Assessment of the Variability of Bearing Capacity of Soils in Selected Districts of Southern Malawi for Shallow Foundations

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Abstract

This study was done to assess the soil bearing capacities of various districts of the southern region of Malawi. The objective was to provide a basic guide for the construction industry and shallow foundation design experts on the ultimate bearing capacity values for the various areas in some districts of the southern region of Malawi for decision making. The methodology applied in this study used the Dynamic Cone Penetrometer (DCP) test to determine the bearing capacity of the various sites. Data for the study was collected from six selected districts in the southern region which were sampled based on the geological regions with regards to southern region of Malawi. The DCP tests were conducted at randomly selected designated secondary schools of these districts. Interpretation of the DCP results was done using conversion equation from DCP values to California Bearing Ratio (CBR) values then to the equivalent bearing capacities. Results have shown that the most probable ultimate bearing capacity amongst the six districts is 115kN/m^2. Although there is variation in the overall results obtained, some similarities were observed in the districts of Blantyre and Mangochi which recorded very hard strata. Further similarities were also observed in the districts of Mulanje, Nsanje and Chiradzulu with results ranging from loose to firm ultimate bearing capacities.

Key words: bearing capacity; foundation design; dynamic cone penetrometer, shallow foundation.

1. Introduction

Murton (2021) defines soil bearing capacity as the maximum load per unit area that a soil can carry without yielding or deforming. Design of shallow foundations requires an understanding of the bearing capacity of the underlying soil on which the structure is to be built on. As described by Ampadu (2006), proper geotechnical engineering practice requires that the scope of a site investigation be made commensurate with the type of geotechnical problem at hand. For small projects especially in developing countries, simple and economical methods of site investigation are required. There exists a simple, rapid and well-established standard cone penetrometer test (CPT) which is mostly used in the developed countries but is rarely used in the developing world. This is because the method is relatively expensive.

Most countries in Africa, Malawi inclusive, have resorted to the use of the Dynamic Cone Penetrometer (DCP) testing method to aid in the determination of the bearing capacity of soils. A typical DCP according to Mohammadi et al. (2008) consists of an 8 kg hammer that drops over a height of 575 mm. This yields a theoretical driving energy of 45 J and drives a 60^o cone tip with 20 mm base diameter vertically into the ground (Figure 1).

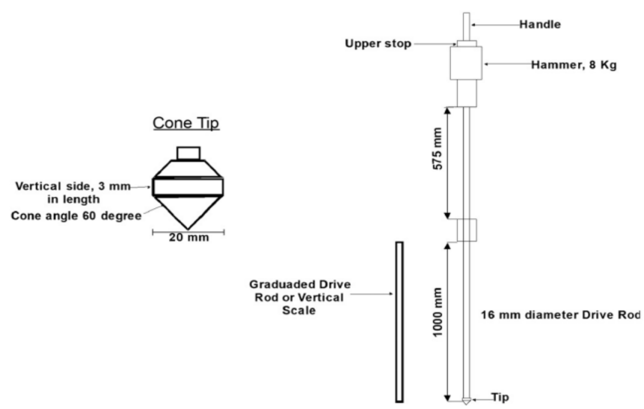


Figure 1: Dynamic Cone Penetrometer (DCP). (Mohammadi et al. 2008; Edil and Benson, 2005)

The steel rod to which the cone is attached has a smaller diameter than the cone (16 mm) to minimize the effect of skin friction. Ground investigation using DCP usually goes to a depth of 1 m to 2 m. The number of blows during operation is recorded with depth of penetration. The slope of the curve defining the relationship between number of blows and depth of penetration (in millimetres per blow) at a given linear depth segment is recorded as the DCP penetration index (DPI). DPI for each depth can also be calculated by Eq. (1) (Mohammadi et al. 2008; Embacher, 2005).

$$DPI = \frac{P_{i+1} - P_i}{B_{i+1} - B_i} \qquad \text{Equation 1}$$

where, DPIis DCP Penetration Index (mm/blow), P is Penetration at $i\ or\ i+1$ hammer drops (mm); and Blow count at $i\ or\ i+1$ hammer drops

