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MAT FOUNDATION DESIGN REFERENCE FOR METRO MANILA, PHILIPPINES

*Jonathan R. Dungca[1], Raynold Y. Pua[2], Raynold, Nelson Que[3], Anne Kristine M. Sangalang[4] and Ayran Nicole Tan[5]

[1]Civil Engineering Department, De La Salle University, Manila, Philippines

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ABSTRACT: To design mat foundations, there are certain values which are required for calculations and analyses, one of which would be the vertical modulus of subgrade reaction. It can be obtained through various deterministic tests such as the Plate Load Test. On the other hand, the study calculated this factor through the use of Standard Penetration Test (SPT) results by using four different methods. Comparative study and validation were also performed to confirm the most recommendable method to be used to compute for the soil spring constant, given the limitations of the SPT results, by correlation of this parameter to the California Bearing Ratio (CBR) test results. Through this, the study considered and used the equation formulated by Bowles to calculate the vertical modulus of subgrade reaction. Then, a Geographic Information Systems (GIS) software was utilized to generate maps of these values by the method of ordinary kriging. These maps presented the locations with the predominantly high and low values of the soil spring constant. They were also used to create a digitized reference of the values of the vertical modulus of subgrade reaction for the design of mat foundations for preliminary design through the use of Visual Basic Applications 2010.

Keywords: mat foundation, modulus of subgrade reaction, standard penetration test foundation design reference

1. INTRODUCTION

With the on-going modernization of the society, more technologically and competitively complex structures are being developed and constructed throughout the Metropolis. Civil engineers are faced with the constant dilemma of ensuring the safety and structural stability of any structure being designed, whether simple or complex. Before all the other safety and stability considerations, the design of foundations is the basic concern when designing any structure. Foundations are best known to be among the primary elements in any structure that provide structural stability. However, the design of any foundation would require the attainment of geotechnical parameters that necessitate extensive analysis and exploration of the soil where the structure would be built.

With a land area of approximately 619.5 square kilometers, Metro Manila covers a large portion of Luzon. Greater coverage means greater variation in the types of soils that are considered in the design of various structures. Along with the change of the soil types comes the adjustment in the foundation requirements, where despite the possibility of constructing exactly the same buildings in two different locations, the surrounding conditions will dictate what type of foundation design would be required.

Among those parameters greatly affected by changing soil conditions is the modulus of subgrade reaction, k, also known as the soil spring constant.

In the different models used to analyze soil, the soil spring constant is used as a quantity that simplifies and generalizes its behavior. Imaginary springs are positioned continuously beneath the structure and a constant value, k, is generated [1]. The dilemma now is that the soil spring constant is not unique for specific types of soils [1] and is affected by various factors such as the depth of the foundation and dimensions of the mat foundation being considered such as its base width which will be considered as a variable in this paper. Therefore, the soil spring constant for a given type of soil cannot be generalized with a specific range unlike other parameters such as density, porosity, and the like. A soil test, specifically the Plate Load Test, can be used to determine such a geotechnical parameter; however, with the limited budget most constructions face, engineers are forced to theoretically propose or estimate conservative values for these to pursue their design.

Mat foundation is a specific type of shallow foundation that is commonly used when the loading on the ground is aimed to be spread throughout an area in consideration. Mat foundations are very useful because it controls differential settlement which causes additional moments in structures thus affecting its stability. Because mat foundations are designed to cover a large area with a slab, it helps in creating uniform settlement along the entire mat. To be able to design a mat foundation fit for a particular soil, there are specific soil parameters that should be obtained with the help of soil reports.

There have been some similar studies related to this research [2]-[8], however, there is not one dedicated to the estimation of subgrade reaction to being used for the design of mat foundations for Metro Manila. This study aims to generate a design reference for mat foundations through the computation of the soil spring constants of the various locations in Metro Manila through Standard Penetration Test (SPT) borehole logs.

