Settlement Analysis of Soft Clay Using Plaxis 2D: A Case Study from Kochi

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Abstract: Rapid urbanization in Kochi has led to increased construction activities in areas underlain by soft marine clay, which pose significant challenges due to their low shear strength and high compressibility. A multistorey building is proposed at a site in Kaloor, where preliminary geotechnical investigation indicated the presence of soft clay deposits, raising concerns regarding structural stability and long-term performance.In this study, settlement estimation was carried out to evaluate the suitability of the site for construction. Numerical estimation was performed using PLAXIS 2D. The input parameters required for modelling were obtained from detailed laboratory testing and supplemented using empirical correlations. Consolidation analysis was adopted to simulate the time-dependent behaviour of soft clay under applied loading conditions.The simulation results revealed a maximum settlement of approximately 1.36 m, indicating excessive deformation. The volumetric strain reached an extreme value of about −6.9%, confirming significant compression within the soft clay layer. The effective mean stress developed in the soil was approximately −243.77 kN/m², while the total mean stress reached about −407.31 kN/m², indicating high stress concentration within the compressible strata. The active pore water pressure reached values up to −205 kN/m², while the excess pore water pressure was observed to be approximately −10.08 kN/m², indicating gradual dissipation of pore pressure during consolidation.The results clearly indicate that settlement is predominantly governed by the soft clay layer due to its high compressibility, low stiffness, and very low permeability, leading to slow consolidation. The magnitude of settlement significantly exceeds permissible limits, confirming that the site is unsafe for direct construction in its existing condition.Based on these findings, suitable ground improvement techniques are recommended to reduce settlement, improve load-bearing capacity, and ensure safe and stable construction.

Index Terms - : Soft clay, Settlement Analysis, Consolidation, Numerical Modelling, PLAXIS 2D, Ground improvement

INTRODUCTION

Kochi is one of the fastest growing urban regions in southern India, with rapid expansion in residential, commercial, and infrastructure sectors. A significant portion of the city consists of reclaimed land and low-lying coastal areas influenced by backwaters, where weak subsoil conditions are common. These regions are typically underlain by soft marine clay deposits formed due to sedimentation processes.Soft clay in Kochi is characterized by high natural water content, high void ratio, low permeability, and very low shear strength. These properties make the soil highly compressible and prone to excessive and time-dependent settlement when subjected to structural loads. In addition, the slow dissipation of pore water pressure results in prolonged consolidation, leading to long-term ground deformation and potential differential settlement.In this study, a proposed multistorey building site at Kaloor is considered, where geotechnical investigation revealed a soft clay layer underlying the site. Such subsurface conditions necessitate careful evaluation of settlement behaviour to ensure stability and serviceability of the structure.The study aims to estimate the settlement under expected loading conditions and to suggest suitable geotechnical solutions to control excessive settlement and improve the engineering performance of the soil for safe construction.

LITERATURE REVIEW

Geotechnical engineering has extensively examined soft clay deposits because they have a complicated behaviour and influence considerably on the performance of foundations. Terzaghi et al. (1996) state that soft clay is highly compressible and of low shear strength and this implies that when subjected to applied load, there is a significant amount of settlement. The consolidation theory gives the basic foundation of time dependent settlement of clayey soils.

Das (2010) indicated that the index properties of soft clay, especially liquid limit, plasticity, and natural water content, are very critical in determining the engineering behaviour of that material. High liquid limit and void ratio means that soil is more compressible and less stiff thus more vulnerable to deformation. Junjie et al. (2025) also highlighted that the low permeability of soft clay will cause a sluggish rate in the dissipation of the pore water pressure thus slowing down the consolidation process and causing delayed settlement.

The phenomenon of structural failures related to soft clay was reported in a number of studies. As Okeke et al. (2019) observed, too much or too little attention to soil properties may result in excess settlement and instability, whereas Hu et al. (2018) found that cracking and serviceability problems in buildings are caused by different settlement most of the time. These results have indicated the importance of the adequate geotechnical assessment prior to construction.

