LOAD SHARING OF PILED-RAFT FOUNDATIONS IN SAND SUBJECTED TO VERTICAL LOADS

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A PH.D. THESIS

IN

THE DEPARTMENT OF

BUILDING, CIVIL AND ENVIRONMENTAL ENGINEERING

CONCORDIA UNIVERSITY

MONTREAL, QUEBEC, CANADA

2012

CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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Entitled: **Load sharing of Piled-Raft Foundation in Sand Subjected to Vertical Loads**

and submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy (Civil Engineering)

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ABSTRACT

Load Sharing of Piled-Raft Foundations in Sand Subjected to Vertical Loads

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Concordia University, 2012

Due to the complexity of piled-raft system, and due to lack of rational solution, the design of piled-raft foundations relies on numerical modeling using techniques such as finite element. This study is directed to develop a numerical model capable to analyse the problem stated and to identify the parameters governing their performance. The model developed was based on the finite element technique and accounts for the complex interaction factors such as pile-to-pile, pile-to-raft, raft-to-raft and pile-to-soil. The results produced by the present model were validated by the available data in the literature.

The model developed herein was then used to conduct a sensitivity analysis on the governing parameters believed to control such behaviour to include: the pile diameter, pile length, pile spacing, pile modulus of elasticity, reduction factor of the pile-soil interface strength, raft width, raft thickness and raft modulus of elasticity. Furthermore, the effects of soil modulus of elasticity, Poisson's ratio, friction angle, dilatancy angle, unit weight, were also examined. The study focussed on the influence of these parameters on the load-settlement relationship and the load sharing between the raft and piles of the system. This study compares the effect of the above parameters on the load-settlement relationship of piled-raft systems at small and large settlements. The study considers the case of a piled-raft supported by a single pile, and piled-rafts supported by (2×2), (3×3), (4×4) and (5×5) pile groups. The result of this phase was useful in optimizing the design of piled-raft foundations.

It is of interest to note that the effect of these parameters ranges from significant to small whereas some parameters have no effect. The piles modulus of elasticity, reduction factor of the pile-soil interface strength, modulus of elasticity of the raft and raft thickness show no effect on the load-settlement relationship of piled-raft foundations at small and large settlements. The pile diameter, pile spacing, raft width, Poisson’s ratio of the soil, angle of internal friction of the soil, dilatancy angle of the soil and unit weight of soil have negligible effect on the load-settlement relationship of piled-raft foundations at small settlements whereas they have significant effect at large settlements. The pile length and soil modulus of elasticity show significant effect on the load-settlement relationship of piled-raft foundations at small and large settlements. Furthermore, the pile diameter, pile length, pile spacing, raft width, and angle of internal friction of soil show significant effect on the load carried by the raft. The raft thickness, modulus of elasticity of soil, Poisson’s ratio of the soil and the modulus of elasticity of the piles show only small effect on the load carried by the raft. The dilatancy angle of the soil, unit weight of soil, the reduction factor of the pile-soil interface strength and modulus of elasticity of the raft have no effect on the load carried by the raft.

Based on the results obtained in the present study, a design theory was formulated for predicting the settlement and the load sharing between the raft and the piles. The theory is based on the stiffness ratio of the piles to that of the raft. The model accounts for the interaction between the raft and piles in piled-raft foundations by using efficiency factors for the piles and the raft. Design procedure based on two design criteria, namely, the settlement and the load sharing between the raft and piles was introduced. The proposed design method is suitable for preliminary design of piled-raft foundations.

ACKNOWLEDGEMENTS

First of all, all praise is due to “Allah” almighty.

I would like to express my sincere appreciation and gratitude to my thesis supervisor, Professor Adel Hanna, for his advices and encouragement throughout all stages of my study and research.

I would also like to thank all the administrative and technical staff in the Building, Civil and Environmental Engineering Department at Concordia University for their support and cooperation.

I would like to thank my country Libya for providing me this opportunity to study abroad. Also, I would like to express my gratitude to the administrative staff in the Canadian Bureau for International Education (CBIE) and Libyan Cultural Section in Ottawa for their help.

Finally, the prayers and support of my parents during my stay in Canada for this study have been most valuable. I would like to express my warmest gratitude to my wife, Sabriah Almuhar for her love, support and patience. I am also grateful to my brothers and sister for their wishes and encouragement. Finally yet importantly, I would like to thank my children Yahia, Mohammed, Belqees and Harith.

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A_g = Area of the raft

A_p = Cross-sectional area of the pile

A_R = Area of the pile group

D = Pile diameter

E = Modulus of elasticity

Ep = Modulus of elasticity of piles

Er = Modulus of elasticity of the raft

Es = Soil Young’s modulus

E_{wall} = Modulus of elasticity of the wall representing the pile row

K_o = Coefficient of the lateral earth pressure

K_p = Stiffness of the pile

K_r = Stiffness of the raft alone

K_{pr} = Stiffness of the piled-raft foundation

L = Pile length

L_r = Length of the raft

n = Number of piles

Q = Distributed load on the raft

R_M = Aspect ratio parameter

s = Pile spacing

t = Raft thickness

u_x = Horizontal displacement

u_y = Vertical displacement

w =Raft width

αr = Efficiency factor to modify the stiffness of the raft due to the effect of the pile

αp = Efficiency factor to modify the stiffness of the piles due to the effect of the raft

μ = Poisson's ratio

μs = Soil Poisson's ratio

φ = Angle of internal friction of the soil

ψ = Soil dilatancy angle

γ = Soil unit weight

CHAPTER 1

INTRODUCTION

1.1 General

In many countries, piled-raft foundations have been used to support different types of structures in different types of soils. In particular, the use of piled-raft foundations in Europe is more common than any other region. In the past, they were used to support structures in certain types of soil. Nowadays, they are used in many types of soil. Piled-raft foundations have been used as foundations to support many types of structures such as bridges, buildings and industrial plants. Piled-raft foundations offer some advantages such as reducing settlement and increasing the bearing capacity of the foundations. Such advantages are attributed to the contribution of the raft to the load carrying capacity and to the efficient use of the piles to reduce the settlement.

The use of piled-raft foundations to support different types of structures has increased significantly in the last three decades. Such a trend of using piled-raft foundations can be attributed to the potential economic advantage of such foundations in comparison with other alternatives. Moreover, the capability of piled-raft foundations to satisfy the most important design requirements with a lower cost has led to an even more preference for piled-raft foundations over other types of foundations. Moyes et al. (2005) reported that piled-raft foundations satisfy the required serviceability performance while providing cost savings estimated to about 30% compared with conventional piled foundations systems.

Piled-raft foundations, known also as piled rafts, are a combination of a shallow foundation (raft or cap) and a deep foundation (pile group). In this type of foundations, the role of the raft is to provide the required bearing capacity and the piles are used mainly as settlement reducers but can also contribute to the bearing capacity. In general, the raft alone can provide the required bearing capacity but it cannot control the settlement. Therefore, the piles are crucial to reduce the settlement of the raft. Due to combining raft and piles in one system, piled-raft foundations are regarded as very complex systems. The complexity of this type of foundations is caused by the presence of many interaction factors involved in the system such as pile-to-pile, pile-to-raft, raft-to-raft and pile-to-soil interactions.

1.2 Need for Research and Motivation

Despite the complexity of piled-raft systems, several models for analyzing piled-raft foundations were developed. However, most of these models are considered complicated because they depend on using sophisticated numerical methods such as the finite difference method, finite layer method, boundary element method and finite element method. These numerical techniques rely generally on using computer programs and special software. They need relatively high computational effort and time as well as a large computer storage space. For example, Katzenbach et al. (2005) reported that three-dimensional finite element simulations of piled raft foundations with an average number of elements in the range of 10,000 to 25,000 elements need about 18 hours of computational time on a Sun-Ultra 2 workstation. Katzenbach et al. (2005) expected that increasing the number of elements and considering other issues in the simulations such as consolidation would lead to an enormous increase of computational time. Small and Liu (2008) reported that settlement calculations for piled raft foundations involve a fair bit of computation. Commercial software such as FLAC, ABAQUS and PLAXIS are used widely to carry out the analysis and design of piled-raft foundations. However, these programs and software are based on complicated numerical techniques and they are not easily available for all engineers because of the relatively high cost of such tools. Complex numerical analyses can be used to carry out detailed parametric studies in order to identify the relationship between the most important design parameters, hence developing simple analyses and design models. They can be considered efficient and useful for carrying out detailed design in the final geotechnical design stage for all types of foundations.

On the other hand, limited research has been devoted to develop simple models and design methods and hence further studies are needed in this regard. Such need for developing simple analysis and design models for piled raft foundations was reported by some workers in this field. For example, Randolph (1994) reported that there is a need to develop new analytical methods that allow simple estimation of the settlement of piled raft foundations, and hence permit design studies to focus on settlement issues rather than capacity. Poulos (2001) stated that considerable further research is needed to develop simplified procedures for routine design, without the need for complex numerical analyses. De Sanctis et al. (2002) stated that analysis methods for piled raft foundations are available now, yet the search for more rational and economic design criteria than the conventional ones is justified. Katzenbach and Moormann (2003) stated that so far neither national or international standards nor definite design-strategies existed for designing piled-raft foundations. Conte et al. (2003) stated that the contribution of the raft to the load carrying capacity is still ignored in the conventional design methods of piled raft foundations. El-Mossallamy et al. (2006) stated that most analysis and design of piled-raft foundations were performed using numerical analyses, yet for all day design practice a simple and modest design method is highly needed to check the feasibility of using the piled raft foundations at least in the first design stage. El-Mossallamy et al. (2009) reported that a simple method which is able to give a quick answer on the design criteria such as the number and length of piles, the piles load share and settlement of piled-raft foundations is highly recommended from the practical point of view.

Due to limited research for developing simple analysis and design methods for piled-raft foundations, design codes are still based on old design methods, which result in conservative designs when applied for designing piled-raft foundations. Design guidelines for such foundations are not available in many countries to assist practitioners in carrying out the design of piled-raft foundations. Conventional design procedures result in very conservative design when used for designing piled-raft foundations due to ignoring the contribution of the raft to the load carrying capacity. Design that is more economical can be performed by developing design methods that account for the contribution of the raft to the bearing capacity of the piled-raft foundations. Contribution of the raft to the load carrying capacity can be determined by developing simple models for estimating the load sharing between the raft and the piles. Mandolini et al. (2005) stated that the load sharing between the piles and the raft is a fundamental quantity in the advanced design methods and in the new codes about piled raft foundations. De Sanctis and Russo (2008) reported that capacity based design, which is still dominant in engineering practice, is often too conservative, mainly because it restricts one to take advantage of the load sharing between the piles and the raft. Comodromos et al. (2009) stated that capacity based design of pile foundations neglects the contribution of the raft. Developing simple models to predict the load sharing between the piles and the raft for piled-raft foundations will contribute to establishing design guidelines in design codes and manuals of foundation structures. The increased use of piled-raft foundations around the world necessitates more research and studies to formulate simple and reliable design procedures and guidelines.

Optimization of the contribution of the raft to the load carrying capacity is of a great importance for establishing design guidelines for the design of piled-raft foundations. Many parametric studies have been carried out to determine the effect of some parameters on the performance of piled-raft foundations in terms of load sharing and settlement. However, most of these studies focus on the effect of the geometrical and mechanical parameters of the piles and the raft on the performance of the piled raft foundations at working load conditions. Limited research has been conducted to study the effect of these parameters on the load-settlement relationship and load sharing of piled raft foundations on sand soil at large settlements. Moreover, the effect of some important mechanical properties of soil such as Poisson's ratio, friction angle, dilatancy angle and soil unit weight, at either small or at large settlement, on the performance of piled raft foundations has not been investigated.

1.3 Purpose and Scope of Thesis

The thesis considers developing a numerical model for analyzing piled-raft systems based on the finite element technique. The validity of the developed numerical model is examined by comparing its results with the results of tests and other numerical models available in the literature. This thesis deals with studying the effect of some important design parameters related to piles and raft dimensions and their mechanical properties as well as some important mechanical properties of the sand soil on the load-settlement relationship and load sharing in piled raft foundations. This thesis aims at developing a theory for predicting the settlement and the load sharing between the raft and piles and then to propose a simple design procedure for preliminary design of piled-raft foundations.

1.4 Organization of Thesis

Chapter 1: Introduction

This chapter presents a general background about using piled raft foundations to support different types of structures and the advantages of using such foundations. It also highlights the current available means for analyzing and designing piled raft foundations.

Chapter 2: Literature Review

In this chapter a review of previous studies on piled raft foundations is presented. These studies were categorized to groups such as experimental, numerical and analytical studies.

Chapter 3: Numerical Modeling

Details of the numerical model are presented. This model was used to analyze piled raft foundations and to conduct parametric study. The results of this model were compared with the results of other models available in the literature to examine the validity of the developed model. Details about the parametric study are presented. The results and discussion of the parametric study is presented in this chapter. A new simple model and design procedure were introduced for analyzing and designing piled raft foundations.

Chapter 4: Conclusion

This chapter summarizes the conclusions of this study along with suggestions for future research work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Since the advantages of using piled-raft foundations have become apparent to geotechnical and structural engineers, a great deal of attention has been paid to studying the different engineering aspects of piled-raft foundations using different approaches. In the literature, the studies on piled raft foundations can be divided into two major categories, namely theoretical studies, and experimental studies. In this chapter a review of previous studies on piled-raft foundations in terms of behaviour, performance, analysis approaches and current design practice will be carried out. The objective of this review is to identify the contributions established by other researchers on piled-raft foundations.

2.2 Experimental Studies

Wiesner and Brown (1980) conducted an experimental study on models of raft foundations in over consolidated clay to investigate the validity of methods based on elastic continuum theory for predicting the behavior of piled-raft foundation subjected to vertical loading. In this study, measurements of settlements, strains and bending moments in the raft were made. They observed that predictions of theory which is based on the assumption that soil is a linearly elastic continuum can provide acceptable predictions for the behavior of piled-raft foundations.

Cooke (1986) presented results of model tests on piled-raft foundations. He compared the behavior of piled-raft foundations with that of un-piled raft and free-standing piled group. Cooke (1986) observed that the load distribution between piles in piled raft foundations depends on the number and spacing of piles. He observed that settlement at the center of the raft foundation is larger than those at the edges of the raft.

Horikoshi and Randolph (1996) conducted centrifuge tests on piled-raft foundations models to study settlement of piled-raft foundations on clay soil. They observed that even a small group of piles could reduce the differential settlement of the raft significantly. This study showed that a small cap on a single pile could increase significantly the bearing capacity of the system. Horikoshi et al. (2003) conducted centrifuge tests on piled-raft foundations models on sand soil subjected to vertical and horizontal loading. They examined the effect of the rigidity of the pile head connection on the behaviour of piled-raft foundations. This study showed that the capacity of the pile increases when the cap is in contact with soil due to the increase in the confining stress around the pile. Horikoshi et al. (2003) observed that the ultimate horizontal capacity of piled-raft is larger than that of the un-piled raft.

Conte et al. (2003) carried out an experimental study using centrifuge tests to determine the effect of the variation of the raft and pile geometry on the stiffness of piled-raft foundations. They found that the stiffness of piled-raft foundations increases with the increase of the aspect ratio parameter, R_M which is given by equation (2.1)

$$R_M = \frac{A_R}{A_g} * \sqrt{\frac{n*s}{L}} \tag{2.1}$$

Where A_R is the area of the raft, A_g is the area of the pile group, n is number of piles, s is the pile spacing and L is the pile length.

Lee and Chung (2005) conducted tests on piled-raft foundations models to investigate the effect of pile installation and interaction between the raft and the piles on the behaviour of piled-raft system. They found that cap-soil-pile interaction effect is influenced by pile location and spacing. They observed that pile installation could compensate the decrease in cap capacity due to cap-soil-pile interaction effect.

Fioravante et al. (2008) presented results of extensive centrifuge tests modeling of a rigid circular piled-raft on sand soil to assist in studying the role of piles as settlement reducers and to quantify the load sharing between the raft and piles. They observed that raft settlement decreases as the number of piles increases. The results showed that displacement piles are more effective in reducing the settlement of the raft than the non-displacement piles. Fioravante et al. (2008) found that the contribution of the raft starts when the piles approach the ultimate capacity. They also observed that piled-raft stiffness increased with the increase in the number of piles supporting the raft.

El Sawwaf (2010) conducted an experimental study to study the effect of using short piles to support raft foundations models on sand soil subjected to eccentric loading. The results of this study demonstrated the effectiveness of using short piles close to the raft edge to reduce settlement and tilt of the raft, and to improve the raft bearing pressure. El Sawwaf (2010) found that the efficiency of short piles for improving the performance of piled-raft foundations depends on the piles configuration and the load eccentricity ratio. Matsumoto et al. (2010) conducted an experimental study on piled-raft foundations models subjected to vertical and horizontal loads to investigate the effect of pile head connection to the raft on the performance of such foundations. They found that the pile head connection condition has little effect on the behaviour of the piled-raft foundations subjected to vertical loading whereas the horizontal load proportion carried by the raft decreased as the pile head connection becomes less rigid. Fioravante and Giretti (2010) conducted centrifuge tests on piled-raft foundations models to study load transfer mechanism between a raft and piles in piled raft systems in sand soil. They found that the piles act as settlement reducers by transferring the load from the raft to larger and deeper volumes of soil. They also observed that the load sharing mechanism is related to the relative stiffness of the piles-soil system.

