regression analysis are similar. The relationship between density, specific gravity, grain size distribution and ultimate bearing capacity is valid for locations in the vicinity of the collected soil samples, and for more accuracy data analysis has to be done on more number of soil samples.

References

1. Venkatramaiah C (2006) Geotechnical engineering, 3rd edition. New Age International (P) Limited, Publishers, pp 607–613
2. Meyerhof GG (1951) The ultimate bearing capacity of foundations. *Geotechnique* 2:301–332
3. Terzaghi K (1928) Theoretical soil mechanics. Wiley, New York
4. Brinch Hansen J (1961) A general formula for bearing capacity. Bulletin No.11, Danish Technical Institute, Copenhagen, Denmark, pp 38–46
5. Vesic AS (1973) Analysis of ultimate loads of shallow foundations. *J Soil Mech Found Div* (1973)
6. IS: 6403-1981 (1981) Code of practice for determination of bearing capacity of shallow foundation. Bur Indian Stand
7. Nikolaou K (2016) SoFA: a matlab-based educational software for the shallow foundation analysis and design. <https://www.sofastatistics.com/>
8. OptumG2 (2018) Optum computational engineering. Version 2018.07.28, Denmark. <https://www.optumce.com/>

9. Adunoye GO, Agbede OA (2013) Statistical modelling of the relationship between bearing capacity and fines content of soil using square footing. *Civ Environ Res* 3(2):75–81
10. IBM SPSS Statistics 24 (2016) IBM corporation, Version 24. <https://www.spss.com/>
11. Minitab® 19 (2019) Minitab statistical software, Version 19.1.1. <https://www.minitab.com/>
12. Uyanik GK, Guler N (2013) A study on multiple linear regression analysis, 4th international conference on new horizons in education. *Procedia Soc Behav Sci* 106:234–240
13. IS: 2720-29 (1975) Determination of dry density of soils in-place by the core-cutter method. Bur Indian Stand (1st Revision)
14. IS: 2720-2 (1973) Determination of water content. Bur Indian Stand (2nd Revision)
15. IS: 2720-3-1 (1981) Determination of specific gravity. Bur Indian Stand (1st Revision)
16. IS: 2720-13 (1986) Direct shear test. Bur Indian Stand (2nd Revision)
17. IS: 2720-4 (1985) Grain size analysis. Bur Indian Stand (2nd Revision)