Furthermore, the analysis of the DCP data obtained must be interpreted following a standard procedure, to generate a representative value of penetration per blow for the material being tested. This representative value is usually obtained by averaging the DPI across the entire penetration depth at each test location. To calculate the representative value, one may use the arithmetic average or the weighted average. According to Mohammadi et al. 2008, Edil and Benson 2005, the arithmetic average can be obtained from Eq. 2.

$$DPI_{avg} = \frac{\sum_i^N DPI}{N} \qquad \text{Equation 2}$$

where N is the total number of DPI recorded in a given penetration depth of interest. In the weighted average technique, Eq. 3 can be used (Mohammadi et al. 2008, Edil and Benson 2005).

$$DPI_{wt.avg} = \frac{1}{H}\sum_i^N[(DPI)_i.(Z)_i] \qquad \text{Equation 3}$$

where Z is the penetration distance per blow set and H is the overall penetration depth of interest.

It should however be pointed out that the characteristics of the DCP used varies with preferences. A study of the literature notes that cones of different sizes and shapes are used in cone penetrometers. Table 1 compiled by Ampadu (2006) summarizes the basic characteristics of some DCPs. From the table, it can be observed that DCPs reported in the literature vary a great deal. However, it appears that most of them have energy per blow per unit cone area of 144 kN-m/m^2.

Table 1: Basic characteristics of Dynamic Cone Penetrometer (Ampadu, 2006)

Type	**Cone Diameter (mm)**	**Mass of Hammer (kg)**	**Height of Fall (mm)**	**Energy per blow per cone area (kN-m/m^2)**
Sowers and Hedges (1966)	38	6.8	508	30
Scala (1956)	20	9.08	508	144
Kleyn (1975)	20	8	575	144
Ampadu (2006)	20	10	460	144
Borros Penetrometer	50	63	750	231

1.1 Relationship between Dynamic Cone Penetrometer and California Bearing Ratio (CBR) Tests.

The interpretation of test results done using DCP method is usually done with respect to the CBR values. Basically, the outcome of a DCP test is a CBR value which is in turn converted to ultimate bearing capacity (q_u) using the modified equation 4, developed by Portland Concrete Association (1955).

$$q_u = 26.22xCBR^{0.664} \qquad \text{Equation 4}$$

where q_u is Bearing capacity (ultimate) kPa/kN/m^2, and CBR is California Bearing Ratio (%)

The results obtained from the overall DCP tests as indicated above are given by the ultimate bearing capacities. However, in practice, the bearing capacity is usually given in terms of safe bearing capacity and/or sometimes referred to as allowable bearing capacity. According to Johnson (2003) the ultimate bearing capacity of a soil is the maximum possible load that can be supported without any failure by for instance overturning. The book further defines allowable bearing capacity as the load on the soil not to be exceeded without causing settlements which would be too great for structural or operational application. As regards safe bearing capacity, Namdar and Feng (2014) noted that the term can be used interchangeably with allowable bearing capacity of a soil. In terms of moisture content, Shirur and Hiremath (2014) noted through experimentation that the CBR values decreases with increase in moisture of the soil. This is in tandem with DCP tests as the soil becomes wet, the effort required to penetrate the soil is significantly reduced which in turn results in the soil being rendered weak in terms of strength.

Determination of safe/allowable bearing capacity requires use of various parameters which sometimes may vary based on the type of soil, the condition of the soil and sometimes the subjective application of the structure being constructed (Craig 2004). With this in mind, this paper will therefore focus on the basic ultimate bearing capacities which can easily be converted to the safe bearing capacities based on the conditions and type of the soil as alluded above.