The classical estimation techniques of settlement using one-dimensional theory of consolidation cannot be applied to model some complex field conditions like layered soils and non-uniform loading. Comparatively, the techniques of numerical modelling, specifically the finite element analysis, offer more dependable simulation of soil behaviour in terms of stress-strain relationships, dissipation of pore pressures, and time-dependent effects.

The use of ground improvement methods has been popular in order to increase the soil properties and settlements. According to Singh et al. (2018), the concept of ground improvement can be defined as a way of changing the soil strength, stiffness, and permeability to satisfy engineering needs. Research by Al-Adhadh et al. (2019) and Karkush and Yassin (2020) revealed that suitable methods can ensure a substantial increase in soil performance and decreased settlement.Soft clay deposits have been widely studied in geotechnical engineering due to their complex behaviour and significant impact on foundation performance.

METHODOLOGY

The methodology adopted in this study follows a systematic approach integrating field investigation, laboratory testing, numerical modelling, and interpretation of results to evaluate the settlement behaviour of soft clay deposits. The overall workflow adopted in the study is illustrated in Fig. 3.1.

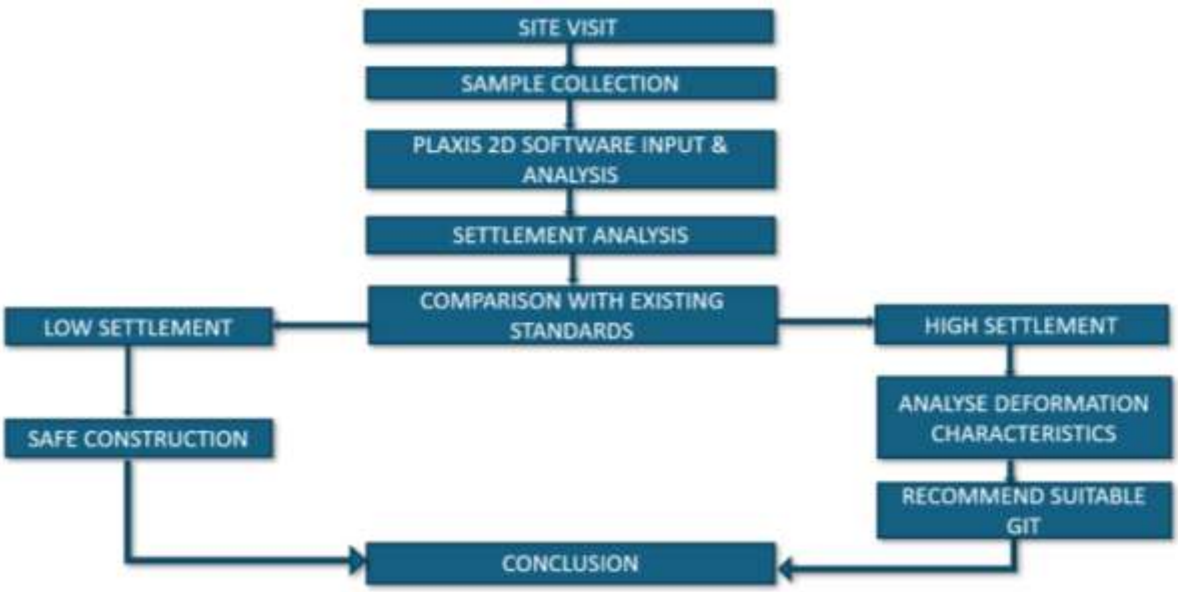

Fig. 3.1 Methodology adopted for settlement analysis of soft clay

The study began by carrying out an elaborate field visit at Kaloor in Kochi to learn the field conditions. This was conducted by subsurface exploration and the bore log profile of the site was gotten to determine the stratification of the soil. Bore log revealed that the soil had a stratified system that comprised of thin layer of sand and deep, thick layer of soft clay which is the main controlling factor of settlement behaviour. The collection of soil samples was done through standard drilling in a manner that caused minimal disturbances. To prepare the samples to be subjected to the laboratory test, they were air-dried and dried at 24 hours in the oven.

