STUDY OF THE RESPONSE OF PILE FOUNDATIONS IN VARYING LOAD AND SOIL CONDITIONS

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ABSTRACT

Pile foundations are one of the most commonly preferred foundation system, mainly for large scale structures like bridges. Piles are however preferred improving soft clays, loose sands, weak soils etc. During installation of piles, various changes occur in the surrounding soil like excess pore water pressure dissipation, compaction of surrounding soil etc. The piles can be subjected to various loading conditions like dynamic loads, embankment loads, cyclic loads etc. according to the requirement. The responses of the pile foundation system to all these type of loading conditions vary adversely for diverse soil types like unsaturated clays, expansive soils, gravel soil etc. The paper presents a review of developments in the field of pile foundations by varying the loads and surrounding soils, encompassing the analytical, experimental, numerical studies and field investigation of their compressive, uplift and seismic responses. The concept of mini-pile installation in clays is also highlighted, which is in use today for small scale structures, due to its less diameter and easy handling. The paper also highlights the dependency of bearing capacity of piles on parameters like pile length, presence of water and type of soil.

Keywords: Pile foundation; Lateral response; Static load tests; Finite element modelling

1 INTRODUCTION

The foundation plays an integral part of structural engineering as well as for geotechnical engineering. The foundation carries the loads of the superstructure and transfer them to the soil beneath the foundation. For adaptability of the superstructure to different dynamic loading, foundations are to be designed with utmost care and supervision. The foundation can be designed either as shallow or deep foundations, depending upon the use and location of the structure. Shallow foundations consist of strip footing, isolated footing, combined footing, strap footing, mat/raft footing. Deep foundations consist of pile foundation, shaft foundation, caissons etc. In this paper, the advancements in the field of pile foundations are highlighted.

Piles are basically long, slender members that transmit the load of the superstructure to the deeper strata of soil or rock beneath the structure either by end bearing or skin friction. Based on the installation technique, piles are classified as pre-cast driven, driven cast-in situ, bored pre-cast, bored cast-in situ, driven steel and driven timber piles. Based on functions, piles are classified as compaction piles, friction pile, end bearing, tension or uplift piles, sheet piles, anchor piles etc.

Many researchers (Li 2020; Hazzar 2017; Wang 2020 etc.) have studied on the various aspects of pile foundations and have presented various results by changing the properties of soils, loading conditions, structural modifications etc. The studies in the field of pile foundation has led to its development and its growing use in recent years. Valikhah et al. [1] established a new analytical-numerical procedure to find the stress and strain fields around the pile by indirectly using the data of cone penetration test. Chung and Yang [2] carried out a numerical analysis of a small- scale pile model driven in unsaturated clay soil. Furthermore, Hazzar et al. [3] presented results of a series of 3D FD analyses using FLAC-3D in order to evaluate the influences of vertical loads on lateral response for sandy and clayey soils. Other researchers like Wang and Zhang [4] presented a study on the geosynthetic reinforced pile supported (GRPS) embankment system which consist of vertical rigid piles and horizontal geosynthetic reinforced platform. Fakharian et al. [5] studied the advantages of mini pile construction in clayey soil. A FEM numerical model to analyse the penetration of piles into fine grained saturated cohesive soil to a certain embankment depth was developed. Liu et al. [6] used p-y method to model the non-linear behaviour of pile-soil interaction to make it simpler and understandable. The most reliable technique of measuring load transfer along piles for static loading was done using French extensometer. It is an alternative to strain measuring device. Kouby and Lacoste [7] carried forward the technique to measure the cyclic or repeated loads as well. The loads transmitted to piles usually fluctuate which can be termed as cyclic loads. Zhou and Xie [8] presented results on improvement of bearing capacity by post grouting at the pile end in loess area. From the Civil engineering perspective, it can be clearly understood that the presence of water in the sub soil layer causes loss in its strength and bearing capacity. During installation of piles or due to the vibrations created because of application of dynamic loads, excess pore water pressure is developed. Mustafa and Fattah [9] measured the amount of pore water pressure by piezometer. Some researchers have often studied the behaviour of piles in expansive soils. Due to the apparent swelling and shrinkage in expansive soil due to change in water content, the uplift pressure increases. In such cases, pile foundations hold good. Jiang et al. [10] carried out a study on non-linear analysis method for calculating the bearing capacity of a single pile in expansive soil.