1.1 Metro Manila

The National Capital Region also referred to as Metropolitan Manila, is the country's leading urban region and is considered as the center for the Philippines' economy, politics and culture. The region is highly urbanized, providing jobs for a huge percentage of the country's population. Metro Manila is the heart of the country's finance, commerce, and industrial development. Within its borders lies the largest economic hub of the country, which is Makati. Other leading business districts which strive to be among the country's best districts are also within NCR, these are Eastwood in Quezon City, Bonifacio Global City in Taguig and Manila Reclamation Area in Manila. Because of this, a huge amount of structures are built to fit the economy and the lifestyle of Metro Manila. Design data concluded from soil conditions are required for a majority, if not all, of the structures that are built in the region.

Metropolitan Manila is bordered by different provinces and water systems which help the region become prosperous. The provinces of Bulacan and Rizal are situated on the north and east of the region respectively. On the south-west lies the province of Cavite while on the south is Laguna. Water systems also envelop the region, these are Manila Bay on the west and Laguna de Bay on the south-east.

Out of all the regions in the Philippines, it is the only one that is subdivided into 17 government units, with no provinces wherein 16 are cities and one is a municipality. The 16 cities include Caloocan, Las Pinas, Malabon, Manila, Marikina, Makati, Mandaluyong, Muntinlupa, Navotas, Paranaque, Pasig, Pasay, Quezon, San Juan, Taguig, and Valenzuela. Pateros is the only municipality in the region. The city sums up to a total of 63.6 square kilometers of land area with Quezon City as the largest and Navotas City as the smallest.

According to the data and maps provided by the Bureau of Mines and Geosciences, the entire region is divided into two major stratifications. These are Quaternary Alluvium and the Guadalupe formation.

The quaternary alluvium soils consist of deposited sediments from nearby water systems such as the Manila Bay and Laguna de Bay. These include detrital deposits composed of mostly silt, sand, and gravel. The locations in the Metropolitan that are found on the coasts or along water systems are those that are consisted mainly of Quaternary Alluvium. These include Pasay City, Manila City, Paranaque and parts of Las Pinas on the west while there are Muntinlupa, Marikina, Portions of Taguig and Pasig on the east.

The Guadalupe tuff formation (GF) is a series of soil classifications that is comprised of rock or tuffaceous materials distributed along Quezon City, Makati, Mandaluyong, parts of Pasig, and Rizal. It is divided into two members namely the Alat Conglomerate and the Diliman Tuff due to their differences in composition and structure. The Alat Conglomerate, the lower member of the formation, is generally composed of conglomerates, mudstones, and sandstones. This member is located in the lowland hills of eastern Bulacan and southern Nueva Ecija. A predominant rock type in the GF member is conglomerate which is massive and poorly sorted with well- rounded pebbles. Cemented by coarse-grained, calcareous, sandy matrix are small boulders of underlying rocks. It also contains mudstone which is medium to thin bedded with some varied characteristics of softness, stickiness, siltiness and tuffaceousness.

The Diliman tuff (the upper member) is made up of tuffs, pyroclastic breccias, and tuffaceous sandstones. This member of the Guadalupe Formation consists of vitric tuffs and welded pyroclastic breccias. It also contains minor fine to medium grained tuffaceous sandstone. Some dark mafic minerals and pumice materials are spread out in the tuff matrix. The Diliman tuff stretches from Quezon city to the southern parts of Metro Manila, namely Pasig, Makati and Rizal province. [9].

2. METHODOLOGY

In designing foundations, geotechnical parameters can be acquired by various soil exploration methods. In the case of mat foundations, the geotechnical parameters that need to be considered are the modulus of subgrade reactions and the bearing capacity of the soil varying in a certain depth. In attaining these variables, plate load test should be performed, but due to availability and cost, the researchers utilized the Standard Penetration Test (SPT) values to derive the modulus of subgrade reactions. This value is significant because aside from that it is the basis of good foundation design, conservative assumptions of one of the factors for foundation design can also be avoided.