2.3 Theoretical Studies

Wiesner and Brown (1980) developed an analysis method of piled-raft foundations based on the elastic continuum theory. The analytical method used by Wiesner and Brown (1980) is an extension of the method developed by Hain (1975). By comparing the results of experimental and analytical studies, Wiesner and Brown (1980) demonstrated that theoretical solutions that are based on the elastic continuum theory can provide satisfactory prediction of the behaviour of the piled-raft system. The analytical solution used by Wiesner and Brown (1980) represents the raft as a thin elastic plate supported by piles and soil as an elastic continuum. This method of analysis is based on the following assumptions (Wiesner and Brown, 1980):

1) Soil is assumed as an isotropic and linearly elastic continuum.
2) Piles are assumed as elastic cylinders in axial compression and their connection to the raft cannot transfer moments.

3) The raft is assumed as a thin elastic plate supported by piles and an elastic continuum.

4) The reaction between the soil and the raft is assumed as a number of zones of uniform vertical stress whereas for zones above the piles this stress is assumed to be zero.

5) The reactions between the soil and the piles are assumed as a number of zones of uniform shear stresses along the shafts of the piles and zones of uniform vertical stresses at the bases of the piles.

Based on the elastic theory, Kuwabara (1989) developed a boundary element analysis method for piled-raft foundations supported by a homogenous soil and subjected to vertical loading. This method of analysis is an extension of the method that was developed by Mattes and Poulos (1969) for a single pile (Kuwabara, 1989). However, Kuwabara (1989) stated that his method of analysis does not account for the effect of the slip between pile and soil, non-homogeneity of soil and end-bearing piles. Clancy and Griffiths (1991) presented a numerical analysis using the finite element method for piled-raft foundation using 4-node quadrilateral plate bending elements for the slab and axial elements for the piles.

Both boundary element methods and finite element methods are limited to analyze piled-raft foundations of a small pile group because the three dimensional nature of the problem can lead to very large stiffness matrices (Clancy and Randolph, 1993a).

Each numerical tool has its advantages and disadvantages when used to analyze piled-raft system. Hybrid models have been employed to achieve some objectives such as avoiding the shortcoming of using one numerical tool, simplifying the analysis and improving the efficiency of the analysis methods of piled-raft foundations. Clancy and Randolph (1993a) employed a numerical method for piled-raft foundations based on a hybrid model that combines the finite element method for modeling the structural elements of the piled-raft foundations and analytical solutions for modeling the soil response.

Zhuang and Lee (1994) employed a three-dimensional finite element analysis for predicting the load distribution between the piles in a piled-raft foundations and used brick elements to model the structure, raft, piles and soil. They investigated the effect of some variables such as the structural stiffness, pile length and spacing and the relative stiffness of the raft and the pile on the load distribution among the piles. They observed that the structural stiffness, the raft rigidity, pile stiffness and pile length to width ratio significantly affect the load distribution among the piles. They also observed that by increasing the length of the piles and decreasing the raft and pile rigidity the load distribution becomes more uniform. On the other hand, as the raft rigidity increases, the effect of structural stiffness on the load distribution among piles becomes small.

Ta and Small (1996) developed a method of analysis for piled-raft foundations on layered soil which takes into account the interaction among the raft, piles and soil by using the finite layer method for the analysis of the soil and the finite element method for the analysis of the raft to avoid the cost of a rigorous three-dimensional analysis. They claimed that their method can be used for the analysis of a raft with any geometry or stiffness because the raft is considered as a thin elastic plate and can be used for rafts on isotropic or cross-anisotropic horizontally layered soil with piles randomly distributed

beneath the raft. They also found that the relative thickness and stiffness of soil layers can also influence the load distribution along the shafts of piles in piled-raft foundations.
Some simplifications are needed to avoid the excessive computing time and other limitations when developing analysis methods of large piled-raft foundations. Ta and Small (1997) proposed an approximate numerical method of analysis to estimate the influence factors for piled-raft foundations that can reduce computer run time. According to a numerical analysis, Ta and Small (1997) observed that the portion of the load carried by the piles increase and that by the raft decrease as the bearing stratum becomes stiffer.

Russo (1998) proposed an approximate numerical method (hybrid model) for the analysis of piled-rafts which accounts for the non-linearity of the unilateral contact at the raft-soil interface and the non-linear load-settlement relationship. Russo (1998) stated that because piles are used as settlement reducers and their ultimate load capacity may be reached, non-linear analysis should be considered for piled-rafts analysis. Russo (1998) reported that most of the numerical analysis efforts have considered solving either simple axial-symmetric or plane-strain problems to reduce the huge computational efforts of analyzing large piled foundations. He claimed that introducing some approximations to the numerical methods can assist in solving such a problem.

Mendonca and de Paiva (2000) introduced a boundary element method for analyzing piled-raft foundations which accounts for the interaction among the raft, the piles and the soil. The method developed by Mendonca and de Paiva (2000) can be used for analyzing piled-raft foundations with rigid or flexible caps. In the analysis method proposed by Mendonca and de Paiva (2000) each pile in the group, the soil and the raft were modeled as a single element, an elastic linear homogeneous half space, and a thin plate, respectively.

Prakoso and Kulhawy (2001) used simplified linear elastic and nonlinear (elastic-plastic) 2-D plane strain finite element models to predict the performance of piled-raft foundations and proposed a displacement-based design procedure for piled-rafts based on this analysis. They used PLAXIS (software based on finite Element Method) in their study and they claimed that a 2-D plane strain analysis could yield satisfactory results for analyzing the piled-raft system without excessive time for modeling and computing.

Poulos (2001) introduced a simplified analysis method for piled-raft foundations as a tool for preliminary design of such foundations. Other solutions for the limitations of numerical modeling techniques were suggested by using hybrid models. Small and Zhang (2002) presented a method of analysis for piled-raft foundations on layered soil subjected to vertical loads , lateral loads and moments by using the finite layer theory to model the layered soil and the finite element theory to model the piles and raft. El-Mossallamy (2002) employed a mixed technique of the finite element and boundary element methods to develop a numerical model which accounts for the raft stiffness, the nonlinear behavior of the piles and the slip along the pile shafts for analyzing piled-raft foundations.

Mendonca and de Paiva (2003) presented a static analysis of piled-raft foundations using a combination of finite element and boundary element methods in which interaction between soil, flexible raft and piles was considered. Kitiyodom and Matsumoto (2003) developed a simple analytical method by using a hybrid model for piled raft foundations embedded in non-homogenous soil considering the effect of vertical and lateral loads.

Reul (2004) conducted a rigorous numerical study using the three-dimensional finite element analysis to study the behavior of piled-raft foundations in overconsolidated clay. He used the finite element method to model the soil and foundation to obtain detailed information about soil-structure interaction. Reul (2004) stated that it is important to understand the interaction among the piles, the raft and the soil which controls the behavior of piled-raft foundations. Reul (2004) observed that pile-raft interaction leads to an increase in the skin friction with an increase of the load or increase of the settlement.

Wong and Poulos (2005) presented a simplified method to estimate the pile-to-pile interaction factor between two dissimilar piles based on a parametric study which was conducted using the computer program GEPAN developed by Xu and Poulos, (2000). The computer program GEPAN is based on the boundary element analysis. They claimed that this method can be beneficial for predicting the settlement behavior of pile groups or piled-raft foundations with dissimilar piles. Garcia et al. (2005) studied piled-raft foundations supported by clay soil using a visco-hypoplastic constitutive law in a three dimensional finite element analysis. Vasquez et al. (2006) used three-dimensional nonlinear finite element analysis to predict the response of piled-raft foundations taking into account the nonlinear behavior of the soil while linear elastic behavior was assumed for the raft and piles.

Comodromos et al. (2009) conducted a parametric study on piled-foundations using the finite difference code FLAC. Comodromos et al. (2009) observed that in case of pile cap loaded by a non-uniform vertical load, the load is mainly carried by the piles in the vicinity of the loaded area if the cap thickness is less than the pile diameter. They found that if the cap thickness is greater than the pile diameter, the type and the location of the applied load have no effect on the distribution of the load to the piles.

2.4 Current Design Practice

In designing pile foundations the piles are assumed to carry the entire applied load whereas in a piled-raft foundation when the raft is in contact with the supporting soil the load is shared between the piles and the raft (Wiesner and Brown, 1980). However, usually in designing piled-raft foundations, the contribution of the raft to supporting the applied load is ignored and as a result the number of piles estimated is excessively higher than needed (Clancy and Randolph, 1993a and Ta and Small, 1997). Aaccurate design should consider the interaction among the raft, piles and soil (Ta and Small, 1997). In designing a piled-raft foundation it is established that, generally, the raft alone has an adequate bearing capacity (Fleming et al., 2009). The question is no longer how many piles are needed to carry the weight of the building but how many piles are needed to reduce the differential settlement to an acceptable level as well as how should those piles be distributed to achieve such an objective (Fleming et al., 2009).

Poulos (2001) stated that for the design of piled-raft foundations the most critical aspects are the ultimate load capacity, maximum settlement and differential settlement under vertical loads. On the other hand, he reported that other issues such as the ultimate load capacity for moments and lateral loads, raft moments and shears for the structural design of the raft, and pile loads and moments for the structural design of the piles should be considered at least at the detailed design stage. Poulos (2001) presented a review of design issues and a discussion of the capability and limitations of some analysis methods of piled-raft foundations under vertical and lateral loading conditions. De Sanctis et al. (2002) discussed the guidelines for an optimum design of piled-raft foundations and concluded that design requirements for piled-raft foundations are different from one case to another. For example, for small rafts bearing capacity and average settlement controls the design, whereas for large rafts it is the differential settlement which controls the design of piled-raft foundations.

De Sanctis and Russo (2008) reported that the load sharing between the raft and the piles is a fundamental quantity as suggested by most of the recent studies. El-Mossallamy et al. (2009) reported that the settlement and the load sharing between the raft and piles are the main factors that control the design of piled-raft foundations. Garcia et al. (2005) reported that the following three coefficients are used for quantifying the performance of piled-raft foundation:

1) The pile raft coefficient which is given by the ratio of the sum of all pile loads to the total load on the foundation.
2) The coefficient of maximum settlement which is given by the ratio of maximum settlement of the piled-raft to that of un-piled-raft.
3) The coefficient of maximum differential settlement which is given by the ratio of differential settlement of the piled-raft to that of un-piled-raft.

De Sanctis et al. (2002) reported that while simple and reliable methods for the analysis of piled-raft foundations are available, the search for a more rational and economical design approach is needed. Cunha et al (2001) stated that optimized parametric procedures should be considered for the design of piled-raft foundations along with local standards and practice. Leung et al. (2010) argued that adopting optimization techniques for designing and analyzing piled-raft foundations may lead to significant advantages in terms of economic savings and reduced environmental impacts because of the reduction in consumed materials while maintaining a competitive level of performance.

To identify the most important parameters in designing piled-raft foundations, many parametric studies were carried out. Cunha et al (2001) reported that the influence of many design variables on the performance of piled-raft foundations is not fully understood. Cunha et al (2001) argued that pile length, number of piles, disposition of piles, the raft thickness and the cost of the foundation are the most important external variables that influence the design of piled-raft foundations. Poulos (2001) reported that when a raft foundation alone does not satisfy the design requirements, using a limited number of piles might improve the performance of such foundations in terms of ultimate load capacity, total and differential settlements.

Reul and Randolph (2004) conducted a parametric study to investigate the effect of some parameters such as the pile position, the pile number, the pile length, the raft-soil stiffness ratio, and the load distribution on the raft on the behavior of piled-raft foundations. They observed the following:

1) Smaller average settlement can be obtained by using longer piles rather than a higher number of piles.
2) As the load level increases, the stiffness of the piled-raft foundations decreases.

3) Raft-soil stiffness ratio and the load configuration have a higher effect on the differential settlement than on the average settlement.

4) Moment in the raft cannot be reduced by using piles to support the raft.

Significant advantages in terms of economic savings and reduced environmental impacts can be achieved by varying the pile lengths across the piled-raft which is not a common practice in deep foundation design (Leung et al., 2010).

Simplified methods are beneficial for the preliminary design of piled-raft foundations whereas the more rigorous computer-based methods are used for detailed design and analysis. According to the Poulos-Davis-Randolph (PDR) method and other simplified methods of analyzing piled-raft foundations, the vertical bearing capacity of a piled-raft foundation can be taken equal to the lesser of the following two values (Poulos, 2001):

1) The sum of the ultimate load capacity of the raft and the piles.
2) The sum of the ultimate load capacity of a block containing the raft and all piles in addition to the ultimate load capacity of the area of the raft outside the periphery of the piles.

Randolph (1994) described three design philosophies for piled-raft foundations as follows (Poulos, 2001):

1) Piles are designed as a pile group to carry the major part of the applied load while the raft is allowed to contribute partially to the ultimate load capacity.
2) Piles are designed to operate at a working load of about 70-80% of the ultimate load capacity. The role of the piles in this case is to reduce the

contact pressure between the soil and the raft to a stress level less than the preconsolidation pressure of the soil.

3) Piles are designed mainly to reduce the differential settlement by strategically locating them to support the raft.

The first design strategy is known also as the conventional approach or the capacity-based approach. Comodromos et al. (2009) reported that design methods of pile foundations based on capacity estimation ignore the contribution of the raft. They also reported that the development of new design criteria facilitates the use of more adequate design methods based on displacement concepts rather than capacity based approaches. Since conventional design approaches ignore soil nonlinearity and effects from the pile group response, it is necessary to adopt a numerical tool that is able to account for the nonlinearity of both the soil and the structure (Comodromos et al., 2009). In fact, such a procedure has not been incorporated in design practice because of complexity and time demand of such an approach (Comodromos et al., 2009).

De Sanctis and Russo (2008) reported that recently it was demonstrated theoretically and experimentally that the capacity based design method is often too conservative for designing piled-raft foundations due to ignoring the load sharing between the raft and the piles in such a method. However, this method is still widely used in many countries because some codes and regulations are imposing the adoption of the settlement based design method which is considered a more rational design approach for piled foundations.

Poulos and Davis (1980) argued that in piled-raft foundation designing piles based on ultimate load concept is not acceptable because such piles are used only to reduce the settlement of a raft that satisfy bearing capacity requirements. Russo (1998) stated that methods of analysis for piled-raft foundations that take into account the soil-structure interaction are needed to move from the conventional capacity-based design to the settlement-based design. De Sanctis and Russo (2008) presented settlement results for a case study in Italy for some tanks to demonstrate the effectiveness of using the settlement-based design approach for piled-raft foundations. The number of piles was less than that required by the conventional capacity-based design approach, thus achieving a considerable saving on the cost.

2.5 Summary

According to the present study it was concluded that considerable research on the performance of piled-raft foundations has been conducted. Significant contributions have been made to studying different aspects of piled-raft foundations. However, most of these models are complicated because they depend on using complicated analytical and numerical methods.

On the other hand, it was found from the literature review that limited research has been devoted to develop simple analysis models and design methods. As a result, design codes are still based on old design methods which result in a conservative design when applied to designing piled-raft foundations. Therefore, further studies are needed to develop simple analysis and design methods. In particular, design models for predicting the load sharing between the raft and the piles, and settlement of piled-raft foundations are needed especially at the preliminary design stage of piled-raft foundations. The need for developing simple analysis and design models for piled raft foundations has been recognized by many workers in this field such as Randolph (1994), Poulos (2001), De Sanctis et al. (2002), Katzenbach and Moormann (2003), El-Mossallamy et al. (2006), El-Mossallamy et al. (2009) and others. More research in this direction may contribute to updating design codes and manuals with regard to designing piled raft foundations, in particular for quantifying settlement and load sharing of such systems.

CHAPTER 3

NUMERICAL MODELING

3.1 Introduction

Based on the literature review presented in Chapter two it can be reported that a large number of studies related to piled-raft foundations have been carried out. Different analysis models have been developed to analyze piled-raft foundations. Due to the complexity of piled-raft foundations, each method of analysis has its advantages and disadvantages. The finite element method is considered the most powerful tool among the other methods of analysis. The finite element method takes into account the effect of the interaction factors such as pile-to-pile, pile-to-raft, raft-to-raft and pile-to-soil interactions in the analysis process. Therefore, the finite element method was selected in this study to develop a numerical model to predict the load-settlement relationship and load sharing between the piles and the raft of the piled-raft foundations. The developed model offers a considerable saving in computational effort and time while improving the accuracy of two-dimensional modeling of piled-raft systems.

3.2 Finite Element Model

Piled-raft foundation is a three dimensional problem, which requires three dimensional modeling. However, in three-dimensional models the computational time and effort are excessive due to the large number of elements in the mesh. The time required for the computations depends on the number of elements used in the model. Katzenbach et al. (2005) reported that three-dimensional finite element simulations of piled-raft foundations with an average number of elements in the range of 10,000 to 25,000 elements need about 18 hours of computational time on a Sun-Ultra 2 workstation. They also expected that increasing the number of elements and considering other issues in the simulations such as consolidation would lead to an enormous increase of computational time. Therefore, reducing the number of elements could save much time in the calculation process. However, reducing the number of elements in the mesh can affect the accuracy of the model.