In this paper, the basic idea is to know about the various aspects of pile foundations from the studies/experiments of various researchers from all over the world. Further, this paper enables us to know the behaviour of pile foundations under various conditions of soils and loads and the effect of the foundations on the surrounding soil.

2 EXPERIMENT AND ANALYTICAL STUDIES

2.1 Experimental studies

2.1.1 Test Requirements

For the various studies, test sites were selected accordingly on the outskirts of the cities to carry out the experiments smoothly. Direct shear test, pile load test, Contact Filter method equipments, French extensometer were used for the purpose of evaluating the behaviour of piles for the studies. Hydraulic jacks of appropriate weights were implemented for fulfilling the requirement of loads. For most of the experiments, soil-cement columns or concrete columns were contemplated as piles for the evaluation of the required tests. The aluminium shafts were also used in some experiments as pile models. The steel plates were used as pile caps. The use of oscilloscope and vibrometer was used to measure the settlement and vertical amplitude of pile in the study. Piezometer was also used in the experiment for the measurement of excess pore water pressure developed. In one of the studies, geosynthetic layers were embedded in embankment to know the stability of piles under the embankment loading.

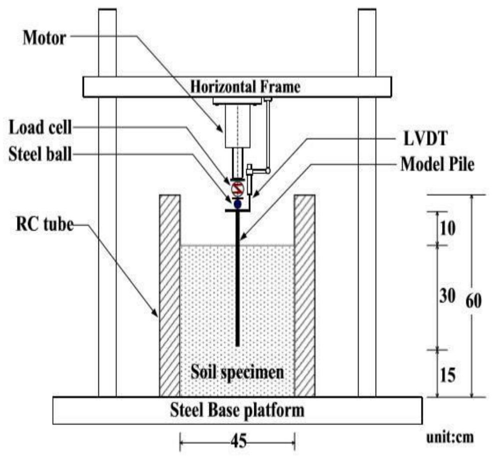

Figure 1: Sketch of pile load test device

Table 1: Database of field and laboratory tests on pile foundations

Reference	Experiment type	Sample size	Soil type	Column materials	Column dimensions	Type of Loading	Load size	Rate of Loading
Wang and Zhang [4]	Field test (group)	1 m X 1 m X 0.3 m	Silty clay underlain by silty sand	Pre-tensioned high strength concrete	d = 18 mm L = 326.5 mm L/d = 18.14	Embankment loading	H = 7.5m Width = 26m 1V:1.5H	Stress controlled (undrained)
Liu et al. [6]	Field static load test (group of 23 piles)	D = 2 m L = 35 m	Gravel improved with cement grouting	Gravel soil	d = 2 m L = 35 m L/d = 17.5	In-situ Lateral loads	70000 kN of design horizontal load	Increments of 150 kN
Kouby and Lacoste [7]	Field (pile group)	D = 0.25 m L = 6 m	Clayey gravel soil underlain by weathered chalk	Soil-cement	d = 0.25 m L = 6 m L/d = 24	Axial cyclic loading	Square plate	Stresscontroll ed
Zhou and Xie [8]	Field (2 piles)	D = 1.5 m L = 22 m	Loess soil	Post grouting pile and conventional pile	d = 1.5 m L = 22 m L/d = 14.67	Vertical loading	Grouting (25 kN)	Stresscontroll ed