1.2 The case of Malawi

Malawian geology lies within the Mozambican mobile belt which is underlain by para and orthogneissic crystalline rocks (Dulanya 2017; Kroner et al. 2001; Kroner 1993; Carter and 115 Bennet 1973). These metamorphic rocks are overlain by Permo-Triassic and Cretaceous sedimentary rocks and intruded by a variety of alkaline rocks of Jurassic to Cretaceous age. These are overlain by younger sediments deposited in the major drainage basins of the country (Dulanya 2017). The geology can further be subdivided into regions as noted by Dill et al. 2005. The Southern region (Dill et al. 2005) can therefore be subdivided into four regions geologically namely; the Shire Highlands (peneplains), the Shire Valley (fluvial drainage system), the Phalombe plain (fluvio lacustrine) as well as the lake shore areas (Lake Malawi and Malombe). With respect to soils, the major soil types of Malawi according to Vargas and Omuto (2016) are dominated by Luvisols, Lixisols, and Cambisols with Cambisols largely predominant along the rift valley and the southern region of the country.

Although the necessity of characterizing soil in terms of its strength for foundation design cannot be overemphasized, the design and construction of structures requiring shallow foundations is usually overlooked in Malawi. Serious and comprehensive ground investigation is usually undertaken on complex structures involving piling and deep foundation excavations only. As for shallow foundations for dwelling houses and other small structures, the decisions are usually left to engineering judgment. This has led to among others the collapse of houses and other structures as well as heavy cracking due to expansiveness of soils under which the structures are built on (Craig 2004). This research will therefore highlight ranges of bearing capacities obtained in various districts of southern region of Malawi. The research further seeks to provide a basic guide as to the ranges of bearing capacities to be anticipated in the mentioned areas for the purpose of aid to the design of shallow foundations.

Das and Sivakugan (2016) defines a shallow foundation as a foundation placed within the soil at a depth less than the width of the foundation. These include pad, strip and mat (or raft) foundations. Pad foundations, also known as pad footings or spread footings, can be square, circular, or rectangular in plan and carry column loads. They spread the column load evenly into the underlying ground. Strip foundations or footings, also known as continuous foundations, support wall loads. Mat foundations can carry multiple column or wall loads. Typical shallow foundation designs for most dwelling houses and single storey structures in Malawi are usually strip or continuous footing.

2 Materials and Methods

2.1 Data sources and Sampling

The research was conducted in selected districts in the southern region of Malawi. Several areas and points were used for the study which were basically secondary schools. The number of secondary schools and/or data sources varied amongst the districts with others having more schools than the other districts. Sampling of the sites was based on the geological regions as described in the preceding paragraphs. Table 2 highlights the geological regions and the respective district(s) that were sampled. It should further be noted that due to the vastness of shire highlands, the sampled districts were on a higher side than the other regions.

Table 2: Sampling of the Districts based on geological Regions

Geological Region	Sampled District(s)
Shire Highlands	Blantyre, Chiradzulu and Zomba
Shire Valley	Nsanje
Phalombe Plains	Mulanje
Lake shore	Mangochi

Table 3 further illustrates the districts in the southern region and the secondary schools with which DCP tests were conducted for the research.