Borehole logs and other soil data from all the 16 cities and 1 municipality of Metro Manila were obtained. Soil data from some cities and municipalities surrounding Metro Manila including Rizal, Cavite, Laguna, and Bulacan were also obtained for the proper interpolation of data. Data from soil tests such as the SPT and Borehole tests from government agencies, structural firms, and geotechnical firms were gathered by the researchers.

A total of 809 borehole data were collected for the study, 776 of which are found within the Metropolitan and 33 are located in areas or provinces bordering around NCR. Factors such as the type of soil tested, undrained shear strength, and the N-values were extracted from these data. Further computations were performed to estimate other soil parameters such as bearing capacity, settlement, and Modulus of Elasticity.

The obtained N-Values were corrected using Eq. 1, standardizing it into the N60 value.

$$N_{60} = (5/3)\,(C_N C_E C_B C_R C_S) \qquad (1)$$

where:
N_{60} = Corrected SPT blow counts;
C_E = Energy Effect depending on hammer type;
C_B = Correction factor for borehole diameter;
C_R = Correction factor for rod length;
C_S = Correction factor for type of samplers;
C_N = Effective overburden pressure coefficient.

Certain parameters that are required for the determination of the Modulus of Subgrade Reaction are the base (width) of the lot area being considered and the flexural rigidity of the materials that will be used for the foundation. Since the base width is a value that is constantly changing and is dependent on the area to be constructed as well as the design of the structural engineer, the authors have deemed it to be a variable along with the values of the flexural rigidity. With the values of N_{60}, modulus of elasticity (Es), Poisson's ratio (ν), and base as a variable, the study calculated the modulus of subgrade reactions through four methods. The first method is by using the definition of the soil spring constant which is a ratio between the applied pressure and the settlement (Se) created by such a pressure. In this study, the soil spring constant was computed through dividing the ultimate bearing capacity (Qu) by the settlement of the corresponding soil; both the bearing capacity and settlement were computed using values that were obtained from the SPT and borehole data. The second method was through a standard equation proposed by Vesic[10] which is usually used in the industry to estimate the value of the soil spring constant. This equation incorporates N-values to estimate elastic constants such as the Modulus of Elasticity of the soil and Poisson's ratio which are required by the said standardized equation.

The third method is the use of Empirical Equations provided by other researchers performed by Moayed and Naeini [11] for gravely soils incorporating N60-values and Ou [12] for sandy and clayey soils incorporating N60-values and undrained shear strength (Su), respectively. The fourth, and last method is the estimation by Bowles [13] that modifies the definition by limiting the settlements at certain values, particularly 25 mm.

From these four methods, a comparative study was conducted by comparing the outcomes of the modulus of subgrade reactions from the different methods to conclude which of these is the most appropriate result. The value chosen from the different methods was mapped for the various cities and locations in Metro Manila.

As for the validation of the result, there can be different deterministic tests that could compute the value of the Modulus of Subgrade Reaction. Plate Load Test is widely used to acquire actual values of the soil spring constant [14]. In this test, a load is applied to the plate in increments depending on the design load. Loading continuously applied until the change in the settlement is significantly reduced to a specified amount. However, many studies also claim the inaccuracy of this test because of the size of the samples and the equipment being used. Other than this, there are issues regarding the availability of the equipment. According to the research of Thornton [15], another method that can be used to estimate the value of the soil spring constant is through the CBR test [16].

The CBR results used in this study were obtained from geotechnical companies that performed the actual CBR testing in various locations in Metro Manila. The collection of CBR data was geared towards the representation of different cities around the National Capital Region, wherein CBR data were collected for each city in Metro Manila. Out of the original 16 data points, only 13 data points were used in the study. This was due to the fact that the other CBR data were collected at shallow depths that are less than one (1) meter from the natural ground surface. This is not within the range of depths that are used in the study. Furthermore, there are many external factors that may affect the soil conditions at such a shallow depth and this may not provide accurate results for the modulus of subgrade reaction.

