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Numerical Investigations on the Behavior of Piled Raft foundation on medium Dense Sand with Finite Difference Method

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FACULTY OF CIVIL AND WATER RESOURCES ENGINEERING

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June, 2019

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A thesis submitted to the School of Research and Graduate Studies of Bahir Dar Institute of Technology, BDU in partial fulfillment of the requirements for the degree of Master of Science in the Geotechnical engineering in the Faculty of Civil and Water Resource Engineering.

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DECLARATION

I, Birhanu Belete, a student of Bahir Dar institute of technology honestly declare that this thesis comprises my own original work. I have acknowledged and refereed all materials used in this work. This document was not submitted to any university or institute.

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Date of submission: ____________

Place: Bahir Dar

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iii

To my Family

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ABSTRACT

In the last four to five decades piled raft foundations has been successfully applied in different parts of the world for optimization of civil engineering structure foundations. This thesis is an extension of research works being carried out to wide spread the concept of piled raft foundation further. A piled raft is a composite foundation in which the piles are used as settlement reducers and they share, with the raft, the load from the superstructure.

Nevertheless, research in this area has been lagging because of the complexity of the problem and lack of field data. Numerical modeling can be used to provide valuable data with a high level of success. A three-dimensional finite-element model of a piled raft foundation was developed to simulate the case of a piled raft foundation. The model was used to examine the effect of the key parameters governing the performance of this foundation during loading and, accordingly, the load shared by the piles and the raft. After validating the numerical model with available data in the literature, the model was used to develop data for a wide range of parameters and to examine the role of the number of piles and foundation geometry, including pile spacing in the group, pile diameter, and raft thickness.

From the parametric study, it is found that as pile number increases the Ultimate Load and Allowable Load capacities, Load Improvement Ratio, Settlement Ratio, Differential settlement Ratio and proportion of load carried by piles are highly improved. Diameter of pile positively affects all except differential settlement. Differentia settlement is not affected by the piled diameter. Raft thickness has significant effect on differential settlement than any other parameter. Raft thickness has no that much significant effect on other effects like Ultimate Load and Allowable Load capacities, Load Improvement Ratio, Settlement Ratio and proportion of load. Spacing considered in this thesis (3D and 4D) have no any significant effect on any of the effects mentioned.

The results explained here are conclusions drawn based on the limited data found from the numerical model analysis.

Keywords: Piled raft, FLAC^{3D}, Pile umber, pile diameter, raft relative stiffness, spacing

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

F_s	-Skin Frictional Stress
Q_f	-Skin Friction
Q_b	-End Bearing
ULC	-Ultimate Load Capacity
ALC	-Allowable Load Capacity
S	-Settlement of Single Pile
Sg	-Settlement of Pile Group
FLAC3D	-Fast Lagragian Analysis for Continua In 3d
LIR	-Load Improvement Ratio
SR	-Settlement Ratio
DSR	-Differential Settlement Ratio
DS_CE	-Differential Settlement Between Center and Mid Edge of raft
NDS	-Normalized Differential Settlement
PileSEL	-Pile Structural Element
LinerSEL	-Liner Structural Element
K_n	-Normal Stiffness
K_s	-Shear Stiffness

1. INTRODUCTION

1.1 Background

To carry the excessive loads that come from the superstructures like high-rise buildings, bridges, power plants or other civil structures and to prevent excessive settlements, piled foundations have been developed and widely used in recent decades. However, it is observed that the design of foundations considering only the pile or raft is not a feasible solution because of the load sharing mechanism of the pile-raft-soil. Therefore, the combination of two separate systems, namely “Piled Raft Foundations” has been developed by Clancy, et al.(1993).

Piled raft foundation system is verified to be an economical foundation type comparing the conventional piled foundations, where, only the piles are used for the reducing both total and differential settlements and the contribution of the raft is generally disregarded. This is verified in the Piled raft foundation for the W-TOWER Tel Aviv as explained in the literature part.

In this study, behavior of the piled raft foundation systems under axial loads will be investigated by comparing the traditional design approaches and the current design approaches by parametric analyses. In the literature, there are plenty of researches focusing of these parameters, like; the number of piles, length of piles, diameter of piles, pile spacing ratio, location of piles, stiffness of piles, distribution of load, level of load, raft thickness, raft dimensions and type of soil. However, through these parameters, the number of piles, diameter of piles, raft thickness and level of load are emphasized in this study. Effects of these parameters will be discussed with the solutions of finite difference models. To this end, parametric analyses will be conducted via the software FLAC^{3D}.

The reason why FLAC^{3D} is being used is that, this software is a highly research tool. Because it has its own programming language, FISH, which gives a great advantage to vary the parameters that are not incorporated in it when the software was developed. For instance, the variation of stiffness of the soil and density varies with depth but most finite element programs do not account this concept. But in FLAC^{3D} we can simply write some fish program that relates the depth variation of stiffness and density of the soil and model it in its real sense which save us from either underestimating the strength (unsafe) or overestimating the strength (compromising the economy).

1.2 Statement of The Problem

Even though many high rising buildings like Burj Khalifa of Dubai; W-TOWER of Tel Aviv and many others are constructed with piled raft foundation system, theories in the literature did not provide accurate and reliable predictions of the load sharing mechanism between the raft and the pile considering all the factors (pile diameter, pile number, raft thickness, and load level etc.) in to account.

Therefore, this research will find out how much load is transferred to the pile as well as to the raft by performing the numerical modelling test with FLAC^{3D} with certain conditions given (pile number, diameter of pile, raft thickness and spacing of piles). This research also discusses the reduction of average and differential settlements of the piled raft foundation on the variation of different parameters of the piled raft foundation (pile number, pile diameter, pile spacing and raft thickness).

1.3 Objectives of The Study

The general objective is assessing the load carrying proportion and settlement characteristics of piled raft foundation systems and determining the percentage of load shared by pile and rafts independently with the given conditions. Specifically, from the general objective stated, specific objectives drawn are the following:

- Load sharing proportion between raft and piles
- Average settlement behavior due to the variation of pile number, pile diameter, raft thickness and spacing.
- Differential settlement behaviour due to the variation of pile number, pile diameter, raft thickness and spacing.

1.4 Scope of The Study

This research work focuses on estimating the relative load magnitude on piles and rafts as well sharing mechanism of loads to piles and a raft under vertical static loading on uniform cohesion less soil. Therefore, this research is limited to the following soil and loading conditions

- Medium dense sand,
- Vertical static concentrated loading with load level starting from 1MN to a load which causes a foundation to settle more than 25 mm average settlement,

Moreover, Numerical analysis is conducted by varying the following parameters

- Pile number,
- Raft thickness,
- Pile diameter and
- spacing.

1.5 Significance of the Study

Rafts are generally considered only as a "cap" which structurally connects the heads of the piles to the overlying column/s. However, the positive contribution of rafts to the load/settlement behavior is disregarded. As structural elements, rafts are mostly in contact with the soil, have a capacity to transfer the load that comes from the superstructure to the soil beneath. Considering this contribution (or load sharing), the total length and diameter of the piles may be significantly decreased. Besides this general significance of the study, this study focuses on some important parameters of the foundation (pile diameter, number of piles, spacing and raft thickness) amongst the many parameters that affect the behavior of piled raft and contributes its part to the concept of piled raft foundation analysis and design. The results of these Numerical model tests provide insight into settlement behavior of rafts on settlement reducing piles, and load sharing between piles and raft and may provide some general guidelines for the economical design of raft on settlement reducing piles.

The results of these Numerical model tests provide insight into settlement behavior of rafts on settlement reducing piles, and load sharing between piles and raft and may provide some general guidelines for the economical design of raft on settlement reducing piles

2. LITERATURE REVIEW

2.1 Introduction

In the design of foundations, shallow foundation is the first option where the top soil has sufficient bearing strength to carry the superstructure load without any significant total and differential settlements to prevent damage of infrastructure and superstructure. However, in the last few decades the need for high-rise buildings and high-loaded superstructures has been increased rapidly, even in the lands with poor subsoil conditions. Therefore, the need for foundations with high bearing capacity and showing low settlement values, both total and differential, has also been increased. These types of foundations can be constructed as a shallow foundation after the application of ground improvement techniques or as a piled foundation which transfers the excessive load to a deeper and stiffer stratum through the piles and reduces the settlements.

This chapter presents a brief review of previous researches on piles, rafts, pile groups and piled raft foundations. However, the main attention is on design methods and analyses of piled raft foundations.

As explained in the first Chapter; rafts are generally considered only as a "cap" which structurally connects the heads of the piles. However, the positive contribution of rafts to the load/settlement behavior is disregarded. As structural elements, rafts are mostly in contact with the soil, therefore has/have a capacity to transfer the load comes from the superstructure to the soil beneath. Considering this contribution (or load sharing), the total length of the piles may be significantly decreased. So, piled raft foundations become an alternative to the piled foundations or foundations with "settlement reducing piles" for an economic/feasible design.

2.2 Piled Raft

In the past few years, there has been an increasing recognition that the use of piles to reduce raft settlements and differential settlements can lead to considerable economy without compromising the safety and performance of the foundation. Such a foundation makes use of both the raft and the piles and is referred to here as a pile-enhanced raft or a piled raft.

2.2.1 Design Concepts

2.2.1.1 Alternative Design Philosophies

Randolph (1994) has defined clearly three different design philosophies with respect to piled rafts:

- The "conventional approach", in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity.
- "Creep Piling" in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80% of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil below the pre-consolidation pressure of the soil.
- Differential settlement control, in which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement.

In addition, there is a more extreme version of creep piling, in which the full load capacity of the piles is utilized, i.e. some or all of the piles operate at 100% of their ultimate load capacity. This gives rise to the concept of using piles primarily as settlement reducers, while recognizing that they also contribute to increasing the ultimate load capacity of the entire foundation system.

De Sanctis et al. (2001) and Viggiani (2001) have distinguished between two classes of piled raft foundations:

1. "Small" piled rafts, where the primary reason for adding the piles is to increase the factor of safety (this typically involves rafts with widths between 5 and 15 m);
2. "Large" piled rafts, whose bearing capacity is sufficient to carry the applied load with a reasonable safety margin, but piles are required to reduce settlement or differential settlement. In such cases, the width of the raft is large in comparison with the length of the piles (typically, the width of the rafts exceeds the length of the piles).

These two categories broadly mirror the conventional and creep piling philosophies considered by Randolph.

Figure 2-1 illustrates, conceptually, the load-settlement behavior of piled rafts designed according to the first two strategies. Curve 0 shows the behavior of the raft alone, which in this case settles excessively at the design load. Curve 1 represents the conventional design philosophy, for which the behavior of the pile-raft system is governed by the pile group behavior, and which may be largely linear at the design load. In this case, the piles take the great majority of the load. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than for Curve 1. Curve 3 illustrates the strategy of using the piles as settlement reducers and utilizing the full capacity of the piles at the design load. Consequently, the load-settlement may be nonlinear at the design load, but nevertheless, the overall foundation system has an adequate margin of safety, and the settlement criterion is satisfied. Therefore, the design depicted by Curve 3 is acceptable and is likely to be considerably more economical than the designs depicted by Curves 1 and 2.

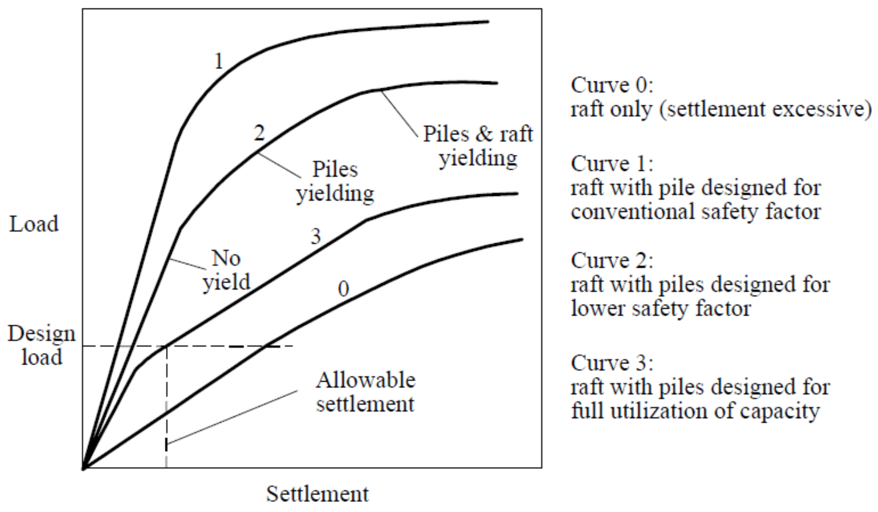

Figure 2-1:- Load settlement curves for piled rafts according to various design philosophies (Poulos 2001).

2.2.1.2 Design Issues

As with any foundation system, a design of a piled raft foundation requires the consideration of a number of issues, including:

1. Ultimate load capacity for vertical, lateral and moment loadings
2. Maximum settlement
3. Differential settlement
4. Raft moments and shears for the structural design of the raft
5. Pile loads and moments, for the structural design of the piles.

2.2.2 Classification of Methods of Analysis

Several methods of analyzing piled rafts have been developed, and some of these have been summarized by Poulos (2001). Three broad classes of analysis method have been identified:

- Simplified calculation methods
- Approximate computer-based methods
- More rigorous computer-based methods.

Simplified methods include those of Poulos and Davis (1980), Randolph (1983, 1994), Van impe and Clerq (1995), and Burland (1995). All involve a number of simplifications in relation to the modelling of the soil profile and the loading conditions on the raft.

The approximate computer-based methods include the following broad approaches:

- Methods employing a "strip on springs" approach, in which the raft is represented by a series of strip footings, and the piles are represented by springs of appropriate stiffness (e.g. Poulos (1991)).
- Methods employing a "plate on springs" approach, in which the raft is represented by a plate and the piles as springs (e.g. Clancy and Randolph (1993); Poulos (1994); Viggiani (1998); Anagnostopoulos and Georgiadis, 1998).

The more rigorous methods include:

- Boundary element methods, in which both the raft and the piles within the system are discretized, and use is made of elastic theory (e.g. Butterfield and Banerjee, 1971; (Brown and Weisner, 1975; Kuwabara, 1989; Sinha, 1997).
- Methods combining boundary element for the piles and finite element analysis for the raft (e.g. Hain and Lee 1978; Ta and small, 1997; Franke et al, 1994; Russo and Viggiani, 1998).
- Simplified finite element analyses, usually involving the representation of the foundation system as a plane strain problem (Desai, 1974) or an axis-symmetric problem (Hooper, 1974), and corresponding finite difference analyses via the commercial program FLAC (e.g. (Hewitt and Gue 1994).
- Three-dimensional finite element analyses (e.g. Zhuang et al, 1991; Lee, 1993; Wang, 1995; Katzenbach et al, 1998) and finite difference analyses via the commercial program $FLAC^{3D}$.

In the following section, a more detailed description will be given of a limited number of the above methods

2.2.3 Simplified Analysis Methods

2.2.3.1 Poulos-Davis-Randolph (PDR) Method

For assessing vertical bearing capacity of a piled raft foundation using simple approaches, the ultimate load capacity can generally be taken as the lesser of the following two values:

- The sum of the ultimate capacities of the raft plus all the piles
- The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

For estimating the load-settlement behavior, an approach similar to that described by Poulos and Davis (1980) can be adopted. However, a useful extension to this method can be made by using the simple method of estimating the load sharing between the raft and the piles, as outlined by Randolph (1994). The definition of the pile problem considered by Randolph is shown in Figure 2-2. Using his approach, the stiffness of the piled raft foundation can be estimated as follows:

$$K_{pr} = \frac{k_p + k_r(1 - \alpha_{cp})}{(1 - \alpha_{cp}^2 \frac{k_r}{k_p})} \qquad (2\text{-}1)$$

Where

$\boldsymbol{k_{pr}}$= Stiffness of piled raft

$\boldsymbol{k_p}$=Stiffness of pile group

$\boldsymbol{K_r}$=Stiffness of the raft alone

$\boldsymbol{\alpha_{cp}}$=Raft pile interaction factor

The raft stiffness $K_r$can be estimated via elastic theory, for example using the solutions of Fraser and Wardle (1976) or Mayne and Poulos (1999). The pile group stiffness can also be estimated from elastic theory, using approaches such as those described by Poulos and Davis (1980), Fleming et al (1992) or Poulos (1989). In the latter cases, the single pile stiffness is computed from elastic theory, and then multiplied by a group stiffness efficiency factor which is estimated approximately from elastic solutions.

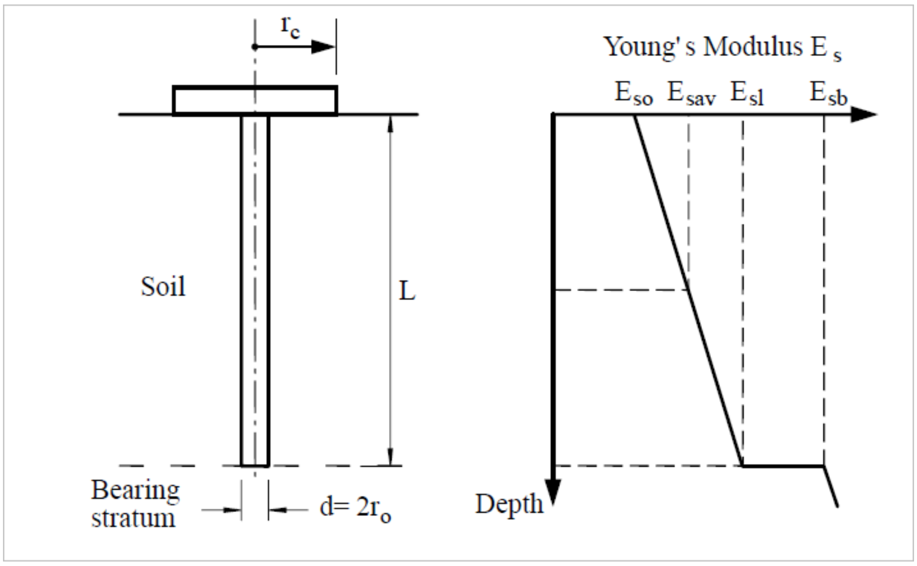

Figure 2-2:- Simplified representation of a pile-raft unit (Randolph 1994)

The proportion of the total applied load carried by the raft is:

$$\frac{P_r}{P_t} = \frac{k_r(1-\alpha_{cp})}{(K_r+k_p)(1-\alpha_{cp})} = X \qquad (2\text{-}2)$$

Where

p_r =Load proportion carried by the raft

P_t=Total applied load

The raft pile interaction factor α_{cp} can be estimated as follows

$$\alpha_{cp} = 1 - ln\,(r_c\,/\,r_0)\,/\,\zeta \qquad (2\text{-}3)$$

where

r_c = Average radius of pile cap, (corresponding to an area equal to the raft area divided by number of piles)

r_0 = Radius of pile

$\zeta = \ln (r_m / r_{0})$

$r_m = \{0.25+\xi\, [2.5\, \rho\, (1-\nu) - 0.25) * L$

$\xi = E_{sl} / E_{sb}$

$\rho = E_{sav} / E_{sl}$

L = Pile length

E_{sl} = Soil Young's modulus at level of pile tip

E_{sb} = Soil Young's modulus of bearing stratum below pile tip

E_{sav} = Average soil Young's modulus along pile shaft.

The above equations can be used to develop a tri-linear load-settlement curve as shown in Figure 2-3. First, the stiffness of the piled raft is computed from equation (2-1) for the number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Making the simplifying assumption that the pile load mobilization occurs simultaneously, the total applied load, P_1, at which the pile capacity is reached is given by:

$$\boldsymbol{P_1 = \frac{P_{up}}{(1 - X)}} \quad (2\text{-}4)$$

Where Pup= Ultimate load capacity of the piles in the group

X = Proportion of load carried by the raft (Equation 2-2).

Beyond that point (Point A in Figure 2-3), the stiffness of the foundation system is that of the raft alone (K_r), and this holds until the ultimate load capacity of the piled raft foundation system is reached (Point B in Figure 2-3). At that stage, the load-settlement relationship becomes horizontal.

The load – settlement curves for a raft with various numbers of piles can be computed with the aid of a computer spreadsheet. In this way, it is simple to compute the relationship between the number of piles and the average settlement of the foundation. Such calculations provide a rapid means of assessing whether the design philosophies for creep piling or full pile capacity utilization are likely to be feasible.

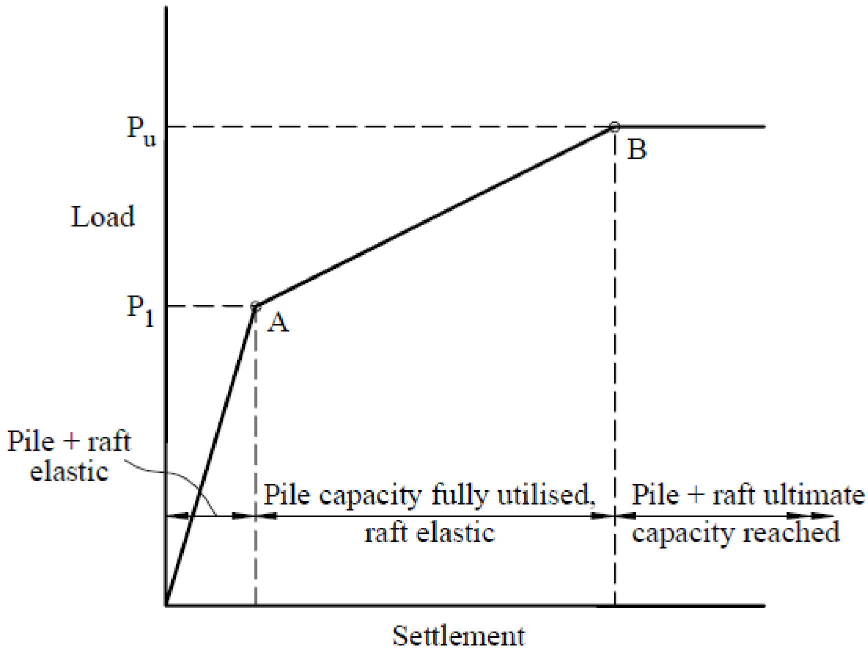

Figure 2-3:-Simplified Load-Settlement Curve for Preliminary Analysis (Randolph 1994)

2.2.3.2 Burland's Approach

When the piles are designed to act as settlement reducers and to develop their full geotechnical capacity at the design load, Burland (1995) has developed the following simplified process of design:

- Estimate the total long-term load-settlement relationship for the raft without piles (see Figure 2-4). The design load P_0 gives a total settlement S_0.
- Assess an acceptable design settlement S_d, which should include a margin of safety.
- P1 is the load carried by the raft corresponding to S_d.
- The load excess $P_0 – P_1$ is assumed to be carried by settlement-reducing piles. The shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. However, Burland suggests that a "mobilization factor" of about 0.9 be applied to the 'conservative best estimate' of ultimate shaft capacity, P_{su}.
- If the piles are located below columns which carry a load in excess of P_{su}, the piled raft may be analyzed as a raft on which reduced column loads act. At such columns, the reduced load Q_r is:

$$Q_r = Q - 0.9P_{su} \tag{2-5}$$

- The bending moments in the raft can then be obtained by analyzing the piled raft as a raft subjected to the reduced loads Q_r.
- The process for estimating the settlement of the piled raft is not explicitly set out by Burland, but it would appear reasonable to adopt the approximate approach of Randolph (1994) in which:

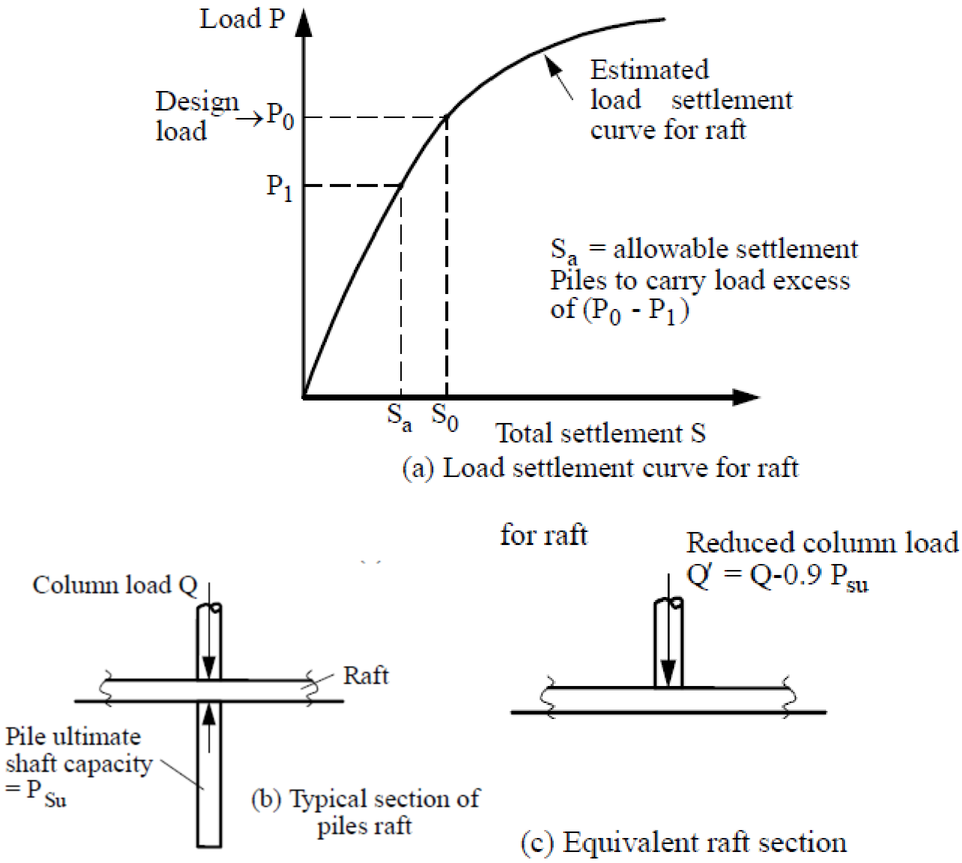

Figure 2-4:-Burland's Simplified Design Concept (Burland 1995)

$$S_{pr} = S_r * K_r/K_{pr} \tag{2-6}$$

where S_{pr} = Settlement of piled raft

S_r = Settlement of raft without piles subjected to the total applied loading

K_r = Stiffness of raft

K_{pr} = Stiffness of piled raft.

Equation 2-20 can be used to estimate K_{pr}.

2.2.4 Approximate Computer Methods

2.2.4.1 Strip on Springs Approach (GASP)

An example of a method in this category is that presented by Poulos (1991) and illustrated in Figure 2-5. A section of the raft is represented by a strip, and the supporting piles by springs. Approximate allowance is made for all four components of interaction (raft-raft elements, pile-pile, raft-pile, pile-raft), and the effects of the parts of the raft outside the strip section being analyzed are considered by computing the free-field soil settlements due to these parts. These settlements are then incorporated into the analysis, and the strip section is analyzed to obtain the settlements and moments due to the applied loading on that strip section and the soil settlements due to the sections outside the raft.

The method has been implemented via a computer program GASP (Geotechnical Analysis of Strip with Piles) and has been shown to give settlement which are in reasonable agreement with more complete methods of analysis. However, it does have some significant limitations, especially as it cannot consider torsional moments within the raft, and also because it may not give consistent settlements at a point if strips in two directions through that point are analyzed.

GASP can take account of soil non-linearity in an approximate manner by limiting the strip-soil contact pressures to not exceed the bearing capacity (in compression) or the raft uplift capacity in tension. The pile loads are similarly limited to not exceed the compressive and uplift capacities of the piles. However, the ultimate pile load capacities must be pre-determined, and are usually assumed to be the same as those for isolated piles. In reality, as shown by Katzenbach et al (1998), the loading transmitted to the soil by the raft can have a beneficial effect on the pile behavior in the piled raft system. Thus, the assumptions involved in modelling piles in the GASP analysis will tend to be conservative.

In carrying out a nonlinear analysis in which strips in two directions are analyzed, it has been found desirable to only consider nonlinearity in one direction (the longer direction) and to consider the pile and raft behavior in the other (shorter) direction to be linear. Such a procedure avoids unrealistic yielding of the soil beneath the strip and hence unrealistic settlement predictions.

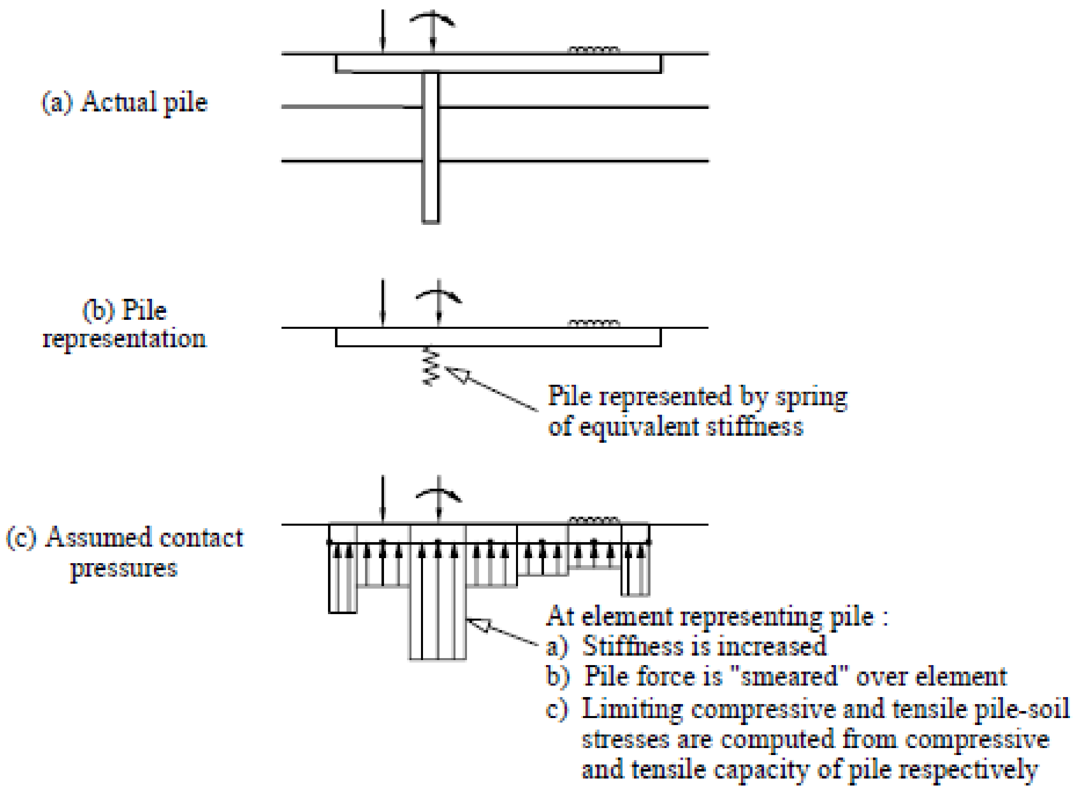

Figure 2-5:-Representation of Piled Strip Problem Via GASP Analysis (Poulos, 1991).

2.2.4.2 Plate on Springs Approach (GARP)

In this type of analysis, the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modelled as interacting springs. Some of the early approaches in this category (e.g. Hongladaromp et al, 1973) neglected some of the components of interaction and gave pile-raft stiffness which were too large.

Poulos (1994) has employed a finite difference method for the plate and has allowed for the various interactions via approximate elastic solutions. This analysis has been implemented via a program GARP (Geotechnical Analysis of Raft with Piles). Allowance has been made for layering of the soil profile, the effects of piles reaching their ultimate capacity (both in compression and tension), the development of bearing capacity failure below the raft, and the presence of free-field soil settlements acting on the foundation system. The approximations involved are similar to those employed in the program GASP for piled strips.

A later version of GARP (Sales et al, 2000) has replaced the finite difference analysis for the raft with a finite element analysis and has employed a modified approach to considering the development of the ultimate load capacity in the piles.

Russo (1998) and Russo and Viggiani (1998) have described a similar approach to the above methods, in which the various interactions are obtained from elastic theory, and non-linear behavior of the piles is considered via the assumption of a hyperbolic load-settlement curve for single piles. Pile-pile interaction is applied only to the elastic component of pile settlement, while the non-linear component of settlement of a pile is assumed to arise only from loading on that particular pile.

Most analyses of piled rafts are based on the raft being treated as a thin plate, and it is of interest to see what the effect of using thick plate theory is on the numerical predictions. Poulos et al (2001) have examined the effect of the method of modelling the raft as a thin plate who analyzed a typical problem using firstly, a three-dimensional finite element program where the raft was firstly modelled using thin shell theory, and then secondly, by making the raft 0.3m thick, and assigning the raft modulus to that part of the finite element mesh representing the raft. It was assumed in the analysis that there was no slip between the raft and the soil or between the piles and the soil. It was found that there was not a great deal of difference in the computed deflections for the raft, for both a stiff raft and a flexible raft.

It was concluded that the use of thin shell elements to represent the raft will lead to reasonable estimates of deflections, and therefore moments, as long as the raft is not extremely thick. Stresses in the soil will be higher for the thin shell analysis, and this effect may become important if yield of the soil due to concentrated loads is of concern.

2.2.5 More Rigorous Computer Methods

2.2.5.1 Two – Dimensional Numerical Analysis (FLAC)

Methods in this category are exemplified by the analyses described by Desai (1974), Hewitt and Gue (1994) and Pradoso and Kulhawy (2001). In the former case, the commercially available program FLAC has been employed to model the piled raft, assuming the foundation to be a two-dimensional (plane strain) problem, or an axially symmetric three-dimensional problem. In both cases, significant approximations need to be made, especially with respect to the piles, which must be "smeared" to a wall and given an equivalent stiffness equal to the total stiffness of the piles being represented. Problems are also encountered in representing concentrated loadings in such an analysis, since these must also be smeared. Unless the problem involves uniform loading on a symmetrical raft, it may be necessary to carry out analyses for each of the directions in order to obtain estimates of the settlement profile and the raft moments.