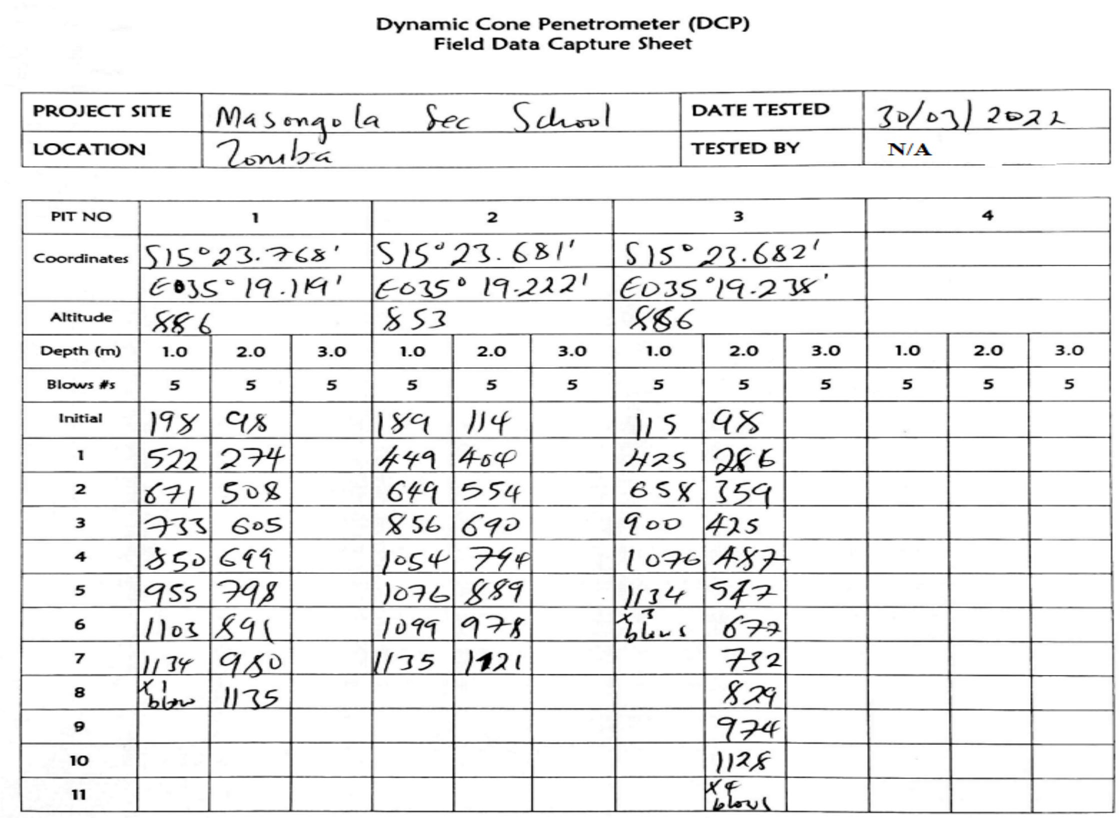
Table 3: Districts in the southern region and their data sources.

District	Secondary School/Data source/DCP test conducted
Blantyre	Lumbira CDSS Nkula CDSS Mdeka CDSS Ngumbe CDSS
Chiradzulu	Chiradzulu Sec. School Chiradzulu CDSS Nankhundi CDSS Mapesi CDSS
Mulanje	Muloza CDSS Mulomba CDSS
Nsanje	Nsanje Sec. School Mpatsa CDSS Nyankhwale CDSS
Mangochi	Tsekwere CDSS Mtuwa CDSS Lungwena CDSS Mbombwe CDSS
Zomba	Masongola Sec. School St Pauls CDSS Balamanja CDSS

2.2 Data Collection

As stated earlier, the data was collected using DCP tests on all the listed areas in table 3. The tests were done using the Kleyn (1975) type of DCP equipment with a 60^0 cone at the tip. This type of DCP equipment was used based on the availability and usage in Malawi. When it comes to determination of DCP tests in Malawi, most (if not all) soil mechanics laboratories use this type of equipment. Hence, for uniformity's sake, the research also used similar equipment. As described above, determination of bearing capacities using the other methods (CPT) has proven to be expensive and usually out of reach for a Malawian set up. Hence DCP provides a cheap and affordable alternative.

Three locations were selected for the tests at each site. Depending on the area of the site (school), the three locations were scattered apart to cover the schools land as much as possible with an average radius apart of 50m. The data collected was interpreted using various charts. A typical sample chart of the tests done in the field and recording is shown as Figure. 2. The recording was based on 5 blow intervals, where after every five blows the penetration reading was recorded. The tests were done to a depth of 2 m for each of the selected three locations at a site.