Two-dimensional modeling provides reasonable simplification for modeling piled-raft systems. Using two-dimensional model has the advantage of simplifying the problem by reducing the size of the model. By reducing the size of the model the required number of elements to create the mesh is much less than that in the case of three-dimensional model. By reducing the number of the elements, considerable saving in computational time can be achieved.

Oh et al. (2008) stated that although some simplifications are needed, the problem of piled-raft system can be analysed using a two-dimensional finite element model if the loading and geometry are symmetrical. A model that can reduce the number of the elements and maintain the accuracy of the model is ideal to solve this problem. The finite element technique is used to solve the equilibrium equations of a continuum which are formulated based on the deformation theory.

In this model, to reduce the number of elements and, hence, provide saving in computational time, the problem of piled-raft foundation was modeled as two-dimensional problem. In order to develop a two-dimensional finite element model, the piled-raft foundation was assumed as a plane strain problem. The continuum considered in this model consists of raft, piles and soil. According to finite element techniques, the continuum was divided into small regions of triangular shapes called finite elements. The elements consist of a number of nodes and each node has two degrees of freedom (DOF). According to the deformation theory, the degrees of freedom correspond to the displacement components in horizontal and vertical directions. Some simplifying assumptions were made to apply a plane strain condition to the piled-raft system. Piled-raft foundation was idealized as only a strip footing with unit length supported by a row of piles and soil. This simplification is mainly related to modeling the out of plane piles supporting the raft. In a pile group, the piles are placed at distance from each other. In two-dimensional modeling, this space cannot be considered in the model. Therefore, each pile within the strip of the raft is idealized as a wall of unit length under the raft strip. To reduce the effect of such assumption on the deformation of the raft, the stiffness of this equivalent wall representing a pile row is taken to be equivalent to the stiffness of the piles in the row using equation 3.1 (Prakoso and Kulhawy, 2001):

$$E_{wall} = (n * E_p * A_p) / (L_r * D) \tag{3.1}$$

where E_{wall} = modulus of elasticity of the wall representing the pile row,

n = number of the piles in the row,

E_p = modulus of elasticity of the pile,

A_p = cross-sectional area of the pile,

L_r = length of the raft,

D = pile diameter.

Since two-dimensional modeling has less accuracy than three-dimensional modeling, improving the accuracy of the two-dimensional model is needed. This objective can be achieved by using element types that can provide higher accuracy compared to other types of elements. In order to improve the accuracy of the two-dimensional model a special element, the so-called 15-node element was employed to model the stresses and deformations of the soil, raft and piles.

The 15-node triangular finite element is a very accurate element because it consists of 15 nodes and 12 stress points (Brinkgreve, 2002) [Reference Manual:-pp3-9]. In this triangular element, each side of the triangle has five nodes and three nodes in the middle of the element. The high numbers of nodes in the 15-node triangular element makes its accuracy comparable to or larger than that of many elements with fewer nodes such as three-node elements or six-node elements. For example, Brinkgreve, (2002) [Reference Manual:-pp3-9] reported that a 15-node triangular finite element is equivalent to a composition of four six-node triangular finite elements because the total number of nodes and stress points is equal. Brinkgreve (2002) [Reference Manual:-pp3-9] stated that one 15-node triangular finite element is more powerful than four 6-node triangular finite elements because the 15-node element provides a fourth order interpolation for displacement whereas the order of interpolation for the 6-node element is two. Even though, the 15-node triangular finite element is very powerful and accurate, the size of the element used can affect the accuracy of the model. Therefore, in regions of high concentration of stresses such as adjacent to pile shafts, the size of the element should be as small as possible. In regions of low concentration of stresses, usually far from the foundations, relatively larger size of elements can be assumed without significant effect on the accuracy of the model. Reducing the size of the elements was accomplished by refining the mesh in regions around to the raft and piles.

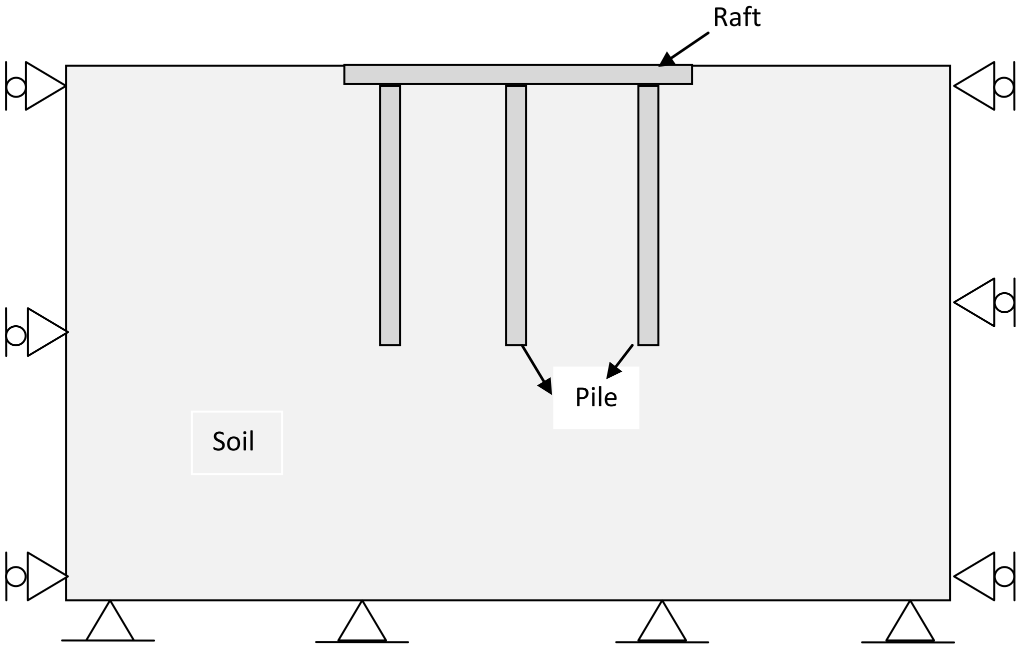

Fig. 3.1: Numerical Model

Figure 3.1 shows the geometry of the two-dimensional finite element model used in this study to analyze piled-raft system. Three components were considered in the numerical model (i.e., raft, piles and soil). Soil, raft and piles were modeled as clusters and each cluster is divided into 15-node triangular finite elements. The soil-pile interface region was modeled by using interface elements along the piles shafts to simulate the frictional interaction in this region. The interface element is compatible with the 15-node triangular element used for the soil and piles. The interface element used in this model is a line element with five pairs of nodes and five stress points. In the mesh the five pairs of nodes in the line interface element are connected to the five nodes on the side of the 15-triangular element.

The piles were assumed as non-displacement concrete piles. The raft was considered as a reinforced concrete slab. The behaviour of the raft and the piles was assumed linear. Therefore, the linear-elastic model was utilized to simulate the materials behaviour of the piles and the raft. For the linear-elastic model two main parameters are used, which are the modulus of elasticity, E, and Poisson's ratio, μ. This model is based on the Hooke's law of isotropic linear elasticity (Brinkgreve, 2002).

The soil was assumed to be homogenous sand soil. To predict the behaviour of piled raft foundations at large settlements a non-linear analysis is required. Therefore, the behaviour of the soil was considered as non-linear. There are many constitutive models used to simulate the soil behaviour such as the Linear Elastic Model, Mohr-Coulomb model, Cam Clay Model, Drucker-Prager, Hardening Soil Model and Lade's Single Hardening Model. The elastic perfectly-plastic Mohr-Coulomb model was used to simulate the non-linear stress-strain behaviour of the sand soil. The Mohr-Coulomb model is a non-linear model which is based on soil parameters that are well-known in engineering practice. For this model, the modulus of elasticity of soil, Es, and Poisson's ratio, μs, are used for the soil elasticity while the friction angle, φ, and the cohesion, c, are used for the soil plasticity and the dilatancy angle is needed to model the increase of volume (Brinkgreve, 2002).

The boundaries of the model were placed at sufficient distances from the foundation so that the influence of the boundaries on the deformations of the foundation is minimized. Nodes on both lateral boundaries of the model are fixed against horizontal movement ($u_x = 0$), yet free to move in the vertical direction. Meanwhile, nodes on the bottom boundary of the model are fixed against both vertical and horizontal movements ($u_x = u_y = 0$), whereas the top boundary was free to move in both directions, as shown in Fig. 3.1. A vertical uniform load is applied on the top boundary along the raft top.

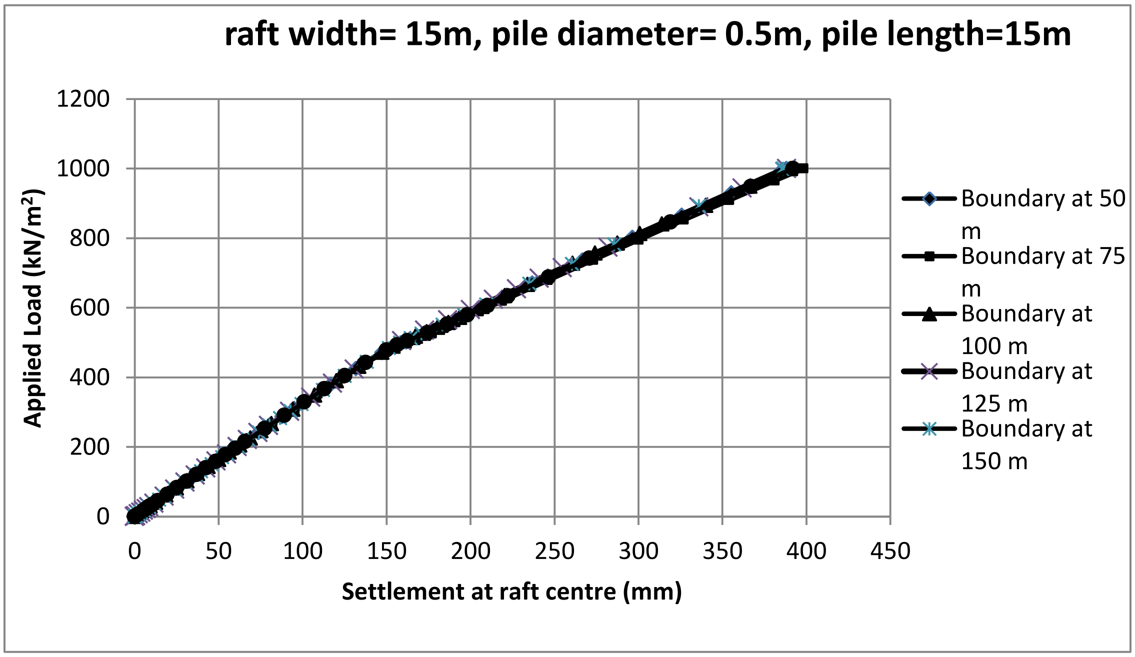

Fig. 3.2: Effect of side boundaries location on load-settlement relationship

The effect of side boundary location on the displacement of the load-settlement relationship is shown in Fig. 3.2. It was found that the location of the side boundaries has no effect on the model when the boundaries are placed at a distance of 50 m or larger measured from the edge of the raft. Therefore, in the lateral direction, the side boundaries of the model were placed at a distance equal to 100 m from the edge of the raft. In the vertical direction, the bottom boundary was placed at a distance equal to 35 m below the surface of the soil. The pile length is 15m.

In order to construct the model described above, some of the available commercial programs were examined to identify the most appropriate program for achieving the objectives of the intended numerical model. Programs such as ABAQUS, FLAC and PLAXIS were considered for comparison. It was found that ABAQUS software, which is based on the finite element method, has applications for many engineering field but it is not specially developed for analyzing geotechnical problems. It is a general-purpose program. FLAC program is software which is developed mainly to be used for solving and modeling geotechnical problems. However, FLAC is based on the finite difference method. It was reported by some researchers that the finite difference method cannot model the interaction between piles in pile group foundations as accurate as the finite element method. It was also reported by some researchers that the most powerful tool for analyzing piled raft foundations is the finite element method because it accounts for the interactions between the piles. PLAXIS is geotechnical software based on the finite element method and it is intended especially for analyzing geotechnical problems. It can be considered as a special-purpose program. PLAXIS can be used as a tool for practical analysis for most areas of geotechnical engineering. Therefore, PLAXIS was selected to be used for developing the two-dimensional finite element model for this study. PLAXIS was developed in 1987 at the Technical University of Delft. In this study, PLAXIS Version 8 was utilized in developing the two-dimensional finite element model.

In general, the steps of modeling piled-raft foundations using PLAXIS can be summarized as follows (Brinkgreve, 2002):

1) Select model type: this step determines the analysis type of the geometry of the model; according to this model plane strain is selected.
2) Select element type: the clusters in the geometry model are divided into small elements; the type of the element used in this model is the 15-node triangular element; this element has 15 nodes and 12 stress points.
3) Determine model geometry: total dimensions of the domain including the soil, piles and raft are determined by specifying the maximum x and y coordinates of the domain.
4) Drawing the model: the geometry of the model is constructed by drawing the piles and raft using their dimensions (pile length, pile diameter and pile spacing, and raft width and thickness.
5) Boundary conditions: the boundary conditions and the degree of freedom (D.O.F.) for each boundary are specified; the nodes along the side boundary are fixed against horizontal movement but free to move in vertical direction; the nodes along the bottom boundary are fixed against both horizontal and vertical movements; the nodes along the top boundary are free to move in vertical and horizontal directions.
6) Placement of boundaries: the model boundaries are placed at different distances from the foundation to find out at which distance the boundary

effect diminishes; in this model side boundaries are placed at 100 m from the raft edge and the bottom boundary at 35 m below the soil surface.

7) Applying loads: information about the loads such as type, position and magnitude are specified; in this model uniform vertical load is applied along the top of the raft.
8) Soil-structure interaction: to simulate the frictional interaction in the pile-soil interface region, interface elements along the piles shafts are used; a virtual thickness is used for each interface to define the material properties of the interface; the value of the virtual thickness factor used in this model is 0.1.
9) Constitutive models: the materials properties for each cluster of the model are assigned; for the material of piles and the raft, the Linear Elastic Model is used; the values of two parameters which are modulus of elasticity, E , and Poisson's ratio, μ) are required for the Linear Elastic Model; for the soil, the Mohr-Coulomb Model is used; the value of five parameters which are modulus of elasticity, E ,Poisson's ratio, μ , ccohesion, c , friction angle, φ , and angle of dilatancy, ψ are required for this model; since the soil type simulated in this study is sand, drained condition was assumed.
10) Generating the mesh: in this model, the mesh was set to medium but the mesh was refined around the shafts of the piles where stress concentration is expected; for the mesh generation, in this step the domain is divided into 15-node triangular finite elements to perform finite element calculations.

In PLAXIS the average element size is multiplied by a factor of 0.5 for each refinement of a point, line or cluster.

11) Calculations (Phase 1 estimating the initial stresses): in this phase, the effective stresses of the soil are calculated using K_o procedure where $K_o=1-\sin\varphi$; K_o is the coefficient of the lateral earth pressure at rest which defines the relationship between horizontal and vertical stresses in the soil.
12) Calculations (Phase 2): the calculation type is specified in this stage; for this model, plastic calculation is used to carry out elastic-plastic deformation analysis; loads are applied and interface elements between the soil and the piles are activated; calculations of stresses and deformations are performed by the program for every node and stress point in the domain.

3.3 Model Validation

To validate the results of the developed model (PLAXIS 2-D model), an example of piled-raft foundations was analyzed. This example was presented by Poulos (2001) to evaluate the efficiencies of different analysis methods for predicting the behaviour of piled-raft foundations. Fig. 3.3 depicts the layout of the piled-raft foundation considered in this analysis.

Poulos (2001) predicted the load-settlement relationship of this piled-raft example using the simple method PDR-Method and numerical models developed using software such as FLAC 3D, FLAC 2D, GARP5 and GASP. The results of the developed model showed a good agreement with the results predicted by Poulos (2001) using different methods.

Comparison between the results of the developed model and other models is summarized in Fig. 3.4 and Table 3.1. Load-settlement predictions using the developed PLAXIS 2D model were in good agreement with the predictions of other models. An improvement in the accuracy of two-dimensional modeling can be seen by comparing the prediction of PLAXIS 2D model with that of FLAC 2D model in Fig. 3.4.