As with the plate on springs approach, this analysis cannot give torsional moments in the raft.

2.2.5.2 Three – Dimensional Numerical Analysis

A complete three-dimensional analysis of a piled raft foundation system can be carried out by finite element analysis (e.g. Katzenbach et al, 1998) or by use of the commercially available computer program $FLAC^{3D}$. In principle, the use of such a program removes the need for the approximate assumptions inherent in all of the above analyses. Some problems still remain, however, in relation to the modelling of the pile-soil interfaces, and whether interface element should be used. If they are, then approximations are usually involved in the assignment of joint stiffness properties. Apart from this difficulty, the main problem is the time involved in obtaining a solution, in that a non-linear analysis of a piled raft foundation can take several days. Such analyses are therefore more suited to obtaining benchmark solutions against which to compare simpler analysis methods, rather than as routine design tools.

2.3 Typical Physical Properties of Sand Soil

This sub-section contains the review of previous works on the characterization of the typical physical properties of sand soil relevant to the research. Several manuals and studies have been published regarding the typical physical properties of sands. Empirical correlations or values for the necessary material characteristics were employed in the present study. The sand soil is modeled as elasto-plastic material and the interacting concrete as perfectly elastic material. The young's modulus and Poisson's ratio define a given perfectly elastic material. Whereas, if one uses the Mohr-Coulomb plastic constitutive model, then cohesion and angle of internal friction will define the plastic behavior of a given material like soil and rocks. In the present study, the Mohr-Coulomb constitutive model was employed. In the subsequent sections, each parameter that defines elastic and plastic behavior of soils is reviewed.

2.3.1 Young's Modulus

The modulus of elasticity or Young's modulus of a soil is an elastic soil parameter most commonly used in the estimation of settlement from static loads. Young's modulus, Es, may be estimated from empirical correlations, laboratory test results and field tests. Typical values of elastic moduli for sand soil are presented in USACE (1990).

Table 2-1:-Typical Elastic Moduli of Sand Soils After USACE Table D-3

Soil	Es, kPa
Sand	
Loose sand	9,500-23,750
Dense Sand	23,750-95,000

2.3.2 Poisson’s Ratio

Poisson's ratio, named after Siméon Poisson, is the negative ratio of transverse to axial strain. When a material is compressed in one direction, it usually tends to expand in the other two directions perpendicular to the direction of compression. This phenomenon is called the Poisson effect. The typical values of Poisson’s ratio were taken from Bowles (1996).

Table 2-2:-Typical Poisson’s ratio of soils after Bowles, 1996

Soil	Poisson’s Ratio
Most clay soils	0.4 to 0.5
Saturated clay soils	0.45 to 0.5
Cohesion less, medium and dense	0.2 to 0.35
Cohesion less, loose to medium	0.3 to 0.4

2.3.3 Angle of Internal Friction

Angle of internal friction for a given soil is the angle on the graph (Mohr's Circle) of the shear stress and normal effective stresses at which shear failure occurs or it is the maximum angle obliquity at which sliding of unstable soil mass over a stable soil mass will occur. One of the empirical correlations of angle of internal frictions with SPT numbers for sands have been given in Meyerhof (1956). The relation is summarized according to Table 2-3 below;

Table 2-3:-Typical Angle of Internal Friction for Sand Soils After Meyerhof, 1956

SPT Penetration, N-Value	Density of Sand	φ (degrees)
<4	Very loose	<29
4 - 10	Loose	29 - 30
10 - 30	Medium	30 - 36
30 - 50	Dense	36 - 41
>50	Very dense	>41

2.3.4 Unit Weight

Unit weight of a soil mass is the ratio of the total weight of soil to the total volume of soil. Empirical values for γ, of granular soils based on the standard penetration number are given in Bowles (1996).

Table 2-4:- Typical Unit Weight Values of Granular Soils After Bowles, 1996

SPT Penetration, N-Value	$\gamma\ (\frac{lb}{ft^3})$	$\gamma\ (\frac{kN}{m^3})$
0 - 4	70 - 100	11-16
4 - 10	90 - 115	14-18
10 - 30	110 - 130	17-20
30 - 50	110 - 140	17-22
>50	130 - 150	20-24

3. NUMERICALMODELING

3.1 General

This study focuses on the determination of behavior of piled rafts embedded in medium dense sand. A numerical model is prepared to undergo the investigation of the problem stated using FLAC^{3D} numerical software. The numerical modeling has such procedures as zone generation, determining the appropriate boundaries, zone sizes and assuring the quality and accuracy of the model by validation process. Thus, mainly this chapter focuses on determining the mesh and boundary sizes of the numerical model to be used in chapter four (parametric study) and validating this model with previously published literatures.

3.2 Interface in FLAC3D

Robinson (2015) explained that factors influencing interfacial friction angle of sand particularly and interface property as a whole between sand and structural material are

- Surface roughness
- Density of sand
- Normal stress
- Rate of deformation
- Size of apparatus
- Grain size and shape
- Type of apparatus

According to Wu,et al. (2011) modeling of soil-structure interaction is very important in geotechnical engineering including hydraulic structures. It is relevant to a wide range of project problems, such as numerical analysis of concrete-faced rock fill dams, retaining walls, shallow foundations, piles, tunnels, reinforced earthworks, and geo-synthetic liners. Based on the results of experiments, researchers have proposed several types of interface constitutive models, including the nonlinear elastic model, elastic-perfectly plastic model, nonlinear elastic-perfectly plastic model, rigid-plastic model, elastic-viscoplastic model, damage model, strain-softening model, monotonic and cyclic model, and cracking model.

The constitutive model in FLAC^{3D} is defined by a linear elastic-perfectly plastic Coulomb shear strength criterion that limits the shear force acting at an interface node, normal and shear stiffness's (k_n and k_s) tensile and shear bond strengths (σ_t and S_s), and a dilation angle (ψ) that causes an increase in effective normal force on the target face after the shear-strength limit is reached (Itasca Consulting Group 2005).The relationship between shear stress and shear displacement is illustrated in Figure3-2; the curve includes two parts: the linear elastic stage and the perfectly plastic stage.

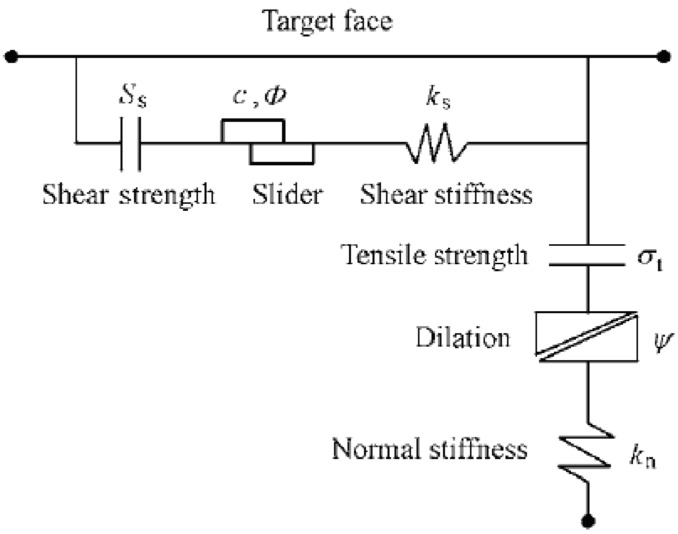

Figure 3-1:-Computation Theory of Interface Element (FLAC3D,2005)

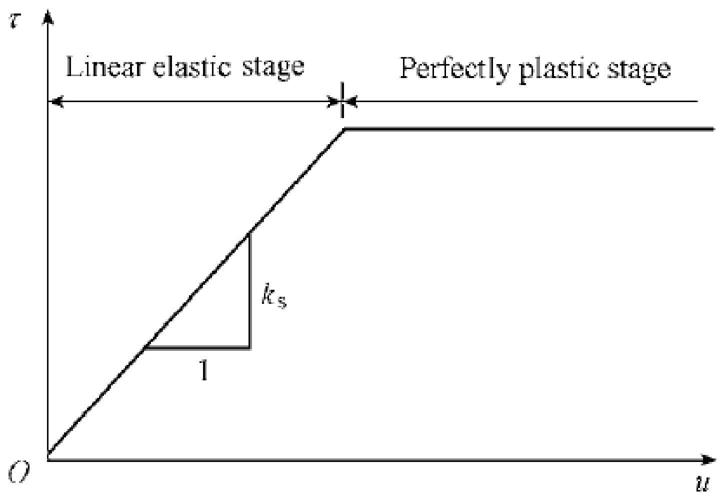

Figure 3-2:-Shear stress τ and shear displacement u of interface element (FLAC3D,2005)

According to Shakir, et al.,(2009) the shape of concrete surface has high effect on the interfacial shear strength when normal stress has relatively high value. According to that it can be said that the shape of concrete surface has a great effect depending on the normal stress intensity. Therefore, from this paper interfacial shear strength is dependent on concrete roughness and intensity of normal stress.

Xia, et al., (2011) also tested the interface for normal stress and concrete stiffness and found that the normal stress is an important factor which determines the mechanical characteristics of soil-structure interface. The roughness of the interface influences not only the shape of the shear stress-shear displacement curve but also the shear strength of the interface. Under same normal stress condition, the shear strength of interface increases with the roughness but the influence degree of interface roughness reduces gradually with the increase of normal stress. The grain breakage degree is different under different normal stress. It increases evidently with the increase of normal stress.

Szczygielski (2014) uses two soil layers namely fine sand and silt sand having shear modulus and bulk modulus of 2.26e7 pa and 4.896e7 pa, and 3.125e7 and 6.771e7 pa respectively. The paper also uses concrete elastic modulus of 30 GPa and the calculated shear and bulk modulus from this elastic modulus are 12.5 GPa and 16.67 GPa. The calculated normal and shear stiffness by using the shear and bulk and bulk moduli of the fine sand, silt sand and concrete are 791 MPa/m,1090 MPa/m and 333,000 MPa/m respectively.

But the author used normal and shear stiffness of 100 MPa/m. From this paper one can conclude that the normal and shear stiffness should be calculated by the non-stiffest material of the model.

Wu, et al., (2015) performed a parametric analysis on the selection of interface parameters and concluded that the most common parameters of the interface element in FLAC^{3D} consist of normal stiffness kn, shear stiffness ks, interfacial cohesion Cc, and interfacial friction angle φc. Apparently, a rational selection of these four parameters can directly affect the accuracy of calculated results. Many researchers have different opinions on the chosen criteria of these four parameters and have not yet obtained a unified understanding, and the determination of these four parameters is still based on experience with certain randomness.

As per the paper the Kn should be 100 times shear modulus of soil surrounding the pile due to the fact that the normal stiffness Kn is relevant to the normal deformation and suggested that Kn should be a relatively large value to avoid the normal penetration and detachment on pile-soil interface. The paper found that the normal stiffness of pile-soil interface should take a relatively large value, on the order of 10^8 N/m3 in general.

The studies about the selection of Kn have shown that a large value of Kn can simulate the actual situation of pile-soil interface well. Therefore, kn will be set to a large value (100 times of the shear modulus of the soil adjacent) in the following studies.
Similarly, parametric study had been performed for the rest of Ks, C and φ and found that the appropriate values to be used in the interface model and found that Ks should be as much as shear modulus of soil, interfacial friction and interfacial cohesion can be reasonably taken as internal friction angle and cohesion of soil respectively.

Alternatively, a good rule-of-thumb is that $k_n$and $k_s$be set to *ten times* the equivalent stiffness of the stiffest neighboring zone. The apparent stiffness (expressed in stress per-distance units) of a zone in the normal direction is

$$\max\left[\frac{\left(K+\frac{4}{3}G\right)}{\Delta Z_{min}}\right] \tag{3-1}$$

Where *K* &*G* are the bulk and shear moduli, respectively; and

Z_{min} is the smallest width of an adjoining zone in the normal direction — see Figure 3-3.

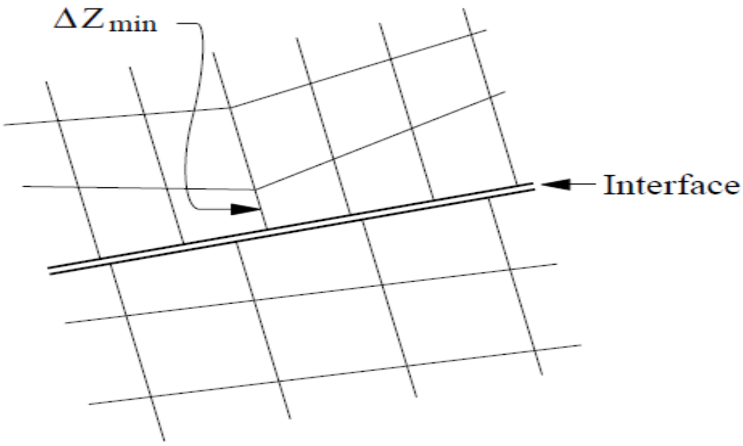

Figure 3-3:-Zone dimension used in stiffness calculation

3.3 Constitutive Model's Parameter Values

Two distinct constitutive models were employed. These are:

a. Elastic Constitutive Model
b. Elasto-Plastic Constitutive Model

The elastic model was used to characterize the stress-strain relationships of the piles, the raft and piled raft because the elastic model provides the simplest representation of material behavior that exhibit the linear stress strain behavior and these materials (the piles, the raft and piled raft) are not supposed to go beyond their elastic limit due to safety concerns. In this particular model, Young's Modulus and Poisson's ratio were defining parameters. The following tables, Table 3-1 and 3-2, summarize the values of these parameters employed in the study of Lee et al (2016). The parameters are taken directly from Lee et al. (2016) for validating the results.

Table 3-1:-Elastic parameter of concrete Lee et al. (2016)

Parameter	concrete
Elastic modulus (E)	70 GPa
Poison's ratio (μ)	0.15
Unit weight (γ)	25 kN/m^3

Table 3-2:-Elastic parameter of soil Lee et al. (2016)

Parameter	soil
Elastic modulus (E)	50 MPa
Poison's ratio (μ)	0.3
Internal friction angle (φ)	43^0
Unit weight (γ)	14.16 kN/m^3

The elasto-plastic model is basically employed for the soil bearing the piled raft foundation. The values of the parameters for the elastic behavior of the soil are shown in Table 3-2. The plastic behavior was modeled by the Mohr-Coulomb failure criterion where cohesion and angle of internal friction are used. The Mohr-coulomb model is the conventional model used to represent shear failure in soils and rocks. As FLAC^{3D} (2005) the laboratory report by Vermeer and deBorst (1984) showed that the test results for sand and concrete match well with the Mohr-coulomb criterion. An angle of internal friction of 33.5^0 is used to represent medium dense sand.

The interface between the pile and the soil was characterized by Coulomb sliding as stated in the previous section. For this, k_n and $k_s$values were computed by the approach indicated in the manual of FLAC^{3D}. The bulk and shear modulus of the stiffest neighboring zone was computed as:

$$G = \frac{E}{2(1+v)} \tag{3-2}$$

$$K = \frac{E}{3(1-2v)} \tag{3-3}$$

Where, G is shear modulus

K is the bulk modulus

E is the young's modulus

v is the poison's ratio

The stiffest neighboring zone (neighbor to the pile, i.e. soil) Young's modulus for the interface is 50 MPa. The poison's ratio is 0.3 and the two parameters known as shear modulus and bulk modulus are calculate using the above formulae.

$$G = \frac{50 * 10^6 pa}{2(1+.3)} = 19.231x10^6 pa$$

$$K = \frac{50x10^6 pa}{3(1-2x0.3)} = 41.667x10^6 pa$$

Then the normal and shear stiffnesses are calculated as

$$k_n = K_s = 10 \max\left[\frac{K + \frac{4}{3}G}{\Delta Z_{min}}\right] = 10\left[\frac{41.667x10^6 pa + \frac{4}{3}x19.231x10^6 pa}{1}\right]$$

$$k_n = K_s = 6.7308x10^8 \frac{N}{m}$$

$\Delta Z_{min}$is assumed as 1m as this will be a fair estimation of the size of zone to be used after convergence-verification analyses is carried out. Moreover, it has been checked that the variation of ΔZ_{min} value has no effect on the outputs as k_n and k_s are very large numbers.

3.4 Finite Elements representing soil, pile and raft

3.4.1 Soil Finite Element Model

In practice, there are two main approaches to model the soil beneath the shallow foundation. These models are known as the Winkler model and the continuum model which makes use of the FE analysis (Jaehwan Lee, 2015).

The continuum model is computationally difficult to exercise and requires extensive training because of the three-dimensional and nonlinear nature of the problem. The time consuming, both in modelling and computation, can be exhausting. However, the Winkler model is relatively easy and simple to exercise. For the design and analysis of the flexible mat foundation, the conventional spring model can be used because this model only needs one parameter to simulate the soil-structure interaction which is preferred by geotechnical engineers due to its simplicity.

In this study the continuum model is applied by using brick elements (eight-nodded, six-sided brick closed volume) as a soil element. Brick element mesh shape has the lowest absolute error and tetrahedral has the highest (Bekele, 2016)

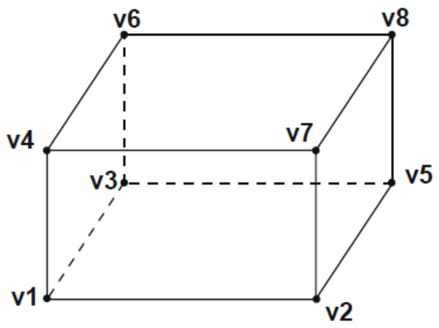

Figure 3-4:-Brick Volume Defined by Eight Vectors

3.4.2 Pile Finite Element Model

In FLAC^{3D} a physical pile can be modeled as a collection of pile structural elements (PileSELs). Each pile structural element is defined by its geometric, material and coupling-spring properties. A pileSEL is assumed to be a straight segment of uniform bisymmetrical cross-sectional properties lying between two nodal points. The stiffness matrix of a pileSEL is identical to that of a beam SEL; however, in addition to providing the structural behavior of a beam, both a normal-directed (perpendicular to the pile axis) and a shear-directed (parallel with the pile axis) frictional interaction occurs between the pile and the grid. In this sense, piles offer the combined features of beams and cables. In addition to skin-friction effects, end-bearing effects can also be modeled.

Piles may be loaded by point or distributed loads. PileSELs are used to model structural-support members, such as foundation piles, for which both normal- and shear-directed frictional interaction with the rock or soil mass occurs.

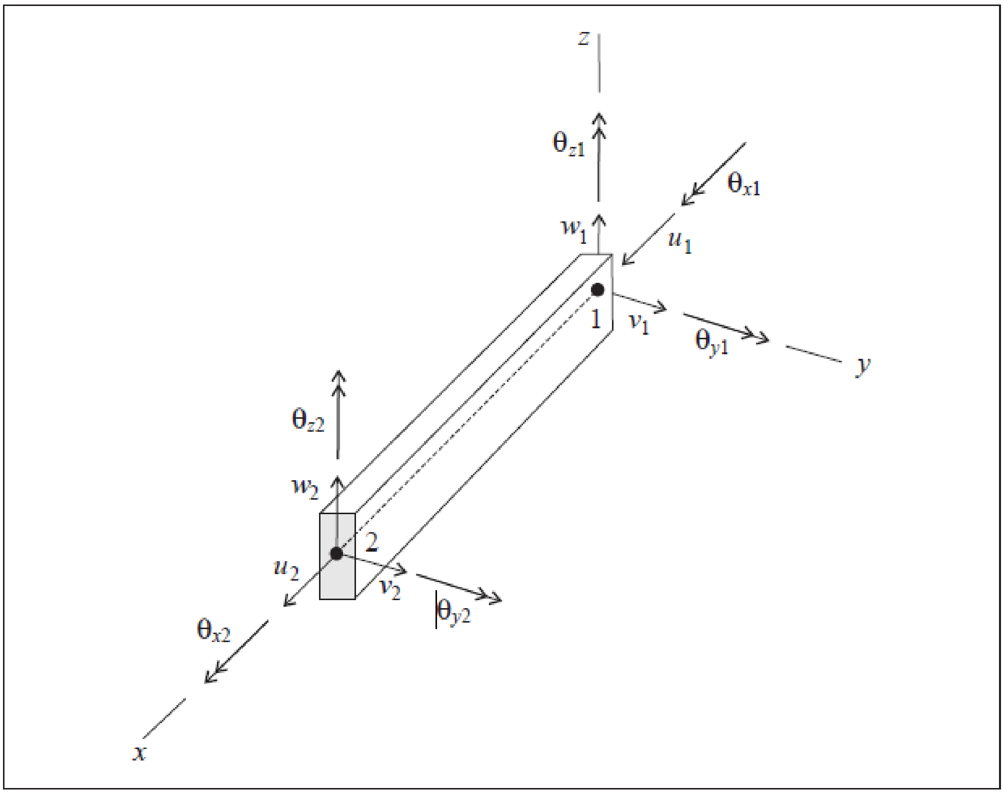

Figure-3-5:-pileSEL Coordinate System and Its12DOFAvailable to pileSEL FE

3.4.3 Raft Finite Element Model

Each shell-type structural element (shellSEL, geogridSEL or linerSEL) is defined by its geometric and material properties. A shell-type SEL is assumed to be a triangle of uniform thickness lying between three nodal points. Each shell-type SEL behaves as an isotropic or anisotropic, linearly elastic material with no failure limit. Because these are all thin-shell finite elements, shell-type SELs are suitable for modeling thin-shell structures in which the displacements caused by transverse-shearing deformations can be neglected. Thick-shell structures should be modeled with FLAC^{3D} zones.

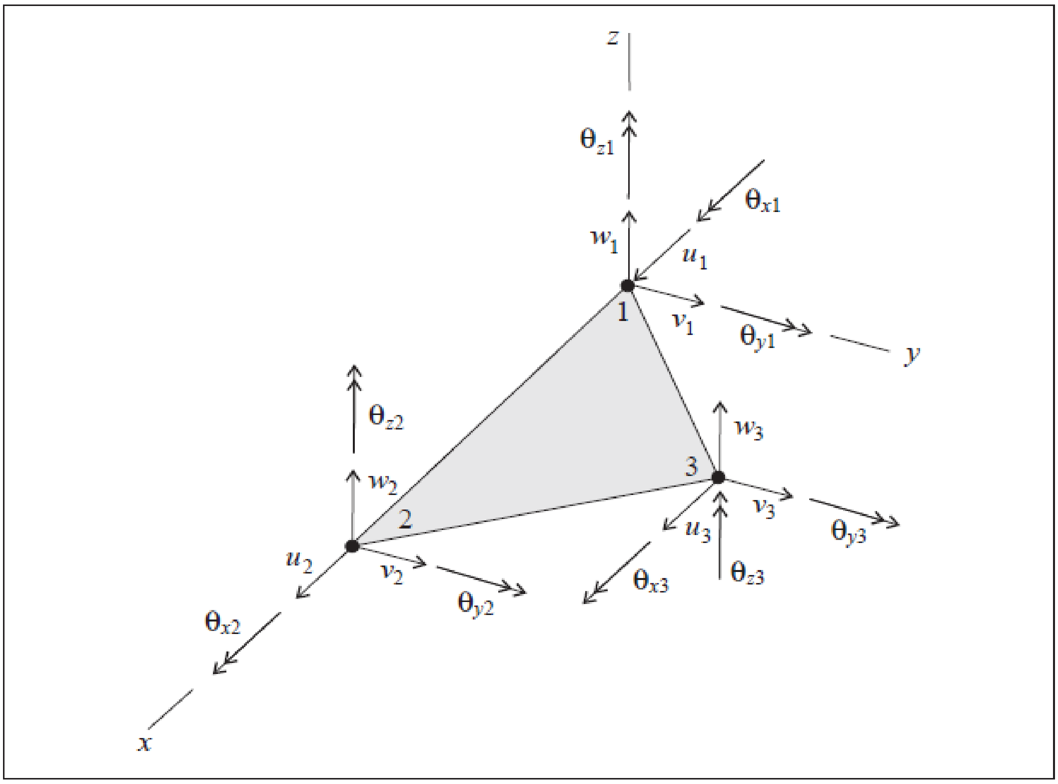

Figure-3-6:-Shell-Type SEL Coordinate System and 18 DOF Available to The Shell FE

The reason why the linerSEL is selected for the rafts is that the shellSELs provide a rigid connection with the soil, whereas the linerSELs provide an elasto-plastic connection that allows gaps to form and slip to occur depending on the interface parameters (FLAC^{3D} 2005). By default, linerSELs are assigned the DKT-CST shell element that resists both membrane and bending loading. Liner structural elements (linerSELs) are three nodded, flat finite elements that can be assigned any of the five finite-element types available for shellSELs. A physical liner can be modeled as a collection of linerSELs that are attached to the surface of the FLAC^{3D}grid. In addition to providing the structural behavior of a shell, a shear-directed (in the tangent plane to the liner surface) frictional interaction occurs between the liner and the FLAC^{3D}grid. Also, in the normal direction, both compressive and tensile forces can be carried, and the liner may break free from (and subsequently come back into contact with) the grid. LinerSELs are used to model thin liners for which both normal-directed compressive/tensile interaction and shear-directed frictional interaction with the host medium occurs, such as shotcrete-lined tunnels or retaining walls and raft foundations.

3.5 Sensitivity Analysis

Having determined elements to model the soil, pile and raft to the FLAC^{3D} model, the next step is to determine the boundary size and mesh size determination of the model to be used for the validation analysis and parametric study.

Sensitivity analysis is the analysis carried out to find out the numerical model out of a number of other numerical models which yields the same response up on variation of model parameters, like size and domain, between each considered models.
As per Daniel, et al., (2012) In order to find the extent of the soil region to be used in the study, many trial analyses were carried out and was found that for the width and the thickness of the soil medium more than 2.5 times the least width of the mat foundation the variation in settlement and the contact pressure was negligible, thus the region of soil medium considered was 2.5 times the width of the raft in all three directions.

FLAC^{3D} meshes may be variable or uniform in order to make the desired position densely discretized or to make it just uniform depending on the assumption the model has got. Bekele, B. M. (2016) showed that uniform meshing gives better result than variable meshing in the pile group analysis. So, since uniform meshing is already confirmed that it is better, the sensitivity analysis that the study perform becomes only uniform mesh.

The effect of boundary size increment was checked by keeping mesh size constant over varying boundary sizes i.e. 24, 36 and 48 meters in all the three directions in models 1,4 and 7 respectively. As can be seen from table 3-3, the value of the force monitored at the head of the piles from models 1, 4 and 7 is not that much significant. Therefore, the boundary sizes that are effective in the calculation is taken, that is 24 m in all the three dimensions. The size of zones was changed eventually to assess the effect of zone size changes up on the response of the model. 10,000 kN central load was applied for different models considered for the piled raft analyses. The forces at the pile heads were monitored. Table 3-3 shows varies boundaries and sizes of zones used based of Figure 3-7.

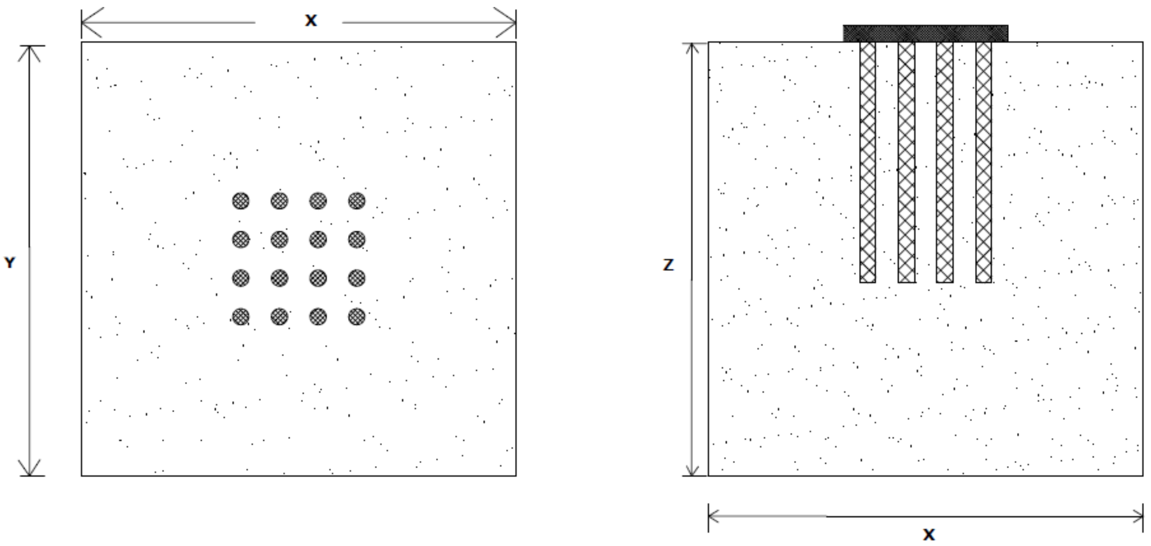

Figure 3-7:-Domain of Discretization

Models 1,2 and 3 are the same in the boundary size but different in mesh (zone) sizes and the same is true for models 4, 5 and 6 and also 7, 8 and 9 respectively.

Table 3-3:- Forces recorded at the monitoring points for 10 MN applied point force

Model					force (KN)		
No.	X	Y	Z	Mesh size	Center pile	Edge pile	Corner pile
1	24	24	24	3.0	887.9	514.5	367.8
2	24	24	24	2.4	886.5	587.6	331.3
3	24	24	24	1.2	745.3	485.9	370.3
4	36	36	36	3.0	860.8	504.6	313.3
5	36	36	36	2.4	852.1	454.6	391.0
6	36	36	36	1.2	720.1	469.2	363.7
7	48	48	48	3.0	858.0	496.4	296.4
8	48	48	48	2.4	857.3	551.9	311.8
9	48	48	48	1.2	712.8	463.8	358.6
11	24	24	24	4.0	1018	1404	1786
12	24	24	24	2.0	1005.0	556.7	228.2
13	24	24	24	1.6	912.0	497.0	384.3
14	24	24	24	1.0	764.0	527.9	371.3

From table 3-3 above, it was easily understandable that the variation of the responses with the variation of boundary size is negligible but for a good generalization the sensitivity analysis for boundary size determination will be performed after selecting appropriate Mesh size. However, the variation of zone size has significant role on the responses. To get a plot with enough amount of data points on a graph (load - mesh size and settlement- mesh size) in determining the effective zone/mesh size of the model, four models were added based on the optimum boundary size of the model (24m) in all directions with decreasing zone size from 4 m to 1m as shown in models 11, 12,13 and 14.

As can be seen from the figure 3-8**,** there is no significant variation of force at the pile heads of the four central piles with the variation of mesh size. But for the eight edge piles and for the four corner piles the variation of mesh size has significant effect on the amount of load carried by the pile heads. The mesh sizes greater than three gives almost linear variation of load with increment of mesh size. As mesh coarseness decreases from 3 to 2.5 it starts to give constant load up on the variation of mesh size but beyond mesh size 2.5, the variation of load becomes constant and the mesh size to be used after this point is 2.25m due to suitability to divide nine-meter raft to even number of elements.

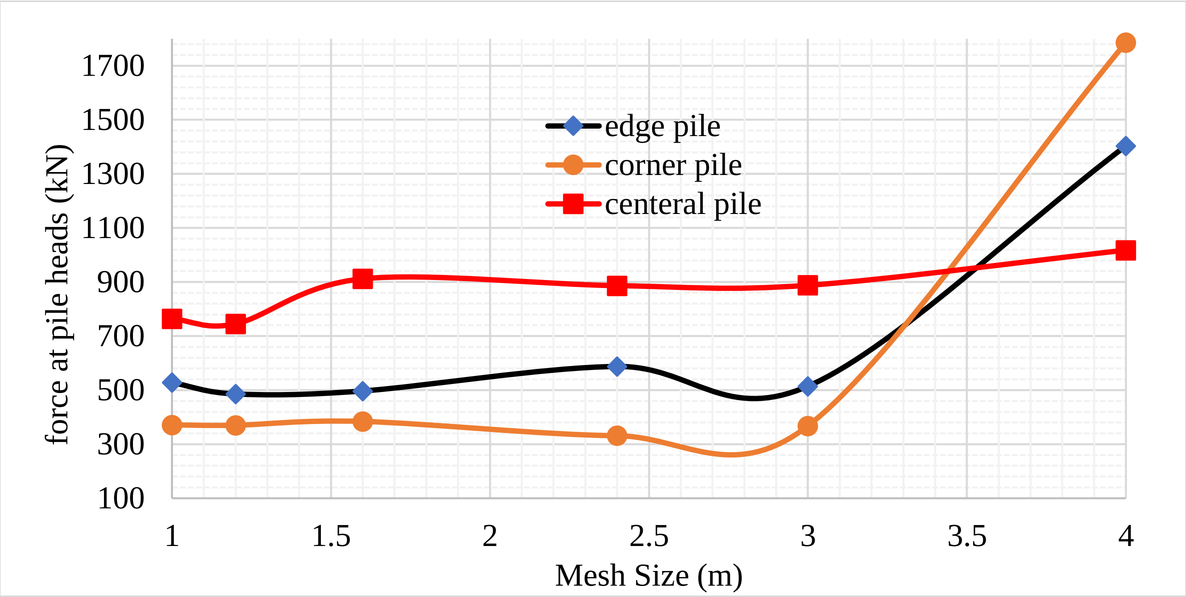

Figure 3-8:-Variation of force at node center, edge and corner with zone size

Table 3-4:-Settlements recorded for 10MN applied point force

model No.	x	y	z	mesh size	Settlement (mm) center pile	edge pile	corner pile
1	24	24	24	3	6.2	5.2	4.5
2	24	24	24	2.4	6.2	5.2	4.4
3	24	24	24	1.2	8.3	5.6	4
4	36	36	36	3	7.4	6.4	5.6
5	36	36	36	2.4	8	6.5	5.75
6	36	36	36	1.2	8.4	7.1	6.1
7	48	48	48	3	8	7	6.3
8	48	48	48	2.4	9.1	6.2	5
9	48	48	48	1.2	9	7.6	6.7
11	24	24	24	4	7.2	7.2	6.4
12	24	24	24	2	6.5	5.2	4.3
13	24	24	24	1.6	6.6	5.3	4.4
14	24	24	24	1	7	5.7	4.8

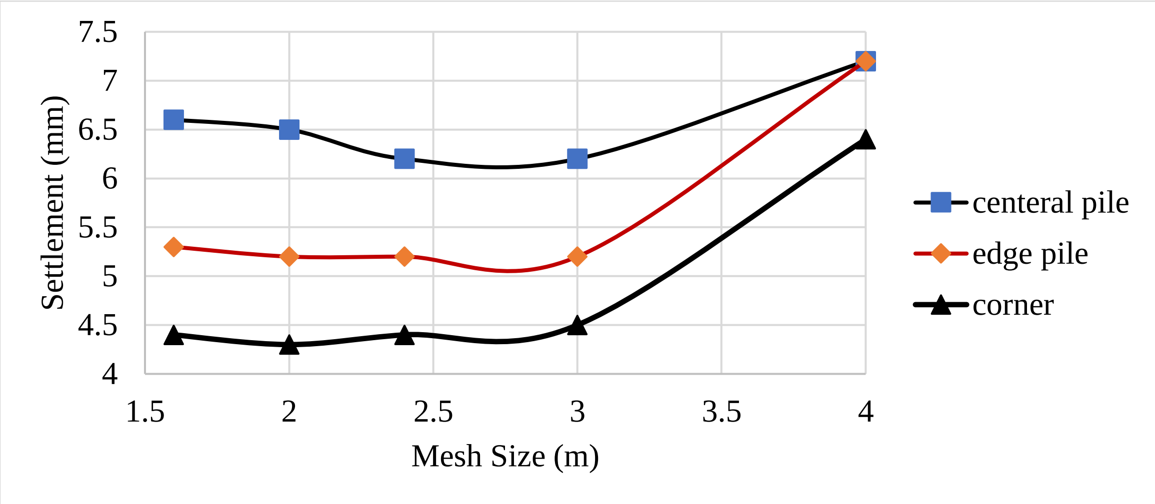

Figure 3-9:-Variation of Settlement at a head of center, edge and corner with zone size

From the figure 3-8 and figure 3-9, one can conclude that the appropriate mesh size can be the mesh size which has a dimension of less than three (3 m) especially 2.5m because the variation of the force or settlements below this mesh size has approximately uniform variation which indicates that refining mesh below this size has no advantage anymore.