Dynamic Cone Penetrometer (DCP)
Field Data Capture Sheet

PROJECT SITE	Masongola Sec School	DATE TESTED	30/03/2022
LOCATION	Zomba	TESTED BY	N/A

PIT NO	1			2			3			4		
Coordinates	S15°23.768'			S15°23.681'			S15°23.682'					
	E035°19.191'			E035° 19.222'			E035°19.238'					
Altitude	886			853			886					
Depth (m)	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0
Blows #s	5	5	5	5	5	5	5	5	5	5	5	5
Initial	198	98		189	114		115	98				
1	522	274		449	404		425	286				
2	671	508		649	554		658	359				
3	733	605		856	690		900	425				
4	850	699		1054	794		1076	487				
5	955	798		1076	889		1134	547				
6	1103	891		1099	978		x3 blows	677				
7	1134	980		1135	1121			732				
8	x1 blow	1135						829				
9								974				
10								1128				
11								x4 blows				

Figure 2: A sample of a typical chart used for data recording.

3 Results and Interpretation

Results for all the locations highlighted in Table 2 were compiled with their corresponding bearing capacity estimates. Figure 3 highlights a typical sample chart of the results compiled for each location.

CLIENT	CLIENT	DATE TESTED	30 March 2022
PROJECT SITE	MBOMBWE CDSS - MANGOCHI DISTRICT	COMPUTED BY	

MEASUREMENT OF INSITU STRENGTH OF SOILS BY DCP METHOD

Dynamic Cone Penetrometer (DCP) - 60° Cone

Trial Pit	Depth (m)	Total Penetration Depth (mm)	Total Blows	DCP Value (mm/Blow)	DCP Value (blows/100mm)	Approximate CBR (%)	Safe Bearing Capacity (kPa)	Remarks
#1	1.0	939	17	55	1	3	115	Soft
	2.0	1012	48	21	4	8	140	Stiff
#2	1.0	972	48	20	4	8	140	Stiff
	2.0	1033	103	10	8	18	190	Very Stiff
#3	1.0	933	35	27	3	6	130	Stiff
	2.0	1027	92	11	7	16	180	Very Stiff

1 kPa = 1 kN/m²

Figure 3: Sample results chart for the DCP bearing capacity tests for Mbombwe site in Mangochi.

Table 8 attached in the appendix highlights the raw data results of the bearing capacities for all the sites in the 6 districts. Table 4 summarizes the results of the bearing capacities obtained to a depth of 2 m by giving a range of the values and the subsequent columns describe the results for the depth from 1 m to 2 m. The average values were based on the overall ultimate bearing capacity values for each site (the 3 points/locations).

Table 4: Summary of results for bearing capacities to a depth of 2 m

District	Site/Location	Bearing capacity range (kN/m^2)-1m depth	Average bearing capacity (kN/m^2)-1m depth	Bearing capacity range (kN/m^2) 1m – 2m depth	Average bearing capacity (kN/m^2) 1m – 2m depth
Blantyre	Lumbira CDSS	115-350	195	115-350	197
	Nkula CDSS	160-200	180	350-350	350
	Mdeka CDSS	120-140	128	165-180	172
	Ngumbe CDSS	115-300	177	115-350	193
Chiradzulu	Chiradzulu Sec. School	125-135	128	115-225	153
	Chiradzulu CDSS	115-190	148	115-180	142
	Nankhundi CDSS	115-120	118	125-145	135
	Mapesi CDSS	115-155	137	150-180	165
Mulanje	Muloza CDSS	115-115	115	120-120	120
	Mulomba CDSS	115-120	117	135-140	137
Nsanje	Nsanje Sec. School	115-115	115	135-150	140
	Mpatsa CDSS	115-135	122	135-150	142
	Nyankhwale CDSS	115-115	115	115-115	115
Mangochi	Tsekwere CDSS	140-180	157	265-350	305
	Mtuwa CDSS	115-120	117	115-130	123
	Lungwena CDSS	115-115	115	115-130	125
	Mbombwe CDSS	115-140	128	140-190	170
Zomba	Masongola Sec. School	120-130	125	125-140	132
	St Pauls CDSS	115-120	117	140-160	148
	Balamanja CDSS	115-130	122	130-180	158

From the results, using Microsoft excel sheets, the most probable values or the mode of bearing capacity in the respective districts can be obtained. This has been highlighted in Table 5. Furthermore, the averages as well as median values of the data sets have also been presented in tables 6 and 7 respectively.