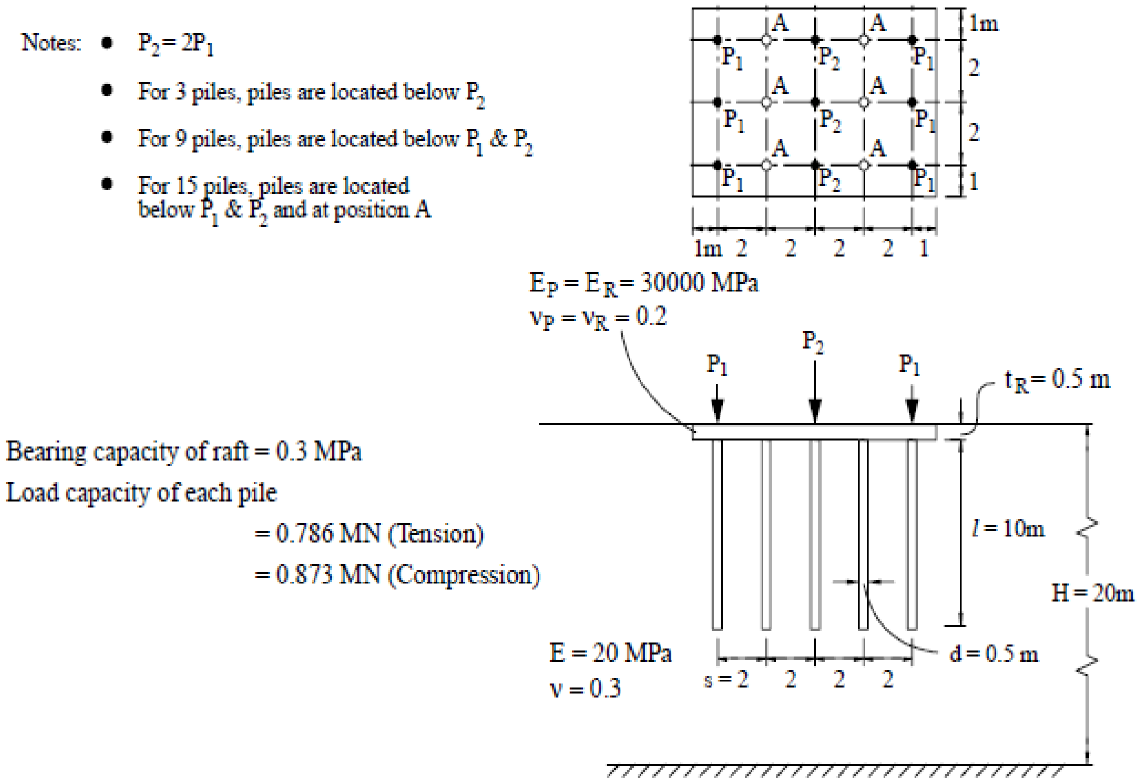

Fig. 3.3: Example of piled-raft foundations (Poulos, 2001)

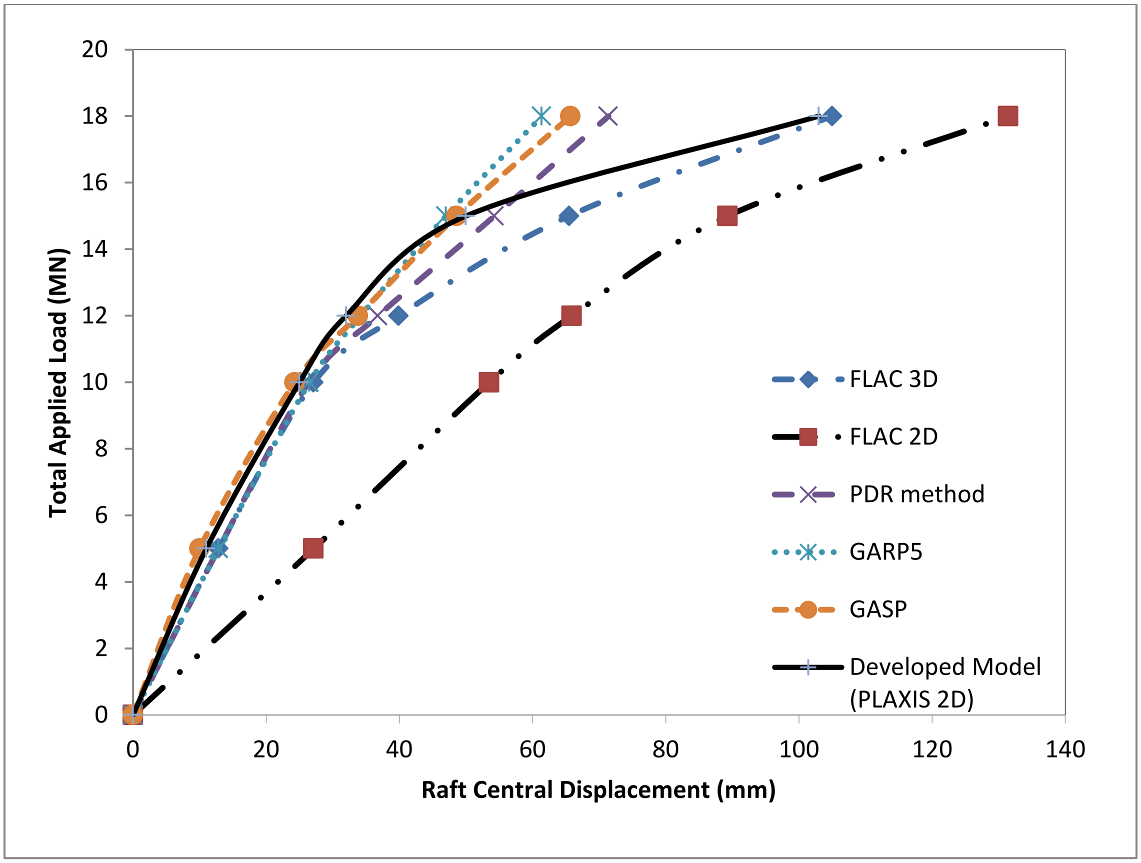

Fig. 3.4: Load-Settlement predictions of an example of a piled-raft foundation supported by 9 piles

Table 3.1: Comparison of the results of PLAXIS 2-D model with other models for a total load of 12 MN

Model	Central Settlement (mm)	Corner Pile Settlement (mm)
FLAC 2D predicted by Poulos (2001)	65.9	60.5
FLAC 3D predicted by Poulos (2001)	39.9	35.8
PDR method	36.8	-
GARP5	34.2	26.0
GASP	33.8	22.0
The Developed PLAXIS 2D	32.0	26.0

The developed model using PLAXIS 2D was also validated by comparing its results for the un-piled-raft foundation of the Savings Bank Building in Adelaide, Australia. A raft of 33.5m x 39.5m having a thickness of 0.9 m was used to support a distributed pressure of 134 kN/m^2. Kay and Cavangaro (1983) predicted the settlement using different approaches. They assumed that the raft was supported by a layered soil consisting of a 2 m clay layer with modulus of elasticity of 44 MPa underlain by an 8 m clay layer with modulus of elasticity of 60 MPa, and then a layer of Hallet Cove sandstone with modulus of elasticity of 10000 MPa. Poisson's ratio was taken 0.2 for all soil layers. The modulus of elasticity and Poisson's ratio for the raft were taken 25000 MPa and 0.15, respectively. Using the same assumptions above, Chow (2007) predicted the settlement of the raft. The developed model using PLAXIS 2D was also used to predict the settlement of this raft using the same assumptions of the above analyzers. Settlement predictions among different approaches were found in good agreement, as shown in Fig. 3.5 and Table 3.2.

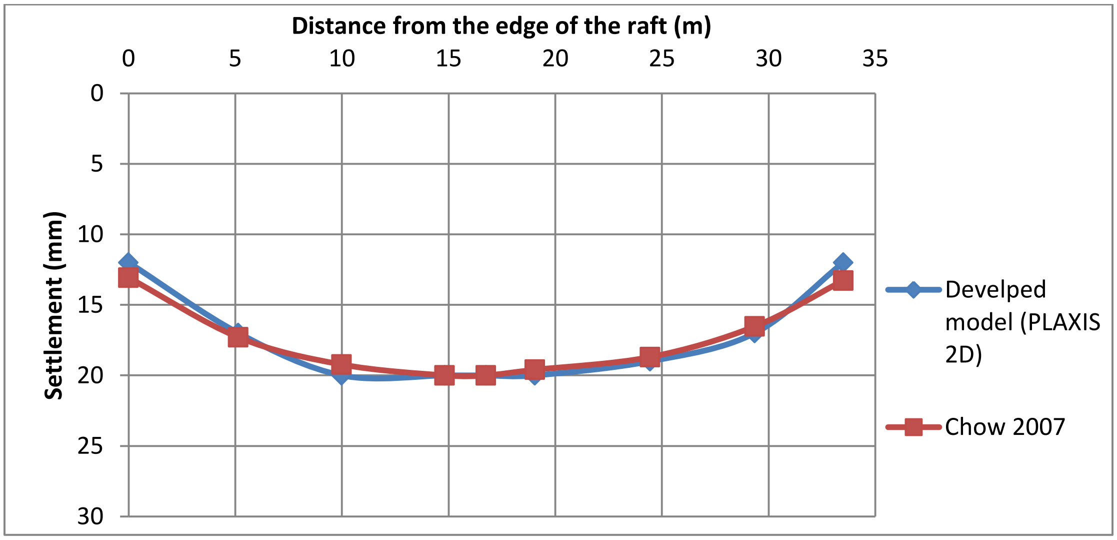

Fig. 3.5: Settlement prediction of un-piled-raft foundation of the Savings Bank Building in Adelaide, Australia

Table 3.2: Comparison between the results of settlement predictions for the un-piled-raft foundation of Savings Bank Building in Adelaide, Australia

Method	Central Settlement (mm)	Differential Settlement (mm)
Conventional: 1D	22	16
Hooke's Law	20	-
Kay and Cavangaro (1983)	20	10
Finite differential method, Chow (2007)	20	6
Developed model (PLAXIS 2D)	20	8
Measured	16-18	7-11

The results of 1g physical model test for a circular piled-raft supported by 4 piles were also used to validate the developed PLAXIS 2D model. Baziar et al (2009) carried out this test. Figure 3.6 shows the comparison between measured settlement and predicted settlement using PLAXIS 2D model. Results of PLAXIS 2D model are in good agreement with measured results.

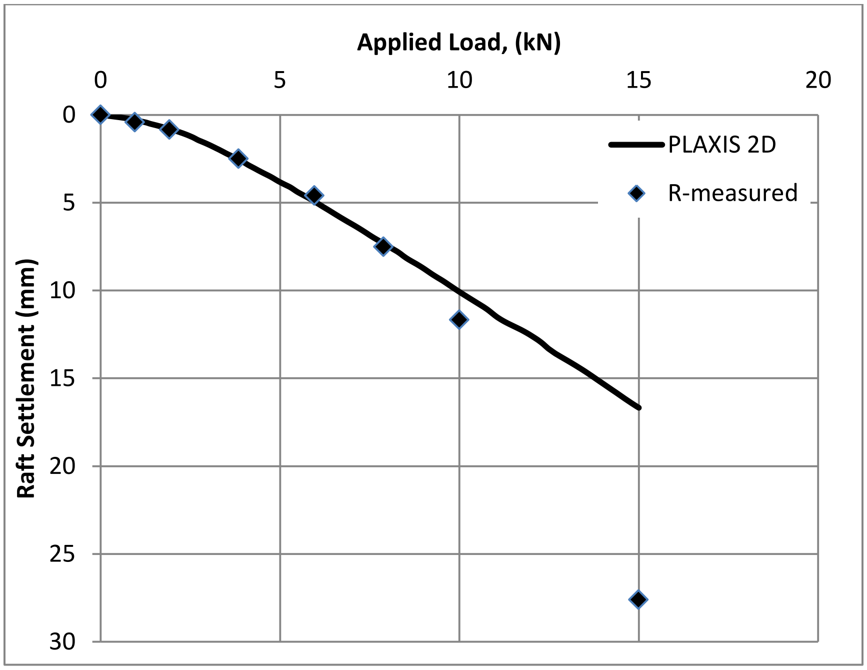

Fig. 3.6: Comparison between measured settlement of circular piled-raft with the results predicted by PLAXIS 2D

Figure 3.7 shows the comparison between the results of centrifuge model tests for a square piled-raft supported by 4 and 9 piles and predicted settlement using PLAXIS 2D model. Fioravante and Giretti (2010) carried out these tests. Predictions of PLAXIS 2D model were in reasonable agreement with measured results.

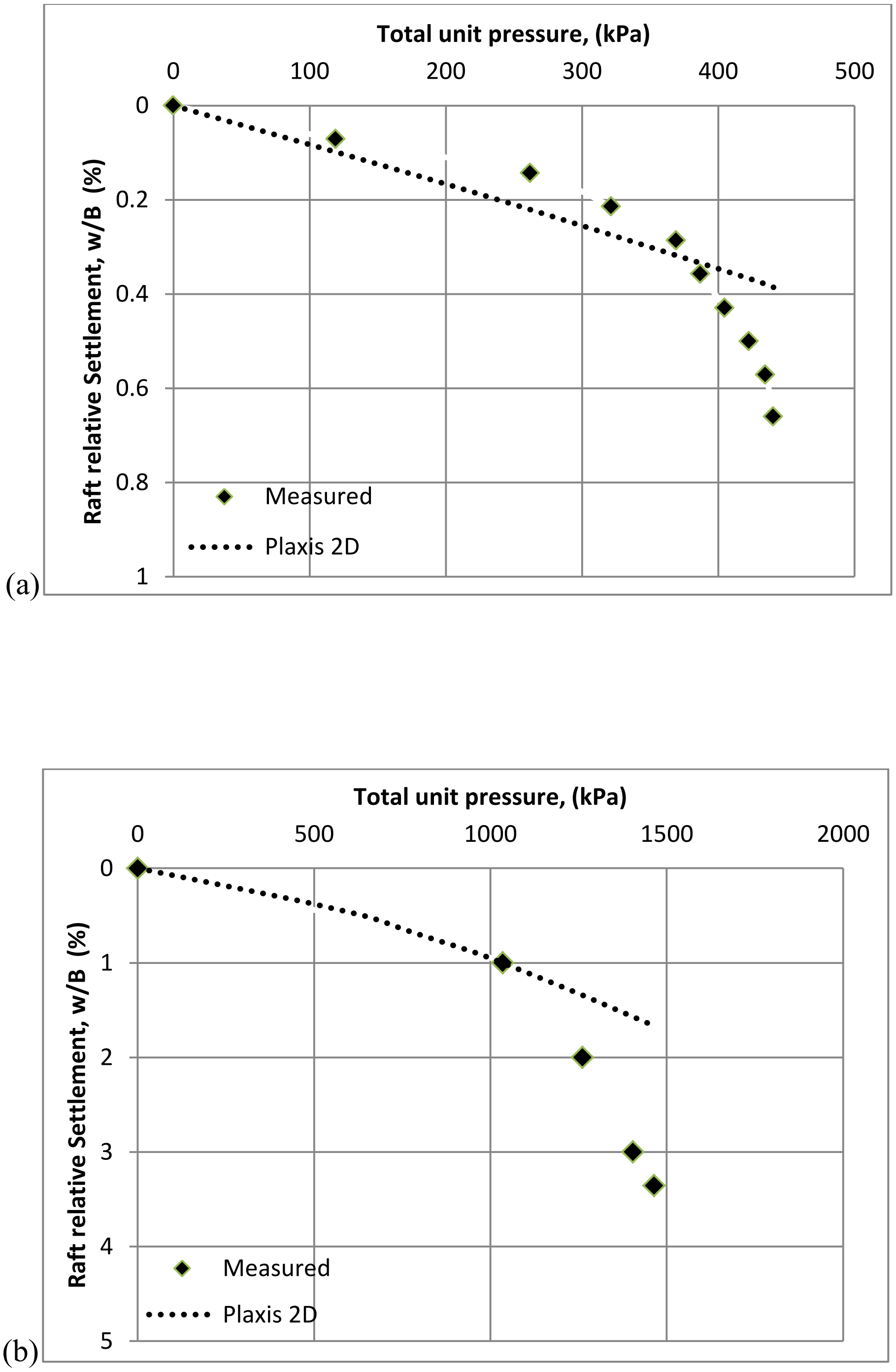

Fig.3.7: Comparison between measured settlement of a square raft with the results predicted by PLAXIS 2D: (a) raft supported by 4 piles, (b) raft supported by 9 piles

3.4 Parametric Study Results

3.4.1 Details of tests and parameters

Piled-raft foundations are a combination between a raft and piles. The load sharing and the load-settlement relationship are the most important aspects in designing piled-raft foundations. El-Mossallamy et al (2009) stated that the main criterion, which governs the design of piled-raft foundations, concerns the load sharing between the raft and piles and the effect of additional pile support on the foundation settlement. In this study, the effect of some parameters on the load-settlement relationship and the load sharing between the raft and the piles was investigated. The aim of this study is to identify the most important parameters which affect the performance of piled-raft foundations and then to develop a model to predict the settlement and the load sharing between the raft and the soil.

Identifying the important parameters which significantly affect the performance of piled-raft foundations can assist in optimizing the design of such foundations. Therefore, studying the effect of different design parameters on the behaviour of piled-raft foundations was carried out.