Therefore, the appropriate mesh size used for boundary size determination is 2.25 m since it is suitable to discretize 9 m raft in even elements.

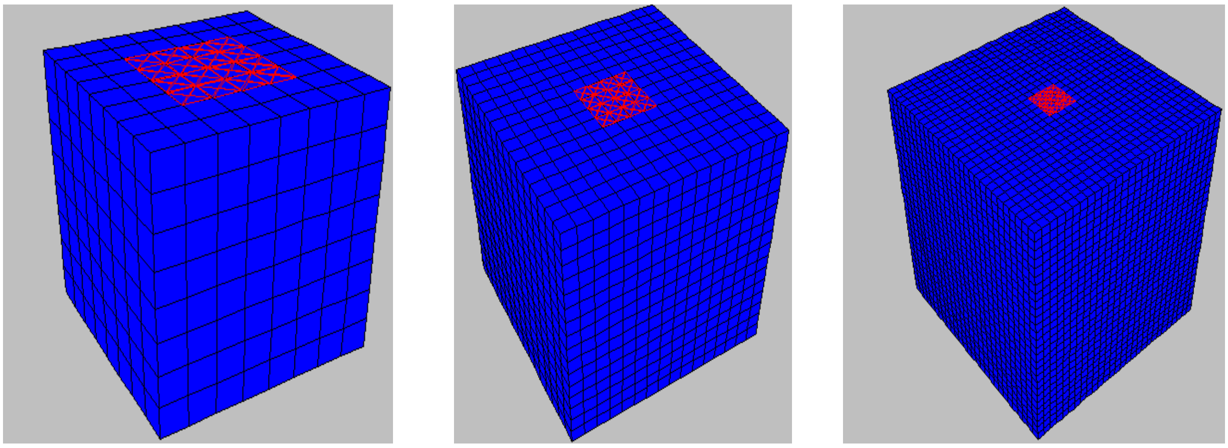

Figure 3-10:-model No. 15 (18 m), 17 (27 m) and 20 (63 m) respectively from left to right

Table 3-5:- Force and settlement recorded for various Boundary sizes

model No.	**X (m)**	**Y (m)**	**Z (m)**	**mesh size (m)**	**force (KN)**		
					center pile	edge pile	corner pile
15	18.00	18.00	18.00	2.25	1031.00	596.00	215.80
16	27.00	27.00	27.00	2.25	890.00	589.30	277.2
17	36.00	36.00	36.00	2.25	870.40	575.20	286.80
18	45.00	45.00	45.00	2.25	872.80	566.50	283.80
19	54.00	54.00	54.00	2.25	869.80	566.40	278.60
20	63.00	63.00	63.00	2.25	860.90	563.40	280.60
model No.	**X (m)**	**Y (m)**	**Z (m)**	**mesh size (m)**	**Settlement (mm)**		
					center pile	edge pile	corner pile
15	18.00	18.00	18.00	2.25	4.20	3.05	2.30
16	27.00	27.00	27.00	2.25	6.80	5.60	4.60
17	36.00	36.00	36.00	2.25	7.60	6.20	5.40
18	45.00	45.00	45.00	2.25	8.00	6.90	5.80
19	54.00	54.00	54.00	2.25	8.40	7.20	6.20
20	63.00	63.00	63.00	2.25	8.60	7.35	6.40

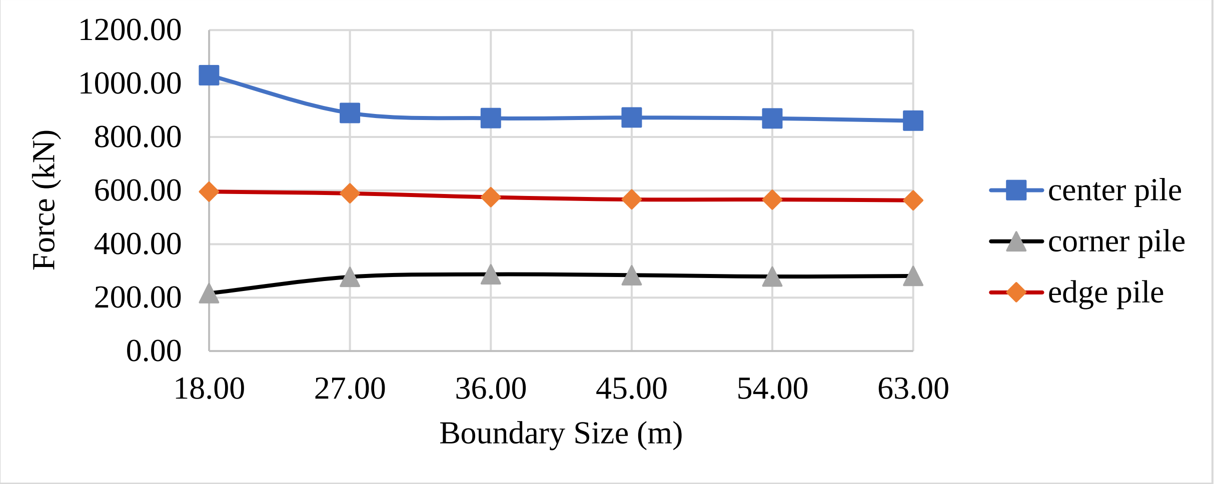

Figure 3-11:- Boundary size versus force (kN) recorded at pile heads

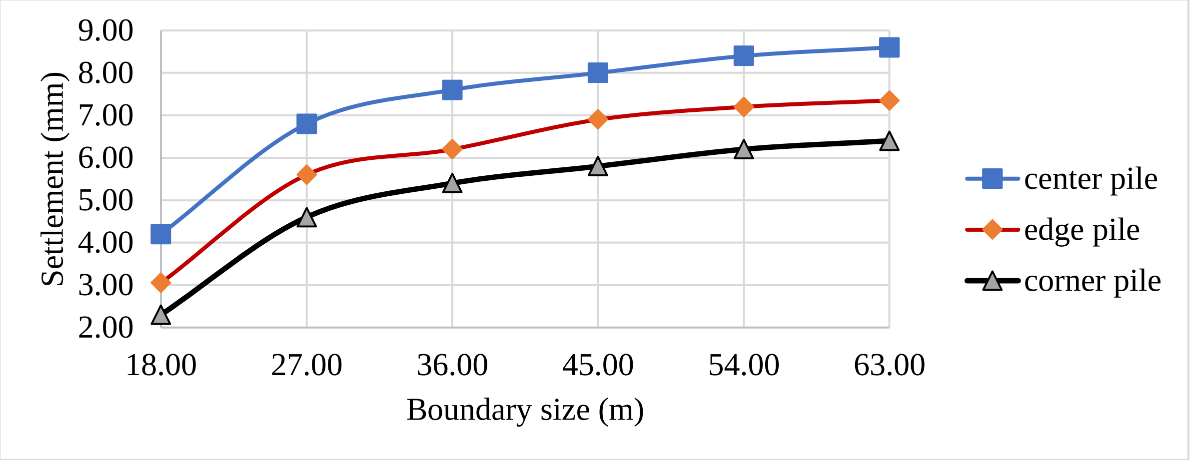

Figure 3-12:- Boundary size versus Settlements recorded at pile heads

From figure 3-11 and figure 3-12, the variation of force and settlement after boundary size of 27 m is almost constant. Therefore, the boundary size to be used for the validation analysis is reasonably taken boundary size greater than or equal to 27m.

3.6 A Validation (Verification) Analysis

The validity of the Finite Difference analyses was confirmed using results from centrifuge load tests included in Lee, et al., (2015). The tests were conducted using Unpiled Raft (UR) and Piled Raft (PR) model foundations. The geotechnical centrifuge testing system adopted in the tests had a platform radius of 5 m and maximum capacity of 240 g ton. As the centrifuge acceleration applied in this study was 60 g the model foundations were all fabricated using a scale of 1/60. The piled rafts consisted of a 9-m square raft and 16 piles with diameter (B_p) and length (L_p) of 0.6 and 15 m, respectively, in prototype scale. The 16 piles of the piled raft were arranged in a $4x4$ square configuration with pile spacing (S_p) of 2.4 m, corresponding to 4 times the pile diameter ($4B_p$). The raft shape and size for unpiled rafts were the same as those for piled rafts. The test soils for the centrifuge tests were clean silica sands with relative density, D_R = 42% and 74%. For the test sand, the maximum and minimum unit weights (γ_d,max and γ_d,min), mean grain diameter (d_{50}), coefficient of uniformity (C_u), and critical-state friction angle (φ_c) were 16.12 kN/m3, 12.19 kN/m3, 0.21 mm, 1.96°, and 33°, respectively. The elastic modulus (E) and friction angle (φ) adopted in $FLAC^{3D}$ analyses were 50 MPa and 43°, respectively, which were obtained from triaxial test results of the test sand.

First there was a load settlement curve of piled raft foundation in which the analysis was performed using centrifuge test from Lee, et al. (2015). Then the pile, raft and soil properties used in the centrifuge test were used also in the numerical model and the results are drawn as shown in table 3-6.

Table 3-6:- load applied to the raft center and monitored settlements

	Settlement (mm)		
Force Applied (MN)	**Center**	**edge**	**corner**
1.00	0.76	0.54	0.40
5.00	3.90	2.60	2.00
10.00	7.80	5.40	4.00
15.00	11.80	8.00	5.60
20.00	16.00	10.50	7.50
30.00	24.10	16.00	10.05
40.00	34.00	22.00	15.00
50.00	46.00	32.00	21.50
60.00	62.00	49.00	38.00
70.00	82.00	70.00	54.00
80.00	104.00	94.00	75.00
90.00	127.00	122.00	99.50
100.00	152.00	150.00	123.00
120.00	207.00	200.00	175.00
150.00	290.00	280.00	250.00
200.00	430.00	415.00	380.00

Table 3-7:- Load Settlement with Centrifuge as Per Lee et al. (2015)

Settlement (mm)	0.00	2.67	5.33	8.00	10.67	13.33	16.00	19.73	21.33	24.00	26.67
Load applied (MN)	0.00	10.00	15.71	20.00	23.14	25.00	28.57	32.14	33.57	35.71	37.86
Settlement (mm)	29.33	32.00	34.67	37.33	40.00	42.67	45.33	59.73	80.00	99.20	
Load applied (MN)	40.00	42.14	43.57	45.00	46.43	48.57	50.79	58.57	70.00	80.00	

Measured and monitored load–settlement curves from the centrifuge tests and Finite Difference analyses from Tables 3-6 and 3-7 are shown in Figure 3-13 for piled rafts. For piled rafts in Figure 3-13, the calculated results from FD analysis showed more or less underestimated load responses. Nonetheless, the overall match between measured and calculated results of the considered foundations in Figure 3-13 appears reasonably close in both magnitude and tendency of load response.

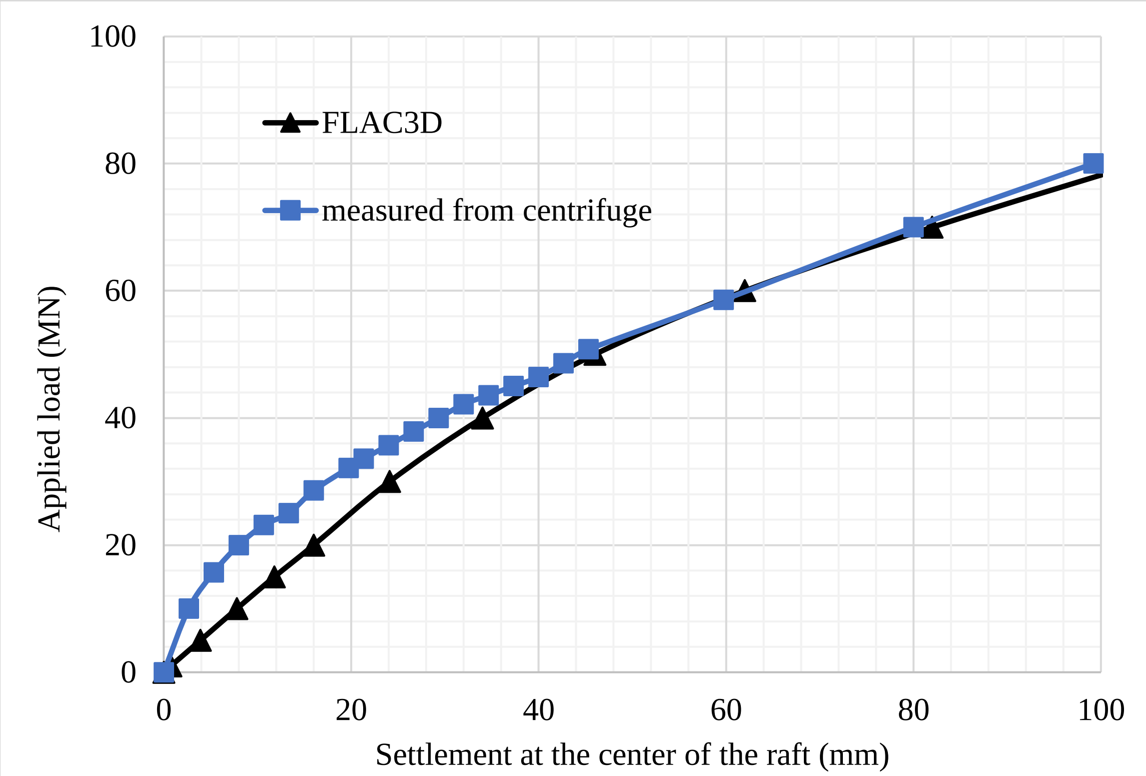

Figure 3-13:-Measured and monitored load–settlement curves of a piled raft

4. PARAMETRIC STUDY, RESULTS AND DISCUSSIONS

4.1 General

The parametric study on this section of the thesis is continued after the sensitivity and validation analysis performed in chapter three. This chapter of the study mainly focuses on designing and performing numerical model analysis on unpiled raft foundation with different thickness (different relative stiffness) and piled raft foundation with different varying parameters like pile diameter, raft thickness, pile spacing, and pile number.

4.2 Experimental Design

The list of parameters is more systematically tabulated in Table 4-1. The independent variables (factors) and the response variables are also presented in Table 4-2 below.

Table 4-1:-Summary of Parameters

Raft Dimension (m)	Raft Thickness (m)	Spacing (m)	Diameter (m)	Number of Piles
9x9	0.50	3d	0.30	0
	1.00	4d	0.50	1
	1.50		0.75	4
				9
				16

Table 4-2:-Factors, Levels and Response Variables

Factors	Levels	Response
spacings (S)	2	Load improvement ratio, LIR
diameter (D)	3	Settlement ratio, SR
raft thickness (t)	3	Differential settlement ratio, DSR
number of piles (N)	5	Load proportion

The full factorial design was prepared as follows for the whole parametric study

Table 4-3:-All Combinations of Parameters for Parametric Analyses

RUN	N	S (m)	D (m)	T (m)
1	-	-	-	0.50
2	-	-	-	1.00
3	-	-	-	1.50
4	1	-	0.3	0.50
5	1	-	0.3	1.00
6	1	-	0.3	1.50
7	1	-	0.5	0.50
8	1	-	0.5	1.00
9	1	-	0.5	1.50
10	1	-	0.75	0.50
11	1	-	0.75	1.00
12	1	-	0.75	1.50
13	4	3D=0.9	0.3	0.50
14	4	3D=0.9	0.3	1.00
15	4	3D=0.9	0.3	1.50
16	4	3D=1.5	0.5	0.50
17	4	3D=1.5	0.5	1.00
18	4	3D=1.5	0.5	1.50
19	4	3D=2.25	0.75	0.50
20	4	3D=2.25	0.75	1.00
21	4	3D=2.25	0.75	1.50
22	4	4D=1.2	0.3	0.50
23	4	4D=1.2	0.3	1.00
24	4	4D=1.2	0.3	1.50
25	4	4D=2.0	0.5	0.50
26	4	4D=2.0	0.5	1.00
27	4	4D=2.0	0.5	1.50
28	4	4D=3.0	0.75	0.50
29	4	4D=3.0	0.75	1.00
30	4	4D=3.0	0.75	1.50
31	9	3D=0.9	0.3	0.50
32	9	3D=0.9	0.3	1.00
33	9	3D=0.9	0.3	1.50
34	9	3D=1.5	0.5	0.50
35	9	3D=1.5	0.5	1.00
36	9	3D=1.5	0.5	1.50
37	9	3D=2.25	0.75	0.50
38	9	3D=2.25	0.75	1.00
39	9	3D=2.25	0.75	1.50
40	9	4D=1.2	0.3	0.50
41	9	4D=1.2	0.3	1.00
42	9	4D=1.2	0.3	1.50
43	9	4D=2.0	0.5	0.50
44	9	4D=2.0	0.5	1.00
45	9	4D=2.0	0.5	1.50
46	9	4D=3.0	0.75	0.50
47	9	4D=3.0	0.75	1.00
48	9	4D=3.0	0.75	1.50
49	16	3D=0.9	0.3	0.50
50	16	3D=0.9	0.3	1.00
51	16	3D=0.9	0.3	1.50
52	16	3D=1.5	0.5	0.50
53	16	3D=1.5	0.5	1.00
54	16	3D=1.5	0.5	1.50
55	16	3D=2.25	0.75	0.50
56	16	3D=2.25	0.75	1.00
57	16	3D=2.25	0.75	1.50
58	16	4D=1.2	0.3	0.50
59	16	4D=1.2	0.3	1.00
60	16	4D=1.2	0.3	1.50
61	16	4D=2.0	0.5	0.50
62	16	4D=2.0	0.5	1.00
63	16	4D=2.0	0.5	1.50
64	16	4D=3.0	0.75	0.50
65	16	4D=3.0	0.75	1.00
66	16	4D=3.0	0.75	1.50

Where N, S, D and T are number of piles, center to center spacing between piles, diameter of piles and thickness of raft respectively. Therefore, as shown on tables 4-1, 4-2, and 4-3, a nine-meter square raft is used with a varying thickness of 0.5 m, 1 m and 1.5 m. for each thickness of the raft a number of piles arrangements such as one single central pile, two by two (4) piles, three by three (9) piles and four by four (16) piles are used. The diameter of the pile was also varied as 0.3 m, 0.5 m and 0.75 m

A total of 66 tests, as shown on table 4-3 (3 rafts only and 63 rafts with different number, diameter and spacing of piles) has been performed. The raft only analyses are performed for the purpose of comparison with the behavior of piled raft.

4.3 Soil and Concrete Properties

The list of soil and concrete (raft and pile) properties used in the numerical analysis of the software FLAC^{3D} are explained in table 4-4 below. The soil properties are based on the literature review on properties of sand in section 2.6 (the property of sand is assessed thoroughly in section 2.6).

Table 4-4:-Parameter Values Used in FLAC^{3D}Analysis

parameters	Soil property	Concrete property	
		Pile	Raft
Young's modulus, E (KPa)	30,000	30,000,000	30,000,000
Poisson's ratio, $\boldsymbol{\nu}$	0.3	0.2	0.2
Angle of internal friction, Φ(°)	30	-	-
Unit weight, $\gamma(^{\mathrm{kN}}/_{\mathrm{m}^3})$	20	25	25
Interface Normal stiffness, k_n (MN/m3)	-	1154	1154
Interface Shear stiffness, k_s (MN/m3)		11.54	11.54
Bulk modulus, K (MPa)	25	-	-
Shear modulus, G (MPa)	11.54	-	-

4.4 Raft Stiffness

The relative stiffness of raft, Krs, compared to the stiffness of soil is one important parameter in piled raft foundation analysis. The relative flexibility of a raft is expressed by the raft-soil stiff-ness ratio, Krs, proposed by Hain and Lee (1978):

$$K_{rs} = \frac{4}{3\pi}\frac{E_r(1-\nu_s^2)}{E_s}\frac{B}{L}(\frac{t_R}{L})^3 \qquad (4\text{-}1)$$

where B and L are the width and length of the raft, respectively; and $t_R$is the raft thickness. The values of Krs ranging from 0.01 to10 cover very flexible to very stiff rafts (Hain and Lee, 1978).

Table 4-5:-Raft-Soil Stiffness Ratios, Krs, for Considered Raft Models

Raft Model Dimensions (m x m x m)	K_{rs}
9 x 9 x 0.5	0.06
9 x 9 x 1.0	0.53
9 x 9 x 1.5	1.78

4.5 Results and Discussions on Unpiled Raft Foundation

The experimental results obtained from the numerical analyses tests are analyzed and discussed in this section. The shapes of the measured load-settlement curves indicate that the load at failure was not achieved due to high settlement values for collapse loads determined by velocity command through FLAC^{3D}. Basically in FLAC^{3D}, the collapse load (the ultimate load capacity) is determined by applying velocity command to the software program. But ultimate load capacities determined by this method have higher settlements than recommended by different literatures like Basuony et al.(2013). Basuony et al.(2013) recommends that the allowable load is a load corresponding to 10 mm average settlement and ultimate load capacity of a foundation is a load corresponding to 25 mm average settlement of a foundation.

Therefore, the study performs a number of simulations for a single model for a number of loads starting from 1 MN to any amount of load greater than a load which cause more than 25 mm average settlement. After that record the settlements at center and mid-edge points corresponding to a given load and determine the average settlement for each step of loading. Now there is a load and a corresponding average settlement, therefore, the load average settlement curve can be drawn. From the load average settlement curve one can determine the allowable load capacity (ALC) of a foundation corresponding to 10 mm average settlement and ultimate load capacity (ULC) of a foundation corresponding to 25 mm average settlement.

The experimental numerical model runs one, two and three are without piles (unpiled raft foundations). The experimental load-average settlement curves for the unpiled raft models of different relative stiffness, Krs (Krs=0.06, Krs=0.53 and Krs=1.78) are illustrated in Figure 4-1. From Figure 4-1, it can be noted that

a. The increase in raft relative stiffness causes a slight increase in the load carrying capacity of unpiled raft with a reduction in settlement.
b. For instance, at 25 mm average settlement, the increase of raft relative stiffness from 0.06 to 0.53 causes an increase in the raft load by 21% and the increase of raft relative stiffness from 0.06 to 1.78 causes an increase in the raft load by 24%.
c. At 10 mm average settlement, the increase of raft relative stiffness from 0.06 to 0.53 causes an increase in the raft load by 22.2% and the increase of raft relative stiffness from 0.06 to 1.78 causes an increase in the raft load by 30%.
d. From the above three points the stiffness increase doesn't give very significant difference in neither the ultimate load capacity (ULC) nor Allowable load capacity (ALC).

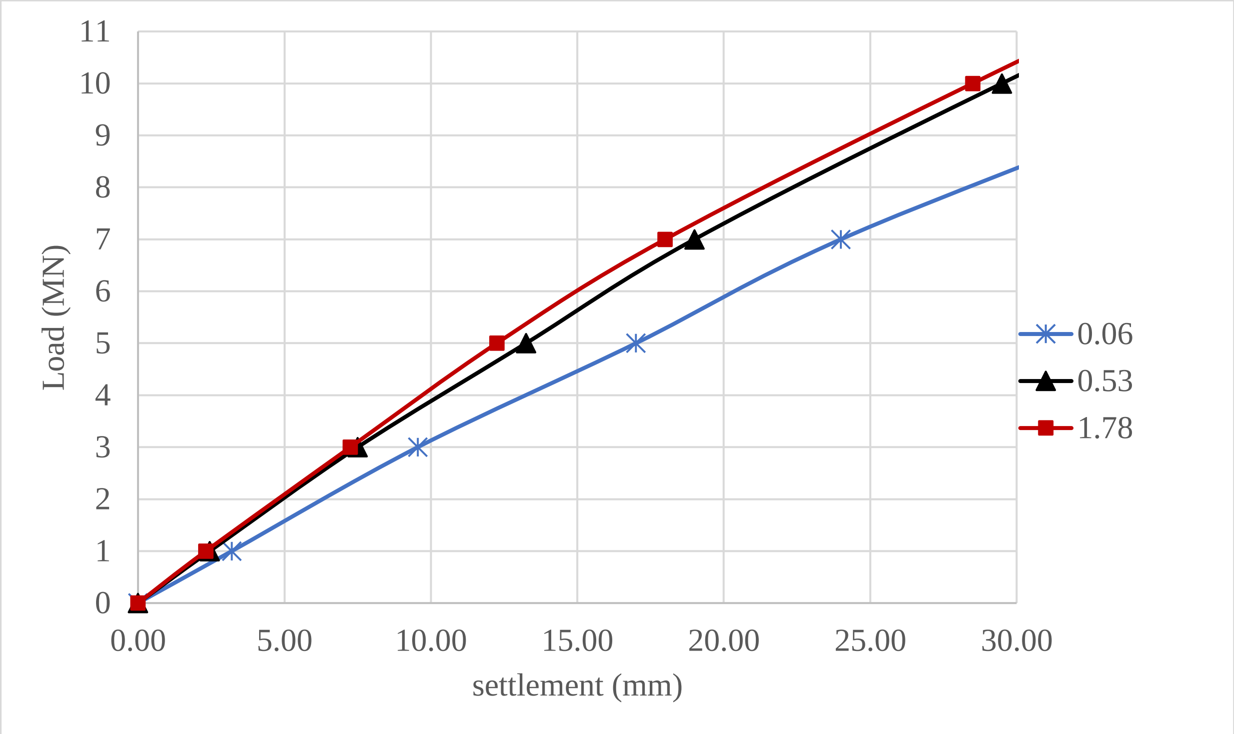

Figure 4-1:- Experimental load-average settlement curves for unpiled rafts

The differential settlement of a square raft is defined as the difference between settlements at the center and the mid-edge points of the raft. The results of the present tests indicate that the raft with Krs equal to 1.78 (stiff) almost had no differential settlement compared to the raft stiffnesses of 0.06 (very flexible) and 0.53 (flexible). This result is expected because the raft with Krs equal to 1.78 is classified as stiff Hain and Lee, (1978), and stiff raft have no such a big differential settlement but it has small difference since it is not rigid.

In this paper, the differential settlement is normalized by the average settlement of the raft. Figure 4-2. shows the variation of normalized differential settlement with the relative stiffness of the raft. As expected, the normalized differential settlement decreases as the raft relative stiffness increases.

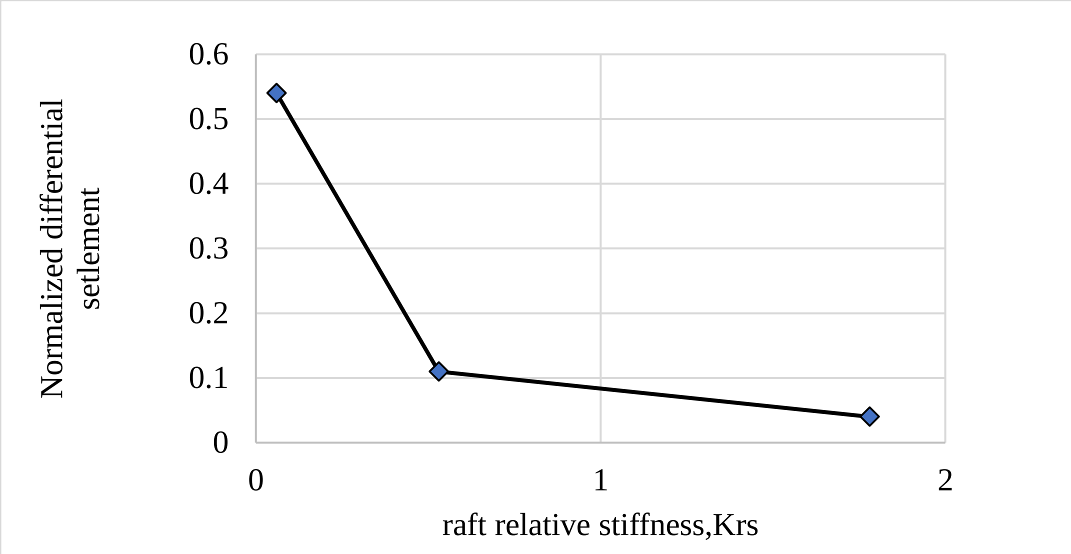

Figure 4-2:-Variation of NDS with the Krs for unpiled rafts

From figure 4-2, One can observe that,

a. The normalized differential settlement at a very flexible raft (Krs=0.06), flexible raft (Krs=0.53) and stiff raft (Krs=1.78) are 0.54,0.11 and 0.04 respectively.
b. The normalized differential settlement decrease percentage from very flexible to flexible raft (from Krs=0.06 to Krs=0.53) is 80% and from very flexible to stiff raft (from Krs=0.06 to Krs=1.78) is 93%.

The two points explained above shows that differential settlement is improved entirely with increasing of raft thickness.

4.6 Results and Discussions on Piled-Raft Foundations

4.6.1 Load Improvement Ratio, LIR, of Raft on Settlement Reducing Piles

In the following sections, the effect of the number of piles, the effect of the diameter of the piles and the effect of the raft stiffness on the behavior of the piled raft foundation is analyzed and discussed. As presented in the previous sections, 63 number of numerical model tests has been performed with different combination of pile number, pile diameter, raft thickness and piles spacing.

4.6.1.1 Effect of Number of Piles

Figures 4-3 to 4-11 show the load-average settlement curves for all the studied cases of unpiled rafts and rafts on settlement reducing piles for spacing 3D and figure 4-12 is the load average settlement curve for all number of piles with Krs of 0.06 and spacing of 4D for the purpose of comparing with figure 4-3.