Table 1 continues

Reference	**Experiment type**	**Sample size**	**Soil type**	**Column materials**	**Column dimensions**	**Type of Loading**	**Load size**	**Rate of Loading**
Fattah and Mustafa [9]	Laboratory – 1g single pile	D = 20 mm (160 X 160 X 20 mm)	Sandy soil (uniform silica) (I_P = 60%)	Polyvinyl chloride (PVC) pipes	L/d = 15,20,25,30	Dynamic load and Static load	Vibrometer probe and LVDT probe	Stresscontroll ed
Chung and Yang [2]	Pile load test, Direct shear test, Contact filter paper method, Interface shear test	D = 1.6 cm L = 40 cm	Unsaturated clayey soil	Reinforced concrete tube	d = 1.6 cm L = 40 cm L/d = 25	Constant pile head displacement of 5 cm/min and static axial loading	Horizontal frame with motor, load cell and a steel ball	Step-wise increment of 0.5 kN

Jiang et al. [10]	Laboratory test- small scale Pile load test	D = 0.05 m L = 0.4 m, 0.6 m, 0.8 m, 1.0 m Expansion active depth, h_0 = 0.4 m	Expansive soil underlain by fine sand, medium sand and gravel in subsequent layers	Aluminum alloy piles	d = 0.05 m L = 0.4 m, 0.6 m, 0.8 m, 1.0 m L/d = 8, 12, 16, 20	Vertical loading	Hydraulic jacks	Stresscontrolled

2.1.2 Test methodologies

Table 1 shows the database of experiments carried out for the behaviour analysis of pile foundations under varying loads and in different soil conditions. Prior to the testing of piles for various loads and soils, the sub-soil exploration was carried out in the fields where the tests were to be carried out. The preliminary tests like water content determination, unit weight determination and Atterberg limits determination were implemented to know the properties of the soil beneath the ground. For many of the studies, pile load test proved to be a mostly used test for the determination of bearing capacity of piles. The parameters to be used for the software were determined using experimental methods like Direct Shear test, Interface Shear test, Contact filter paper method etc. For the study of improvement of soft soils, pre-tensioned high strength concrete piles were used under geosynthetic reinforced and pile supported (GRPS) embankment. Further, field tests were carried out at an arch bridge site where the substructure consisted of low-cap pile group foundation and also in Rouen, France. The gravel soil around the pile was improved by jet grouting with cement upto a depth of 6 m from the ground. The experiments as listed in table 2 was carried out for the various studies in order to evaluate the behaviour of piles in different soil and load conditions.

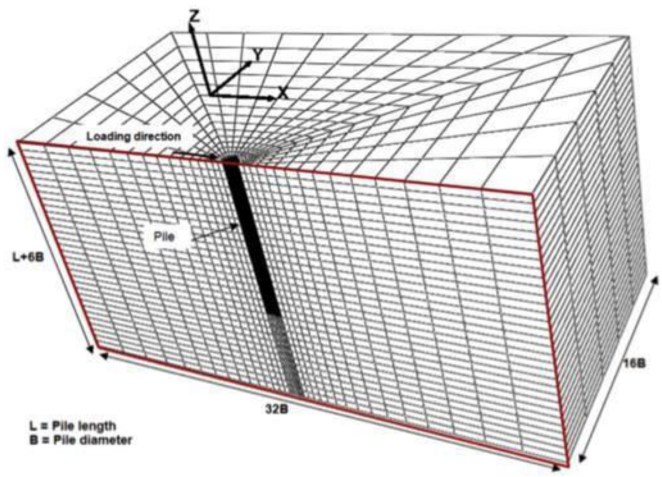

Figure 2: The general layout and meshing of the FD model used for analysis of soil-pile system

2.2 Modelling

2.2.1 Finite Element modelling

Table 2 shows the database of analytical studies on response of pile foundations under various conditions of soil and loading. For many of the studies, the researchers modelled their pile structures in softwares for appropriate evaluation of their studies. The finite element method (FEM) was the popular concept being used by many researchers for their studies.