This study focused on the effect of some parameters on the load-settlement relationship and the load sharing between the raft and piles of piled-raft foundations. The effect of the selected parameters on the load-settlement relationship will be investigated at small and large settlements. The tests in this study were carried out using the developed PLAXIS 2D model. Five pile arrangements were considered in this study. Square piled-rafts supported by 1, 4, 9, 16 and 25 piles, as shown in Fig. 3.8, were studied. The parameters considered in this study can be summarized as follows:

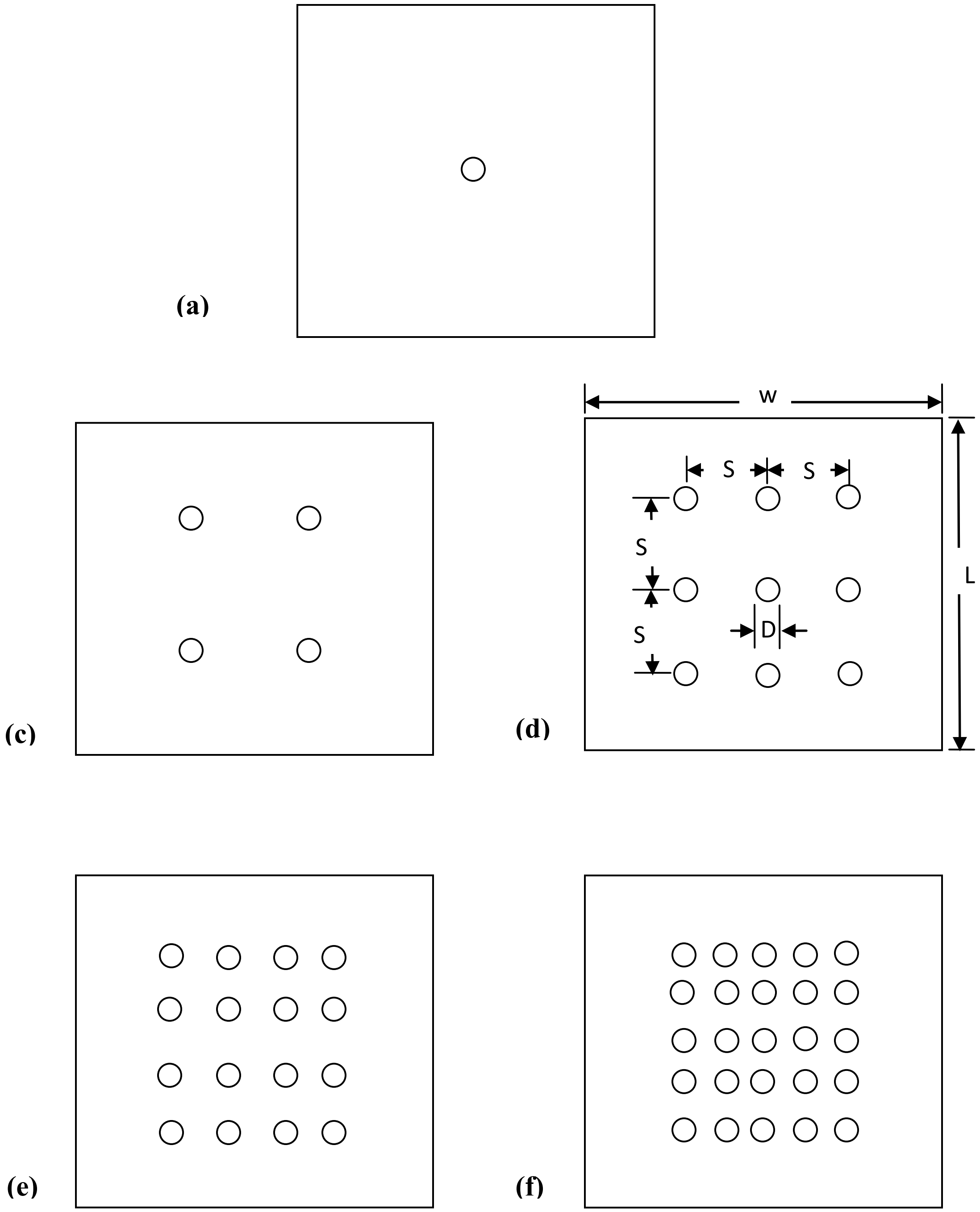

Fig. 3.8: (a) Series No.1: piled-raft with a single pile; (b) Series No.2: piled-raft with a 2×2 pile group; (c) Series No.3: piled-raft with a 3×3 pile group; (d) Series No.4: piled-raft with a 4×4 pile group; (e) Series No.5: piled-raft with a 5×5 pile group.

1) Pile diameter, *D*, pile length, *L*, number of piles and pile spacing, *s*,

2) Raft width, *w* and raft thickness, *t*,

3) Modulus of elasticity of the soil, *Es*, modulus of elasticity of the raft, *Er* and modulus of elasticity of the piles, *Ep*.

4) Soil properties, such as Poisson's ratio, μs, angle of internal friction, φ, dilatancy angle, ψ, and unit weight, γ.

5) Reduction factor of the strength of the pile-soil interface, *r*, to model the slip between the piles and soil at higher loads.

6) Effect of uniform pressure, *Q*, of 200, 400, 600, 800 and 1000 kN/m^2.

Details about the five series are given in Tables 3.3 to 3.7. The effect of the above parameters on the behaviour of piled-raft foundations subjected to a uniform pressure, *Q,* of 200, 400, 600, 800 and 1000 kN/m^2 was studied. Cohesion of sand soil is assumed to be 1 kN/m^2. Poisson's ratio for the raft, μ_r and the piles, μ_p are the same and assumed to be 0.2 for all tests. The total number of tests is about 345 tests. Piles and raft parameters were set to be related to the pile diameter. The test name is designed to indicate the series number followed by the parameter name and its value. The meaning of the test name (S5-*L*10D) can be explained as follows: this test is in series number 5 which represents a raft supported by a 5×5 pile group; the letter or symbol after the series number represents the parameter name which is the pile length in this example; 10D represents the value of this parameter. In the following tables the symbol "#" was used in the test name to indicate that the parameter value will be used instead of this symbol when referring to a specific test. A constant value is selected for each parameter when investigating the effect of other parameters. This value was set to represent the most practical value of the parameter and to be in the middle of the parameter range. Tables 3.3 to 3.7 summarize the cases of the parametric study.

Table 3.3: Testing program for Series No.1 (Piled-raft with a single pile)

Test name	**Parameter name**	**Range of parameter**				
S1-*D*#	Pile diameter, D (m)	0.3	0.4	0.5*	0.6	0.7
S1-*L*#	Pile length (m)	10D	20D	30D*	40D	50D
S1-*w*#	Raft width (m)	20D	25D	30D*	35D	40D
S1-*t*#	Raft Thickness (m)	0.6D	0.8D	D*	1.2D	1.4D
S1-*Es*#	Modulus of elasticity of soil (MPa)	20	25	30*	35	40
S1-μ_s#	Poisson's ratio of soil	$(1\mu_r) = 0.2$	$(1.25\mu_r) = 0.25$	$(1.5\mu_r) = 0.30$*	$(1.75\mu_r) = 0.35$	$(2\mu_r) = 0.40$
S1-φ#	Angle of internal friction of soil (degrees)	25	30	35*	40	45
S1-ψ#	Dilatancy Angle (degree)	0	3	5*	8	10
S1-γ#	Unit weight of soil (kN/m^3)	16	17	18*	19	20
S1-*r*#	Reduction factor for pile soil interface strength	0.6	0.7	0.8*	0.9	1.0
S1-*Er*#	Modulus of elasticity of the raft (MPa)	$(0.5Es)\, 10^3 = 15\times 10^3$	$(0.75Es)\, 10^3 = 22.5\times 10^3$	$(1Es)\, 10^3 = 30\times 10^3$*	$(1.25Es)\, 10^3 = 37.5\times 10^3$	$(1.5Es)\, 10^3 = 45\times 10^3$
S1-*Ep*#	Modulus of elasticity of piles (MPa)	$(0.5Es)\, 10^3 = 15\times 10^3$	$(0.75Es)\, 10^3 = 22.5\times 10^3$	$(1Es)\, 10^3 = 30\times 10^3$*	$(1.25Es)\, 10^3 = 37.5\times 10^3$	$(1.5Es)\, 10^3 = 45\times 10^3$
S1-*Q*#	Uniform pressure (kN/m^2)	200	400	600*	800	1000

*Value of this parameter when investigating the effect of the other parameters.

Table 3.4: Testing program for Series No.2 (Piled-raft with a 2×2 pile group)

Test name	Parameter investigated	Range of parameter				
S2-*D*#	Pile diameter, D (m)	0.3	0.4	0.5*	0.6	0.7
S2-*L*#	Pile length (m)	10D	20D	30D*	40D	50D
S2-*s*#	Pile Spacing (m)	2D	3D	4D*	5D	6D
S2-*w*#	Raft width (m)	20D	25D	30D*	35D	40D
S2-*t*#	Raft Thickness (m)	0.6D	0.8D	D*	1.2D	1.4D
S2-*Es*#	Modulus of elasticity of soil (MPa)	20	25	30*	35	40
S2- μ_s #	Poisson's ratio of soil	0.25	0.30	0.35*	0.40	0.45
S2-φ#	Angle of internal friction of soil (degrees)	25	30	35*	40	45
S2-ψ#	Dilatancy Angle (degree)	0	3	5*	8	10
S2-γ#	Unit weight of soil (kN/m^3)	16	17	18*	19	20
S2-*r*#	Reduction factor for pile soil interface strength	0.6	0.7	0.8*	0.9	1.0
S2-*Er*#	Modulus of elasticity of the raft (MPa)	(0.5*Es*) $10^3=15\times10^3$	(0.75*Es*) $10^3=22.5\times10^3$	(1*Es*) $10^3=30\times10^3$*	(1.25*Es*) $10^3=37.5\times10^3$	(1.5*Es*) $10^3=45\times10^3$
S2-*Ep*#	Modulus of elasticity of piles (MPa)	(0.5*Es*) $10^3=15\times10^3$	(0.75*Es*) $10^3=22.5\times10^3$	(1*Es*) $10^3=30\times10^3$*	(1.25*Es*) $10^3=37.5\times10^3$	(1.5*Es*) $10^3=45\times10^3$
S2-*Q*#	Uniform pressure (kN/m^2)	200	400	600*	800	1000

*Value of this parameter when investigating the effect of the other parameters.

Table 3.5: Testing program for Series No.3 (Piled-raft with a 3×3 pile group)

Test name	Parameter investigated	Range of parameter				
S3-*D*#	Pile diameter, D (m)	0.3	0.4	0.5*	0.6	0.7
S3-*L*#	Pile length (m)	10D	20D	30D*	40D	50D
S3-*s*#	Pile Spacing (m)	2D	3D	4D*	5D	6D
S3-*w*#	Raft width (m)	20D	25D	30D*	35D	40D
S3-*t*#	Raft Thickness (m)	0.6D	0.8D	D*	1.2D	1.4D
S3-*Es*#	Modulus of elasticity of soil (MPa)	20	25	30*	35	40
S3- μ_s #	Poisson's ratio of soil	0.25	0.30	0.35*	0.40	0.45
S3-*φ*#	Angle of internal friction of soil (degrees)	25	30	35*	40	45
S3-ψ#	Dilatancy Angle (degree)	0	3	5*	8	10
S3-*γ*#	Unit weight of soil (kN/m^3)	16	17	18*	19	20
S3-*r*#	Reduction factor for pile soil interface strength	0.6	0.7	0.8*	0.9	1.0
S3-*Er*#	Modulus of elasticity of the raft (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S3-*Ep*#	Modulus of elasticity of piles (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S3-*Q*#	Uniform pressure (kN/m^2)	200	400	600*	800	1000

*Value of this parameter when investigating the effect of the other parameters.

Table 3.6: Testing program for Series No.4 (Piled-raft with a 4×4 pile group)

Test name	Parameter investigated	Range of parameter				
S4-*D*#	Pile diameter, D (m)	0.3	0.4	0.5*	0.6	0.7
S4-*L*#	Pile length (m)	10D	20D	30D*	40D	50D
S4-*s*#	Pile Spacing (m)	2D	3D	4D*	5D	6D
S4-*w*#	Raft width (m)	20D	25D	30D*	35D	40D
S4-*t*#	Raft Thickness (m)	0.6D	0.8D	D*	1.2D	1.4D
S4-*Es*#	Modulus of elasticity of soil (MPa)	20	25	30*	35	40
S4- μ_s #	Poisson's ratio of soil	0.25	0.30	0.35*	0.40	0.45
S4-*φ*#	Angle of internal friction of soil (degrees)	25	30	35*	40	45
S4-ψ#	Dilatancy Angle (degree)	0	3	5*	8	10
S4-*γ*#	Unit weight of soil (kN/m^3)	16	17	18*	19	20
S4-*r*#	Reduction factor for pile soil interface strength	0.6	0.7	0.8*	0.9	1.0
S4-*Er*#	Modulus of elasticity of the raft (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S4-*Ep*#	Modulus of elasticity of piles (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S4-*Q*#	Uniform pressure (kN/m^2)	200	400	600*	800	1000

*Value of this parameter when investigating the effect of the other parameters.

Table 3.7: Testing program for Series No.5 (Piled-raft with a 5×5 pile group)

Test name	**Parameter investigated**	**Range of parameter**				
S5-*D*#	Pile diameter, D (m)	0.3	0.4	0.5*	0.6	0.7
S5-*L*#	Pile length (m)	10D	20D	30D*	40D	50D
S5-*s*#	Pile Spacing S (m)	2D	3D	4D*	5D	6D
S5-*w*#	Raft width (m)	20D	25D	30D*	35D	40D
S5-*t*#	Raft Thickness (m)	0.6D	0.8D	D*	1.2D	1.4D
S5-*Es*#	Modulus of elasticity of soil (MPa)	20	25	30*	35	40
S5- μ_s #	Poisson's ratio of soil	1.25	0.30	0.35*	0.40	0.45
S5-*φ*#	Angle of internal friction of soil (degrees)	25	30	35*	40	45
S5-ψ#	Dilatancy Angle (degree)	0	3	5*	8	10
S5-*γ*#	Unit weight of soil (kN/m^3)	16	17	18*	19	20
S5-*r*#	Reduction factor for pile soil interface strength	0.6	0.7	0.8*	0.9	1.0
S5-*Er*#	Modulus of elasticity of the raft (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S5-*Ep*#	Modulus of elasticity of piles (MPa)	$(0.5Es)10^3=15\times10^3$	$(0.75Es)10^3=22.5\times10^3$	$(1Es)10^3=30\times10^3$*	$(1.25Es)10^3=37.5\times10^3$	$(1.5Es)10^3=45\times10^3$
S5-*Q*#	Uniform pressure (kN/m^2)	200	400	600*	800	1000

*Value of this parameter when investigating the effect of the other parameters.

3.4.2 Effect of applied load

The effect of applied load was examined by applying uniform pressure in a range of 200 to 1000 kN/m^2 in order to simulate working and ultimate load conditions. Figure 3.9 shows the load-settlement relationship at the center of a piled-raft supported by single pile. The load-settlement relationship of the system starts as a linear relationship up to a certain load level then the stiffness of the system is reduced and the relationship continues to be almost linear up to the maximum applied load.

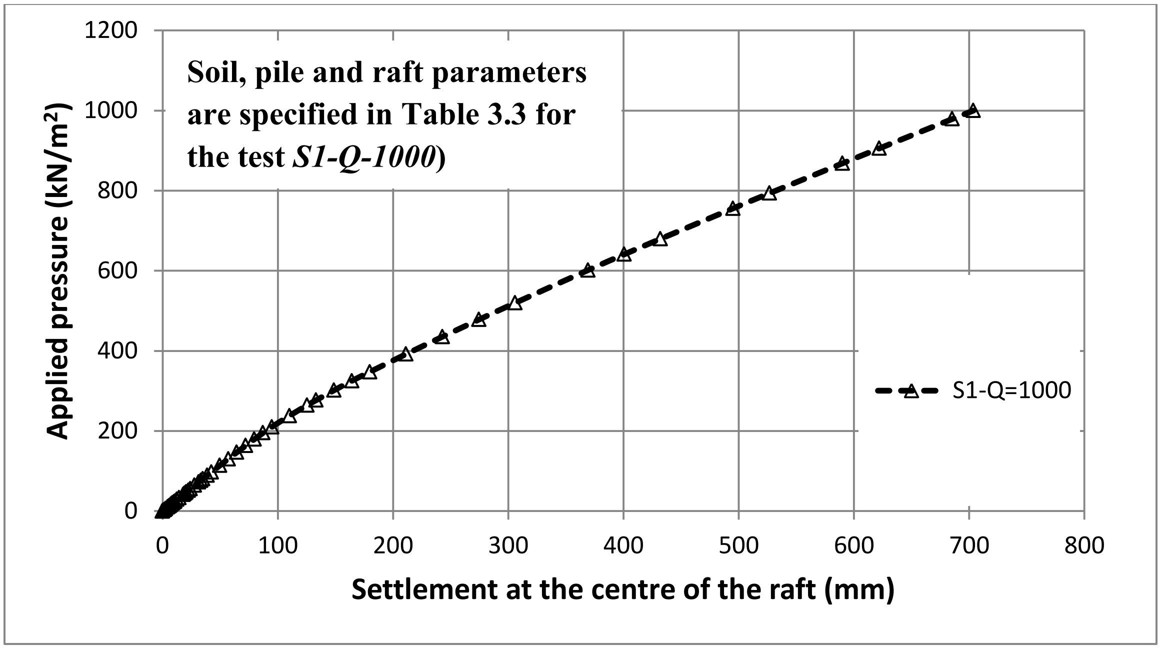

Fig. 3.9: Effect of the applied pressure on the load-settlement relationship of piled-raft supported by single pile

Although the settlement is somewhat large (about 4.7% of the raft width), the ultimate capacity of the piled-raft system is not reached. Other researchers also reported a similar observation of large settlement without reaching the ultimate capacity. In an experimental study, Horikoshi and Randolph (1996) reported that the settlement recorded was as large as the raft diameter without reaching the full capacity of the piled-raft system.