Using the equation formulated by Thornton [15] through the correlation of the CBR test results to the soil spring constants, values of the vertical modulus of subgrade reaction were computed. The results were concluded based on the nearness of the values (from the four methods) to the value obtained using the CBR test. This was done with the help of the statistical method of t-test analysis. A graph was also generated to present the differences of the values visually.

Since the aim of this paper is to provide a design reference for mat foundations, the values of spring constants calculated were plotted out onto the map of Metro Manila. To provide values for places where there are not enough available data, the Kriging method for optimal interpolation was performed so that a map of the values will be generated [17]. This is the reason why soils in places outside Metro Manila were analyzed as well, to provide reliable interpolation of the values. The said contour maps were generated for every 1m layer interval and were done with the help of a Geographic Information System software.

3. RESULTS AND DISCUSSIONS

With the aim of this study to generate a map by choosing the most recommendable method of obtaining the values of the modulus of subgrade reaction. To do so, a simple comparison of the values obtained for all four methods of computations of the modulus of subgrade reaction was performed.

The first method is by definition. The soil spring constant (*k*) is defined as the ratio between the soil pressure(*q*) applied on the soil and the settlement (δ) produced by such an applied soil pressure, mathematically represented as:

$$k=q/\delta \quad (2)$$

The second method is an estimation of k through standard equations. Different standard equations are readily available for the computation of the Modulus of Subgrade reaction. The same comparisons were performed by the Sadrekarimi & Akbarzad [18]. They compared the resulting values with each other and have concluded that the equation provided by Vesic [10] provided the most accurate variable. The value of the soil spring constant in this method can be computed by:

$$\boldsymbol{k = \frac{0.65E_s}{(1-v_s^2)} \sqrt[12]{\frac{B^4E_s}{EI}}} \quad (3)$$

where:
E_s = Modulus of Elasticity of the soil (kPa);
EI = Flexural Rigidity of Mat (kN-m^2);
B = Slab width (m);
v_s = Poisson's Ratio.

The third method Estimation of k through empirical equations. The research by Moayed & Naeini [19] uses the N-values obtained from the Standard Penetration test and correlated it with the plate load test to be able to derive an equation that represents the relationship between the standard $N_{1,60}$ value (blow counts corrected to 60% hammer energy and overburden pressure) and k. Once the value of the $N_{1,60}$ was obtained, it was statistically correlated to the results of the plate load test on the same soil sample and a relationship was determined by Eq. (4):

For Gravelly Soil:
$$k= 3.143\ (N1)_{60}^{0.489} \quad (4)$$

The derivation of Eq. (4) only focuses on gravelly soils and the other soil types were delimited in the study performed by Moayed & Naeini [19]. Because of this, the empirical formula provided by Ou [20] would be helpful in the estimation of the values of the Modulus of Subgrade Reaction for clayey and sandy soils. These equations are as follows:

For Clayey Soil: $k = 40 – 50\ s_u$ (5)
For Sandy Soil: $k = 70 – 100\ N$ (6)
where:
k in (t/m^3);
s_u = undrained shear strength (t/m2) and;
N = SPT N-values.

The fourth method is k through estimation of Bowles [13]. It is a variation of the estimation of the modulus of subgrade reaction by definition. The only difference is that the author chose to limit the settlement to certain structurally acceptable values such as 25 mm, 20 mm, 12 mm and the like. The value of the modulus of subgrade reaction can be obtained through the equation shown below:

$$k = 40(SF)(q_u) \quad (7)$$

where:
SF = factor of safety;
q_u = ultimate bearing capacity.

A screening of individual values per layer was done to compare the results obtained for all four methods of calculation for the soil spring constant. This is to provide a better understanding of how the values turned out as they have and what factors may have played roles in such an outcome to occur.