A set of laboratory tests were carried out to identify the engineering properties of the soil as per the deft codes of Bureau of Indian Standards. Such tests were specific gravity, Atterberg limits, grain size analysis permeability tests, shear strength tests and consolidation tests. The findings of these tests were tabulated and major parameters needed to determine settlement analysis were determined. Lab findings the soil has high compressibility, low shear strength and very low permeability, and this means that the soil is prone to high levels of settlement by means of consolidation.

The input soil parameters used for numerical modelling are presented in Table 3.1.

Table 3.1 Input soil parameters used in numerical modelling

PARAMETER	**SAND**	**CLAY**
Unsaturated unit weight (kN/m^3)	17.15	17.21
Saturated unit weight (kN/m^3)	19.5	18.66
Young's Modulus(kN/m^2)	25000	22000
Poisson's ratio	0.30	0.35
Cohesion (kN/m^2)	1	2.76
Friction angle (^{o})	27.46	20
Permeability (m/s)	1×10^{-5}	1.1×10^{-9}

These parameters were based on laboratory tests and further enhanced with the help of empirical correlations as necessary. The values are the engineering characteristics of both sand and clay layer required for simulation.

Numerical modelling was performed with the help of PLAXIS 2D based on the obtained soil parameters and bore log data. The two dimensional plane strain model was designed to replicate the conditions in the field, which is in the form of an ongoing foundation system. The profile of the soil was modeled using the right layer thicknesses and groundwater conditions have been put in place using site data. The Mohr-Coulomb constitutive model was assumed to describe the behaviour of soils because it is simple and can be adopted to conduct preliminary analysis. The model boundaries were maintained large enough to avoid the effects of the boundary and provide the realistic stress distribution.

The adequate loading conditions in accordance with the proposed structure were loaded with a uniformly distributed load of 150 kN/m2, which was obtained and calculated using IS 875 (Part 2) with references to both dead and live loads. The time dependent settlement behaviour of the soil was analysed through consolidation analysis considering the generation and dissipation of pore water pressure. In the analysis, a time period of 20440 days was taken to get the long-term settlement properties. The outcomes of the numerical analysis, such as settlement, stress distribution and behaviour of pore water pressure are discussed and presented in the next section.

NUMERICAL MODELLING

The numerical modelling for the present study was carried out using PLAXIS 2D to realistically simulate the field conditions and evaluate the settlement behaviour of soft clay under structural loading.

A two-dimensional plane strain condition was adopted, which is appropriate for modelling long structures with uniform cross-section. The geometry of the model was developed based on the bore log data obtained from the site investigation.

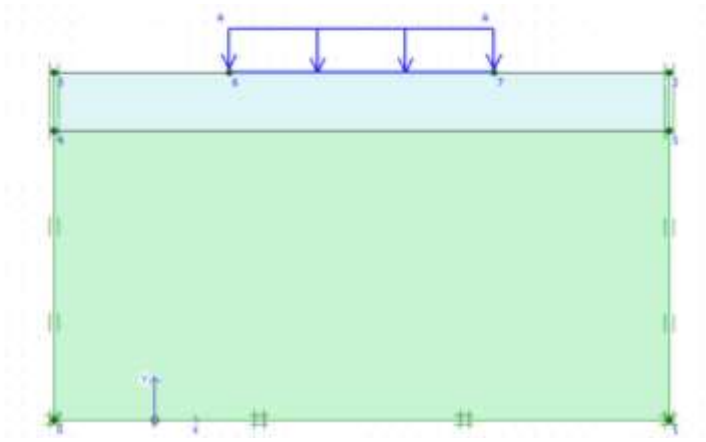

Fig 4.1 Finite Element Model Geometry with Boundary

The subsurface profile consisted of a top sand layer of 3.5 m thickness underlain by a soft clay layer extending up to a depth of 17.5 m. The groundwater table was incorporated at 0.5 m below the ground surface, as observed from site conditions. The lateral and bottom boundaries of the model were kept sufficiently far from the loaded area to avoid boundary influence on the results.