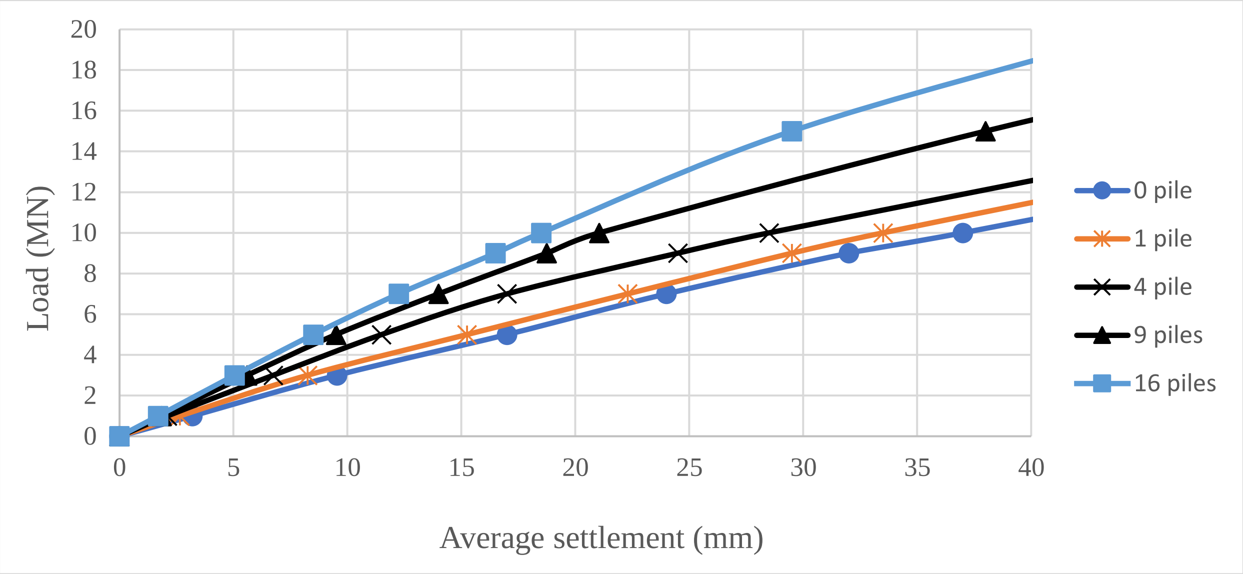

Figure 4-3:-Load average settlement curve for Krs=0.06, D=0.3, S=3D

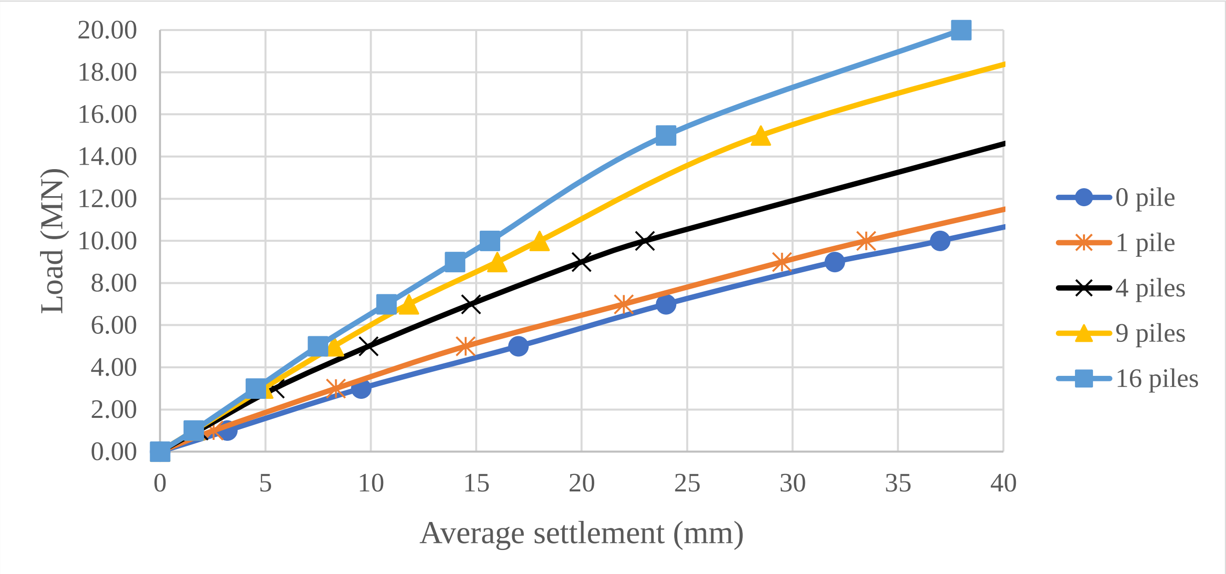

Figure 4-4:-Load average settlement curve for Krs=0.06, D=0.5, S=3D

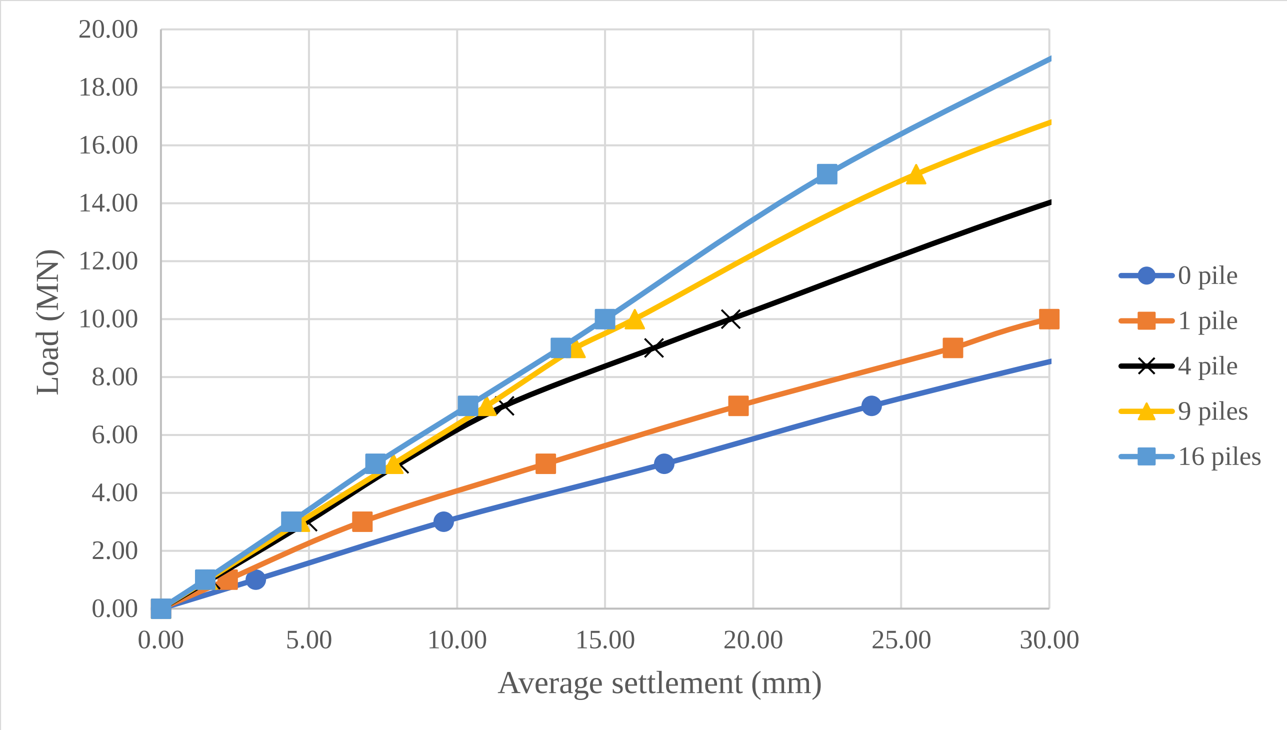

Figure 4-5:-Load average settlement curve for Krs=0.06, D=0.75, S=3D

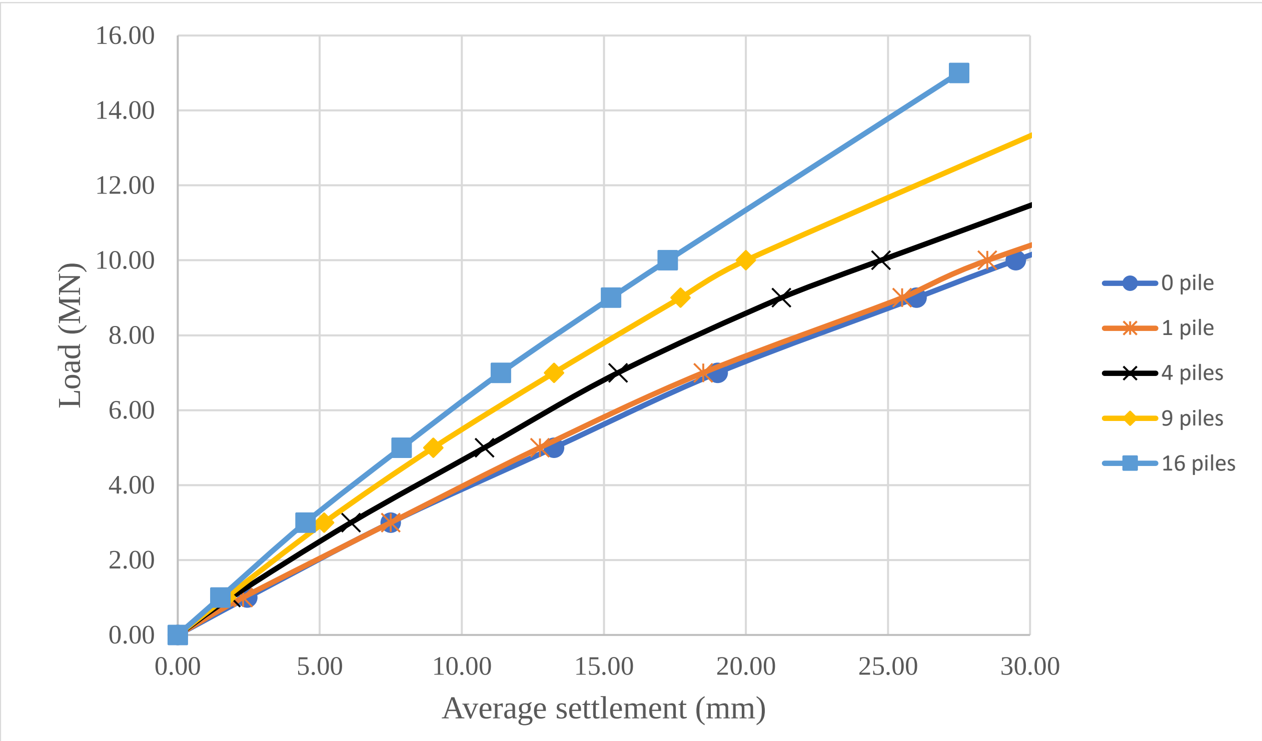

Figure 4-6:-Load average settlement curve for Krs=0.53, D=0.3, S=3D

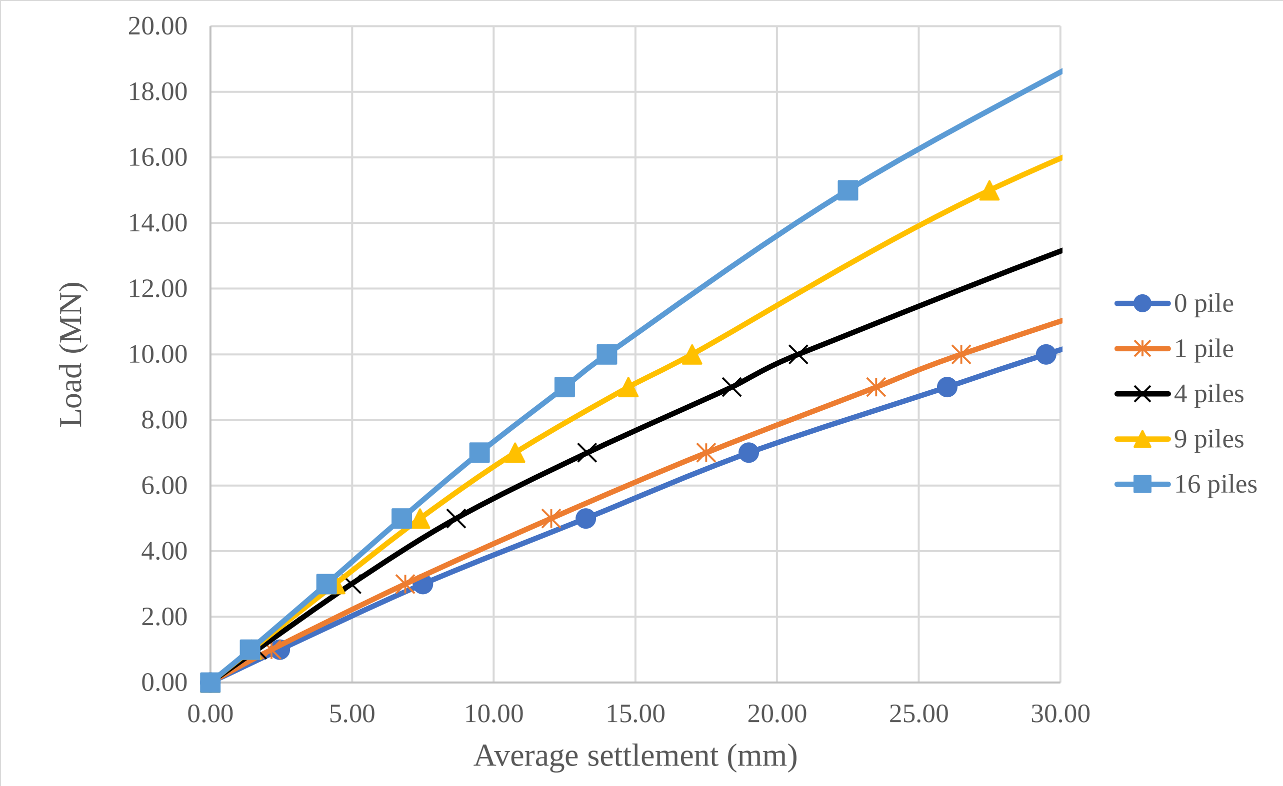

Figure 4-7:-Load average settlement curve for Krs=0.53, D=0.5, S=3D

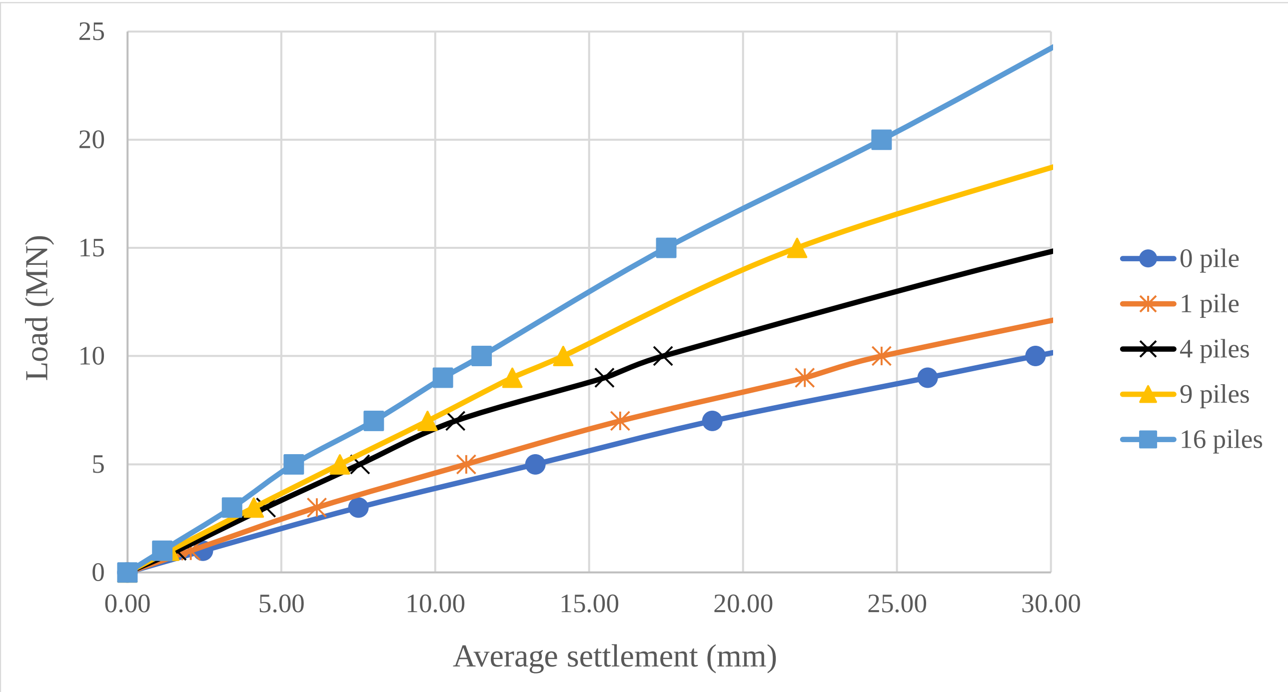

Figure 4-8:-Load average settlement curve for Krs=0.53, D=0.75, S=3D

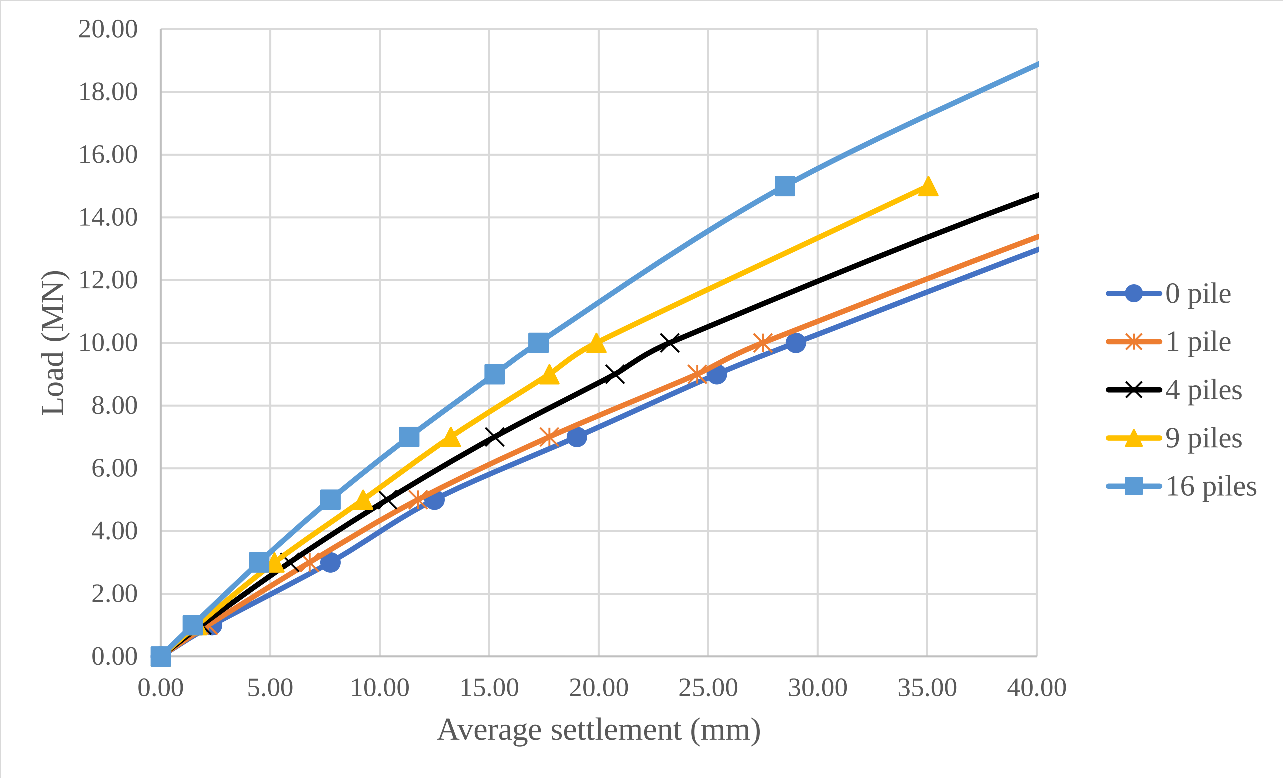

Figure 4-9:-Load average settlement curve for Krs=1.78, D=0.3, S=3D

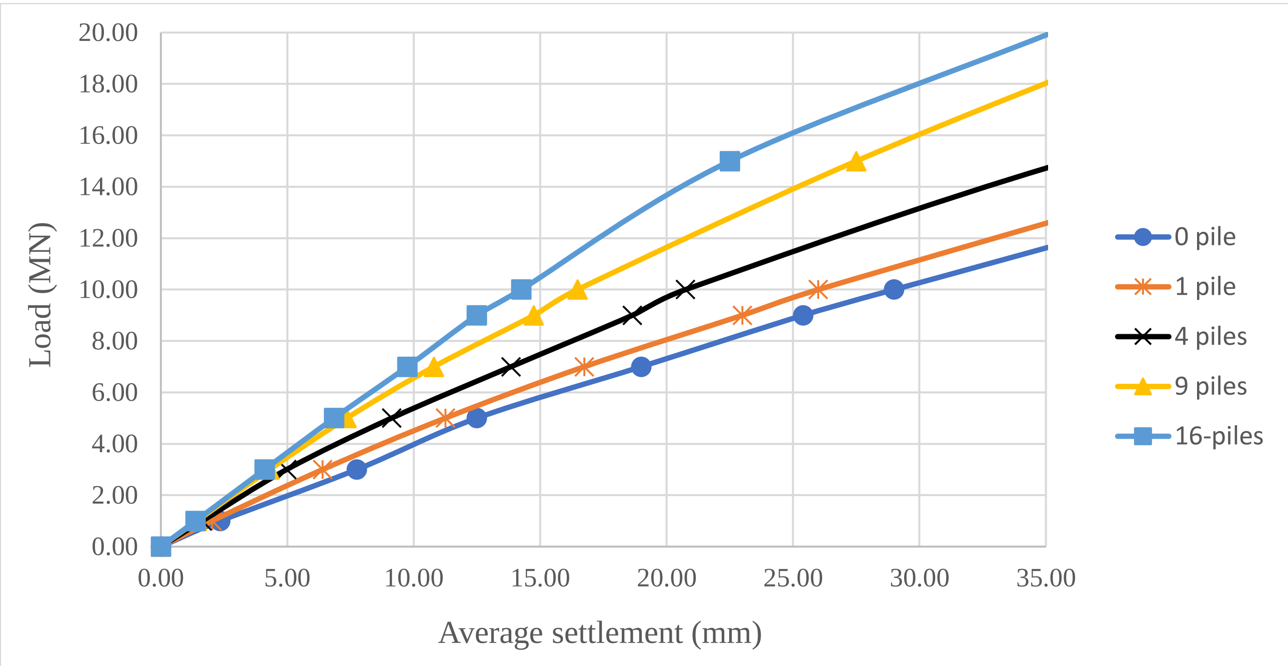

Figure 4-10:-Load average settlement curve for Krs=1.78, D=0.5, S=3D

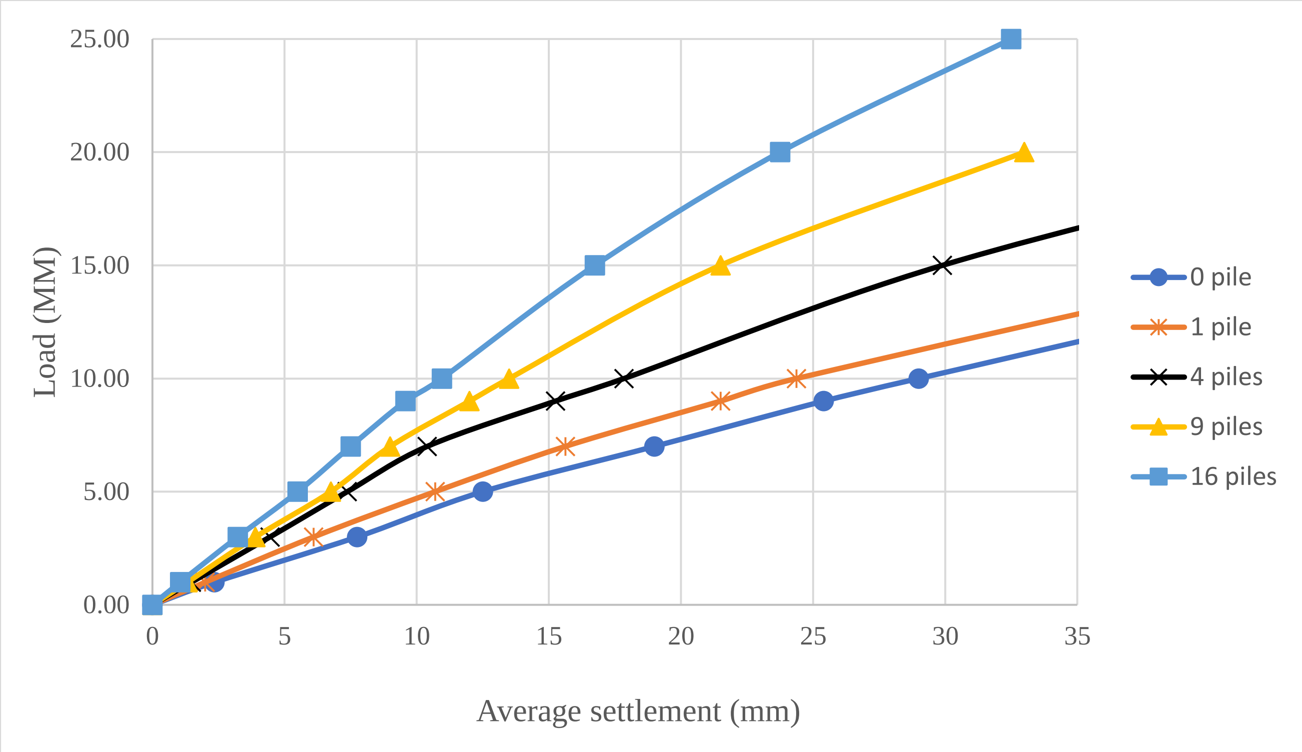

Figure 4-11:-Load average settlement curve for Krs=1.78, D=0.75, S=3D

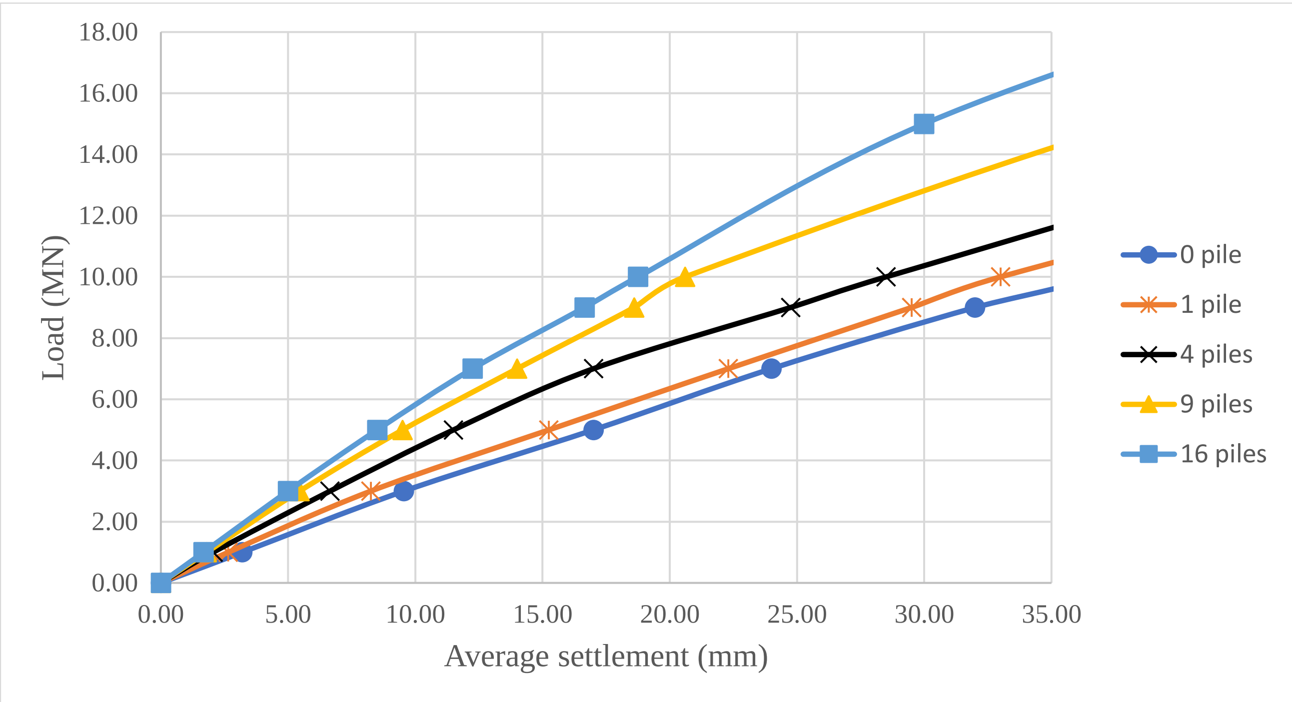

Figure 4-12:-Load average settlement curve for Krs=0.06, D=0.3, S=4D

Spacing has no significant effect on the ultimate load (ULC) and allowable load (ALC) capacities for the considered spacings in this study (3D,4D), only limited figures with spacing of 3D which show the effect of number of piles is drawn and one additional figure with a spacing of 4D (figure 4-12.) is drawn to show the effect of number of piles and in addition to compare effect of spacing on ALC and ULC with a figure having a spacing of 3D drawn (figure 4-3). Comparing figure 4-3 (with S=3D) with figure 4-12 (with S=4D) for spacing difference to show that spacing have no such big difference in both ultimate load and allowable load capacities is given in the table 4-7.

Table 4-6:- Comparison of the ULC and ALC Increase with Spacing

	Figure 3. (3D)		**Figure 12. (4D)**		**Difference (%)**	
	ULC Increase (%)	**ALC Increase (%)**	**ULC Increase (%)**	**ALC Increase (%)**	**ULC**	**ALC**
No Pile-1 Pile	7	11	7	11	0	0
No Pile-4 Pile	26	43	24	40	2	3
No Pile-9 Pile	55	67	55	67	0	0
Nopile-16 Pile	79	83	80	86	-1	-3

As shown in table 4-7, the percentage increase or decrease is at maximum 3% and this shows that the spacing difference have no significant effect on the ULC and ALC of the piled raft foundation for the specific arrangement, number length etc. presented in previous sections. only. Due to this reason only 10 figures have been drawn here but others have checked for this case too and the same result is observed.

Summary from the figure 4-3 to 4-12.

a. As shown in these figures (figure 4-3 to 4-12), the load carrying capacity of piled raft increases as the number of settlements reducing piles increases, for all the studied cases. This increase is mainly due to the increase in the portion of load carried by the central piles due to the increase of the number of piles.
b. The addition of one central pile increases the allowable load (ALC) and ultimate load capacities (ULC) up to a maximum of 30% and 17% respectively in case of figure 4-5 (Krs=0.06, D=0.75, and S= 3D) compared to unpiled raft. The other figures have percent increase below these values and the average increase in ULC and ALC are 8.7 % and 13 % respectively.
c. The addition of four central piles increases the allowable load (ALC) and ultimate load capacities (ULC) up to a maximum of 98% and 67% respectively in case figure 4-5 (Krs=0.06, D=0.75, and S= 3D) compared to unpiled raft. The other figures have percent increase below these values and the average increase in ULC and ALC are 36 % and 51 % respectively.

d. The addition of nine central piles increases the allowable load (ALC) and ultimate load capacities (ULC) up to a maximum of 99% and 103% respectively in case figure 4-5 (Krs=0.06, D=0.75, and S= 3D) compared to unpiled raft. The other figures have percent increase below these values and the average increase in ULC and ALC are 66 % and 71 % respectively.
e. The addition of sixteen central piles increases the allowable load (ALC) and ultimate load capacities (ULC) up to a maximum of 127% and 131% respectively in case figures -5 and 4-8 compared to unpiled raft. The other figures have percent increase below these values and the average increase in ULC and ALC are 95 % and 96 % respectively.
f. High increase of both ALC and ULC found when diameter is high keeping other parameters constant. All the maximum increases have been observed from the combination of a diameter of 0.75 m and a raft relative stiffness of 0.06. This shows that the percentage increase of both ULC and ALC is maximum for a least raft relative stiffness and maximum diameter.

In the other way, the improvement in the load capacity of the raft, at 10 mm and 25 mm settlements, due to the presence of settlement reducing piles is represented by a non-dimensional parameter called load improvement ratio, LIR, as follows:

$$LIR = \frac{P_{pr}}{P_r} \qquad (4\text{-}2)$$

where P_r and P_{pr} are the loads of unpiled raft and central piled raft at 10 mm and 25 mm settlements, respectively.

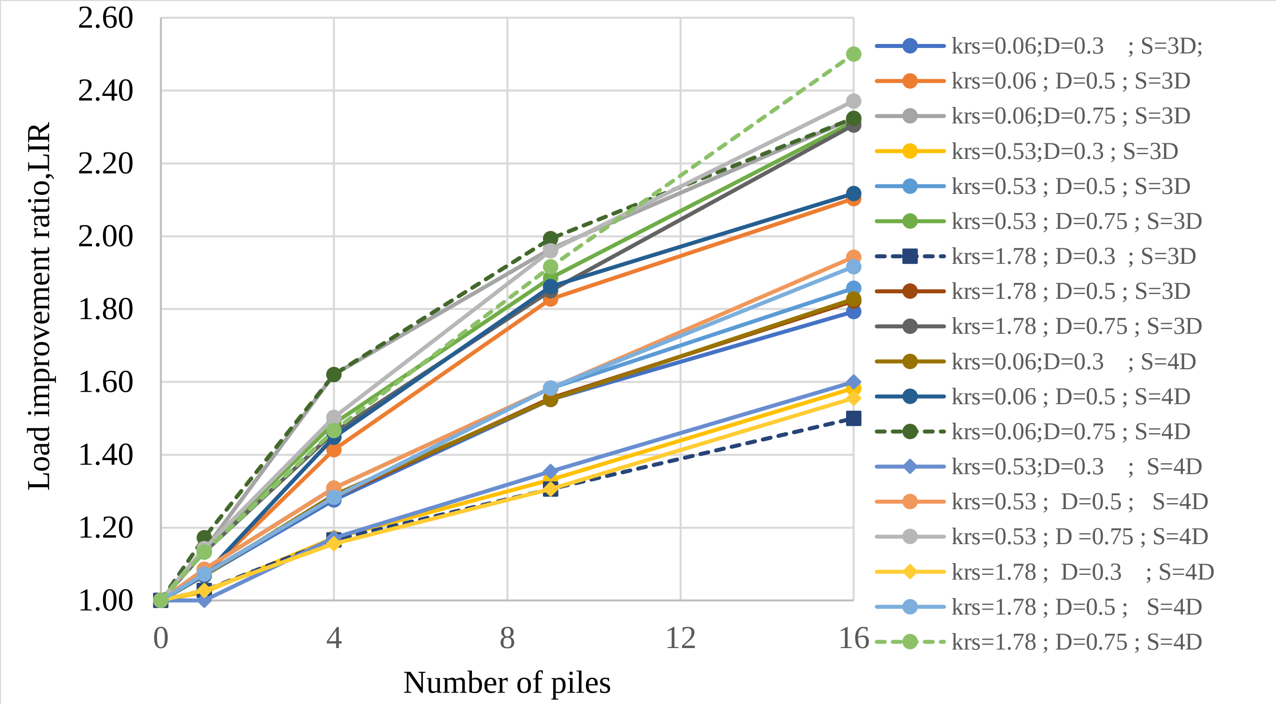

Figure 4-13:-Variation of LIR with the number of piles at 25 mm settlement

Figures 4-13 and 4-14 show the variation of the load improvement ratio, LIR, with the number of settlement reducing piles at 25 mm and 10 mm settlements, respectively.