The stiffness of the piled-raft system is a combination of the raft stiffness and pile stiffness. For piled-raft foundations, the load-settlement relationship is linear in the beginning because both the piles and the raft are still elastic. When the pile capacity is fully mobilized, the stiffness of the pile is significantly reduced. Fioravante (2011) reported that the load-settlement curve of piled-raft is characterized by a sharp change of its stiffness when the full capacity of the pile is reached. As a result, the stiffness of the piled-raft system is reduced and becomes mainly equal to the raft stiffness alone, as reported by Poulos (2001). Similarly, Fioravante (2011) reported that before the yielding point of the system the piled-raft stiffness modulus can be roughly estimated as given by equation (3.2):

$$K_{\mathrm{pr}} = K_{\mathrm{p}} + K_{\mathrm{r}} \qquad (3.2)$$

where

K_{pr} is the piled-raft stiffness,

K_{p} is the pile stiffness, and

K_{r} is the raft stiffness

After the yielding point of the piled-raft system, the load-settlement curve becomes almost non-linear. This observation can be attributed to the fact that before the yielding point the relationship is linear because the load-settlement relationships for both the piles and the raft are still elastic. On the other hand, after the yielding point the relationship is non-linear because it is a combination between the load-settlement relationship of the pile, which is plastic, and the load-settlement relationship of the raft, which is still elastic. The load-settlement relationship of the raft continues to be elastic up to the maximum applied load as shown in Fig. 3.9 within settlement range between 150 to 700mm.

The same trend of the load-settlement relationship for piled-raft supported by a single pile was observed for piled-raft foundations supported by 2×2, 3×3, 4×4 and 5×5 pile groups as shown in Figs. 3.10 to 3.13. However, it can be seen that as the number of piles increases in the pile group the load level at which the system yields increases. This increase in the yielding load is due to the increase of the stiffness of the piled-raft system as the number of piles increases.

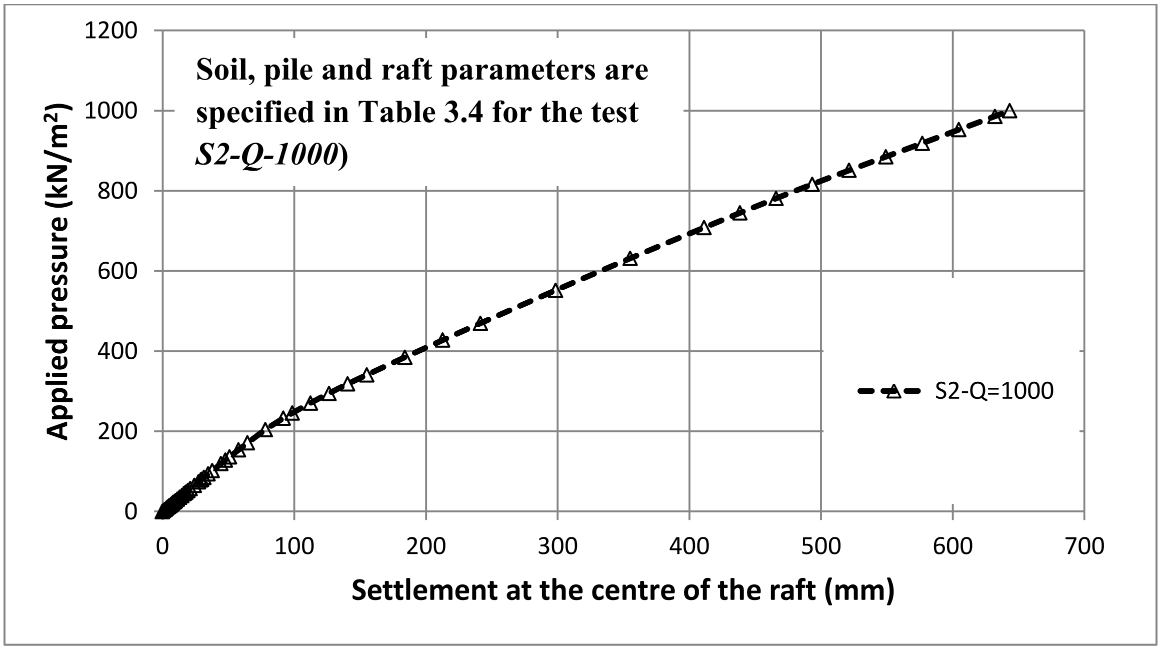

Fig. 3.10: Effect of the applied pressure on the load-settlement relationship of piled-raft supported by 2×2 pile group

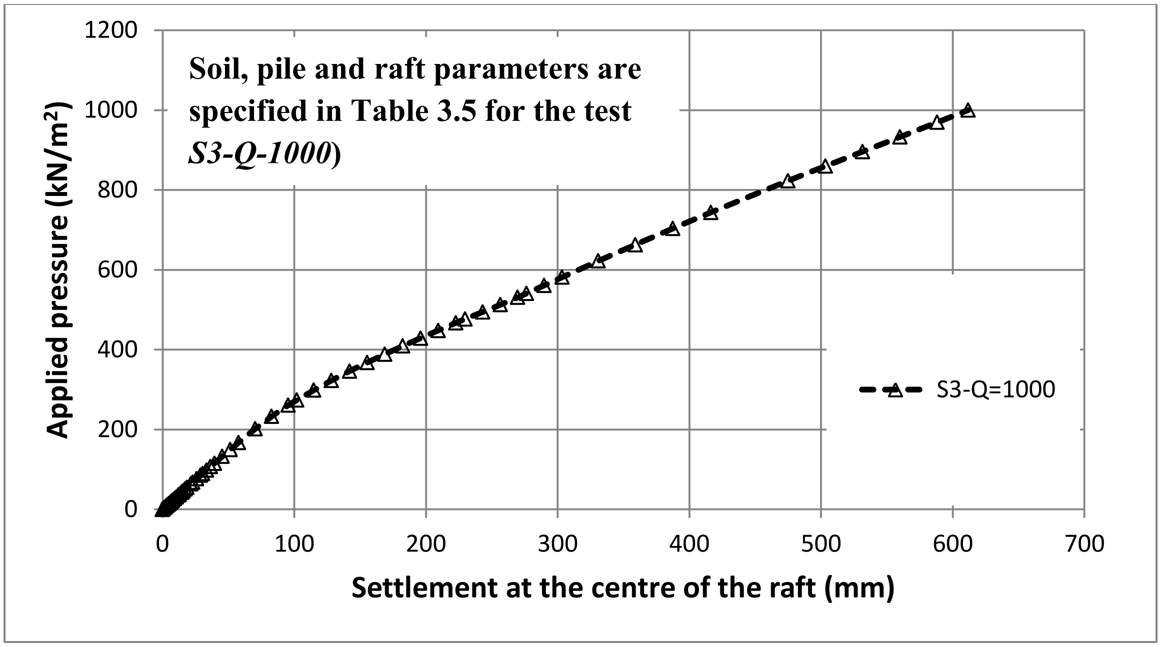

Fig. 3.11: Effect of the applied pressure on the load-settlement relationship of piled-raft supported by 3×3 pile group

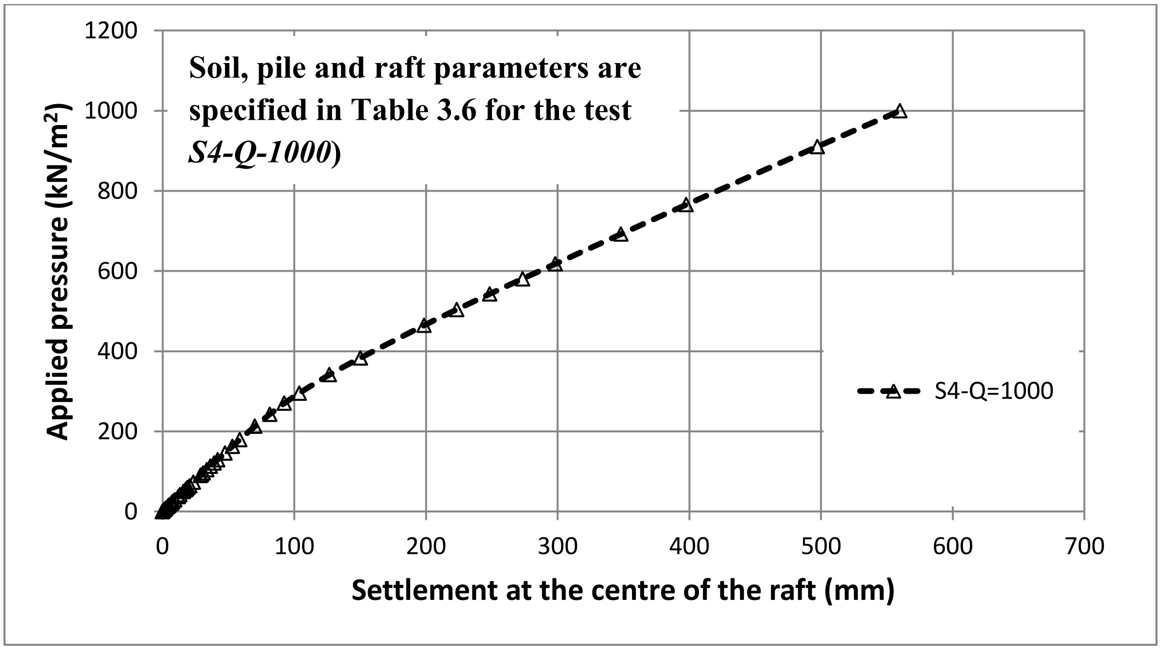

Fig. 3.12: Effect of the applied pressure on the load-settlement relationship of piled-raft supported by 4×4 pile group

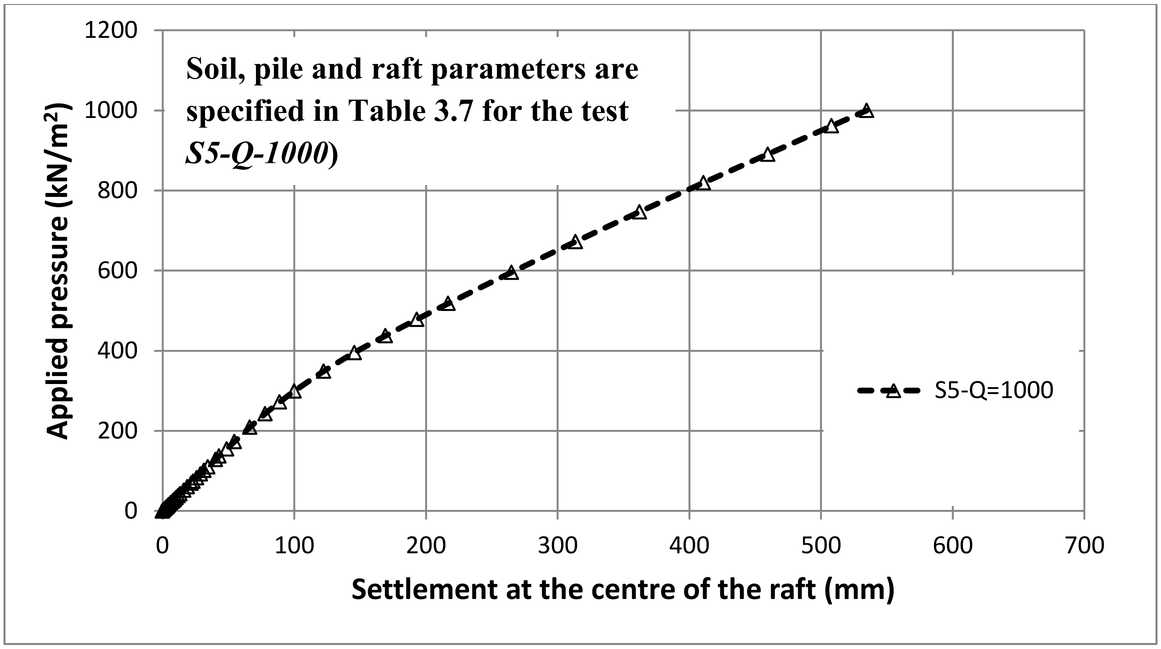

Fig. 3.13: Effect of the applied pressure on the load-settlement relationship of piled-raft supported by 5×5 pile group

The increase of the stiffness of piled-raft system with the increase of the number of piles at load values of 200, 400, 600, 800 and 1000 kN/m^2 can be clearly seen in Figs. 3.14 to 3.18. Similarly, Fioravante et al. (2008), based on results from an experimental study, reported that as the number of the piles increases the stiffness of piled-raft foundations increases. At working load conditions, the load-settlement curve was linear up to 200 kN/m^2 for all the cases as shown in Fig. 3.14. Between 200 kN/m^2 and 400 kN/m^2 the curve becomes non-linear as shown in Fig. 3.15. Then it becomes almost linear from 400 kN/m^2 up to 1000 kN/m^2 as shown in Figs. 3.16 to 3.18.

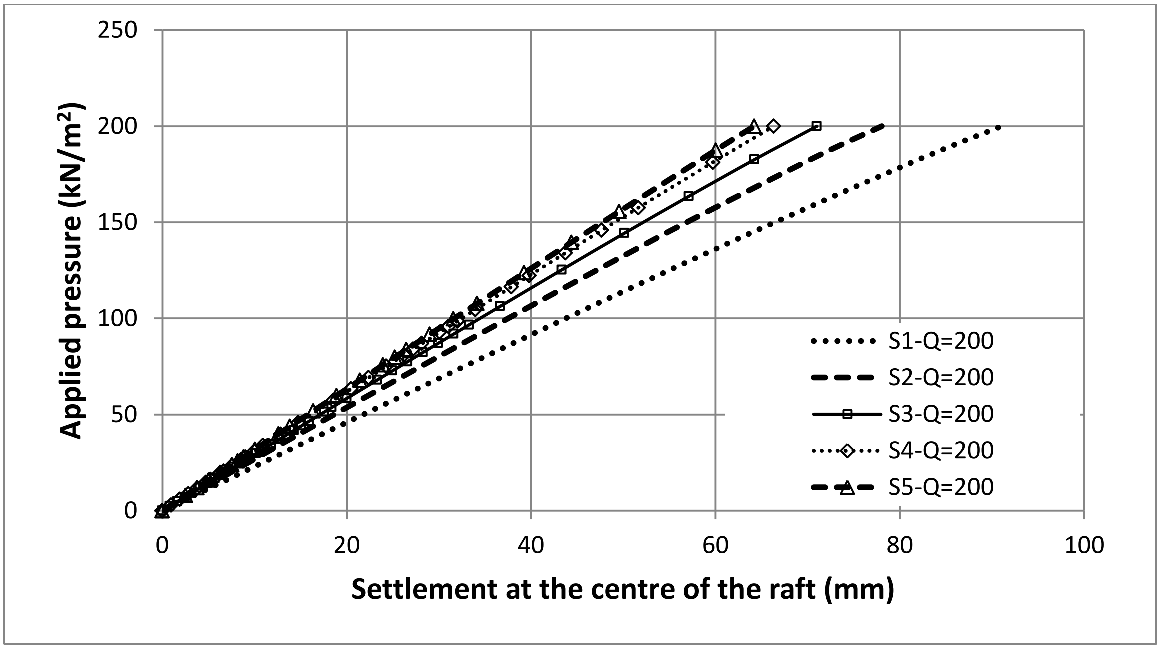

Fig. 3.14: Effect of number of piles on the load-settlement relationship (Applied pressure =200 kN/m^2)

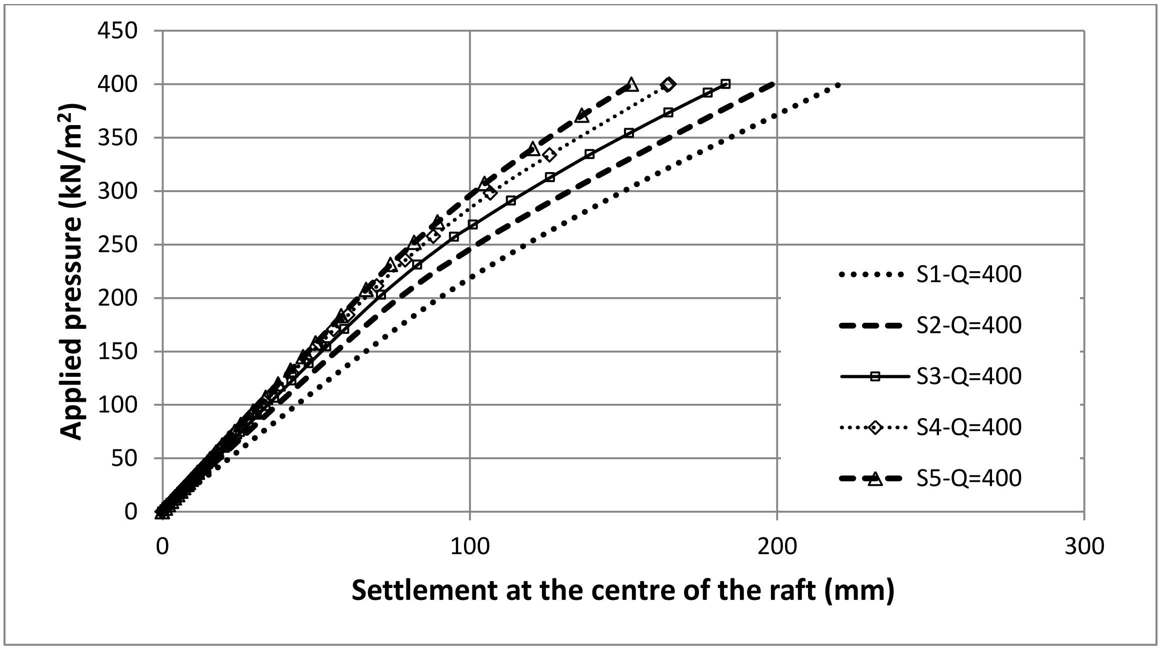

Fig. 3.15: Effect of number of piles on the load-settlement relationship (Applied pressure =400 kN/m^2)