The soil behaviour was represented using the Mohr-Coulomb constitutive model, which is widely used for preliminary geotechnical analysis due to its simplicity and reliability. The analysis was performed under consolidated drained conditions to simulate the long-term behaviour of the soil, where pore water pressure dissipation plays a critical role in settlement.

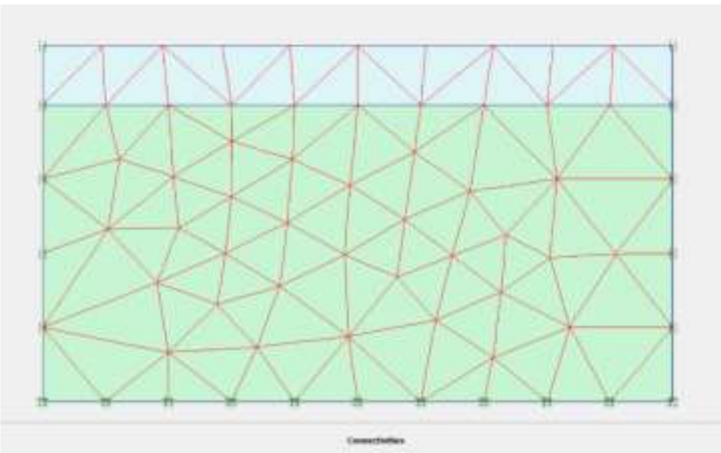

Fig 4.2 Finite Element Mesh Generated for the Numerical

The input parameters required for modelling, such as unit weight, cohesion, angle of internal friction, Young's modulus, Poisson's ratio, and permeability, were obtained from laboratory testing of soil samples. Where direct measurements were not available, parameters were estimated using empirical correlations based on relevant Bureau of Indian Standards codes and standard geotechnical references. These parameters were carefully assigned to each soil layer to ensure realistic simulation of soil behaviour.

The loading condition was applied as an equivalent uniform pressure of 150 kPa on the ground surface, representing the combined effect of dead load and live load of the proposed multistorey structure. The load values were selected in accordance with guidelines from standard design codes.

Mesh generation was carried out using medium to fine discretization to ensure accuracy in results while maintaining computational efficiency. The analysis was performed in stages, beginning with initial stress generation followed by application of structural loading.

A consolidation analysis was carried out to evaluate the time-dependent settlement behaviour of the soft clay layer. A time period of 20440 days (approximately 56 years) was considered in the simulation to capture the gradual dissipation of excess pore water pressure and the corresponding increase in effective stress. This approach enabled the prediction of both the magnitude and rate of settlement.

The modelling approach adopted in this study allows for realistic representation of layered soil conditions, groundwater effects, and consolidation characteristics, thereby providing a reliable estimation of settlement behaviour. The results obtained from this analysis are presented and discussed in the subsequent section.

RESULTS

The results obttained from the numerical analysis using Plaxis 2D are summarized in table below.

Table 5.1 Summary of PLAXIS 2D Analysis

PARAMETER	SYMBOL/UNIT	VALUE OBTAINED	INTERPRETATION
Maximum vertical displacement	Uy (m)	1.36m	Extremely high settlement
Volumetric strain	εv (%)	-6.9%	Significant soil compression
Effective mean stress	p′ (kN/m²)	-243.77 kN/m²	Indicates stress transfer to soil skelton
Total mean stress	p (kN/m²)	-407.31 kN/m²	High stress concentration in clay layer
Active pore water pressure	u (kN/m²)	-205 kN/m²	High pore pressure generation
Excess pore water pressure	Δu (kN/m²)	-10.08 kN/m²	Partial dissipation during consolidation
Settlement duration	t (days)	20440 days	Long-term consolidation behaviour
Soil behaviour	–	Highly compressible	Dominated by soft clay response

The results obtained from numerical analysis are further illustrated using contour plots generated from PLAXIS 2D, which provide insight into the deformation behaviour, stress distribution, and pore pressure response of the soil. The vertical displacement contour (Fig. 4.1) indicates a maximum settlement of 1.36 m at the centre of the loaded region, confirming excessive deformation of the soft clay layer. The volumetric strain distribution (Fig. 4.2) shows significant compression within the clay, consistent with its high compressibility. The effective stress contour (Fig. 4.3) highlights the transfer of stress to the soil skeleton during consolidation, while the pore water pressure distribution (Fig. 4.4) indicates high pore pressure generation under loading. The excess pore pressure contour (Fig. 4.5) demonstrates gradual dissipation over time, confirming that the settlement behaviour is governed by consolidation.