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Table 2: Database of analytical studies on pile foundations

Reference	Numerical method(Code)	Type of analysis	Nature of pile	Constitutive behaviour/ model: Soil	Pile	Pile-cap	Mesh type	External load
Hazzar et al. [3]	FEM (FLAC-3D)	3D	Conventional Floating pile	Sandy- CY Clayey Modified Cam Clay	Mohr Coulomb		FDM grid	Vertical load
Wang and Zhang [4]	FEM (ABAQUS)	3D	Conventional	Modified Cam Clay	Mohr Coulomb	Elasto-plastic	8-node linear brick elements	GRPS embankment load
Fakharian et al. [5]	FEM (ABAQUS) (GAP/CTM)	2D axisymmetric	Mini-pile	Modified Cam Clay	Isotropic elastic (CAX4)	Coulomb friction contact law	2-phase 4node	Pile Driving
Liu et al. [6]	FEM (PLAXIS3D)	3D	Conventional single pile	Mohr Coulomb, hyperbolic p-y (cement improvement)	Mohr Coulomb (Linear elastic)		10-node tetrahedral elements	Lateral load

Chung and Yang [2]	FEM (PLAXIS2D)	Axisymmetric	Single pile (small scale)	Mohr Coulomb	Mohr Coulomb (Linear elastic)	15-node triangular elements	Distributed load

2.2.2 Numerical Approach

There are various numerical approaches done using the principles of soil dynamics to validate the results of the experiments. The approaches are quite tedious and require utmost knowledge of mathematical interpretation. In the study of analysis of behaviour of laterally loaded single piles in improved gravel soil, Liu et al. [6] carried out a compiled MATLAB procedure to implement the calculated process in which approximation and interpolation techniques were undertaken. The accuracy of assumptions taken while mathematical calculations were improved by numerical simulation. A hyperbolic p-y model was used to study the non-linear response of pile in improved gravel soil. This method assumed soil medium as some discrete non-linear springs supporting laterally loaded piles.

In the study of load-displacement behaviour of driven piles in sand, Valikhah et al. [1] obtained the bearing capacity of foundations by slip line method where both the equilibrium and yield equations were satisfied along the slip line directions. This method is also called as method of stress characteristics as the equations are transformed into ordinary differential equations along the slip lines. The Mohr stress circle was used to visualize the characteristics directions.In the study of response of pile foundations in expansive soil, Jiang et al. [10] carried out numerical analysis using some assumptions. A new analytical solution to the elastic theory of load transfer of a single pile was put forward by using shear displacement method and considering the law of soil shear modulus changing with depth. A non-linear analysis method for calculating the bearing capacity of single pile in expansive soil after immersion was also introduced in this study.

3 PARAMETRIC STUDIES

3.1 Effect of pile length

In many studies related to the response of pile foundations under various loadings and in different soils, it was shown that the pile length plays an important role in the stability of the system. From the studies, it was found that the increase in length of floating piles increases the bearing resistance of pile, thereby reducing the lateral soil pressure which even increases the lateral friction resistance of pile. This leads to reduced overall settlement of pile foundation. In many experiments, L/d ratio, i.e., the normalized length of pile was considered, where ‘L’ is the length of pile and ‘d’ is the diameter of pile. Also, for the pile foundations in expansive soil, it was found that increase in pile length effectively reduces the uplift of pile top and improves the bearing capacity of pile when part of the pile is under the expansion action. In actual case, the bearing capacity first increases and then decreases with increase in pile length. But when the full pile body is subjected to expansion, the increase in pile length does not lead to continuous increase in bearing capacity of pile but the increase in bearing capacity is smaller.