Graphical plots using MATLAB software (The MathWorks Inc. 2016) for the data variations prescribed above were plotted and presented in the subsequent figures to better understand the behaviour of the bearing capacity values in the respective districts with respect to the most probable bearing capacity values, the average bearing capacity values as well as the median values for the same (Figure 4 – 6).

Table 5: Most Probable values of bearing capacity for the given districts.

District	Most Probable bearing capacity values (kN/m³)-1m depth	Most Probable bearing capacity values (kN/m³)- 2m depth
Blantyre	115	350
Chiradzulu	115	115
Mulanje	115	120
Nsanje	115	135
Mangochi	115	130
Zomba	120	130

Table 6: Average values of bearing capacity for the given districts.

District	Average bearing capacity values (kN/m³)-1m depth	Average bearing capacity values (kN/m³)-2m depth
Blantyre	175	223
Chiradzulu	133	167
Mulanje	116	128
Nsanje	117	132
Mangochi	129	181
Zomba	121	146

Table 7: Median values of bearing capacity for the given districts.

District	Median bearing capacity values (kN/m³)-1m depth	Median bearing capacity values (kN/m³)-2m depth
Blantyre	125	170
Chiradzulu	125	148
Mulanje	115	125
Nsanje	115	135
Mangochi	118	135
Zomba	120	140

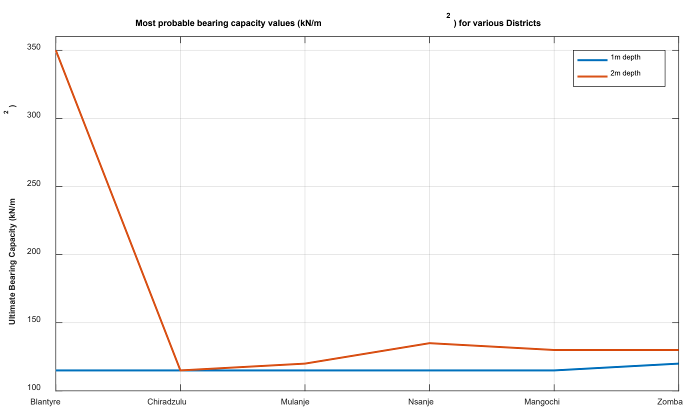


Figure 4: Comparison of the most probable bearing capacity values amongst the districts

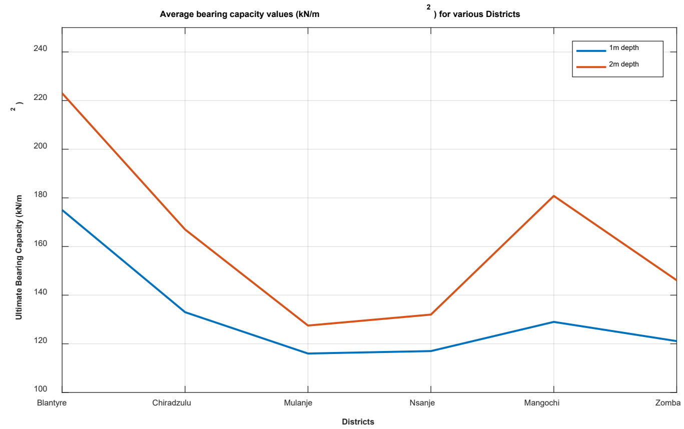


Figure 5: Comparison of the average bearing capacity values amongst the districts