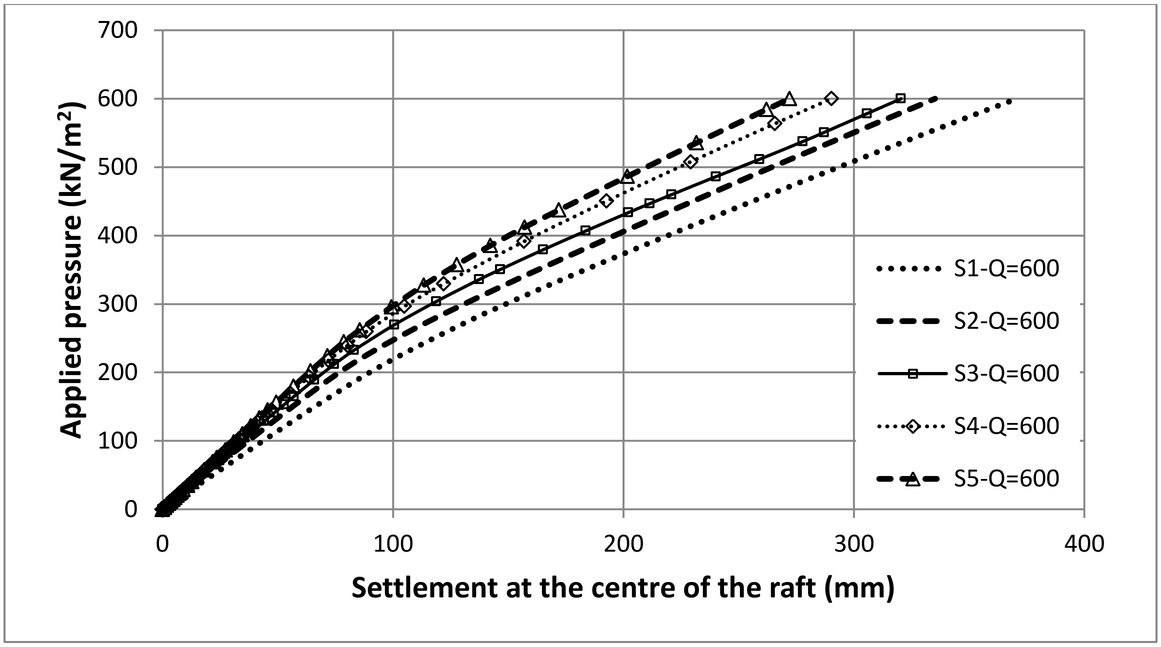

Fig. 3.16: Effect of number of piles on the load-settlement relationship (Applied pressure =600 kN/m^2)

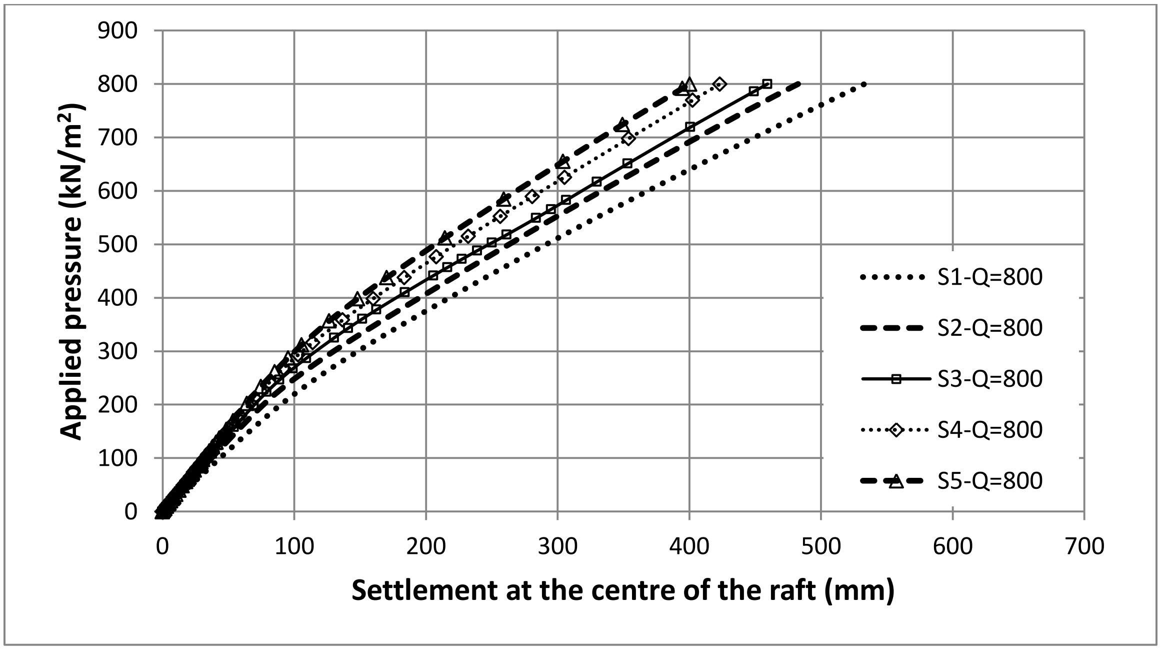

Fig. 3.17: Effect of number of piles on the load-settlement relationship (Applied pressure =800 kN/m^2)

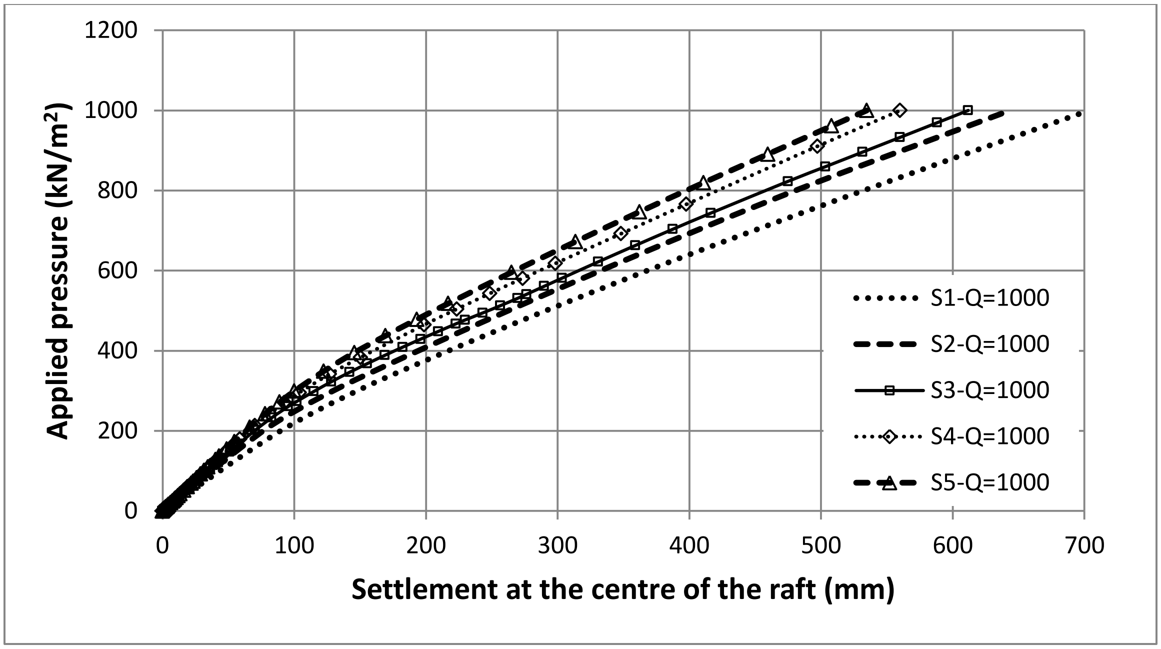

Fig. 3.18: Effect of number of piles on the load-settlement relationship (Applied pressure=1000 kN/m^2)

The load-settlement curve can be divided to three parts as follows:

1. First part which is linear because the load-settlement relationships of the piles and the raft are still elastic.
2. Second part which is non-linear because the piles reached their full capacity. The stiffness of the piled-raft system equals the stiffness of the raft alone. However, since the stiffness of the piles is still relatively high, this will have some effect on the stiffness of the piled-raft system.
3. Third part which is almost linear. The pile stiffness is very small in this part and the raft is still elastic so that the stiffness of the piled-raft system is mainly equal the stiffness of the raft alone.

3.4.3 Effect of pile diameter

The effect of the pile diameter on the load-settlement relationship of piled-raft foundations supported by a single pile, 2×2, 3×3, 4×4 and 5×5 pile groups is shown in Figs. 3.19 to 3.23. It can be seen that the increase in the pile diameter from 0.3 m to 0.7 m has a minor effect on the load-settlement curve and this effect becomes even smaller as the number of piles supporting the raft increases. Similarly, Seo et al. (2003) observed that the pile diameter effect is minimal on the total settlement of piled-raft foundations on clay soil. It can be stated that the effect of pile diameter on load-settlement relationship of piled-raft foundations is almost the same at small or large settlement levels.

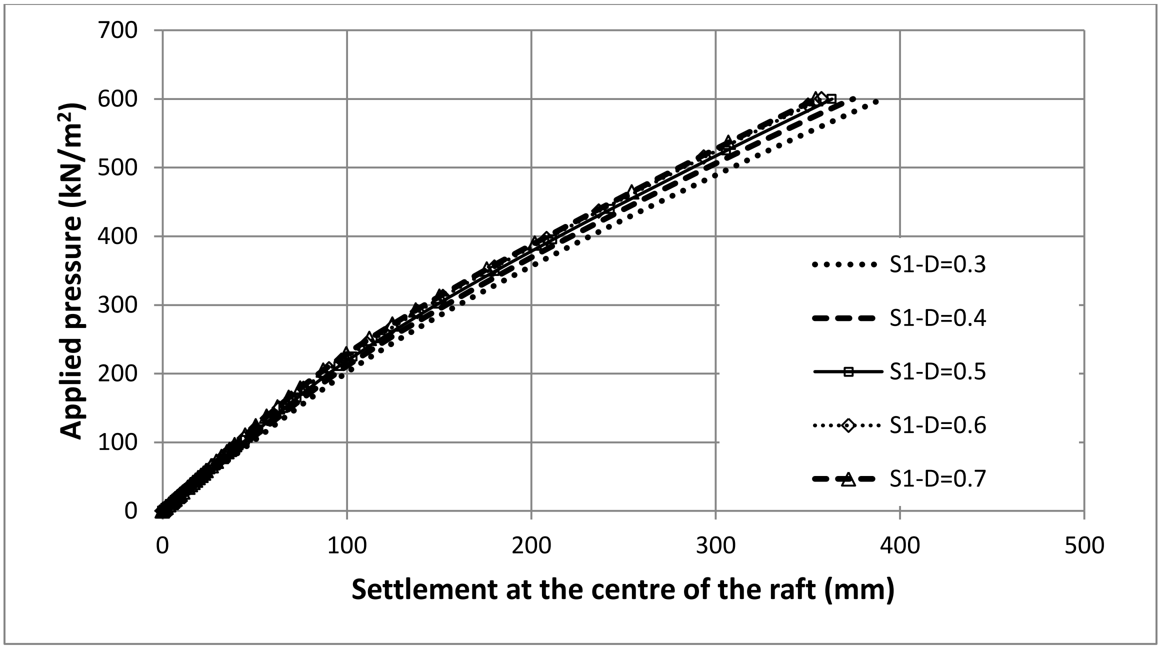

Fig. 3.19: Effect of pile diameter on the load-settlement relationship of piled-raft supported by single pile

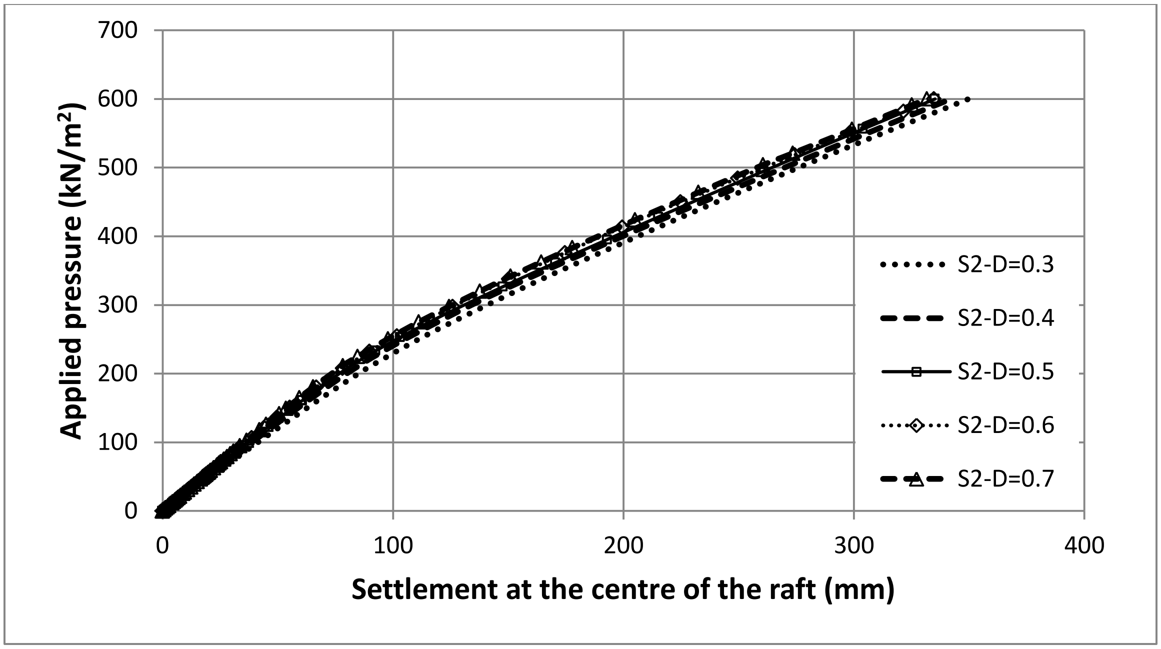

Fig. 3.20: Effect of pile diameter on the load-settlement relationship of piled-raft supported by 2×2 pile group

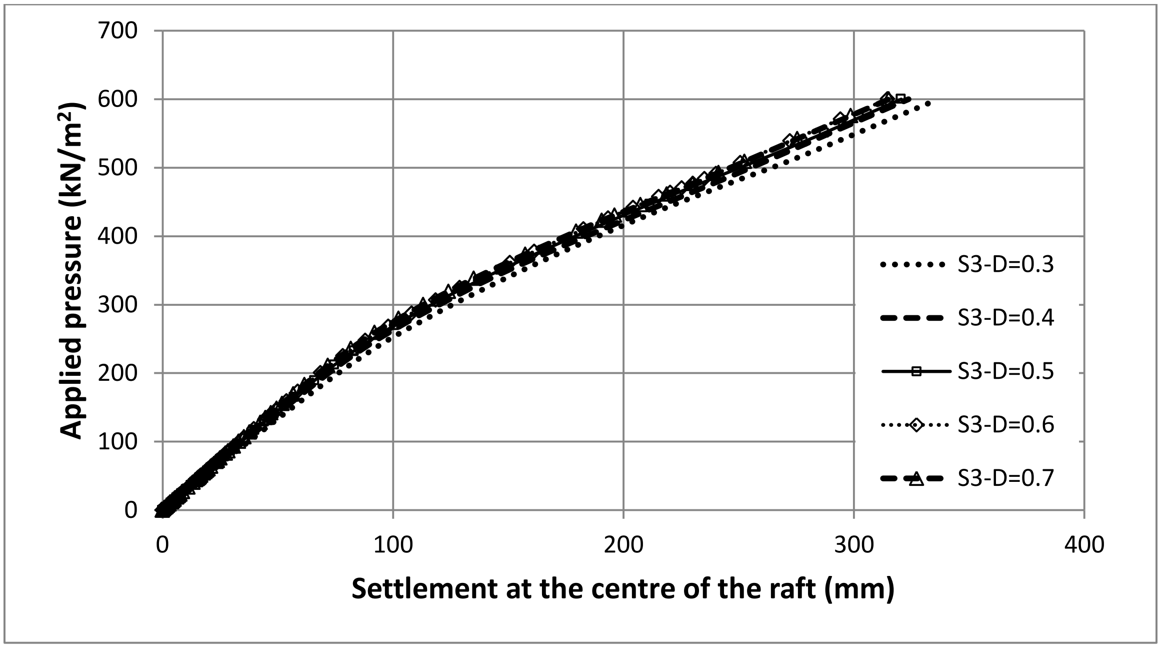

Fig. 3.21: Effect of pile diameter on the load-settlement relationship of piled-raft supported by 3×3 pile group