From these figure (figure 4-13 and 4-14), it can be noted that:

a. At the same raft relative stiffness, diameter, and spacing of piles, the value of LIR increases as the number of piles increases (e.g. at 25 mm settlement, for raft of 0.06 relative stiffness, installing 9 settlement reducing piles with D=0.75m and spacing of 3D, causes an increase in the raft load by 103%, while installing 16 piles with the same D=0.75 and with a spacing of 3D ratio increases the raft load by 128%).
b. For all the study cases, as diameter of the pile increases, the load improvement ratio, LIR, increases. (From figure 4-15 shown for instance, for 9 number of piles under Krs of 0.06, LIR for a diameter of piles of 0.3,0.5, and 0.75 are 1.55,1.83, and 1.97 respectively).
c. The value of load improvement ratio decreases with increasing of raft relative stiffness, K_{rs}. It means that, at low raft relative stiffness, K_{rs}, of a raft, the addition of piles on low relative stiffness raft improves its load carrying capacity more than adding of piles on high raft relative stiffness, K_{rs}, raft compared to its corresponding unpiled raft load carrying capacity. But it does not mean that load carrying capacity at low K_{rs} is greater than at high K_{rs} rather the reverse is true. (e.g. from figure 16 for 16 number of piles

for diameter of 0.3 m and a spacing 3D, the LIRs for Krs of 0.06, 0.53, and 1.78 are 1.79,1.58 and 1.50 respectively.)

d. As shown in figure 4-17 spacing have no any significant effect on load improvement ratio, LIR, of the piled raft foundation. From the figure, results of LIR for Krs of 0.06 for diameters of 0.3 and 0.75 at a spacing of 3D and 4D for each diameter are drawn and the lines coincide to show spacing have no any significant effect.

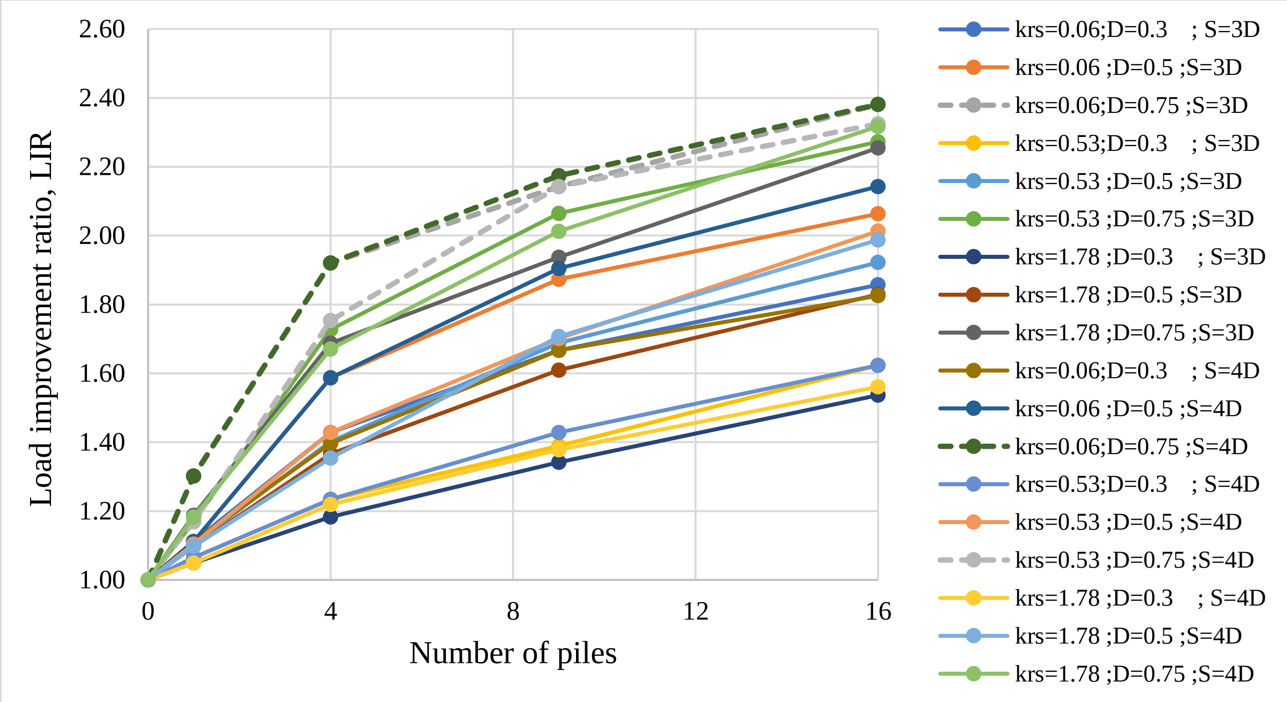

Figure 4-14:-Variation of LIR With the Number of Piles At 10 Mm Settlement

To breakdown the figures 4-13 and 4-14 for LIR under number of piles, let us draw the following figures

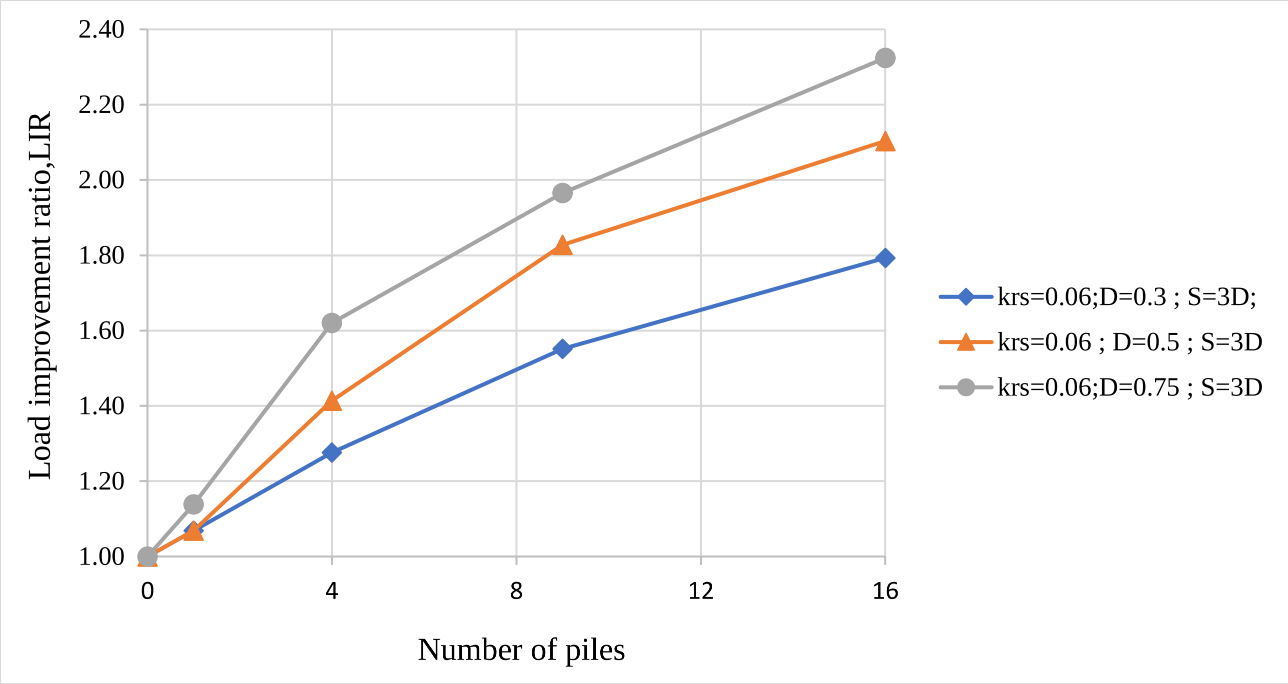

Figure 4-15:-LIR versus Number of piles at 25mm settlement.

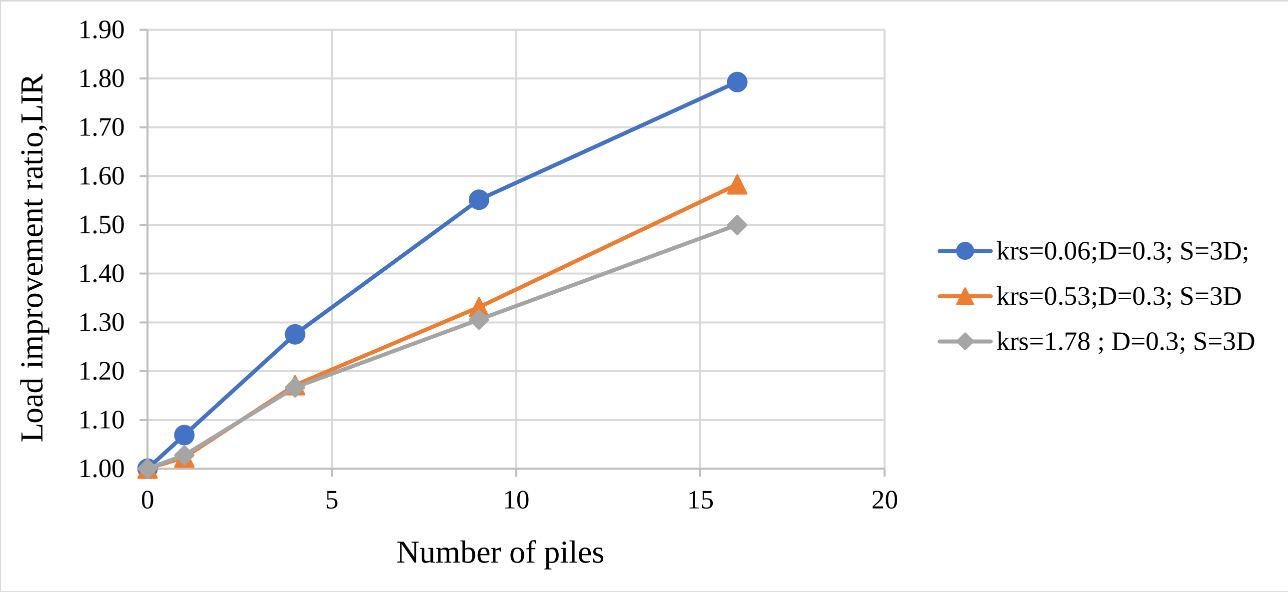

Figure 4-16:-LIR versus number of piles for variable Krs at 25mm settlement.

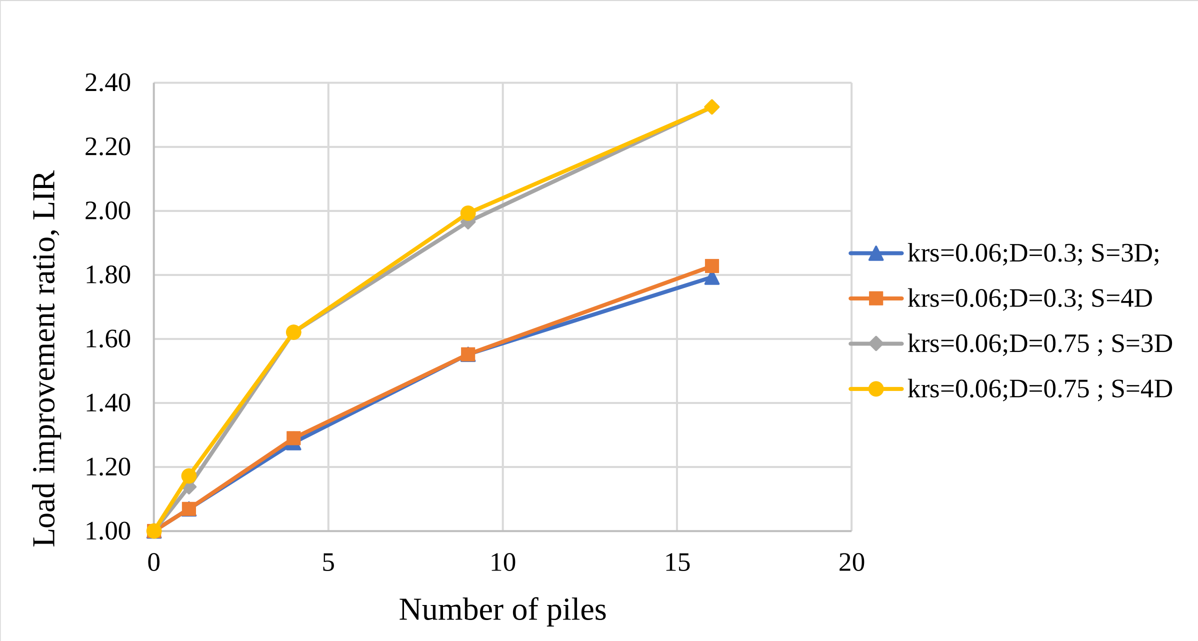

Figure 4-17:-LIR vs Number of piles under variable spacing at 25mm settlement.

4.6.1.2 Effect of Raft Relative Stiffness

From figures above for number of piles effect on LIR, pile spacing has no significant difference between the LIR of the foundation for the considered spacings. Therefore, use only one spacing 3d to evaluate the effect of raft relative stiffness on different parameters of the foundation

For all the studied cases, the value of LIR at 10 mm settlement is greater than that at 25 mm settlement. This is clearly shown in Figures 4-18,4-19 and 4-20 that the variation of LIR with the raft relative stiffness for the raft on 4, 9 and 16 settlement reducing piles with diameters of 0.3 m, 0.5 m and 0.75 m can be observed respectively. A similar observation has been reported by Phung (2010) from experimental test results on piled rafts. This explains the mechanism of load sharing between raft and piles (i.e. at the beginning of central piled raft loading, the piles carry major portion of the load, and with the settlement increasing, the load is transferred to the raft).

When the raft is very flexible (Krs=0.06) the LIR is greater than the other two raft types (flexile and stiff rafts). After Krs of 0.53 the LIR is almost constant for all case. Therefore, the stiffness of the raft has no significant effect on load carrying capacity of the piled raft foundation.

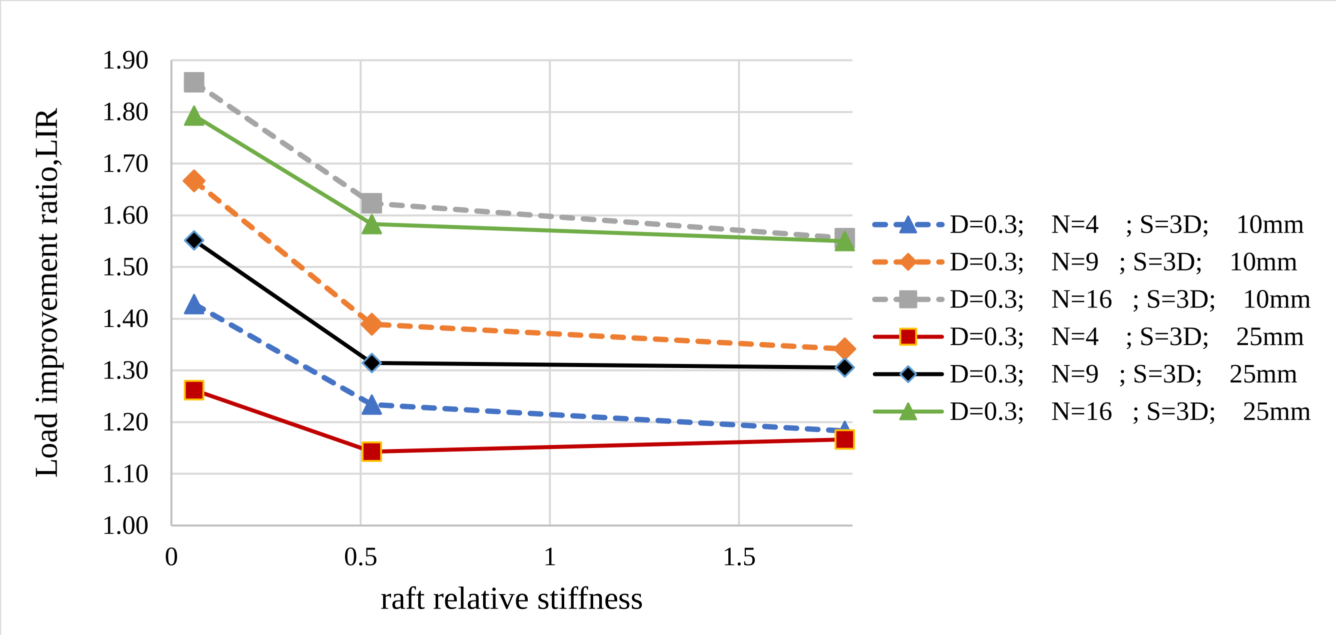

Figure 4-18:-Variation of LIR with Krs at 10 mm and 25 mm settlements

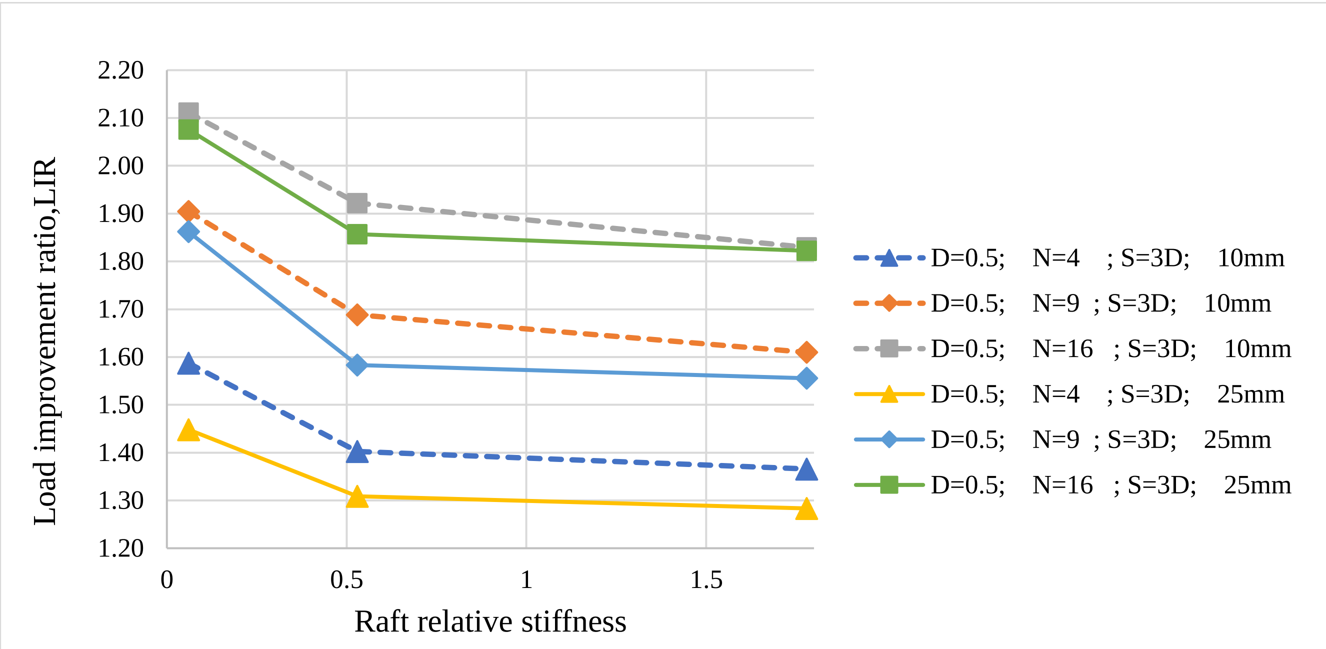

Figure 4-19:-Variation of LIR with Krs at 10 mm and 25 mm settlements.

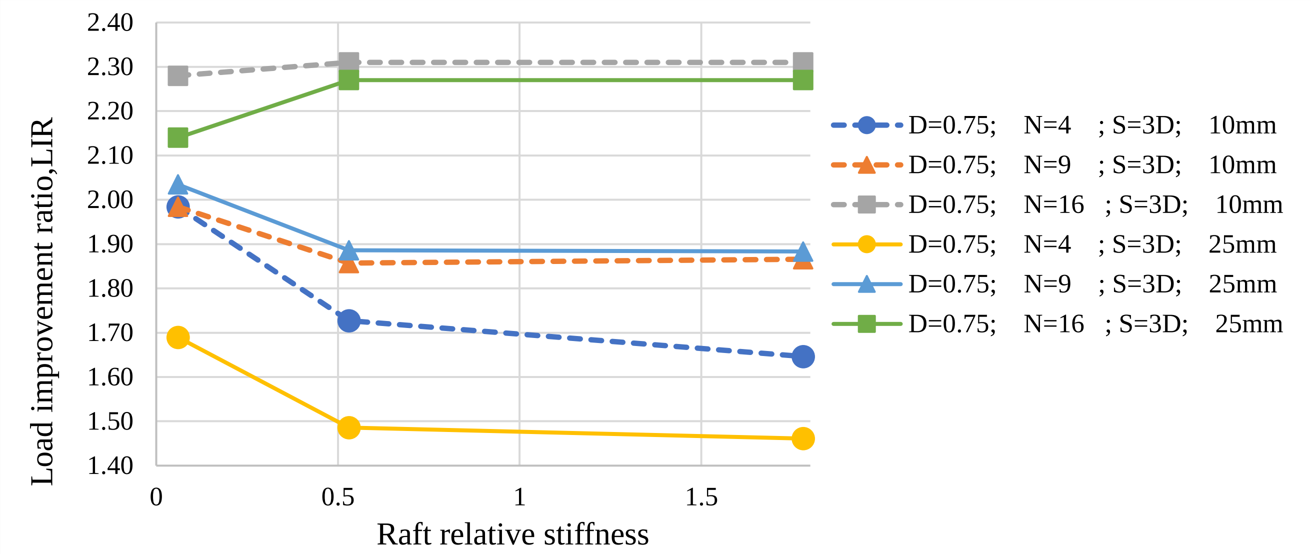

Figure 4-20:-Variation of LIR with Krs at 10 mm and 25 mm settlements.

4.6.1.3 Effect of Diameter On LIR

As shown from figures 4-3 to 4-12, for load average settlement curves of different number of piles, as the number of piles increase, load carried by the foundation increases without further increase of average settlement. Therefore, take 4 number of piles only to check effect of diameter on load improvement ratio, LIR, of a foundation due to the diameter change of the pile. The ULC and ALC are considered with all three-raft relative stiffnesses (Krs of 0.06, 0.53, and 1.78) parameters and two spacings (S of 3D and 4D).

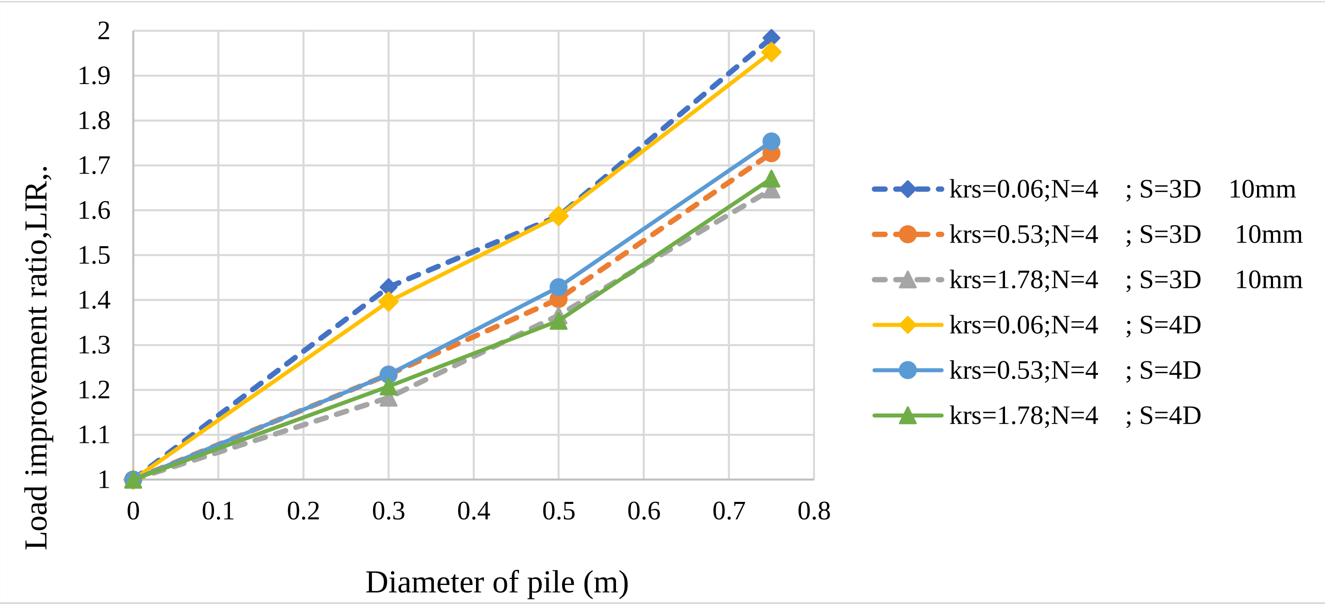

Figure 4-21:-LIR versus diameter of pile for 10 mm settlement

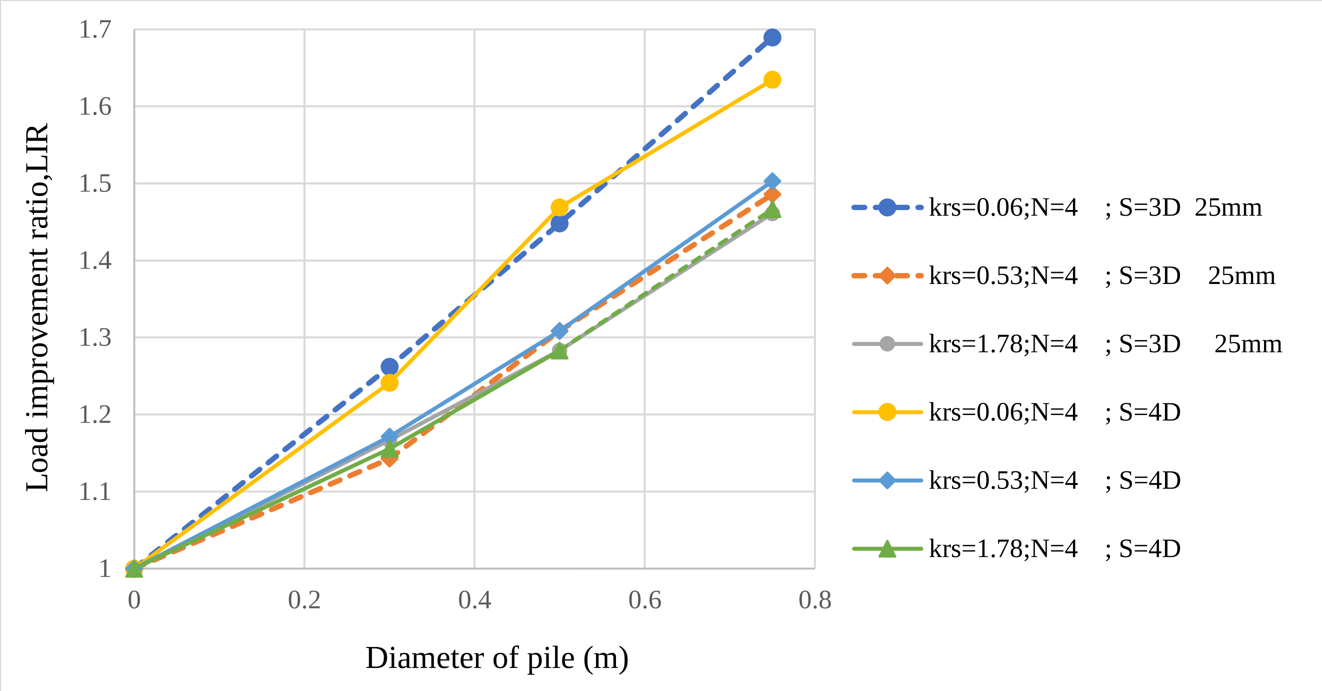

Figure 4-22:-LIR versus diameter of pile for 25mm settlement

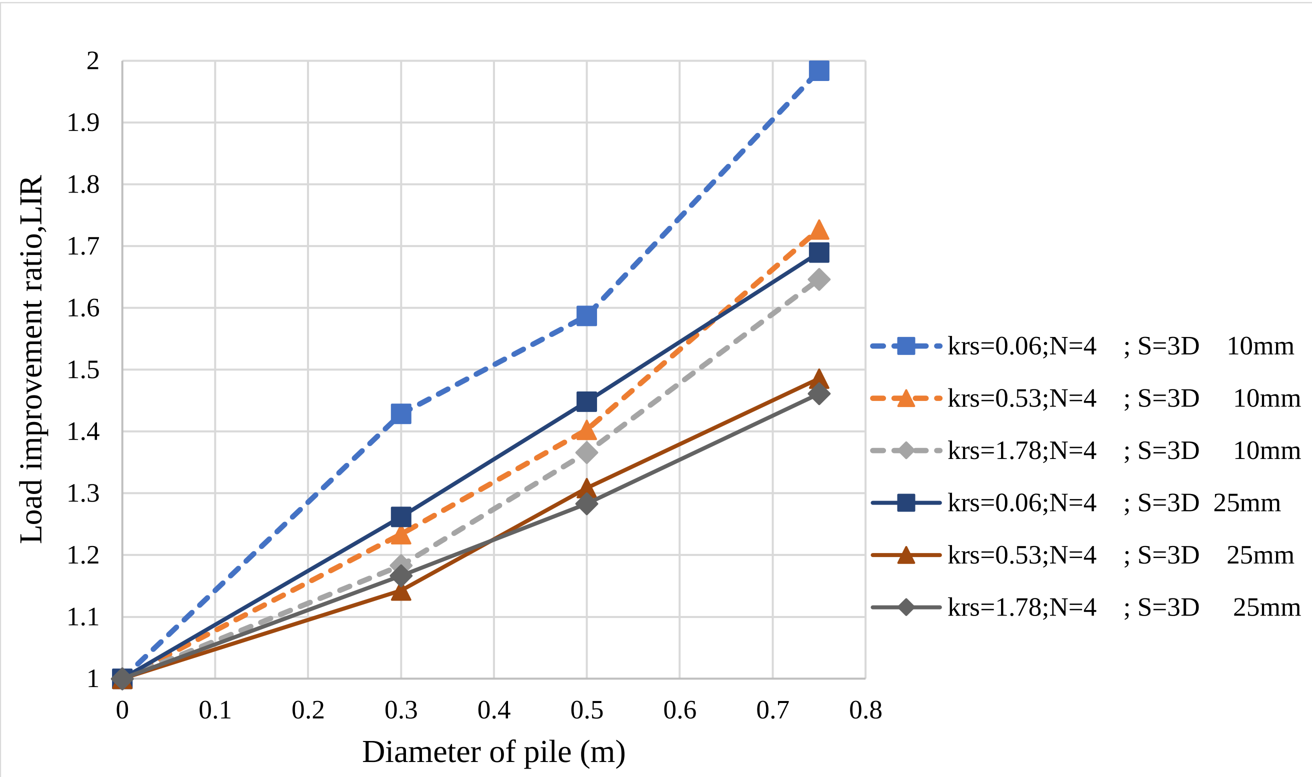

Figure 4-23:-Comparison of LIR Versus Diameter of Pile At 10 Mm And 25 Mm

From figures 4-21,4-22 and 4-23, one can draw the following conclusions.

a. As the diameter of the pile increase the load improvement ratio increases dramatically. For example, from figure 4-21 for curve having Krs of 0.06, Number of piles of 4 and a spacing of 3D at 10 mm average settlement (ALC), the LIR for pile diameters of 0.3, 0.5, and 0.75 are 1.43, 1.59, and 1.98 respectively.
b. As the relative stiffness of raft increases, the LIR decrease as shown in figures 4-21 to 4-23.
c. As the spacing of piles increase, the LIR have no any significant difference at all in all cases.
d. The LIR in all case is greater at 10 mm average settlement than at 25 mm average settlement as shown in figure 4-23, and this explains the mechanism of load sharing between the pile and the raft as explained earlier.

4.6.1.4 Effect of Spacing of Piles

To see the effect of piles spacing on Load improvement ratio, LIR, take 16 piles under the raft with all three-raft relative stiffnesses (Krs of 0.06, 0.53, and 1.78) and also three pile diameter parameters (D of 0.3, 0.5, and 0.75 m).

From the figures 4-24 and 4-25 below, one can draw the following conclusions

a. From both figures LIR have no any significant difference between 3D and 4D.
b. LIR of 10mm settlement are a little greater than LIR of 25 mm as shown on figure 4-25 and this shows the load sharing mechanism between the piles and the raft.