With the individual analyses of the methods for the computation of the Modulus of Subgrade reaction, the method by Bowles and by definition provided the most recommendable values. Contrary to what the authors expected, the most conservative estimation of the modulus provided the value closest to the actual k values as shown in the validation through CBR testing. This may be because of the fact that both the Bowles and computation by definition are limited to existing soil specific data and required minimal assumptions. One of the methods used in this study, the computation by the standard equation, required too many parameters majority of which are basic design data that are usually assumed. An example of this would be the Poisson's ratio. Perhaps this method can be best used if only a theoretical analysis of the modulus would be done. As for the empirical methods, these calculations resulted in very low values and has a high per cent difference from the site-specific k values obtained from the validation. This may be because these are obtained from correlations with the Plate load test, which as claimed by various literature is unreliable for obtaining the modulus of subgrade reaction. Because of all these reasons, the authors have mapped only the values obtained through the Method of Bowles.

Despite the lack of uniqueness among the values of the modulus of subgrade reaction, there are some general trends in the values that can be observed for each level of soil stratum. One trend is that the values of the modulus of subgrade reaction increase as the depth increases. This is due to the fact that as the depth of the analysis increases, it approaches the rock formation further. As the rock formation is reached, the soil becomes more compact and dense that it would have greater resistance to forces acted upon the soil as compared to the previous layers. This greater resistance is manifested by the increase in the values of the Modulus of subgrade reaction.

Shown in Figure 1 is the map generated by the study from the collected data for depths 1 meter from the ground surface to 4 meters. It can be seen from Figure 1 and Figure 2 that the values of the modulus of subgrade reaction are high where the depth of the rock formation is shallow.

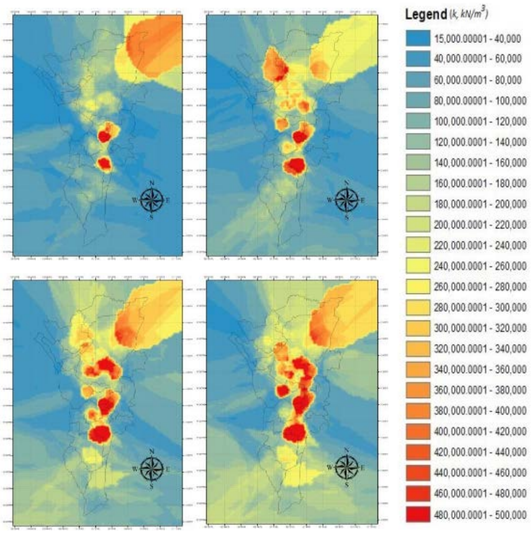
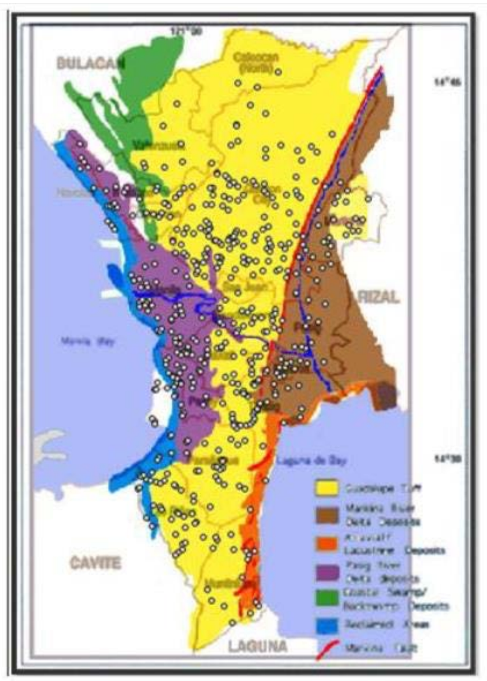


Fig. 1 Map of Metro Manila with values of modulus of subgrade reaction (all values are in kN/m³) using Bowles [13]