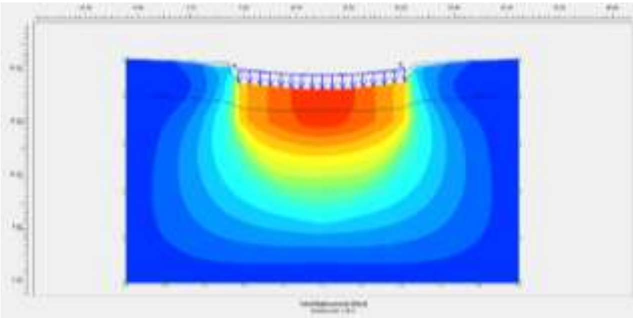

Fig. 4.1 Total displacement (Utot) contour showing maximum settlement

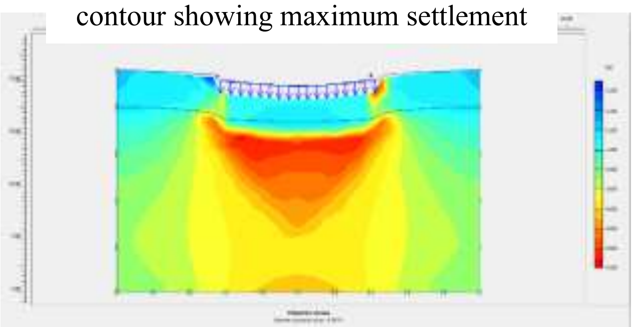

Fig. 4.2 Volumetric strain (εv) distribution indicating soil compression

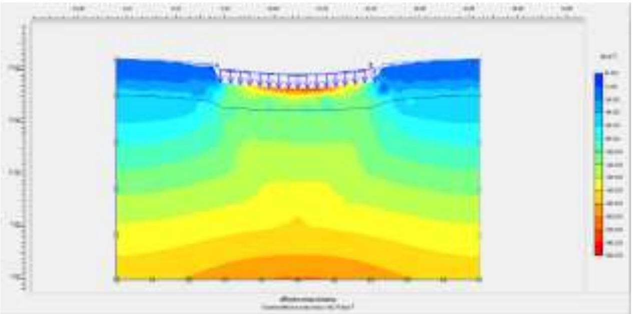

Fig. 4.3 Effective mean stress (p′) distribution within the soil mass

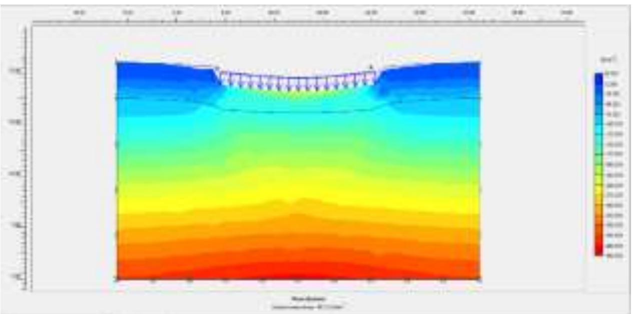

Fig. 4.4 Total mean stress (p) distribution in the soil

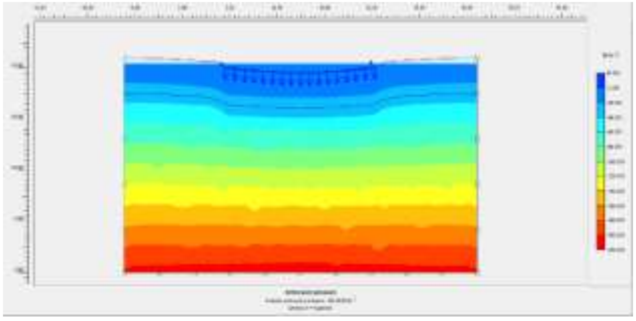

Fig. 4.5 Active pore water pressure (u) distribution under loading

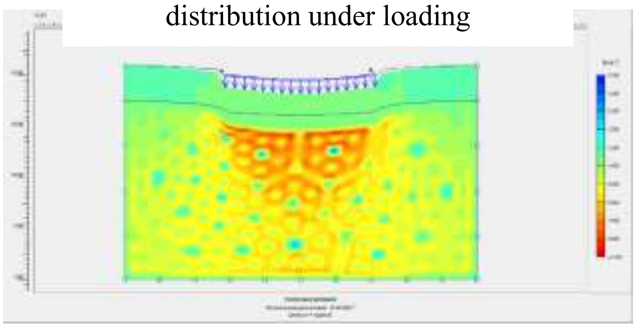

Fig. 4.6 Excess pore water pressure(Δu) distribution during consolidation

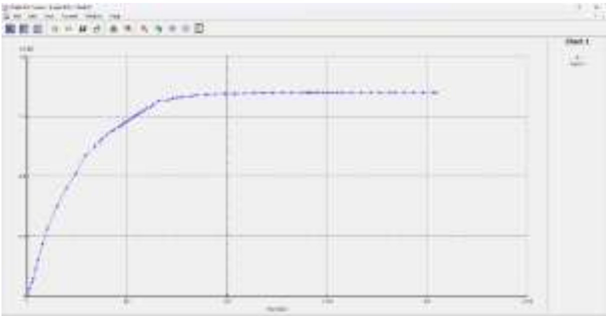

Fig. 4.7 Time–Settlement Curve

VALIDATION OF RESULTS

To verify the reliability of the numerical modelling results, theoretical settlement calculations were carried out based on classical consolidation theory. The primary consolidation settlement was estimated using standard soil parameters obtained from laboratory tests, such as compression index, initial void ratio, thickness of the clay layer, and effective stress conditions.

$$Sc = \frac{C_C \cdot H}{1+e_0} \log_{10}\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right) \qquad (1)$$

Using the above relationship, the theoretical settlement was calculated as 1.15 m. The theoretical analysis yielded a settlement value of approximately 1.15 m, which is in close agreement with the numerical modelling result of 1.36 m. The slight variation between the two values can be attributed to the assumptions involved in theoretical calculations, such as considering homogeneous soil conditions and simplified loading, whereas numerical modelling accounts for layered soil behaviour, stress distribution, and boundary conditions more realistically.

The close correlation between the theoretical and numerical results indicates that the soil parameters used in the analysis are appropriate and that the modelling approach is reliable. This agreement validates the accuracy of the numerical simulation in predicting the settlement behaviour of soft clay at the study site.

Hence, both approaches consistently demonstrate that the site is prone to excessive settlement under the given loading conditions, confirming the need for appropriate ground improvement measures before construction.

DISCUSSIONS

The numerical analysis which was done and the theoretical validation of the same results are clear indications that the subsoil at the study site is highly susceptible to excessive settlement. The peak settlement rate of approximately 1.36 m was an indication that there was significant compressive behaviour of the soft clay layer to the structural load exerted on it. This is characteristic of soft marine clays and particularly in coastal areas such as Kochi where such soils are characterised by extreme compressibility.

Geotechnical qualities of the clay are the primary aspects that determine the magnitude of settlement. The high initial void ratio ($e_0 \approx 1.76$) indicates that it has a fine structure of soil that has many volumes of voids thus more prone to compression when it is loaded. Besides this, the permeability is extremely low (approximately 10-9 m/s) and this limits the flow of pore water, which reduces the rate of dissipation of excess pore pressure. Due to this, it settles over a long period as opposed to settling once loaded.