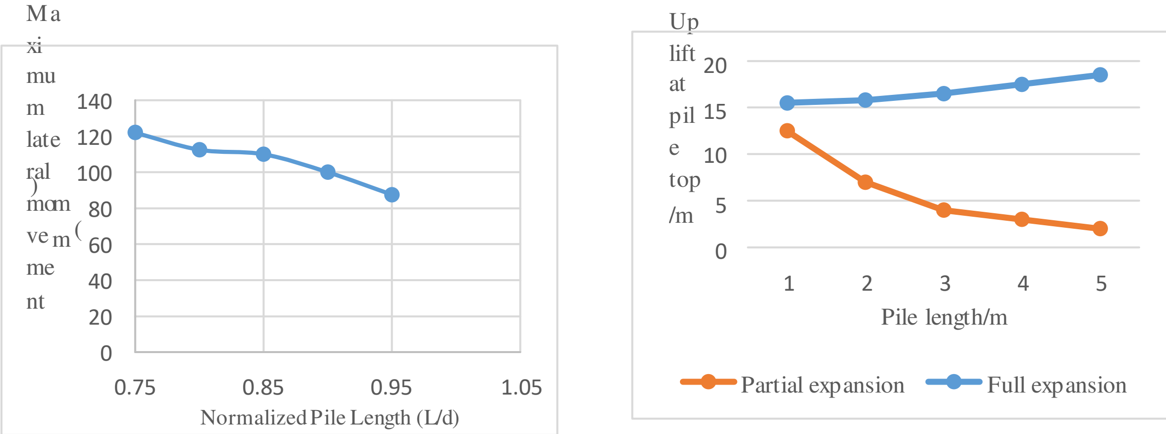

Figure 3: Effects of increase of pile length on lateral movement and uplift on pile top

3.2 Effect of presence of water

In some of the experiments, the variation of water level was taken into account. It was observed that when water content of soil increases, the matric suction drops drastically, Ultimately, due to the increase in water content, the ultimate bearing capacity of pile decreases. When the water table is low and the soil has higher matric suction, the suction seems to develop a resistance to slippage at the contacts between the soil particles. Instead of slipping, rolling between the soil particles occur, resulting in dilatant behaviour. The soil compacted at low water content has larger dilatancy angle than that at higher water content. In saturated clays, the excess pore water pressure proves to be a predominant part in the design procedure of pile foundations. The OCR value also plays an important role on the generation of pore water pressure of soil. When the pile was penetrated in soils with higher OCR values, the rate of dissipation of excess pore water pressure was higher.

3.3 Effect of type of soil

For various studies, the pile foundations considered were driven or bored in different soil types. The behaviour of piles were different for different soil types. In sandy soils under lateral loads, there is no influence of vertical loads in the piles and in clayey soils, the vertical loads decrease the lateral load capacity of piles. In case of normally consolidated clays, the pore water pressure generation is higher which occurred due to pile penetration. The piles were also driven in improved gravel soil, i.e., jet grouted gravel with cement. This provided lateral resistance with better integrity than virgin soil as the cohesion and angle of internal friction increases. In case of pile foundation in unsaturated soil, matric suction is

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higher, hence bearing capacity of pile increases. Furthermore, the behaviour of pile in expansive soil is dependent on the uplift of pile top which ultimately governed the bearing capacity of piles.