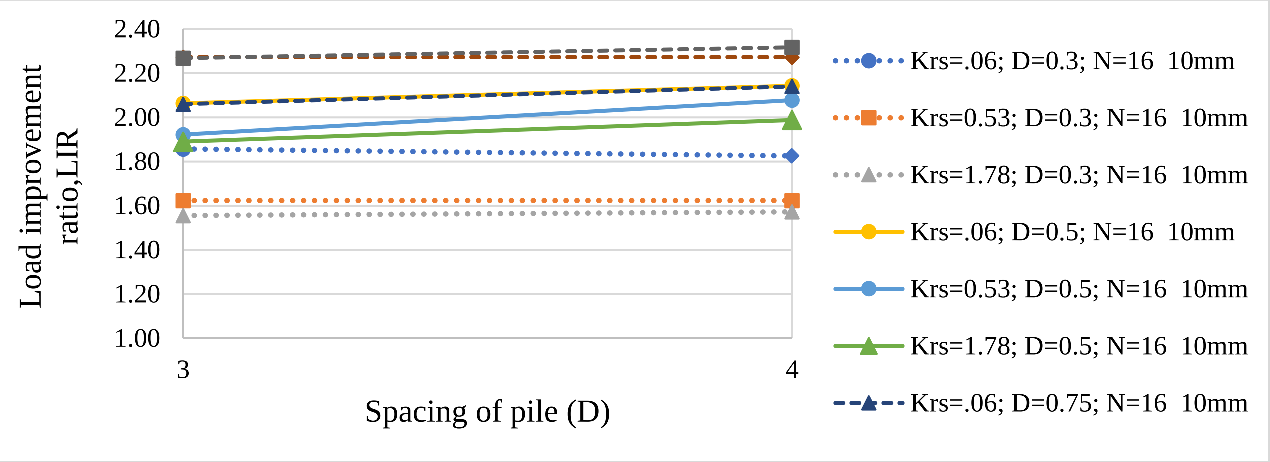

Figure 4-24:-LIR vs spacing for 16 number of piles

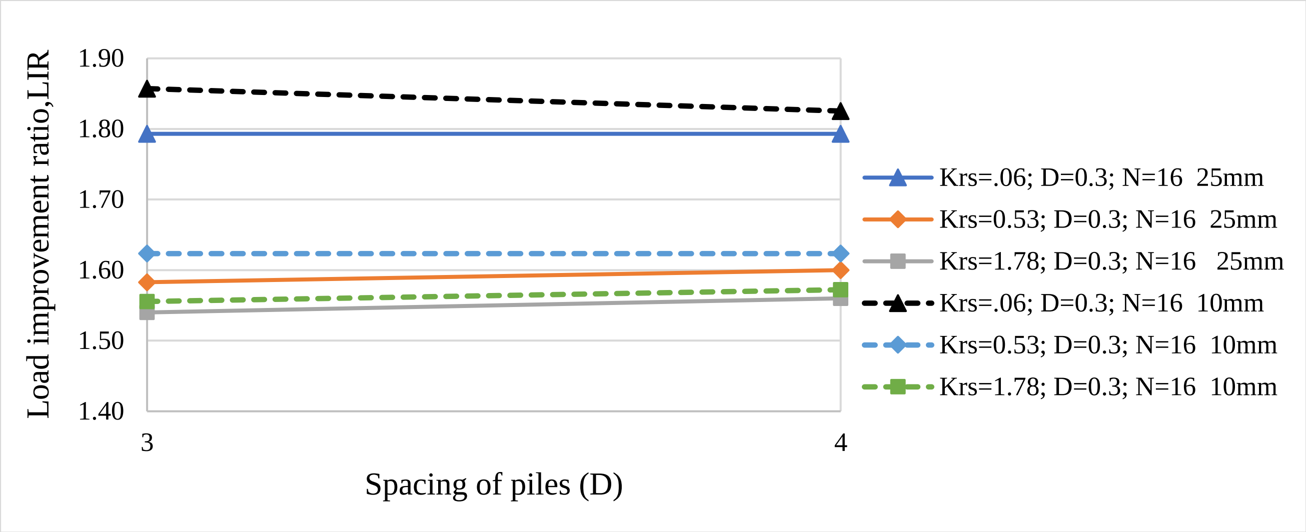

Figure 4-25:-Comparison of LIR Vs Spacing At 10 And 25 mm

4.6.2 Settlement Ratio

In order to analyze the reduction in average and differential settlements due to the presence of piles under the central area of the raft, average and differential settlements of raft on settlement reducing piles and unpiled raft corresponding to a constant load, P, (i.e. the load corresponding to 25 mm settlement for unpiled raft) are obtained for all the studied cases.

The reductions in average and differential settlements of raft due to the presence of settlement reducing piles are represented by non-dimensional factors, called settlement ratio, SR, and differential settlement ratio, DSR, as follows:

$$\mathrm{SR} = \frac{\mathrm{w_{pr}}}{\mathrm{w_r}} \quad (4\text{-}3)$$

$$\mathrm{DSR} = \frac{\Delta \mathrm{w_{pr}}}{\Delta \mathrm{w_r}} \quad (4\text{-}4)$$

Where SR=settlement ratio

DSR =differential settlement ratio

w_{pr} = settlement on piled raft foundation

w_r= settlement of unpiled raft foundation

4.6.2.1 Effect of Number of Piles on Settlement Ratio, SR

As shown in figure 4-26, as the number of piles increase from the zero number of piles to 16 number of piles the settlement ratio, SR, decreases from unity to the minimum of 0.38.

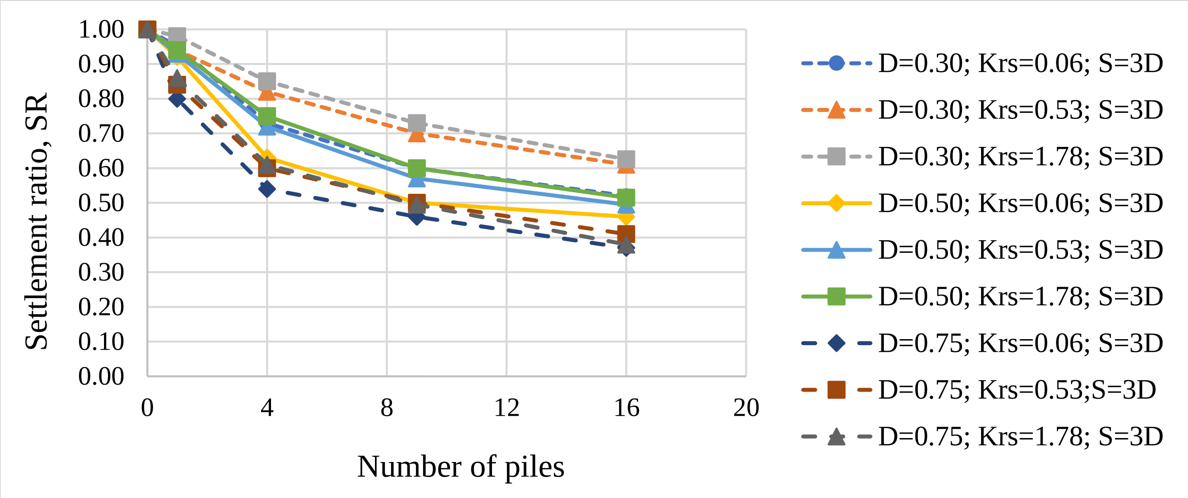

Figure 4-26:- Settlement Ratio, SR, Versus Number of Piles with A Spacing Of 3D

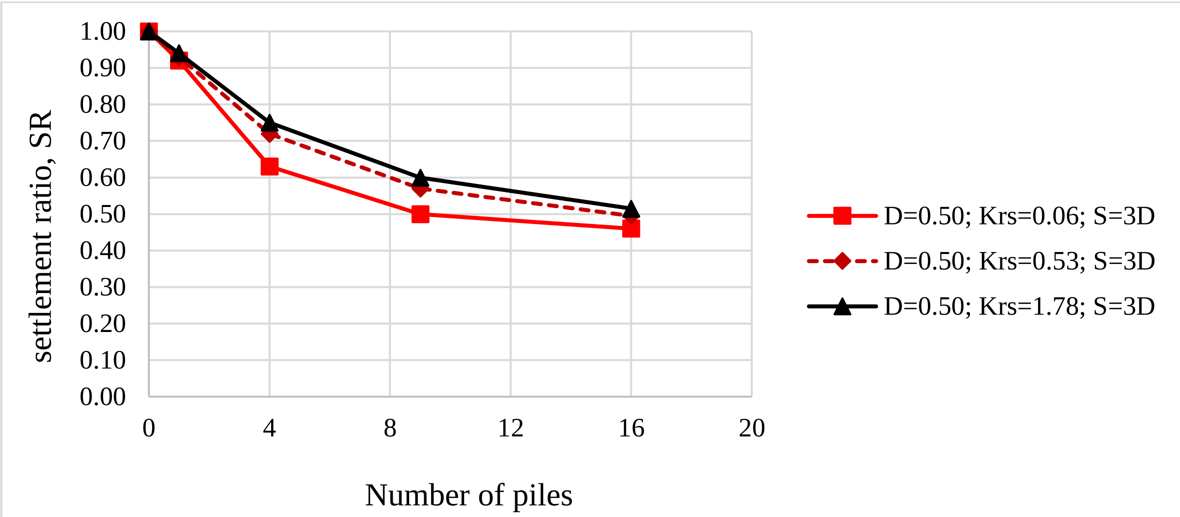

Figure 4-27:- SR Versus Number of Piles to Show Effect Raft Relative Stiffness On SR

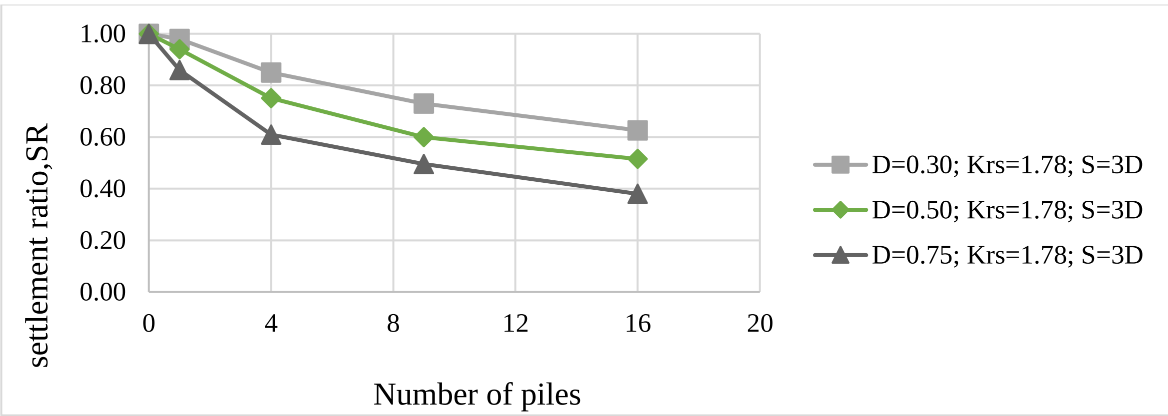

Figure 4-28:- SR Versus Number of Piles to Show Effect of Pile Diameter On SR

Figures 4-26, 4-27 and 4-28 shows the variation of settlement ratio, SR, with the number of piles for rafts with relative stiffness of 0.06, 0.53 and 1.78.

From figures 4-26, 4-27 and 4-28, it is observed that:

a. The settlement ratio decreases as the number of piles increase in all the three cases. For instance, for the raft with 0.06 raft relative stiffness, installing 9 piles with D=0.75 m causes a decrease in the average settlement of the raft by 54%, while installing 16 piles with D=0.75 m causes a decrease in the raft settlement by 63% compared to unpiled raft foundation.
b. Generally, the rate of decrease of SR decreases as the number of settlement reducing piles increases. For instance, for the raft with 0.06 relative stiffness, installing 1,4,9, and 16 piles with D=0.75 m causes a decrease in the average settlement ratio of the raft by 20%,46%, 54%, and 63% respectively. Therefore, the difference between the consecutive percentages are 26%, 10% and 7% respectively. Therefore, to reduce average settlement of a piled raft foundation a limited amount of piles around the central area of raft is satisfactory.
c. For a given number of piles, the settlement ratio increases as the raft relative stiffness increases as shown in figure 4-27. (e.g. for 9 piles at a pile diameter of 0.5 m and a spacing of 3D, the settlement ratio, SR, for raft relative stiffness of 0.06, 0.53 and 1.78m are 0.5, 0.57 and 0.6 respectively).
d. For a given number of piles, the settlement ratio decreases as the diameter of the pile increases as shown in figure 4-28. (e.g. for 9 piles at a raft relative stiffness of 1.78 and a spacing of 3D, the settlement ratio, SR, for piles of diameter 0.3, 0.5 and 0.75 m are 0.73, 0.63 and 0.5 respectively). This confirms the observations reported by Katzenbach et al. (1998) and Poulos (2001) from numerical analyses of raft on different numbers of settlement reducing piles.

4.6.2.2 Effect of Raft Relative Stiffness on Settlement Ratio, SR

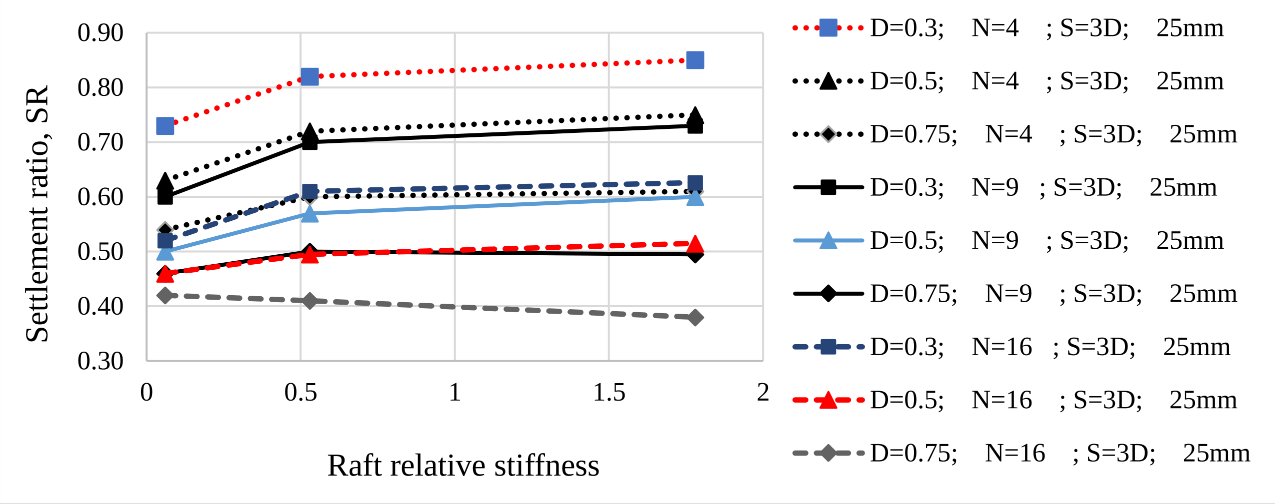

Figure 4-29:-Variation of SR with The Raft Relative Stiffness, Krs.

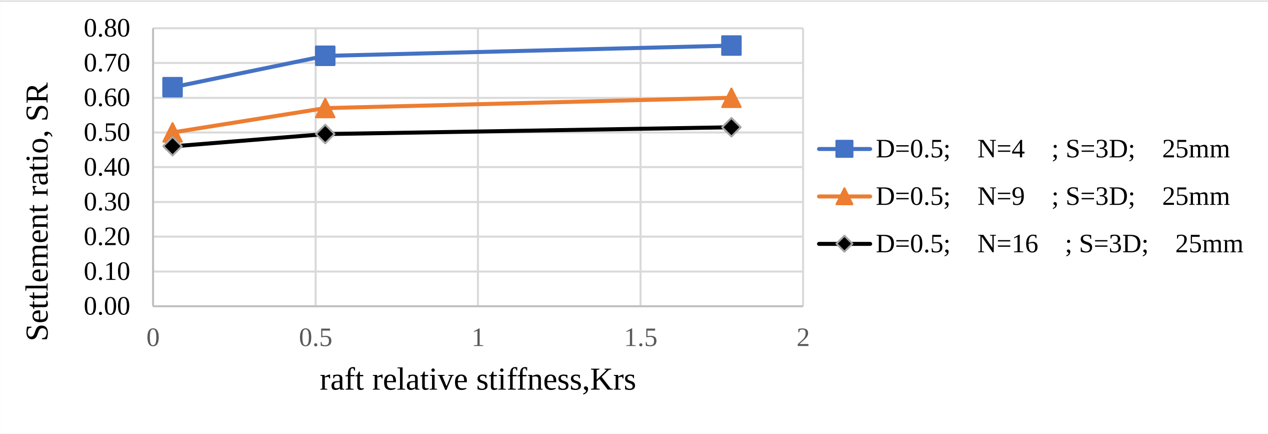

Figure 4-30:-Variation of SR with The Raft Relative Stiffness, Krs.

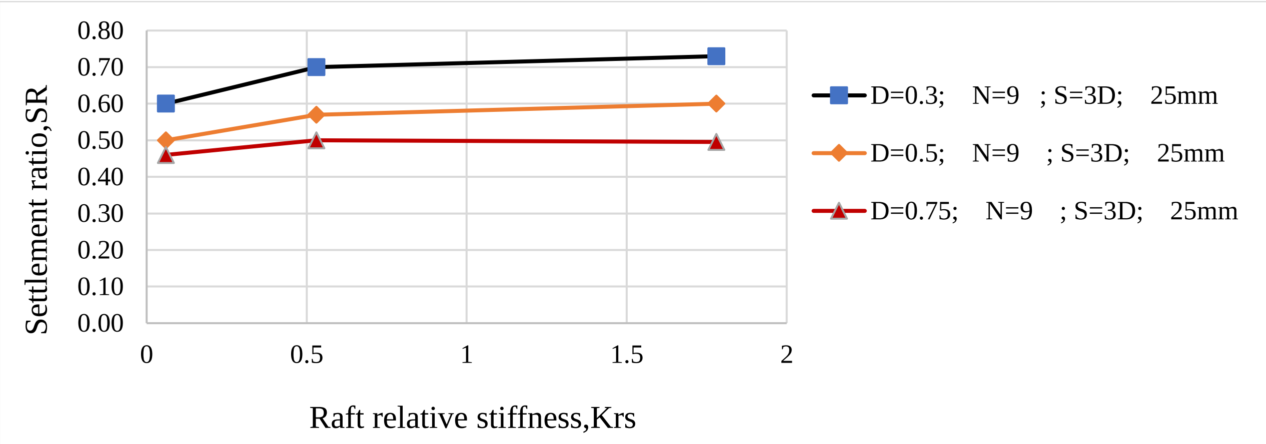

Figure 4-31:-Variation of SR, With the Raft Relative Stiffness, Krs.

The variation of settlement ratio, SR, with the raft relative stiffness at different number of settlement reducing piles (4,9, and 16), different diameter (0.3, 0.5, and 0.75 m) of piles at a spacing of 3D (no need to see effect of spacing 4D because, it has been shown that spacing have no significant effect) for an average settlement of 25 mm are shown in figures 4-29, 4-30 and4-31.

From the figures 4-29, 4-30 and 4-31 one can noted the following points.

a. It can be observed that the raft relative stiffness, Krs, has little effect on the average settlement of piled raft.
b. Settlement ratio, SR, decreases as number of piles increase in the piled raft foundation system.
c. The rate of decrease of settlement ratio, SR, decrease as the number of piles increase.
d. Settlement ratio, SR, decreases as diameter of piles increase in the piled raft foundation system.

4.6.2.3 Effect of Diameter of Pile on Settlement Ratio, SR

As shown from figure 4-32, settlement ratio with pile diameter is drawn for four number of piles (since effect of pile number is explained on section 4.3.1.) at each raft relative stiffnesses (Krs of 0.06, 0.53 and 1.78) and a spacing of 3D (spacing have no any significant effect as explained in previous sections).

From figure 4-32, one can note the following points

a. Settlement ratio, SR, decrease as the diameter of pile increase.
b. The effect of pile diameter on settlement ratio is not significant. As seen from the figure the minimum settlement ratio is 0.54 for a Krs of 0.06 and diameter of 0.75 m and the other settlement ratios, SR, are above this which shows diameter of pile have no any significant effect.
c. Settlement ratio, SR, decrease as the raft relative stiffness, Krs, decrease

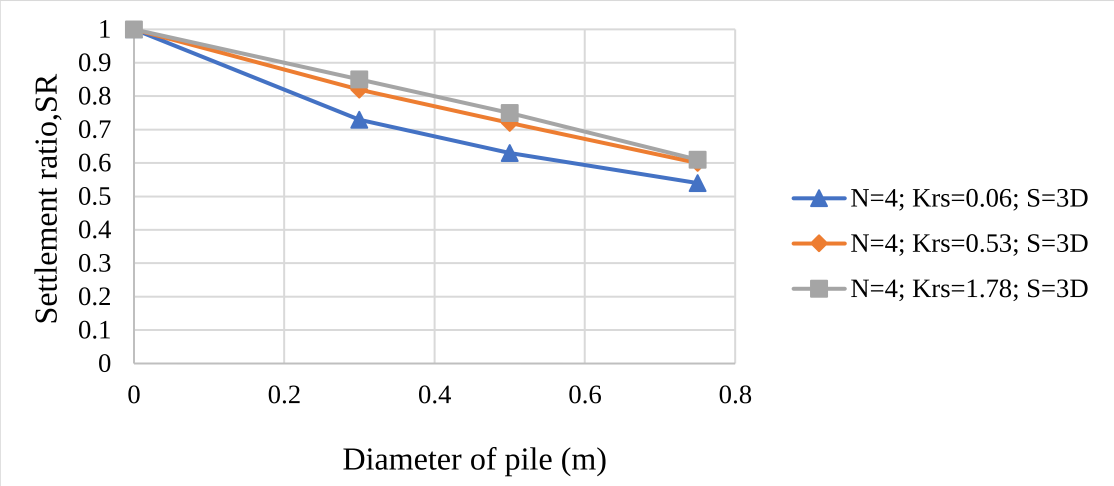

Figure 4-32:- SR Versus Diameter of Pile For 4 Number of Piles on Each Krs.

4.6.3 Differential Settlement Ratio

Unequal settlement of raft foundation between the center and the mid-edge of a raft is said to be the differential settlement of the foundation taken in to account. Due to the reason that unitless parameters are simpler to understand the effect of each parameter (pile number, diameter of pile, raft relative stiffness and spacing) on differential settlement of the piled raft, take differential settlement ratio, DSR, to understand the effects of parameters on differential settlement.

From figures 4-33, 4-34 and 4-35 the effect number of piles, diameter of piles, raft relative stiffness, and spacing are analyzed on the reduction of differential settlement ratio.

4.6.3.1 Effect of Number of Piles on Settlement Ratio, DSR

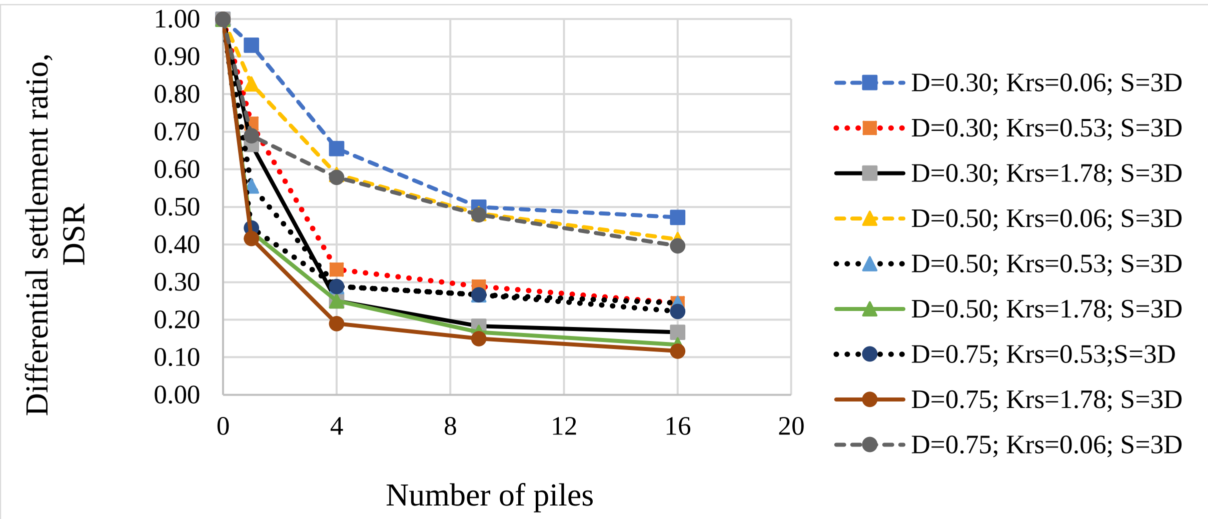

Figure 4-33:- DSR Versus Number of Piles with A Spacing Of 3D

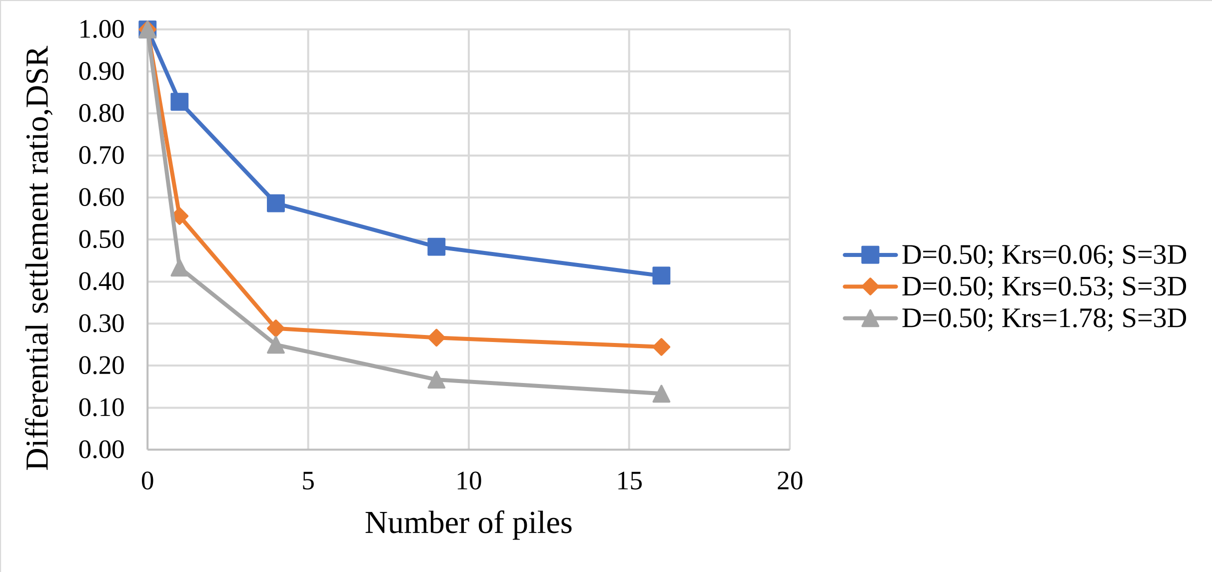

Figure 4-34:- DSR Versus Number of Piles to Show Effect Krs on DSR

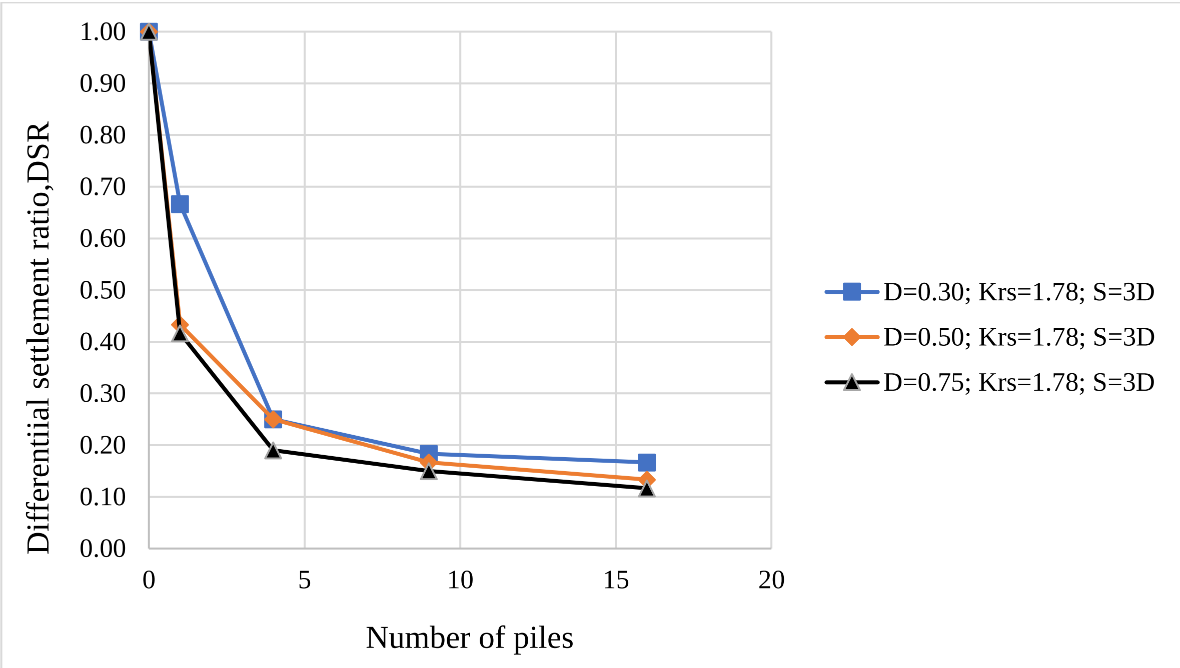

Figure 4-35:- DSR Versus Number of Piles to Show Effect of Diameter on DSR.

Figures 4-33, 4-34 and 4-35 show the variation of differential settlement ratio, DSR, with the number of piles for rafts with relative stiffness of 0.06, 0.53 and 1.78.

From figures 4-33, 4-34 and 4-35, it is observed that:

a. The differential settlement ratio decreases as the number of piles increase in all the three cases. For instance, for the raft with 0.06 relative stiffness, installing 9 piles with D=0.75 m causes a decrease in the differential settlement of the raft by 52%, while installing 16 piles with D=0.75 m causes a decrease in the raft differential settlement by 60% compared to unpiled raft foundation.

b. Generally, the rate of decrease of DSR decreases as the number of settlement reducing piles increases. For instance, for the raft with 0.06 relative stiffness, installing 1,4,9, and 16 piles with D=0.75 m causes a decrease in the differential settlement ratio of the raft by 31%,42%, 52%, and 60% respectively. Therefore, the difference between the consecutive percentages are 11%, 10% and 8% respectively. This shows that the rate of decrease is decreasing.

c. For a given number of piles, the differential settlement ratio, DSR, decreases as the raft relative stiffness increases as shown in figure 28. (e.g. for 9 piles at a pile diameter of 0.5 m and a spacing of 3D, the differential settlement ratio, DSR, for raft relative stiffness of 0.06, 0.53 and 1.78m are 0.48, 0.27 and 0.17 respectively).

d. For a given number of piles, the differential settlement ratio, DSR, decreases as the diameter of the pile increases as shown in figure 4-29 (e.g. for 9 piles at a raft relative stiffness of 1.78 and a spacing of 3D, the differential settlement ratio, DSR, for piles of diameter 0.3, 0.5 and 0.75 m are 0.18, 0.17 and 0.15 respectively). This shows that, although DSR decrease as pile diameter increases, the rate of decrease is much more insignificant compared to other parameters like raft relative stiffness. Therefore, differential settlement doesn't influence by pile diameter.

e. As per the three figures 4-33, 4-34, and 4-3, one can see that the differential settlement ratio, DSR, of the foundation is almost constant after 4 number of piles. This means that the optimum performance may be achieved by a small number of piles beneath the central area of the raft instead of using a large number of piles distributed beneath the whole area of the raft.