Based on the deformation pattern, it can be seen that the greater part of settlement is documented in the layer of the soft clay, whereas the layer of sand that is located over it does not play a significant role. The profile of the settlement that is observed is in the form of a bulb indicating that the applied load is shifted deep in the soil causing a large thickness of compressible clay to be impacted. This emphasizes the part played by the thickness of the layers because the thicker the clay deposits, the more settlement will occur.

The consolidation properties of the soft clay are also validated by the time-dependent settlement behaviour. At first, some instant settlement takes place as a result of elastic deformation. This is then succeeded by slow settlement as the excess pore water pressure will reduce with time. With the reduction of pore pressure, the effective stress of soil grows, resulting in the volume loss and consolidation. The low pace of such a process is directly connected with the low permeability of clay.

Numerical and theoretical findings are in good agreement, which shows that the modelling method and the parameters of the selected soil are valid. These slight variations can be explained by the fact that simplified assumptions are made in the course of calculations that are carried out by theories, like homogeneous soil conditions but numerical modelling models take into account more real phenomena, such as the layered soil behaviour and boundary conditions.

As compared to the permissible settlement limits that are suggested by the Bureau of Indian Standards, the projected settlement turns out to be very high in comparison to the acceptable values. This type of over settling may cause a differential settlement, structural damages, cracking and long term serviceability. This is a clear pointer that the site as it is naturally occurring cannot sustain structures without ground enhancement.

Engineering wise, the research has indicated the necessity to take into account the magnitude and the rate of settlement in soft clay soils. The large settlement is not the only critical feature, and the long period of consolidation which may influence construction schedules and long-term performance also.

On the whole, the results prove that the behaviour of the soft clay at the site is controlled by consolidation. Hence, all buildings on such soils should incorporate proper ground improvement methodologies so that they can be strengthened, made to consolidate faster and minimized to acceptable and safe settlement levels.

RECOMMENDATIONS

According to the findings of settlement analysis, the soft clay found on the study site in Kochi is very compressible and it experiences excessive settlement under the imposed loading and therefore it cannot be used as it is found in nature. Out of all the ground improvement methods, the stone columns are advised as the most appropriate and the main approach to use in this site. Stone columns help a great deal in enhancing the shear strength of the soil, compressibility, and give good drainage routes, which speed up the process of consolidation, and minimize excess settlement.

Besides the stone columns, other methods like prefabricated vertical drains (PVD) including preloading can be embraced as a supplementary approach to enhance the process of consolidation and minimal time to settle. Nevertheless, the implementation of stone columns should be considered as the key subject because these columns are more efficient in enhancing the strength and settlement properties at the same time.

In some cases where ground improvement cannot be done, some deep foundation system like pile foundations can be taken as an alternative to spread the load to lower stable strata. In addition, carrying out an appropriate settlement monitoring during and after construction to make sure that the structure is safe and performing well is advised. In general, the construction of stone columns, suitable design and monitoring is important in order to provide safe and stable construction on the soft clay deposits.

CONCLUSION

The present study was an evaluation of the settlement of the soft clay on a planned construction site at Kochi. The results indicate that subsoil material is fine soft clay layer with low shear strength, high void ratio and low permeability. These characteristics expose the soil to significant and time-dependent deformation to structural loading.

The settlement analysis was found to reach a maximum settlement of approximately 1.36m which is very high as compared to the permissible depths of building foundations. The results also had gradual settlement with time and it established that the behaviour of consolidating the clay was due to slow dissipation of the pore water pressure. The accuracy of the analysis is supported by the large similarity in the final results of the analysis of the numerical and theoretical settlement values.

According to the findings, one can say that the site cannot be directly built without the ground enhancement due to the possibility of structural instability and serviceability issues in case of excessive settlement. It gives stone columns as the most suitable among the available alternatives to improve the strength of the soil which prevents compressibility and accelerates the motion of solidifying the soil.

Overall, the paper has highlighted the necessity of carrying out sufficient geotechnical investigation and coming up with suitable ground improvement measures in order to come up with safe, stable and long term properties of structures on soft clay soil.

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