- Yellow = Guadalupe Tuff;
- Brown = Marikina River Delta Deposits;
- Orange = Alluvial / Lacustrine Deposits;
- Violet = Pasig River Delta Deposits;
- Green = Coastal Swamp / Backswamp Deposits;
- Blue = Reclaimed Area; and
- Red Line = Marikina Fault / Valley Fault System

Fig. 2 Geologic Map of Metro Manila [21]

Another trend is that it is evident that the results are highly affected by the soil compositions of a particular region. Some areas, particularly where the upper layers of soil are composed of a tuffaceous material, have observably higher values for the modulus of subgrade reaction compared to other areas where the rock layers are at a greater depth. The high values of the modulus of subgrade reaction are underlain by the Guadalupe Tuff and the low values are underlain by alluvial, delta deposits. It can also be observed in the comparison of the two maps (Figure 1 and Figure 2) that there is a sudden change in the values of the modulus of subgrade reaction (from dark red suddenly changed to blue) in areas that are divided by or are passed by the West Valley fault systems.

Areas, where the values of the modulus are highest, would be for the cities of Mandaluyong, Makati, Paranaque and Quezon City or all those cities that are away from the large basins or bodies of water and are underlain by the Guadalupe tuff formation. This is because, through time, continuous deposition of soils on locations near the bodies of water have compacted the soil strata of those places found in the middle of the region. As expected also, the values of the subgrade reaction decrease as data points approach the large bodies of water particularly the Manila Bay and the Laguna de Bay. These cities that are nearest the bodies of water stated previously, are Manila, Pasay, Navotas and Muntinlupa. The decrease in the values of the modulus may explain by the soils found in these locations which are locations are mainly made up of silt and clay materials, or generally alluvial deposits. Furthermore, the values of the modulus of subgrade reaction increase again once the data points are moving away from large bodies of water and into mountainous areas and even the central part of the region. These trends can be seen in Figure 1 which is a sample map of the values of the modulus of subgrade reaction using the method suggested by Bowles.

4. CONCLUSIONS

The design of mat foundations considers the resistance of the soils to any force applied to it. The study has limited the study depths from 2 to 6 meters because any deeper than this would not be recommendable for the construction of mat foundations. To assess such a resistance from the soil, the final output of the study has been to compute for the values of the modulus of subgrade reaction which are determined through borehole logs collected all over the region. These borehole logs were collected from different private testing companies, city government offices, and national government offices in Metro Manila. However, certain places in Metro Manila are not yet as fully represented in this study. The cities of Caloocan, Valenzuela, Muntinlupa, and the Municipality of Pateros are among those that have data points that represent only around 60% of the total area. The calculation of the Modulus of subgrade reaction was performed through an excel program wherein soil properties, SPT N-values, and RQD were used to obtain information that would lead to the estimation of the k values.

The locations in Metro Manila that provided the low values of the Modulus of subgrade reaction are Manila, Pasay, Navotas, and Muntinlupa, which could be attributed to the type of soil layers underlain in these cities which is mainly composed of loose silty sand and clay materials. It could be because of the large bodies of water that are bordering these locations such as Manila Bay and Laguna de Bay which can be considered as a good source of sand, silt, and clay deposits in the area. It could be safe to claim that the modulus of subgrade reaction has significantly low values if the areas are located in these cities and may not be recommendable for the use of mat foundations.

On the other hand, cities such as Mandaluyong, Paranaque, Makati, and Quezon provided significantly high values of the modulus of subgrade reaction. This may be attributed to the tuffaceous material from the Guadalupe tuff formation that is underlying these cities. Soils within the Guadalupe tuff formation are highly dense compared to other soils within Metro Manila and the rock formation is at very shallow depths. Because of these, computed settlements were small and the allowable bearing capacity is of a remarkable value making the modulus of subgrade reaction significantly high. It is for these locations where the use of mat foundations is recommendable.

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