4.6.3.2 Effect of Raft Relative Stiffness On DSR

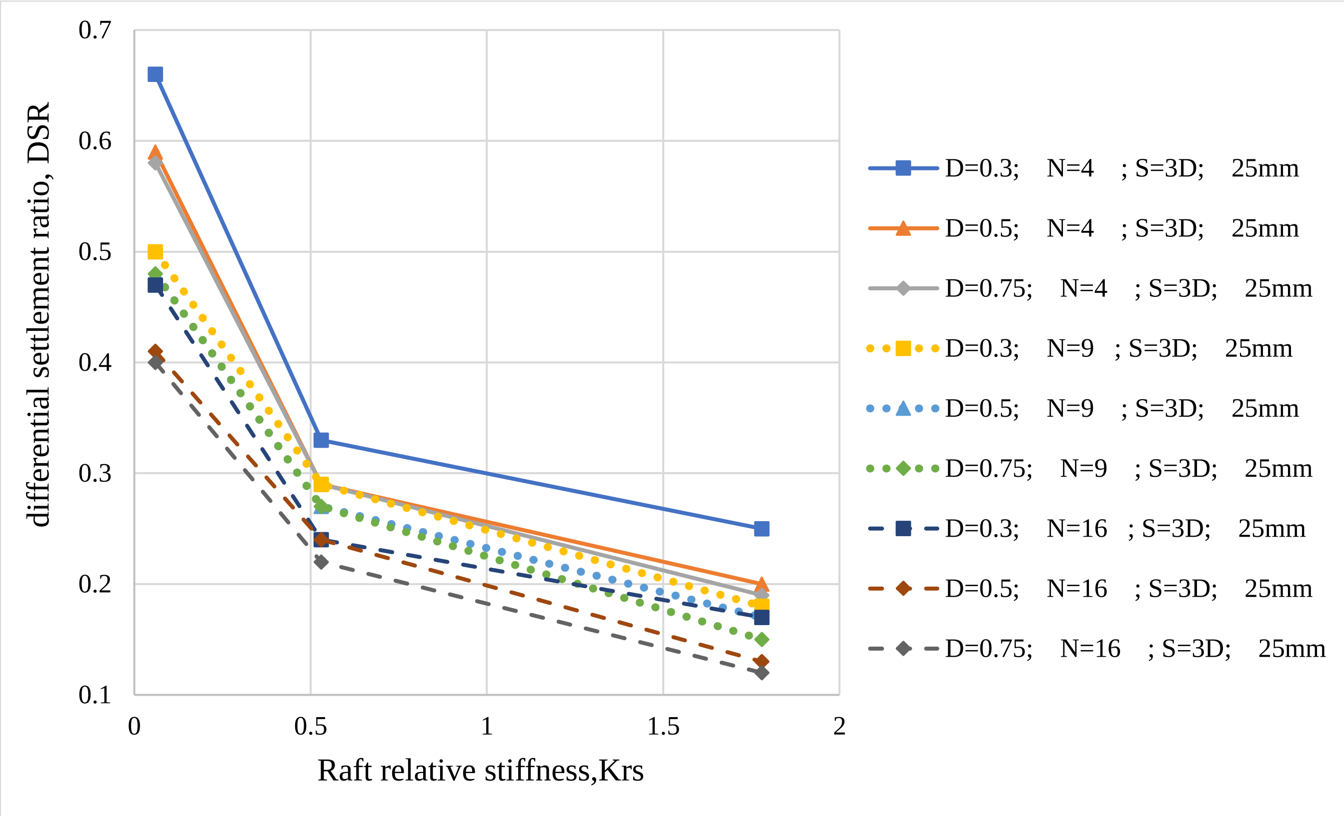

Figure 4-36:-Variation of DSR With the Raft Relative Stiffness,

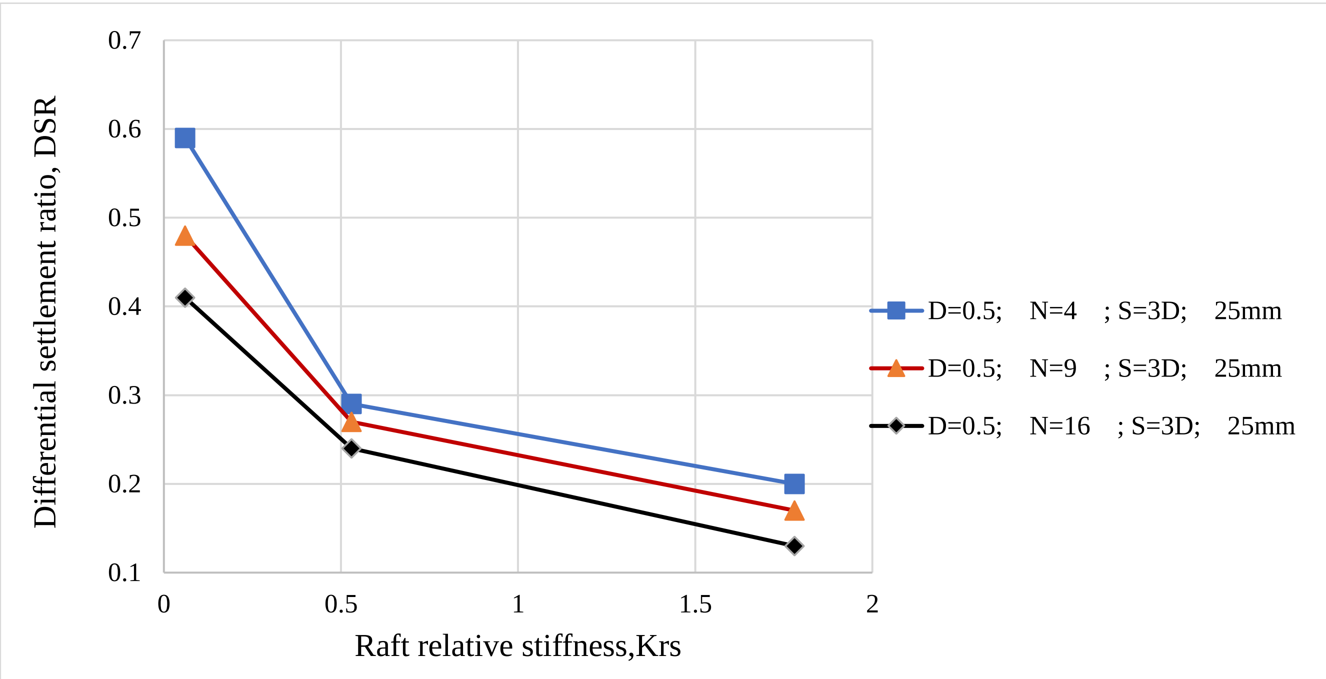

Figure 4-37:-Variation of DSR With the Krs for Number of Piles 4,9 and 16

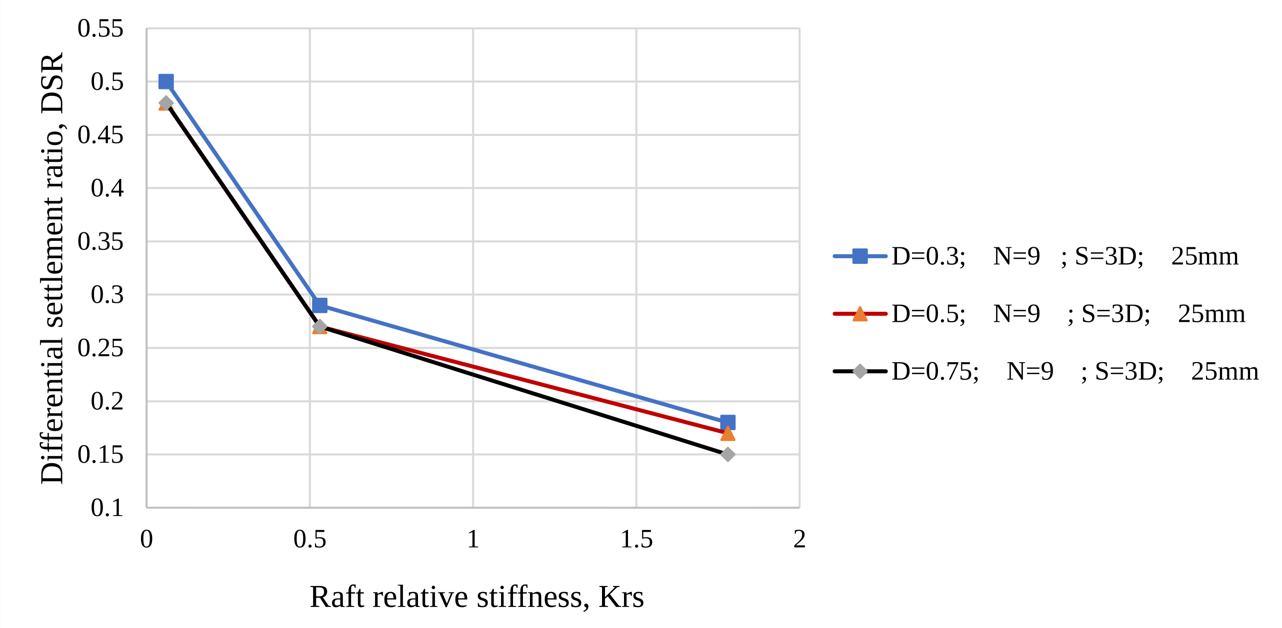

Figure 4-38:-Variation of DSR with the Krs at a pile diameter of 0.3,0.5 and 0.75 m.

The variation of differential settlement ratio, DSR, with the raft relative stiffness at different number of settlement reducing piles (4,9, and 16), different diameter (0.3, 0.5, and 0.75 m) of piles at a spacing of 3D (no need to see effect of spacing 4D because, it has been shown that spacing have no significant effect) for an average settlement of 25 mm are shown in figures 4-36, 4-37 and 4-38.

From figures 4-36, 4-37 and 4-38., the following points are observed.

a. It has been observed from the figures that the raft relative stiffness has a major effect on the differential settlement. The differential settlement ratio, DSR, decreases with the increase of raft relative stiffness as shown in Figures 4-36, 4-37 and 4-38.
b. The rate of decrease of DSR decreases as the raft relative stiffness, Krs, increases (e.g. For 4 piles and diameter of 0.5 m, the DSR at different raft relative stiffness, Krs, of 0.06, 0.53, and 1.78 are 0.59, 0.29 and 0.2 respectively. The difference between the two consecutive DSR’s are 0.2 and 0.09). in the case of this paper Krs of 1.78 stiff and some differential settlement is expected.
c. Number of piles have significant effect on DSR of piled raft foundation next to the relative stiffness, Krs, compared to the diameter of the pile and the spacing of piles. Diameter of the pile have no any significant effect on the differential settlement as shown in figure 4-38.
d. From figures 4-36, 4-37 and 4-38, the differential settlement ratio, DSR, becomes close to zero at a raft relative stiffness of 1.78, but not exactly zero, that is because the raft is

not purely rigid. Rafts are considered purely rigid for Krs of greater than 10 and we do not expect differential settlement at Krs of greater than 10 because of the raft rigidity.

4.6.3.3 Effect of Pile Diameter on Differential Settlement Ratio, DSR

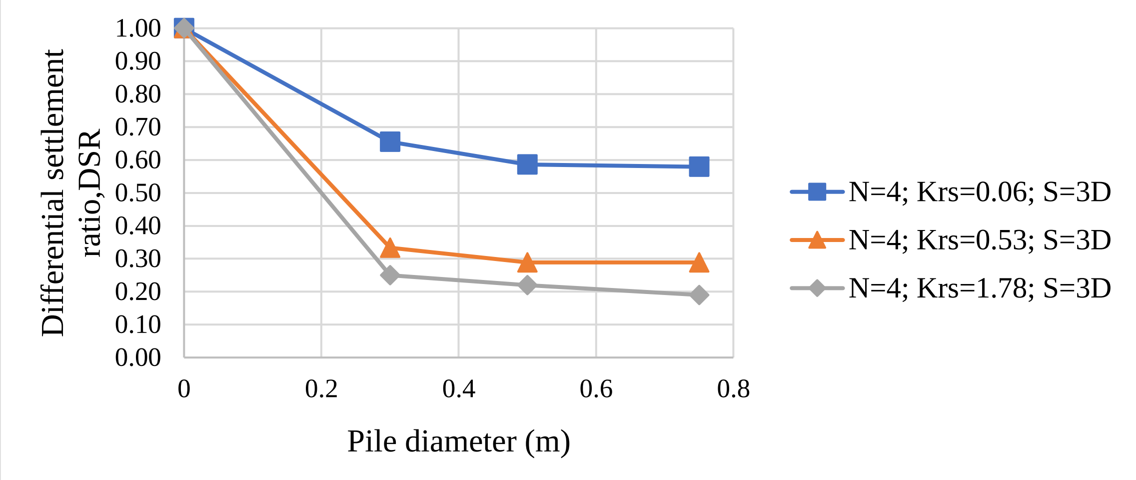

Figure 4-39:-variation of DSR with pile diameter at Krs of 0.06,0.53 and 1.78

From figure 4-39, differential settlement ratio, DSR, with pile diameter is shown for 4 number of piles at different raft relative stiffnesses, Krs, of 0.06,0.53 and 1.78 and the following points are noted.

a. Pile diameter have no any significant effect on the differential settlement of the foundation. For example, for 4 number of piles at a Krs of 0.06, the DSR at a diameter of 0.3,0.5, and 0.75 are 0.66, 0.59 and 0.58 respectively.
b. A DSR decrease as pile diameter increase even though it is insignificant.
c. As shown from the figure raft relative stiffness have significant effect on differential settlement ratio, DSR, but after a Krs of 0.53 the difference in DSR is not that much significant.

4.6.4 Proportion of Load Sharing

4.6.4.1 Effect of Pile Number

Proportion of load carried by piles and rafts at the ultimate and allowable load capacities can be simply found from load improvement ratio, LIR, Since LIR is the proportion of the loads carried by the piled raft foundation and unpiled raft foundation at the allowable and ultimate load capacities, the proportion of the load carried by rafts is the inverse of the load improvement ratio, LIR, whereas the proportion of the load carried by the piles is given by one minus load carrying proportion of the raft.

$$\mathrm{LIR} = \frac{\mathrm{P_{pr}}}{\mathrm{P_r}} \quad (4\text{-}5)$$

$$\frac{\mathrm{P_r}}{\mathrm{P_{pr}}} = \frac{1}{\mathrm{LIR}} \quad (4\text{-}6)$$

$$\frac{\mathrm{P_p}}{\mathrm{P_{pr}}} = 1 - \frac{1}{\mathrm{LIR}} \quad (4\text{-}7)$$

Figures 4-40, 4-41 and 4-42 show the variation of the proportions of loads carried by piles and raft with the number of settlement reducing piles for raft model with relative stiffness of 0.06, 0.53, and 1.78 respectively. Similar figures can be obtained from analysis results at allowable load capacity of the piled-raft foundation (10 mm) and from results for a spacing of 4D for raft models with relative stiffness of 0.06, 0.53 and 1.78 but not presented here for space limitation. The following points are noted from the figures

a. The proportion of load carried by piles increases as the number of piles increases, and inversely the proportion of load carried by raft decreases as the number of piles increases as shown in Figures 4-40, 4-41 and 4-42.
b. The proportion of load carried by piles increase as dimeter of the pile increase, for instance for 16 piles and Krs of 0.06 raft, the proportion of load carried by the piles are 44%, 52% and 57% for diameters 0.3, 0.5, and 0.75 m respectively.
c. The proportion of load carried by the piles or the raft are not affected highly with the variation of raft relative stiffness, Krs, (e.g. at 16 piles Krs of 0.06, 0.53, and 1.78 at a diameter of 0.75 gives raft load proportion as 43% for all three cases). Even though proportion are not similar for the other cases, the difference is not significant.
d. The average proportion of load carried by a raft at 0, 1, 4, 9, and 16 number of piles are 100 %, 92 %,75 %, 61 % and 52 % respectively while the average proportion of load carried by piles are 0 %, 8 %, 25 %, 39 %, and 48 %.
e. As a summary the proportion of load carried by the rafts is averagely 52% and the pile is 48 % for the case of 16 piles at the ULC of the piled raft foundation at the ULC.

Table 4-7:-proportion of load carried by piles and rafts

proporstion of load carried by raft=inverse of load improvement ratio, LIR, at 25 mm average settlement									
number of piles	krs=0.06 ;D=0.30; S=3D;R	krs=0.06 ;D=0.50; S=3D;R	krs=0.06; D=0.75; S=3D;R	krs=0.53 ;D=0.30; S=3D;R	krs=0.53; D=0.50; S=3D;R	krs=0.53; D=0.75; S=3D;R	krs=1.78; D=0.30; S=3D;R	krs=1.78; D=0.50; S=3D;R	krs=1.78; D=0.75; S=3D;R
0	100%	100%	100%	100%	100%	100%	100%	100%	100%
1	94%	94%	88%	98%	92%	88%	97%	93%	88%
4	78%	71%	62%	85%	76%	67%	86%	78%	68%
9	64%	55%	51%	75%	63%	53%	77%	64%	54%
16	56%	48%	43%	63%	54%	43%	67%	55%	43%

proporstion of load carried by piles=1-inverse of load improvement ratio, LIR, at 25 mm average settlement									
number of piles	krs=0.06 ;D=0.30; S=3D;P	krs=0.06 ;D=0.50; S=3D;P	krs=0.06; D=0.75; S=3D;P	krs=0.53 ;D=0.30; S=3D;P	krs=0.53; D=0.50; S=3D;P	krs=0.53; D=0.75; S=3D;P	krs=1.78; D=0.30; S=3D;P	krs=1.78; D=0.50; S=3D;P	krs=1.78; D=0.75; S=3D;P
0	0%	0%	0%	0%	0%	0%	0%	0%	0%
1	6%	6%	12%	2%	8%	13%	3%	7%	12%
4	22%	29%	38%	15%	24%	33%	14%	22%	32%
9	36%	45%	49%	25%	37%	47%	23%	36%	46%
16	44%	52%	57%	37%	46%	57%	33%	45%	57%

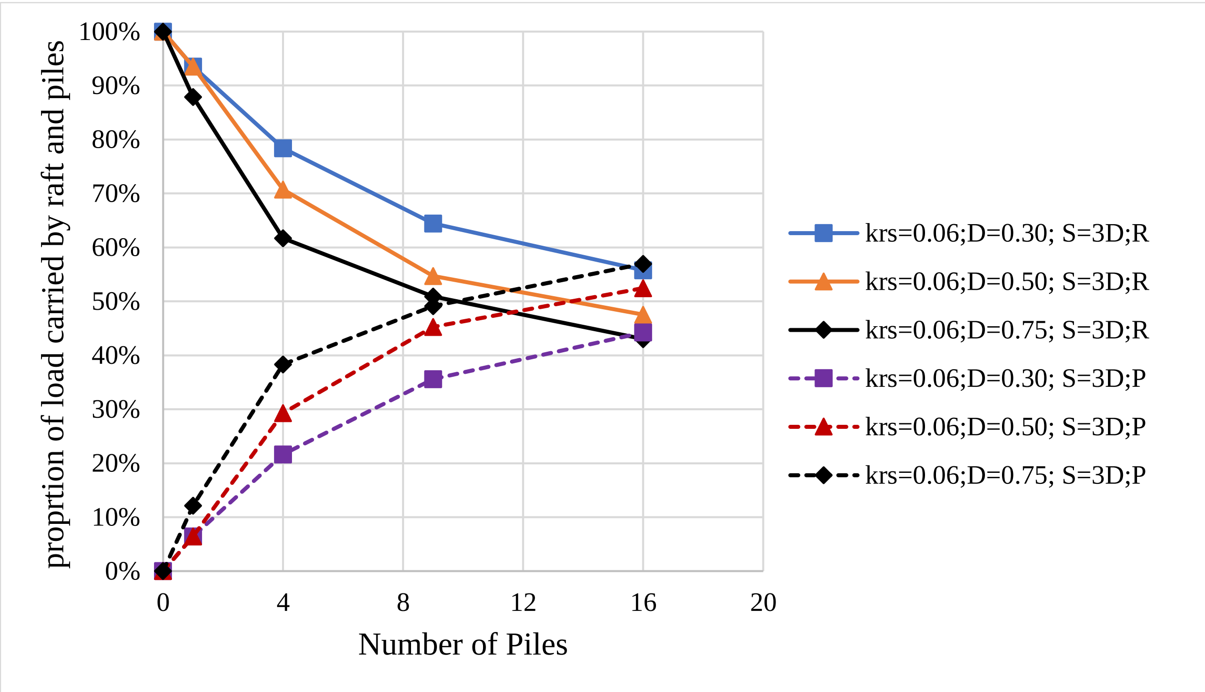

Figure 4-40:-Load Sharing Between Raft and Piles with Krs Equal to 0.06 And S=3D

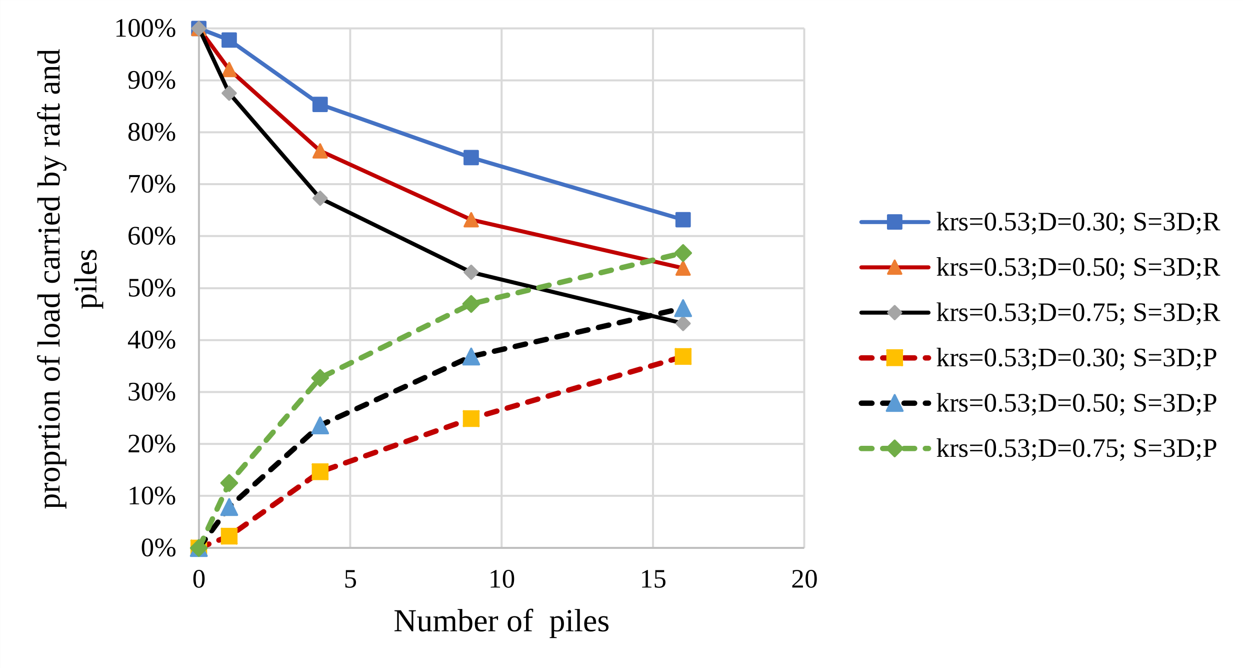

Figure 4-41:-Load Sharing Between Raft and Piles with Krs Equal to 0.53 S= 3D

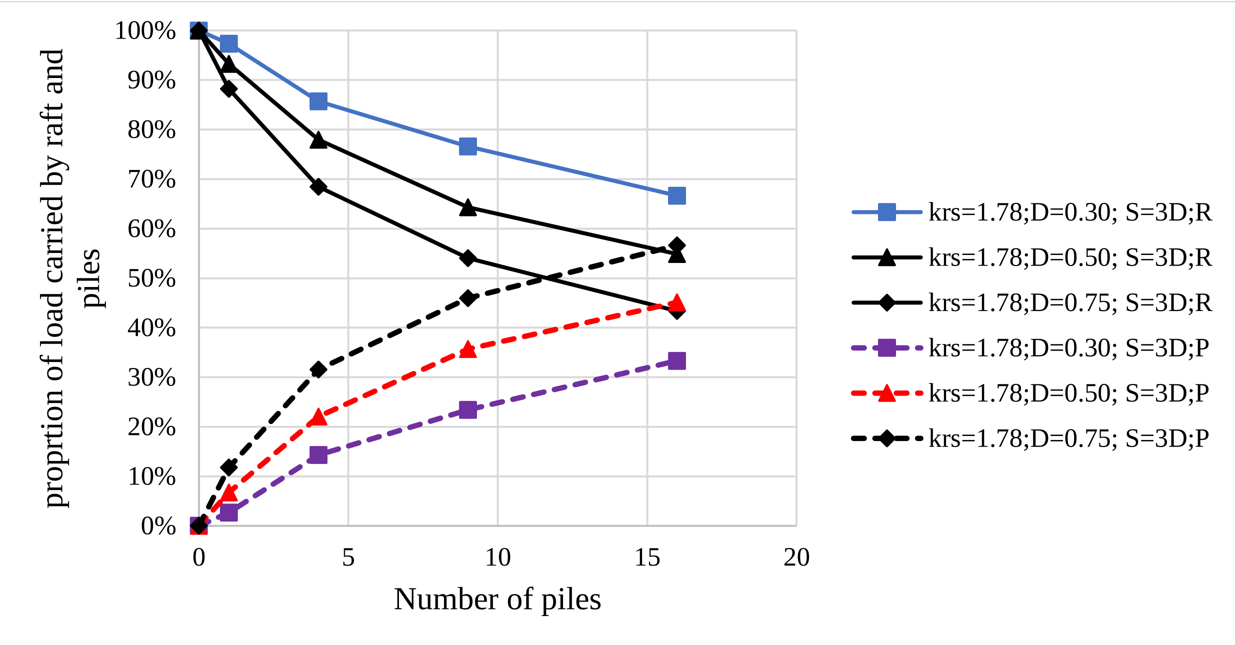

Figure 4-42:-Load Sharing Between Raft and Piles with Krs Equal to 1.78 & S= 3D

Where R and P in the legends represent raft and piles respectively. In practice, the inverse of the load improvement ratio, $\frac{1}{LIR}$, (i.e. equal to the proportion of load carried by raft) presented in this thesis can be used in a preliminary design stage to estimate the load-settlement curve of piled raft as described by Poulos (2001).

4.6.4.2 Effect of Raft Relative Stiffness

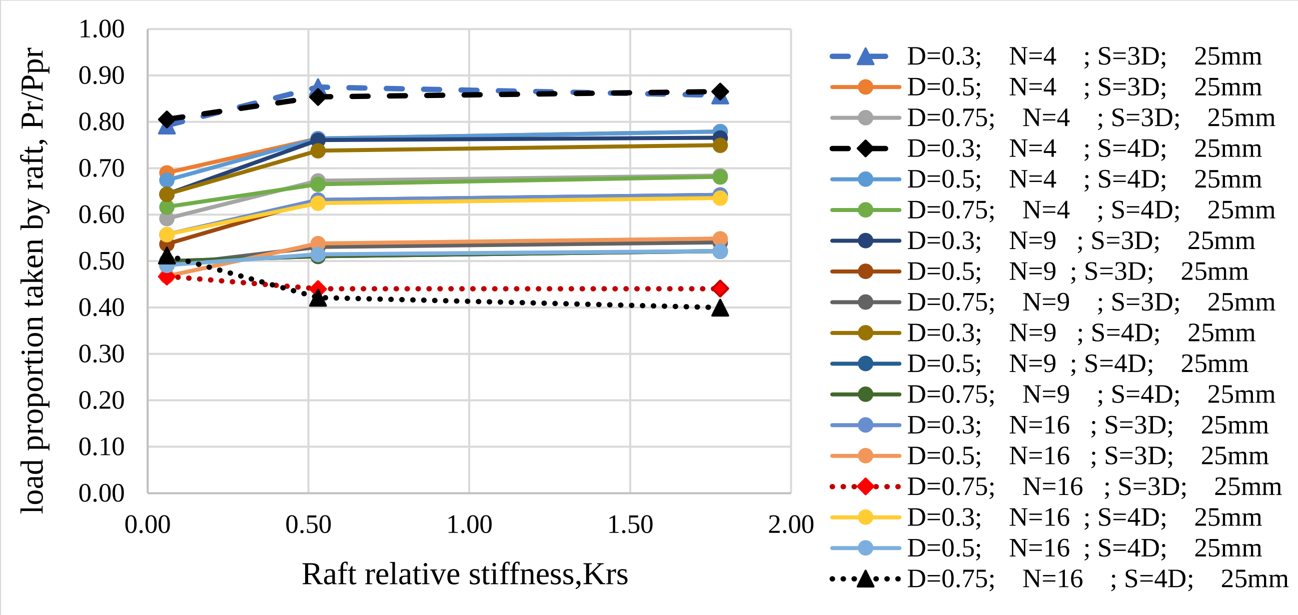

Figure 4-43:-Variation of Pr/Ppr with at 25 Mm Average Settlement.

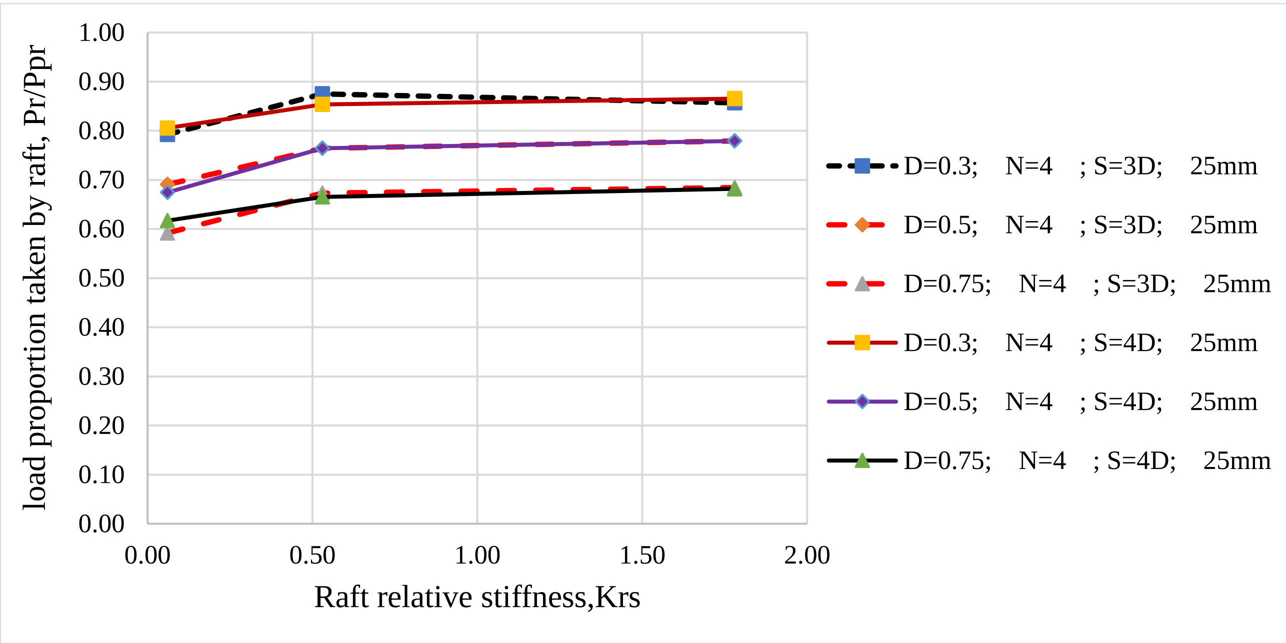

Figure 4-44:-Variation of Pr/Ppr at 25 mm average settlement.

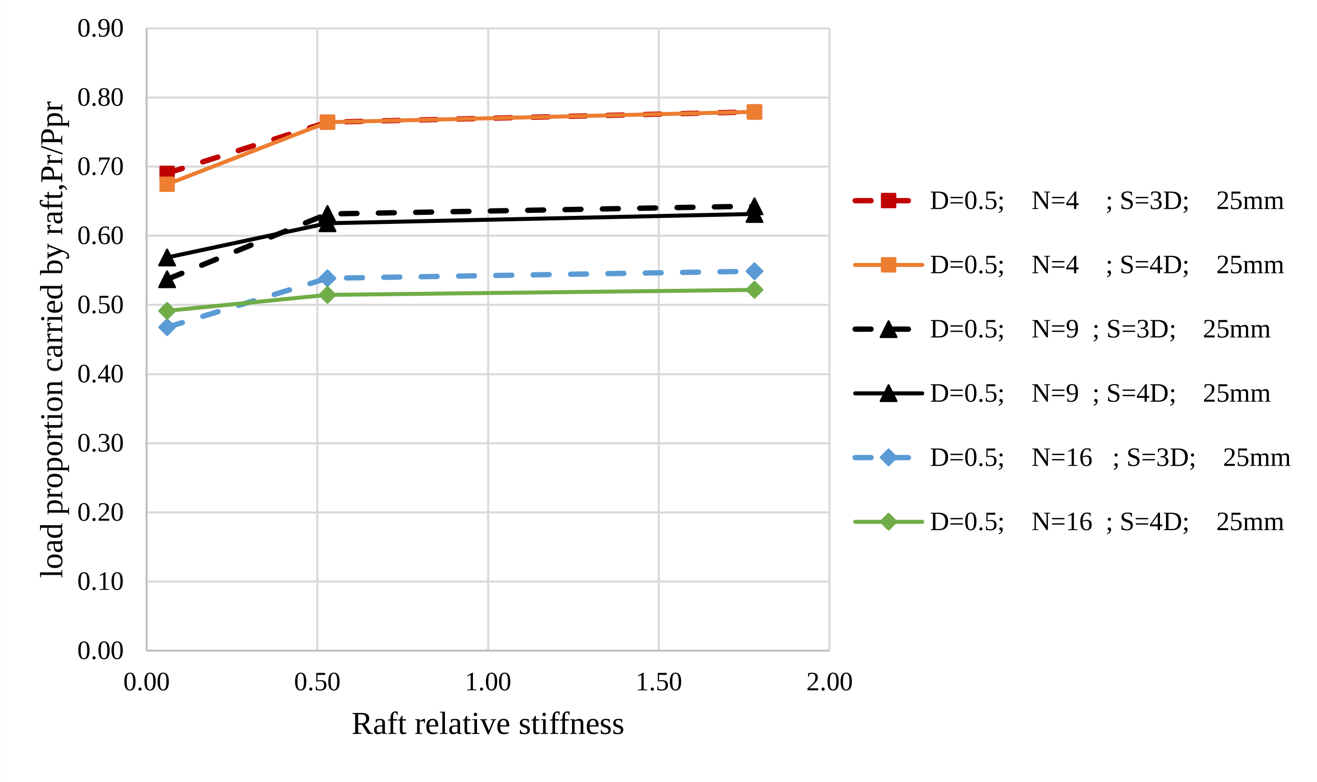

Figure 4-45:-Variation of Pr/Ppr With At 25 Mm Average Settlement.

figures 4-43, 4-44, and 4-45 show the variation of the percentage of load taken by raft, Pr/Ppr, with the raft relative stiffness at different number of settlement reducing piles, different pile diameter, and different pile spacing at 25 mm average settlement. The curves for 9 and 16 piles are missed here for space limitation.

From figures 4-43 and 4-44, and 4-45 the following observations can be noted:

a. As shown in figures 4-43,4-44 and 4-45, the effect of raft relative stiffness on the percentage of load carried by raft is insignificant. Similar observations were obtained by Poulos (2001) and Singh (2011) from numerical analysis of piled raft with different number of piles.
b. As shown in figure 4-43 in general and figures 4-44 in particular for only four piles, the spacing difference shows no significant variation (almost constant) in the percentage or proportion of load carried by rafts.
c. The proportion of load carried by the raft increase as the diameter of the pile decreases as shown in figure 4-44 for four number of piles (e.g. For 0.06 raft relative stiffness, spacing 3D and 25 mm average settlement at 4 number piles, the proportion of load carried by the raft at 0.3, 0.5 and 0.75 m diameter of piles are 0.79, 0.69, and 0.59 respectively.)

d. The proportion of load carried by raft decreases as the number of piles increase as shown in figure 4-45 and explained earlier in previous sections.