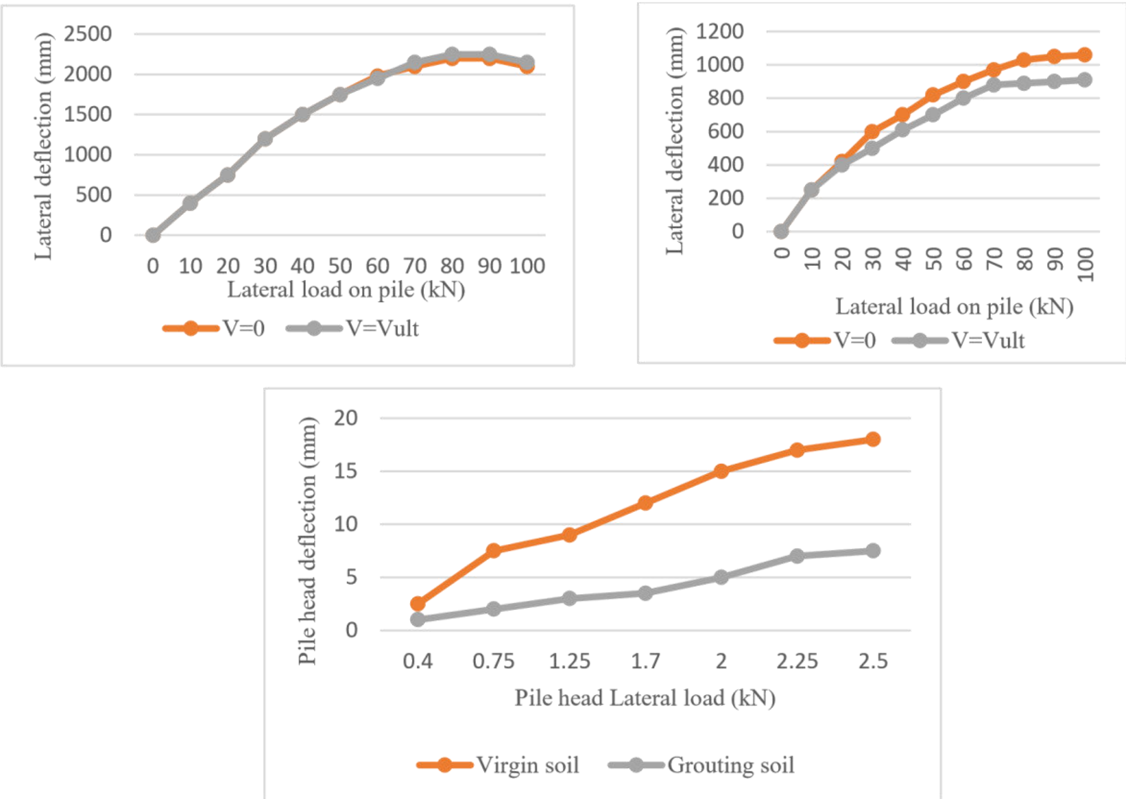

Figure 4: Variation of pile deflection for sandy, clayey and grouting soil

4 VALIDATION OF MODELS

After carrying out simulation of the modelled pile foundations in various softwares like PLAXIS, FLAC3D, ABAQUS etc., the models are validated using some literatures or using the laboratory and field test results. In most of the assessments, both experimental and analytical works were executed for acquiring the actual responses of the structure as well as for the verification of the outputs. Hazzar et al. [3] in the study, validated the model by following some case studies carried out by Comodromos (2003), Karasev et al. (1977) etc. Fakharian et al. [5] in the study of stress state variations in soil due to mini pile penetration in clays verified the numerical model using the results of a physical model in which a piezocone was penetrated into a consolidation chamber containing saturated clay. Furthermore, Liu et al. [6] verified the proposed model used for the analysis of behaviour prediction of laterally loaded piles in improved gravel by conducting the laterally loaded single pile load test. In some other studies carried out by Jiang et al. [10], the validities of the methods suggested for the analysis of pile foundations in expansive soils were confirmed through comparison with the laboratory and field test results. Adding further, Valikhah et al. [1] suggested a new analytical-numerical solution for determining the stress and state fields around piles using CPT values, whose results were verified by the subsequent results of 98 full scale pile load tests. All the new interpretations of the methods for the determination of the responses of pile foundations under various loading conditions as well as for different soil conditions were precisely verified by conducting physical experiments in field or in laboratories. The introduction of such new processes have led to simple conclusions and explanations of results, thereby avoiding cumbersome analyses.

5 DISCUSSION

The experimental studies and analytical studies carried out by the researchers emphasized on some relevant observations of the studies which led to develop more detailed knowledge of pile foundations for the geotechnical engineers. The studies were mainly carried out by demonstrating the pile foundations to different conditions like in saturated soil, in unsaturated soil, under GRPS embankment, in expansive soil, loess soil etc. The objective was mainly to determine the response of pile foundations under various conditions of loads and in various soil strata.

Some studies show that the response of a pile to an applied axial load cannot be considered as pile ultimate capacity, rather is a function of stress and strain conditions around the pile. To determine the load-displacement behaviour of piles [1], pile load test proves to be a reliable method, but due to its cost inefficiency and time consumable property, alternate simple numerical or analytical methods have been introduced which are based on limited test results. The behaviour of pile foundations in unsaturated clays were studied by Chung and Yang [2] where they stated the decrease in ultimate bearing capacity with increase in water content of soil. It was also found that the soil compacted at low water content has a larger dilatancy angle than that at high water content. This phenomenon is due to the matric suction developed in dry soils. Further, for the piles tested under GRPS embankments [4], it was found that the effect of geosynthetic layers on the stability of GRPS embankments is not very significant. The lateral response of rigid piles in GRPS embankment systems depend on pile length. When the normalized pile length (L/d) increases, the critical height of embankment also increases. The lateral movement and bending moment of piles under the embankment loading increased from central piles to the side piles. Therefore, the side piles were more severely affected by the lateral displacement of soft soils, thereby increasing the chance of collapsing of the embankment.