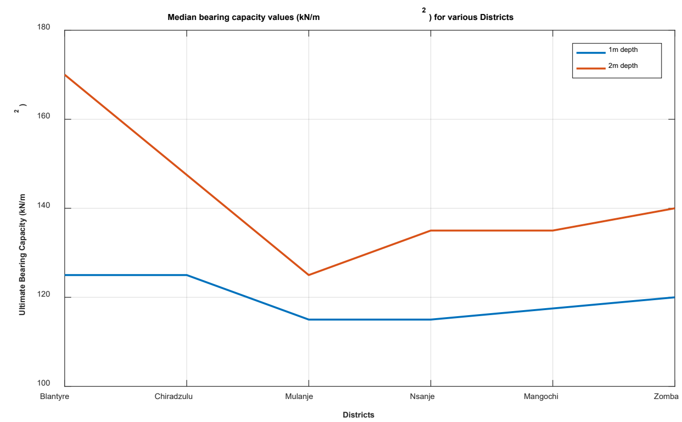


Figure 6: Comparison of the median bearing capacity values amongst the districts

4 Discussion and Conclusion

The results obtained from the various sites showed a variety of description in terms of the bearing capacity values. These ranged from loose/very soft, stiff or firm, very stiff, hard to bedrock. Description of loose (for instance loose sands) as well as soft or very soft simply means that the soil material in that area is loosely bound. It therefore means that the DCP equipment penetrated the soil section with little effort applied. Therefore, any value of ultimate bearing capacity of less than 120kN/m^2 has been termed loose or soft in this paper. Firm and stiff were used interchangeably during determination of the results. This ranged from the bearing capacities of more than 120kN/m^2 to around 160kN/m^2. Results ranging from 165kN/m^2 to around 240kN/m^2 have been described as very stiff. It therefore follows that results ranging from 245kN/m^2 to 300kN/m^2 have been described as hard or very hard depending on the difficulty with which the DCP equipment penetrated the soil profile. Any bearing capacity beyond 300kN/m^2 was therefore termed bedrock since there was little penetration of the machine into the rock.

The variability of the bearing capacities amongst the districts can be attributed to several factors. Among them could be issues to do with alluvial deposits for instance Nsanje and Mulanje districts. Blantyre and Mangochi had a variety of results because some sites were on hilly locations whilst other sites were situated in areas with loose soil deposits. Regardless, these districts have shown to have relatively stable soils although much attention from the design engineers still need to be directed to the locations along Lake Malombe in Mangochi. It should however be borne in mind that the tests were undertaken during the rainy season (March) in the country. It would be arguable that the values of the ultimate bearing capacities obtained might not be the same if the tests were conducted during the dry season. The author accepts this argument as it is basically logical that with wet ground, the penetration of the DCP machine would be achieved with less effort unlike doing the same in the dry season. However, in as far as engineering design is concerned, it is encouraged to design bearing in mind the worst-case scenario a site would be exposed to. With this notion, it is therefore believed that these tests were done at the right worst-case scenario and that they would be of great importance in as far as worst case (conservative) design considerations are concerned.

A quick look at Figure 1 (most probable bearing capacity) reveals that for a depth of up to 1m, although there still exists a variety of results amongst the districts, the most probable bearing capacity value obtained was around 115kN/m^2. This is the most likely bearing capacity an engineer or a designer might expect in areas around the six districts. The same can also be said for foundations reaching a depth of 2m where minus Blantyre, the rest of the districts have nearly similar probable ultimate bearing capacities. In terms of average values amongst the districts (Figure 2), there is a linear correlation between the two depths (1m and 2m). It can be observed from Figure 2 that variations in average bearing capacity values amongst the districts is nearly a mirror of one another in terms of depth. Although as per definition the median is an approximate of an average (Figure 3), in this case the median acts as a value at the very middle between the highest and lowest range of values. This can provide a certain level of confidence for the designer who wishes to design shallow foundations in these areas. In addition, the design of engineering structures is based on achieving optimization. This entails coming up with a design which is economically viable and at the same time able to achieve the purpose it is intended to. It is therefore believed that Figure 3 can provide such kind of optimization when it comes to shallow foundation design in these southern region of Malawi districts for the respective depths (1m and 2m).