4.6.4.3 Effect of Pile Diameter

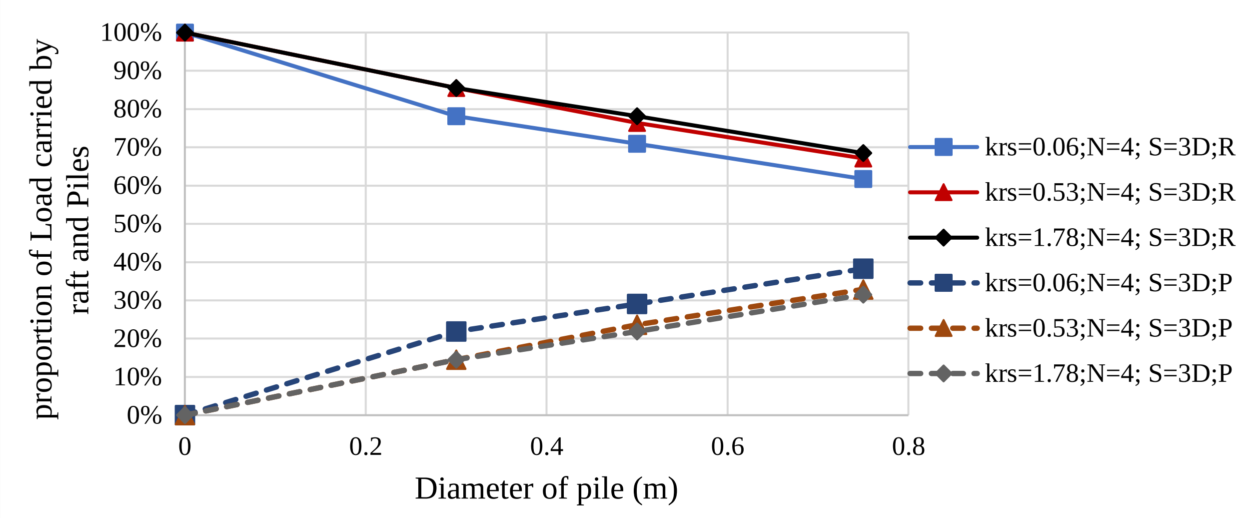

Figure 4-46:-Variation of Proportion of Load Carried by Rafts and Piles At 4 Piles

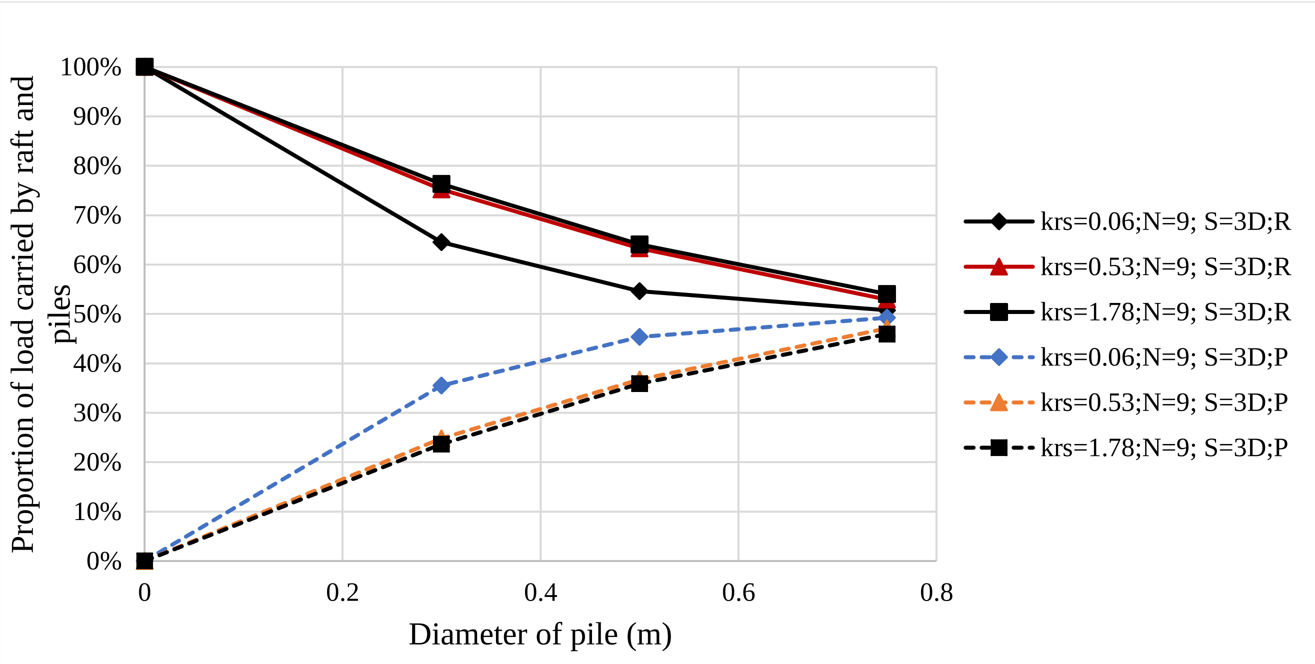

Figure 4-47:-Variation of Pr/Ppr And Pp/Ppr for 9 Number of Piles

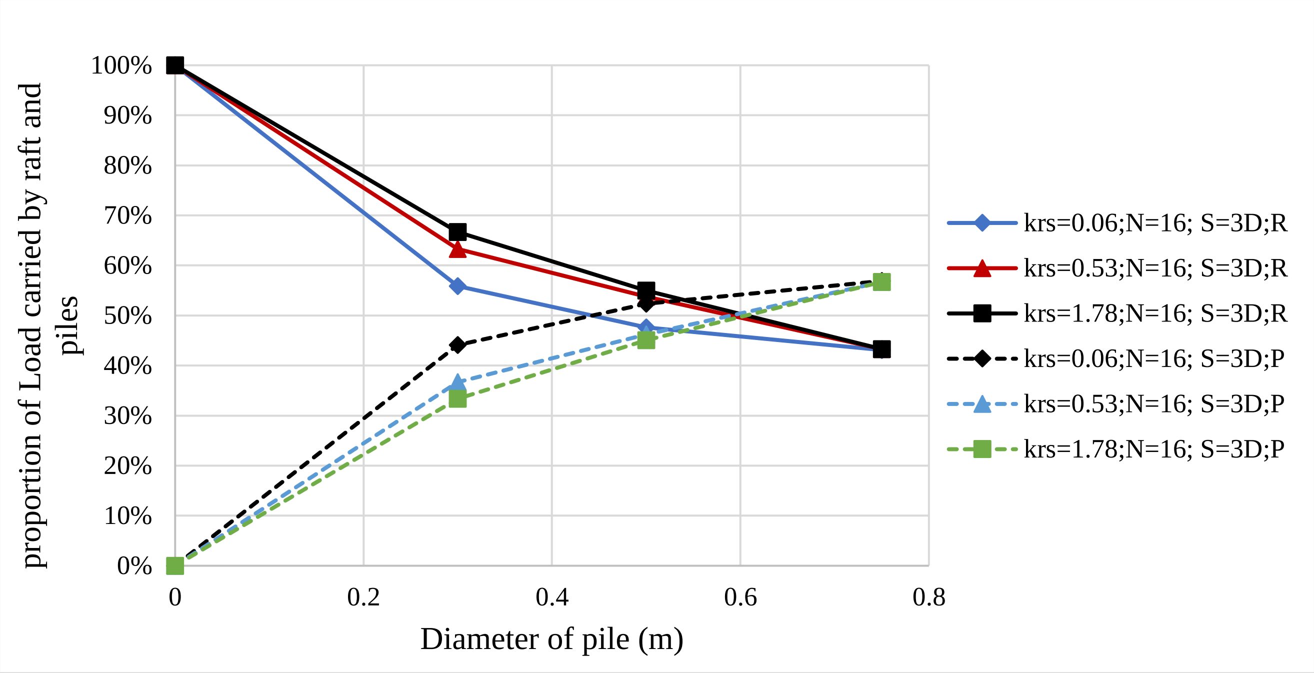

Figure 4-48:-Variation Pr/Ppr And Pp/Ppr for 16 Number of Piles

From figures 4-46,4-47 and 4-48 effects of diameter of piles under raft relative stiffness and number of piles are studied on the load proportion ratio of rafts and piles and here are some points from those figures.

a. Pile diameter has significant effect on the load proportion carried by both piles and rafts as shown in figures 4-46, 4-47 and 4-48. For example, for 16 number of piles and Krs of 1.78 the load proportion taken by the raft at 0.3, 0.5, and 0.75 m diameters are 67 %, 55 % and 43 % respectively.
b. As diameter of pile increases the load proportion carried by the raft decrease from unity while the proportion of load carried by pile increases from zero.
c. The average load proportion carried by the raft at 4,9 and 16 piles are 65.5 %, 52 %, and 42.5%, while the average load proportion carried by the piles are 34.5 %, 48 % and 57.5 % respectively.
d. The average load proportion carried by the raft at 0.3, 0.5, and 0.75 m diameter piles are 72 %, 62 %, and 53 %, while the average load proportion carried by the piles are 28 %, 38 % and 47 % respectively.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this thesis Numerical analysis of Unpiled raft (3 models) and settlement reducer piled rafts (63 models) embedded in sand soil have been performed. The effects of number of piles, Raft thickness (raft relative stiffness), pile diameter, and spacing of piles on the load carrying capacity (ULC and ALC), average settlement, differential settlement and proportion of load carried by raft and piles have been assessed.

The results of these Numerical model tests provide insight into settlement behavior of rafts on settlement reducing piles, and load sharing between piles and raft and may provide some general guidelines for the economical design of raft on settlement reducing piles. Based on the results of Numerical model tests, the following conclusions are drawn: -

a. The addition of even a small number of piles beneath the central area of the raft increases the load bearing capacity of the piled raft (both ULC and ALC), and this enhancement effect increases as the number of piles increases and as the diameter of pile, D, of the piles increases and even in some extent in increase of raft relative stiffness. The average increase in ULC and ALC for 1, 4, 9, and 16 piles are 8.7 % and 13 %, 36 % and 51%, 66% and 71 %, and 95 % and 96 % respectively compared to the unpiled raft capacities.
b. Load improvement ratio, LIR, of piled raft foundation is highly affected by two parameters (pile number and diameter of pile) while the other two (raft relative stiffness and spacing of piles) have no any significant effect. i.e., as pile diameter and pile number increase the LIR increases but LIR shows small decrease with increase in Krs and have any change with spacing.
c. Settlement ratio, SR, of the piled raft foundation is affected by three parameters (pile number, pile diameter, and the raft relative stiffness). As the number of piles and diameter of piles increase, the settlement ratio decreases but as the raft relative stiffness increases the settlement ratio increases which shows that the settlement of small raft relative stiffness, Krs, is highly improved.
d. Differential settlement ratio, DSR, of the piled raft foundation is highly affected by raft relative stiffness, Krs, whereas the increase in pile number and pile diameter have positive effect on DSR but not significant. Especially after 4 number of piles the DSR

is constant which shows that beyond some number of piles at the center the addition of piles has no significant effect on differential settlement of piled raft foundation.

f. The parameters pile number and pile diameter have significant effect on the load proportion carried by piles and rafts whereas the difference in raft relative stiffness have no any effect on the load sharing. As pile number and pile diameter increases the load proportion carried rafts decrease where as proportion of load carried by piles increases. The average proportion of load carried by a raft at 0, 1, 4, 9, and 16 number of piles are 100 %, 92 %,75 %, 61 % and 52 % respectively while the average proportion of load carried by piles are 0 %, 8 %, 25 %, 39 %, and 48 %. The average load proportion carried by raft at diameter of pile of 0.3, 0.5, and 0.75 m are 72 %, 62 %, and 53 % respectively.

5.2 Recommendations

The following recommendations are given for future research:

a. The four parameters studied are not the only parameters that affect piled raft foundation. The are many parameters that affect the behavior of piled raft foundation other than pile number, pile diameter, raft thickness, and spacing explained in different literature that are not well studied.
b. Laboratory experimentation and validation of the analysis's outputs obtained from $FLAC^{3D}$ V3.00 on the load sharing, settlement, and differential settlement between rafts and piles.
c. Extending the present study to complex loading patterns like eccentric, lateral loadings and dynamic loading cases.
d. Extending the present study to complex soil strata conditions. The assumption of homogenous medium dense sand through the whole part of soil where pile passes is hypothetical and hardly seems practical. So, there should have to be real strata of soil with known properties to analyze the piled raft foundation.
e. Extend this research with increasing shear modulus of soil with depth

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A. APPENDIX 1: -SAMPLE OF BATCH FILES

Table A-1:-Batch File Used to Create the Geometry and Initial Stresses

```
new
gen zone brick p0 -18 -18 -36 p1 18 -18 -36 p2 -18 18 -36 p3 -18 -18 0 size 16 16 16 group sand
;===========================
; Constitutive Model for Sand
model mohr range group sand
prop bulk=25000000 shear=11538460 fric 30 coh 0 range group sand
prop dens 2000 range group sand
; Boundary conditions
=============================
ini szz 0 grad 0 0 20000
ini sxx 0 grad 0 0 10000
ini syy 0 grad 0 0 10000
fix z range z= (-36.1, -35.9)
fix x range x= (-18.1, -17.9)
fix x range x= (17.9,18.1)
fix y range y= (17.9,18.1)
fix y range y= (-18.1, -17.9)
set grav (0,0, -10)
; set mech force=50
hist unbal
plot show base
pause
solve
save geometry.sav
```

Table A-2:-Batch file used to install the piles and raft

```
new
restore geometry.sav
;==============================
; Raft geometry
;=============================
sel liner id=1 elemtype=dkt_cst crossdiag range x -4.5 4.5 y -4.5 4.5 z -0.1 0.1
sel liner id=1 prop iso=(3e10,0.2) thick=0.5
sel liner prop cs_nk=11538460e2 cs_sk=11538460 cs_scoh=0 cs_ncut=0 cs_sfric 30
=============================================================
=
sel pile id=2 begin=0 0 0 end=0 0 -15 nseg=20
=============================================================
=============
sel pile prop Emod=3.0e10 Nu=0.2 XCArea=0.0707 XCJ=0.0 XCIy=0.0 XCIz=0.0
sel pile prop per=0.943
sel pile prop CS_sK=11538460 CS_sCoh=0.0 CS_sFric=30 range z -16 0.1
sel pile prop CS_nK=11538460e2 CS_nCoh=0.0 CS_nFric= 0.0 CS_nGap=off range z
-16 0.1
sel pile prop slide on range z -16 0.1
;=================================================
; fixed support at the raft
;=================================================
sel delete link range id 42
sel link id 400 42 target zone
sel link attach ydir=free zdir=free range id 400
sel link attach xrdir=free yrdir=free zrdir=free range id 400
sel link attach xdir=rigid range id=400
; ====================================================next page
```

```
; end bearing effect
;===========================================================
sel delete link range id=62
sel link id=2000 43 target zone
sel link attach ydir=free zdir=free range id=2000
sel link attach xrdir=free yrdir=free zrdir=free range id=2000
sel link attach xdir=nydeform range id=2000
sel link constit nydeform 1 area=1.0 k=0.849e10 ycomp=190.85e3 ytens 0 range id=2000
==============================================================
===========
ini state 0
ini xdis 0 ydis 0 zdis 0
;==========================================================
save install_piled_raft.sav
```

Table A-3:-Batch file used to apply load and monitor the response of the model

```
new
rest install_piled_raft.sav
sel node apply force 0 0 -1e6 range id=18
;========================================================
sel set damp combined
set large
plot show base
; force at the raft
============================================================
; hist id=14 sellinersel node 18 fz 0 0 0.5
; hist id=15 sellinersel node 22 fz 4.7 0 0.5
; hist id=16 sellinersel node 40 fz 4.7 4.7 0.5
===========================================================
; settlement at the raft
==========================================================
hist id=17 sel node zdisp id=18
hist id=18 sel node zdisp id=22
hist id=19 sel node zdisp id=40
===========================================================
solve step 10000
save result_point1.sav
```

B. APPENDIX 2: -CALCULATIONS OF LIR, PR/PPR, SR, AND DSR

For the batch files written in appendix A, the settlements of raft at center, mid-edge, and corner points of the raft at 1 MN central point load are shown in figure B-1.

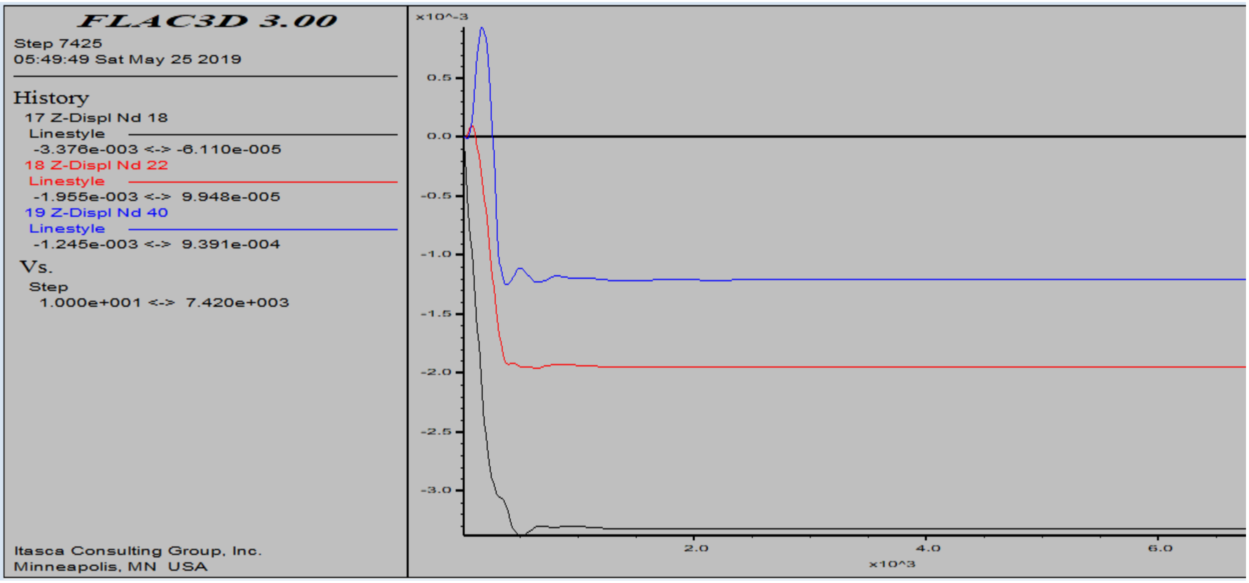

Figure B-1:-Settlement at Center, Mid-Edge, Corner Points of The Raft for 1MN Central Load

From figure B-1, the settlement values are taken at the center and mid-edge points of the raft as 3.3 mm and 2.0 mm respectively. Similar to 1 MN force the model is analyzed for 3 MN, 5 MN, 7 MN, 9 MN, 10 MN, 15 MN, 20 MN etc. the settlement results for different number of loads are shown in table B-1.

Table B-1:-The Load Applied and The Corresponding Settlements for 1 Central Piled Raft

Load applied (MN)	Settlements (mm)		
	center	Mid-edge	Average
0	0	0	0.00
1	3.3	2	2.65
3	10.5	6	8.25
5	19.5	11	15.25
7	29	15.6	22.30
9	37	22	29.50
10	38.5	24	31.25
15	70	41	55.50
20	100	55	77.50

Depending on table B-1, the load settlement curve is drawn for model number 4 (1-pile piled raft foundation with properties given in appendix A.) as shown in the figure B-2.

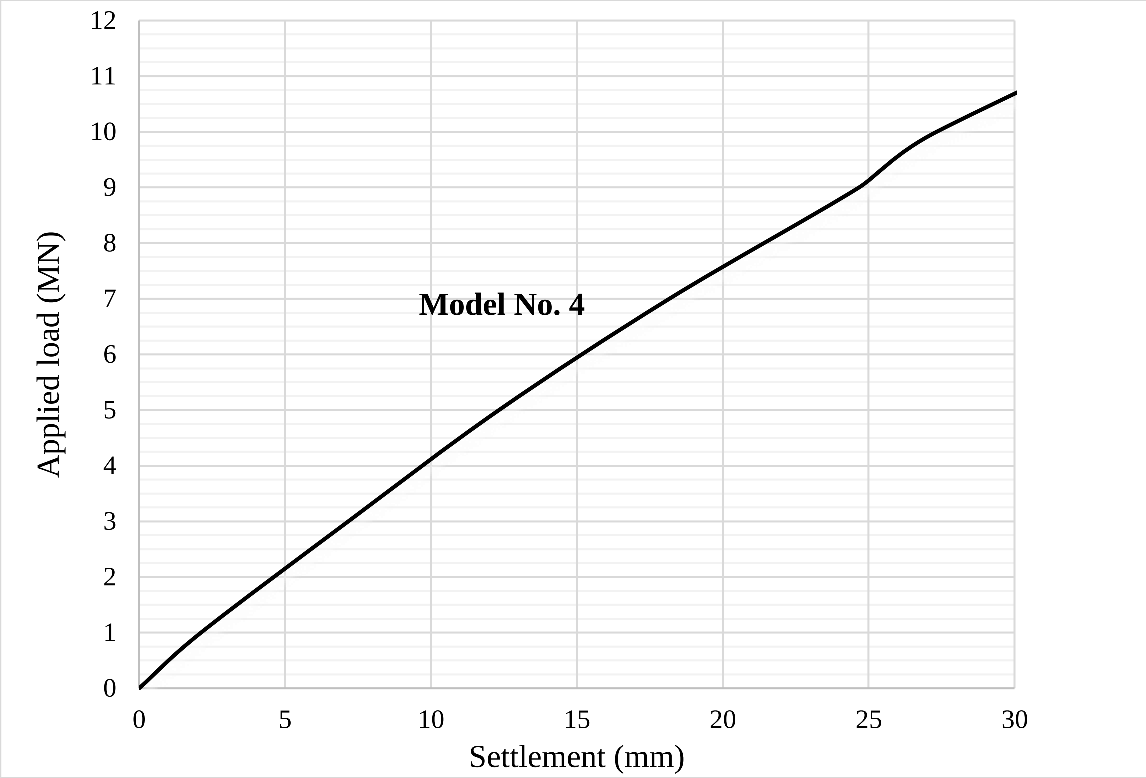

Figure B-2:- Load Settlement Curve for Model Number 4 Used to Determine ALC and ULC

From figure B-2, the allowable and ultimate load capacities, ALC and ULC, are the loads from the curve to the corresponding average settlements of 10 mm and 25 mm respectively. Therefore, the ALC and ULC are 3.5 MN and 7.75 MN respectively.

Thus, for the rest of the models, the ALC and ULC are calculated similar to model number 4 and all ALC and ULC for all models are given in table B-2.

The Load improvement ratio, LIR, is the calculated at the Allowable Load capacity, ALC, and Ultimate load capacity, ULC, by dividing the load capacities of piled raft by load capacities of un piled raft foundation.

The proportion of load carried by raft is defined earlier in chapter four as the inverse of load improvement ratio, 1/LIR, at both the allowable and ultimate load capacities and given in table B-2.

Table B-2:-ALC and ULC, LIR and proportion of load carried by raft for all number of models.

model No.	ALC (Load at 10 mm)	ULC (Load at 25 mm)	LIR at ALC	LIR at ULC	Pr/Ppr (ALC)	Pr/Ppr (ULC)
1	3.15	7.25	1.00	1.00	100%	100%
2	3.85	8.75	1.00	1.00	100%	100%
3	4.10	9.00	1.00	1.00	100%	100%
4	3.50	7.75	1.11	1.07	90%	94%
5	4.10	8.95	1.06	1.02	94%	98%
6	4.30	9.25	1.05	1.03	95%	97%
7	4.50	7.75	1.43	1.07	70%	94%
8	4.25	9.50	1.10	1.09	91%	92%
9	4.50	9.65	1.10	1.07	91%	93%
10	4.10	8.50	1.30	1.17	77%	85%
11	4.50	10.00	1.17	1.14	86%	88%
12	4.75	10.20	1.16	1.13	86%	88%
13	4.50	9.15	1.43	1.26	70%	79%
14	4.75	10.00	1.23	1.14	81%	88%
15	4.85	10.50	1.18	1.17	85%	86%
16	5.00	10.50	1.59	1.45	63%	69%
17	5.40	11.45	1.40	1.31	71%	76%
18	5.60	11.55	1.37	1.28	73%	78%
19	6.25	12.25	1.98	1.69	50%	59%
20	6.65	13.00	1.73	1.49	58%	67%
21	6.75	13.15	1.65	1.46	61%	68%
22	4.00	9.00	1.27	1.24	79%	81%
23	4.75	10.25	1.23	1.17	81%	85%
24	5.00	10.40	1.22	1.16	82%	87%
25	5.00	10.75	1.59	1.48	63%	67%
26	5.50	11.45	1.43	1.31	70%	76%
27	5.55	11.55	1.35	1.28	74%	78%
28	5.85	11.75	1.86	1.62	54%	62%
29	6.75	13.15	1.75	1.50	57%	67%
30	6.85	13.20	1.67	1.47	60%	68%
31	5.25	11.25	1.67	1.55	60%	64%
32	5.35	11.50	1.39	1.31	72%	76%
33	5.50	11.75	1.34	1.31	75%	77%
34	6.00	13.50	1.90	1.86	53%	54%
35	6.50	13.85	1.69	1.58	59%	63%
36	6.60	14.00	1.61	1.56	62%	64%
37	6.25	11.75	1.98	1.62	50%	62%
38	7.15	16.50	1.86	1.89	54%	53%

39	7.75	16.65	1.89	1.85	53%	54%
40	5.25	11.25	1.67	1.55	60%	64%
41	5.50	11.85	1.43	1.35	70%	74%
42	5.65	12.00	1.38	1.33	73%	75%
43	6.00	12.75	1.90	1.76	53%	57%
44	6.75	14.15	1.75	1.62	57%	62%
45	7.00	14.25	1.71	1.58	59%	63%
46	6.75	14.50	2.14	2.00	47%	50%
47	8.25	17.15	2.14	1.96	47%	51%
48	8.45	17.25	2.06	1.92	49%	52%
49	5.85	13.00	1.86	1.79	54%	56%
50	6.25	13.85	1.62	1.58	62%	63%
51	6.30	14.00	1.54	1.56	65%	64%
52	6.50	15.50	2.06	2.14	48%	47%
53	7.40	16.25	1.92	1.86	52%	54%
54	7.50	16.40	1.83	1.82	55%	55%
55	6.75	16.50	2.14	2.28	47%	44%
56	8.75	20.25	2.27	2.31	44%	43%
57	9.30	20.75	2.27	2.31	44%	43%
58	5.75	13.00	1.83	1.79	55%	56%
59	6.25	14.00	1.62	1.60	62%	63%
60	6.40	14.15	1.56	1.57	64%	64%
61	6.75	14.75	2.14	2.03	47%	49%
62	8.00	17.00	2.08	1.94	48%	51%
63	8.15	17.25	1.99	1.92	50%	52%
64	6.50	14.15	2.06	1.95	48%	51%
65	8.75	20.75	2.27	2.37	44%	42%
66	9.50	22.50	2.32	2.50	43%	40%

For analysis of average and differential settlements, to see the effect of different parameters of piled raft foundation, the ultimate load capacity of unpiled raft foundations are applied on the piled raft foundation and the settlements are recorded as shown in table B-3

Table B-3:-Average and Differential Settlement Analysis

model No.	center settlement (mm)	Mid-edge settlement (mm)	Average settlement (mm)	settlement ratio, SR	differential settlement	DSR
1	32.25	17.75	25.00	1.00	14.50	1.00
2	27.25	22.75	25.00	1.00	4.50	1.00
3	26.50	23.50	25.00	1.00	3.00	1.00
4	30.50	17.00	23.75	0.95	13.50	0.93
5	25.50	22.25	23.50	0.94	3.25	0.72
6	25.50	23.50	24.50	0.98	2.00	0.67
7	29.00	17.00	23.00	0.92	12.00	0.83
8	24.50	22.00	23.25	0.93	2.50	0.56
9	24.00	23.00	23.50	0.94	1.30	0.43
10	25.00	15.00	20.00	0.80	10.00	0.69
11	22.00	20.00	21.00	0.84	2.00	0.44
12	21.75	21.25	21.50	0.86	1.25	0.42
13	23.00	13.50	18.25	0.73	9.50	0.66
14	21.25	19.75	20.50	0.82	1.50	0.33
15	21.50	21.00	21.25	0.85	0.75	0.25
16	20.00	11.50	15.75	0.63	8.50	0.59
17	18.65	17.35	18.00	0.72	1.30	0.29
18	19.00	18.50	18.75	0.75	0.75	0.25
19	16.00	9.00	13.50	0.54	8.40	0.58
20	15.65	14.35	15.00	0.60	1.30	0.29
21	15.50	15.00	15.25	0.61	0.57	0.19
31	18.50	11.50	15.00	0.60	7.25	0.50
32	18.15	16.85	17.50	0.70	1.30	0.29
33	18.50	18.00	18.25	0.73	0.55	0.18
34	16.00	9.00	12.50	0.50	7.00	0.48
35	14.90	13.60	14.25	0.57	1.20	0.27
36	15.25	14.75	15.00	0.60	0.50	0.17
37	15.00	8.00	11.50	0.46	6.95	0.48
38	13.50	11.50	12.50	0.50	1.20	0.27
39	12.75	12.00	12.38	0.50	0.45	0.15
49	16.50	9.50	13.00	0.52	6.85	0.47
50	20.50	12.00	15.25	0.61	1.10	0.24
51	16.00	15.00	15.65	0.63	0.50	0.17
52	15.00	8.00	11.50	0.46	6.00	0.41
53	13.25	11.50	12.38	0.50	1.10	0.24
54	13.75	12.00	12.88	0.52	0.40	0.13
55	14.50	7.00	10.50	0.42	5.75	0.40
56	11.50	9.00	10.25	0.41	1.00	0.22
57	10.00	9.00	9.50	0.38	0.35	0.12

C. APPENDIX 3: - SAMPLE NUMERICAL ANALYSES RESULT PLOTS

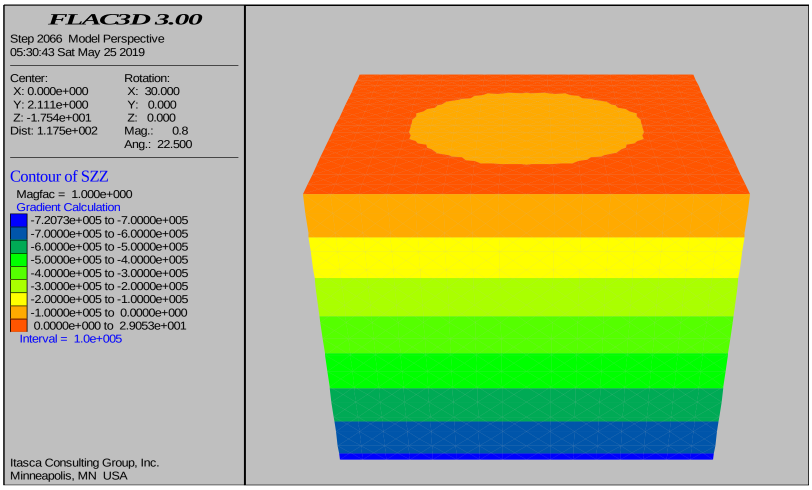

Figure C-1:-Vertical normal stress contour of Run-13 (4 piles, S=3D, D=0.3 m, Krs=0.06)

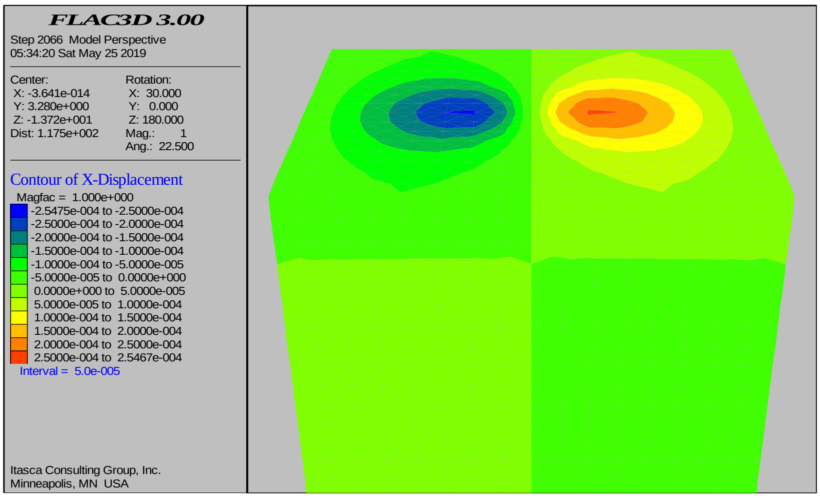

Figure C-2:-horizontal displacement contour of Run-13 (4, piles, S=3D, D=0.3 m, Krs=0.06)

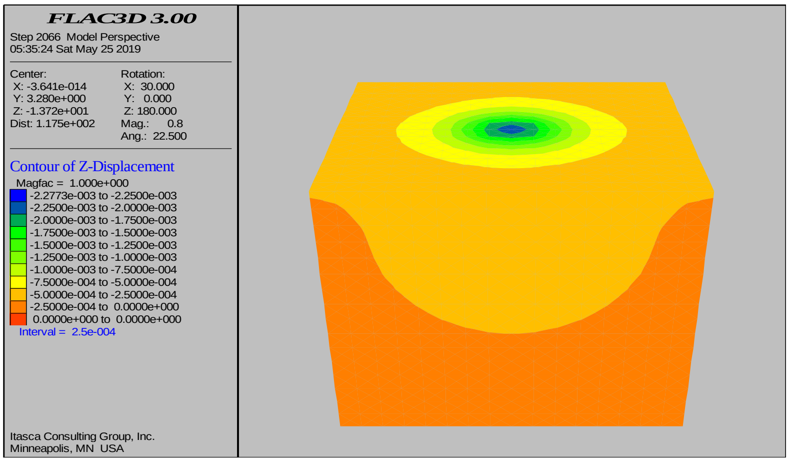

Figure C-3:-Vertical displacement contour of Run-13 (4, piles, S=3D, D=0.3 m, Krs=0.06)