In a study carried out for the analysis of behaviour of laterally loaded single piles in improved gravel soil [6], it was found that the jet grouting gravel soil on the front of pile provides lateral resistance with better integrity than virgin soil does because of increase in its cohesion and angle of internal friction.

Furthermore, in the study of behaviour of pile foundations under cyclic loading [7], it was observed that near the pile head, the soil could withstand large straincontrolled type of cyclic loading due to pile flexibility. In a comparative study between conventional pile and post grouting pile [8], it was observed that the settlement of post grouting pile is greater than conventional pile in the initial stages but with increasing load, the latter has become higher than former one. Slurry climbing changes the properties of the interface between soil and pile, thus increasing the lateral friction of climbing part and decreasing the relative displacement of pile and soil, which ultimately results in slowing down of overall settlement of pile. The behaviour of pile foundations were further studied in saturated soil [9], where it was found that for single pile and group of piles in saturated soils, the generated excess pore water pressure depends on operating frequency, pile length and permeability of soil. Using high L/d ratio in saturated soil reduces the effects of presence of water on the responses of foundation when compared with dry soil. Furthermore, for the single pile in the expansive soil after immersion [10], it was found that the length of the pile should be atleast 3 times the expansion active depth for stability of the pile in the soil. Moreover, some comparative studies of piles in clays and sands [3] reveal that the response of piles in sandy soils under lateral loads is not influenced by the presence of vertical loads, whereas, the presence of vertical loads decreases the lateral loading capacity of piles in clayey soil.

The results of the studies are mostly interpreted by showing the effects of various parameters in the behaviour prediction of pile foundations. Some parameters like pile length, water content, soil type play an important role in behaviour prediction in experimental as well as analytical procedures of finding the response of pile foundations under different loading conditions and in different soils.

6 CONCLUSION

Various developments in pile foundations in the recent past have been reviewed and are organized into various sections like analytical studies, experimental studies etc. From all the studies reviewed, it was clear that the response of pile foundations under various conditions of soil and loading was significantly different. The studies revealed the changes in the bearing capacity of pile by introducing some new techniques to be implemented in pile design. The response of the surrounding soil during driving of piles was also observed and henceforth, the effects were examined with various parameters.

- The foremost step in construction of piles is to know about the soil lying beneath the ground so as to contemplate its behaviour with respect to pile and carry out the appropriate pile design. Different soils interact with the loads applied on it differently. One of the important parameters to be considered in design of piles is the pile length. Increase in pile length can lead to various improvements related to bearing capacity of pile, decrease in uplift of top of pile (in case of expansive soil), etc. are observed.

- The water content of the surrounding soil should be properly examined prior to the construction of pile. As this may lead to dissipation of excess pore water pressure, which ultimately lead to disturbances in pile foundation system.
- The various strengthening techniques like to construct embankment reinforced with geosynthetics, post grouting the driven pile, improving the gravel soil by jet grouting with cement were carried out and significant interaction of pile and soil were examined.

7 FUTURE PERSPECTIVES

The studies considered for review were competent from the point of view of the topic which is about the response of pile foundations under various loads and in varying soil conditions. But there were some limitations in all the reviewed studies which are to be brought into notice for future experimentation.

- In practical engineering, there are limited studies on the FEM analyses of pile foundations in unsaturated soil. Thus more studies are to be carried out to comprehend the differences between reality and simulation by FEM for load bearing capacity of small scale pile model in unsaturated soil.
- The effect of cyclic loading on piles in sand has been unrecognized till date. There are fewer papers available on this concept.
- In the study of the response of pile foundations in expansive soils, the variation of shear modulus and elastic modulus with depth was ignored and taken to be constant during the analysis but in actual, the value increases with depth which may lead to underestimated results. So future studies can be carried out by considering the variation.

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