In a nutshell, Nsanje, Mulanje and some parts of Chiradzulu have similar soil characteristics. The soils in these districts are basically loose. It therefore follows that the strength of soils in the shire valley as well as the Phalombe plains are relatively loose to a significant depth (2m). The shire highlands and some parts of the lake shore areas (Blantyre and Mangochi) have exhibited ultimate bearing capacity values with stiff to very hard strata for depths of up to 2m. It has also been observed that some parts of Zomba, Blantyre as well as Chiradzulu, which also forms part of the shire highlands, share some similar characteristics of stiff or firm soils for both depths of 1m and 2m.

It should further be emphasized that the bearing capacity strength of the soil alone is not enough determination of the ultimate behaviour of the soil. Other factors for instance organic content, the unit weight, the shear strength of the soil as well as atterberg limits which are equally important need to be taken into consideration in determining the overall behaviour of the soil for shallow foundation purposes. This paper also wishes to stress that the values of bearing capacities provided herein are ultimate. This means that in terms of application, the designer or user need to make necessary adjustments with the use of relevant equations to obtain safe and/or allowable bearing capacity values for effective use. This, therefore, further stresses the point highlighted above that the results of this research merely pose as a guide in decision making for shallow foundation designers within the mentioned districts and their surrounding areas.

In terms of challenges, one that stands out was rainfall. At times it was difficult to conduct the DCP tests efficiently due to overflowing of water in the dug pits.

Conflict of Interest

The author declares no competing interests.

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Appendix

Table 8: Raw data for the results obtained in the field for all the 3 locations/pits per site in each district.

District	Site/Location	Pit Number	Bearing Capacity (kN/m^3)-1m	Bearing Capacity (kN/m^3)-2m
Blantyre	Lumbira CDSS	1	120	115
		2	350	350+ (rock)
		3	115	125
	Nkula CDSS	1	200	350+ (rock)
		2	160	350+ (rock)
		3	180	350+ (rock)
	Mdeka CDSS	1	140	165
		2	125	180
		3	120	170
	Ngumbe CDSS	1	300+ (rock)	350+ (rock)
		2	115 (fill)	115
		3	115 (fill)	130
	Lumbira CDSS	1	120	115
		2	350+ (rock)	350+ (rock)
		3	115	125
Chiradzulu	Chiradzulu Sec. School	1	125	225
		2	125	115 (fill)
		3	135	Rock fill
	Chiradzulu CDSS	1	140	130
		2	190	180
		3	115	115 (fill)
	Nankhundi CDSS	1	120	125
		2	115	145
		3	120	135
	Mapesi CDSS	1	115 (fill)	180
		2	140	150
		3	155	165
Mulanje	Muloza CDSS	1	115	120
		2	115	120
		3	115	120
	Mulomba CDSS	1	115 (Very loose sands)	135
		2	115 (Very loose sands)	130
		3	120	140
Nsanje	Nsanje Sec. School	1	115 (very loose sands)	135
		2	115 (very loose sands)	150
		3	115 (very loose sands)	135
	Mpatsa CDSS	1	135	150
		2	115 (very loose sands)	140
		3	115 (very loose sands)	135
	Nyankhwale CDSS	1	115 (very loose sands)	115 (very loose sands)
		2	115 (very loose sands)	115 (very loose sands)
		3	115 (very loose sands)	115 (very loose sands)
Mangochi	Tsekwere CDSS	1	140	265
		2	150	300
		3	180	350+ (rock)
	Mtuwa CDSS	1	115 (loose)	115 (loose)

		2	115 (loose)	130
		3	120	125
	Lungwena CDSS	1	115 (loose)	130
		2	115	115
		3	115 (loose)	130
	Mbombwe CDSS	1	115	140
		2	140	190
		3	130	180
Zomba	Masongola Sec. School	1	125	130
		2	130	125
		3	120	140
	St Pauls CDSS	1	115 (loose)	145
		2	115 (loose)	140
		3	120	160
	Balamanja CDSS	1	130	180
		2	115 (loose)	130
		3	120	165