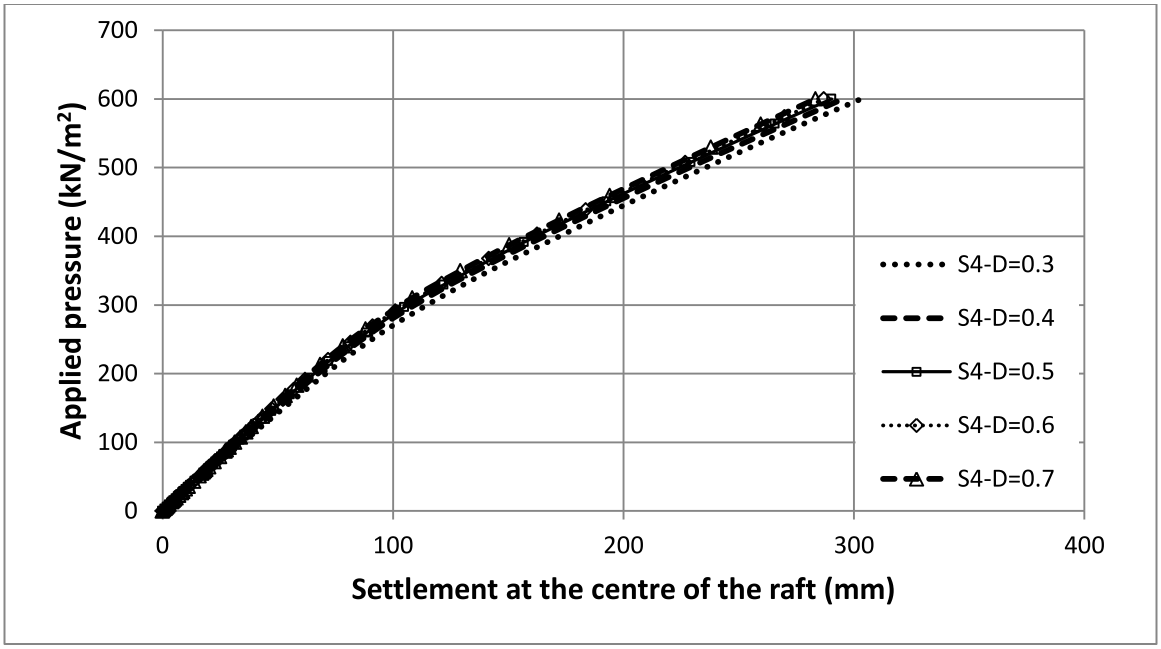

Fig. 3.22: Effect of pile diameter on the load-settlement relationship of piled-raft supported by 4×4 pile group

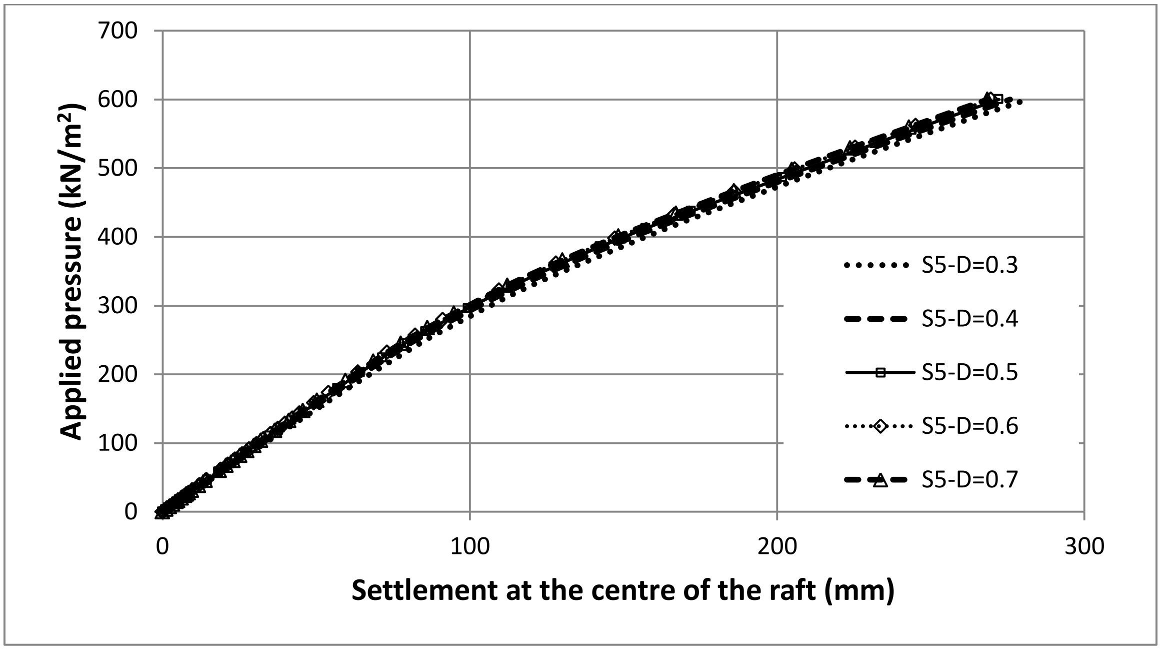

Fig. 3.23: Effect of pile diameter on the load-settlement relationship of piled-raft supported by 5×5 pile group

The number of the piles and the size of the pile diameter have considerable effect on the load sharing between the piles and the raft as shown in Fig. 3.24. It is shown that as the number of the piles supporting the raft increases the load carried by the raft decreases. This can be attributed to the increase in the stiffness of the pile group with the increase in the number of piles.

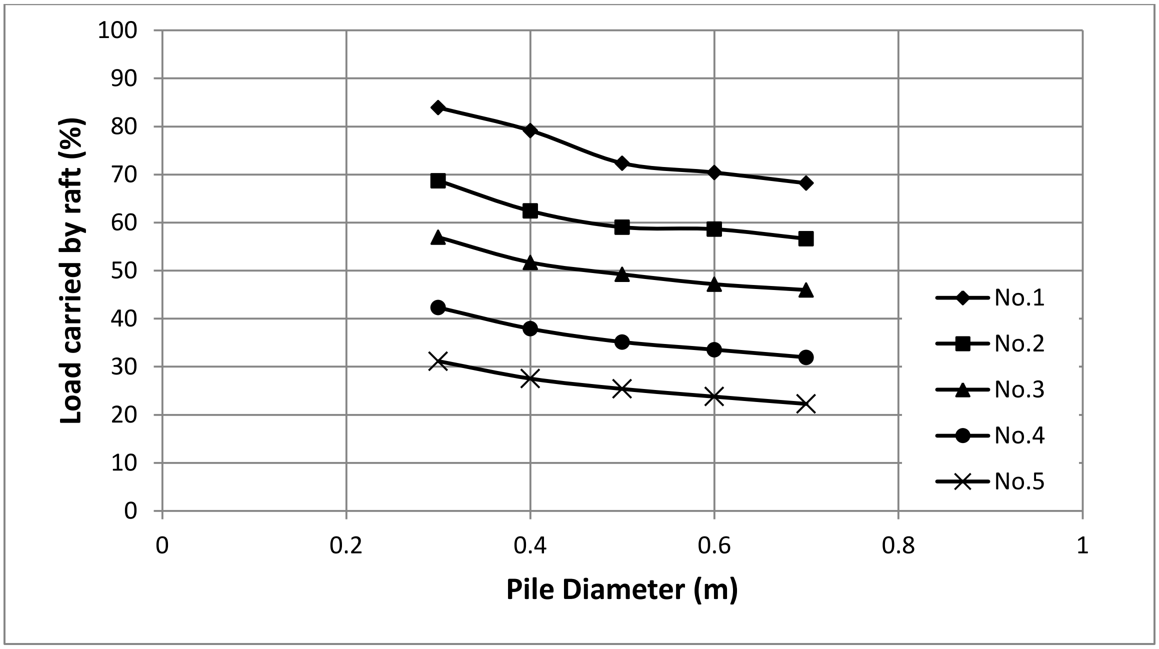

Fig. 3.24: Effect of pile diameter on the load sharing between the raft and piles

It can be seen that the larger the pile diameter the smaller the load carried by the raft. This effect can be attributed to the increase in the end bearing resistance of the pile as the cross-section of the pile increases. Although the settlement of the raft does not significantly increases with decreasing pile diameter, the load carried by the raft is significantly affected by the change in pile diameter due to decreasing differential settlement as pile diameter increase. It can be stated that for homogenous sand soil the load carried by the raft increases as the settlement increases. However, Vasquez et al.

(2006) reported an opposite result for piled-raft foundations on layered soil with a layer of stiff clay to a depth of about 5 m under the raft. They observed that the load carried by the raft decreases as the settlement of the piled-raft increases. It can be argued that the soil type and strength supporting the raft could affect the trend of the contribution of the raft to the load carrying capacity with the increase in the settlement level of the piled-raft foundation.

The decrease of the load carried by the raft with the increase in pile diameter becomes less as the number of piles increases because as the number of piles increases the change in the settlement of the piled-raft becomes smaller as can be seen in Figs. 3.19 to 3.23. It can be observed that for the piled-raft supported by a small number of piles the effect of pile diameter on the load carried by the raft becomes small for pile diameters greater than 0.5 m as shown in Fig. 3.24.

3.4.4 Effect of pile length

The effect of the pile length on the load-settlement relationship of piled-raft foundations supported by a single pile, 2×2, 3×3, 4×4 and 5×5 pile groups is shown in Figs. 3.25 to 3.29. It can be seen that before the yielding point of the system the stiffness of the piled-raft system increases as the length of the pile increases and it becomes larger as the number of the piles supporting the raft increases. A similar observation regarding the effect of pile length on settlement was reported by other researchers. Rabiei (2009) observed that the settlement of piled-raft foundations decreases as the length of the piles increases. Similarly, Seo et al. (2003) observed that the total settlement of piled-raft foundations on clay soil reduced as pile length increased.

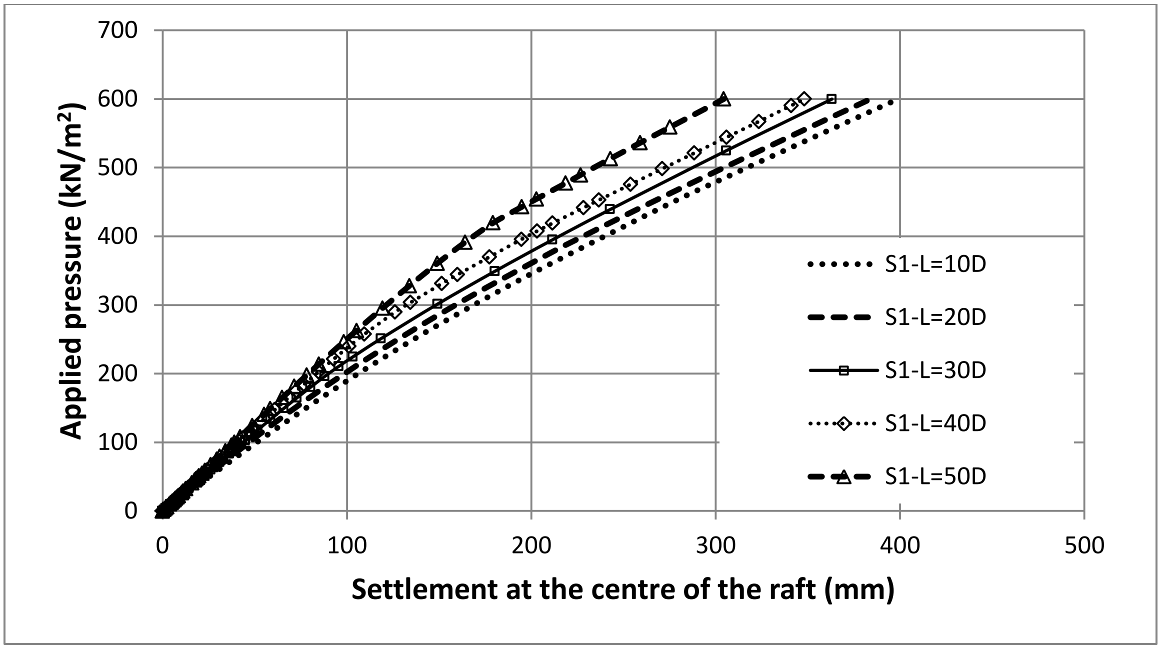

Fig. 3.25: Effect of pile length on the load-settlement relationship of piled-raft supported by single pile

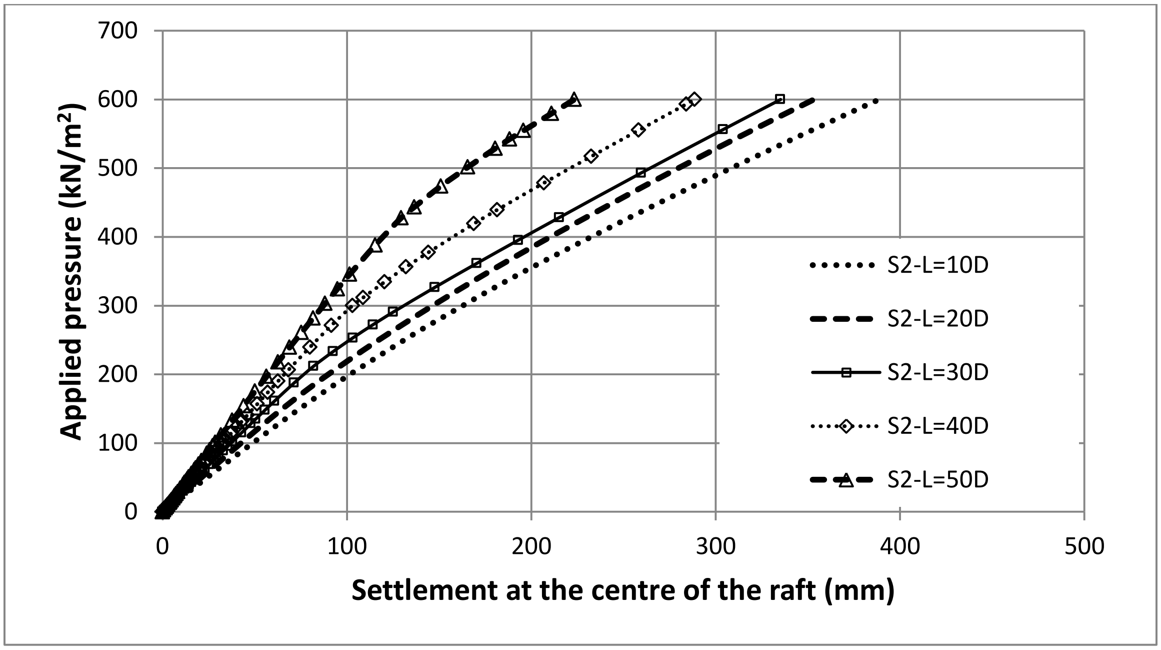

Fig. 3.26: Effect of pile length on the load-settlement relationship of piled-raft supported by 2×2 pile group

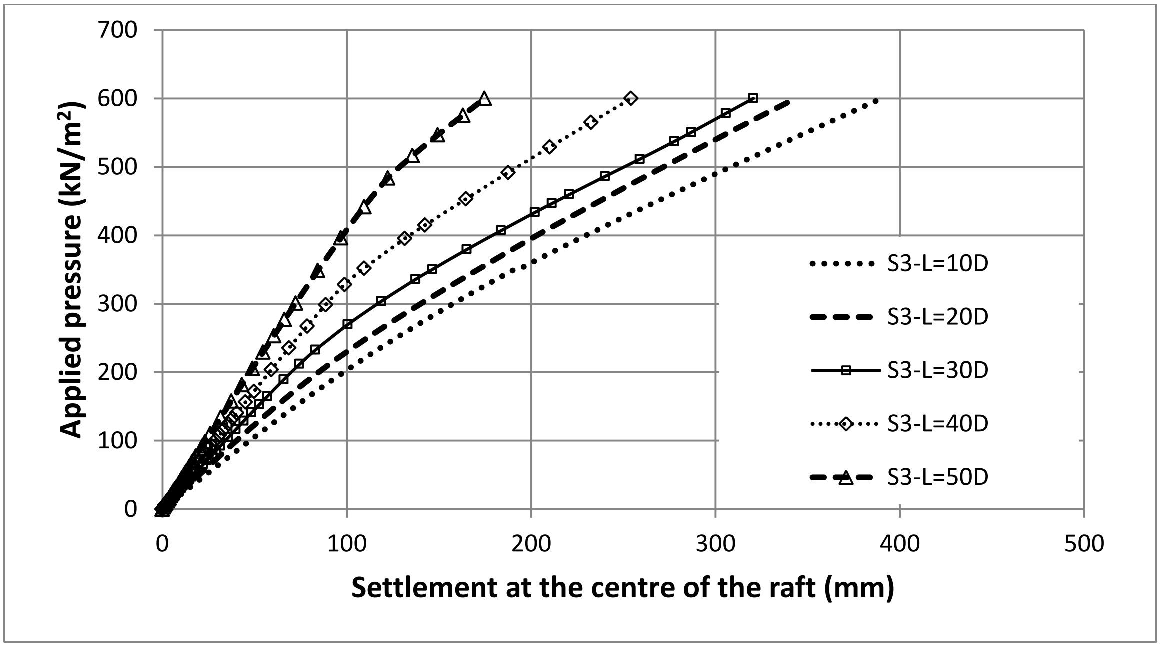

Fig. 3.27: Effect of pile length on the load-settlement relationship of piled-raft supported by 3×3 pile group

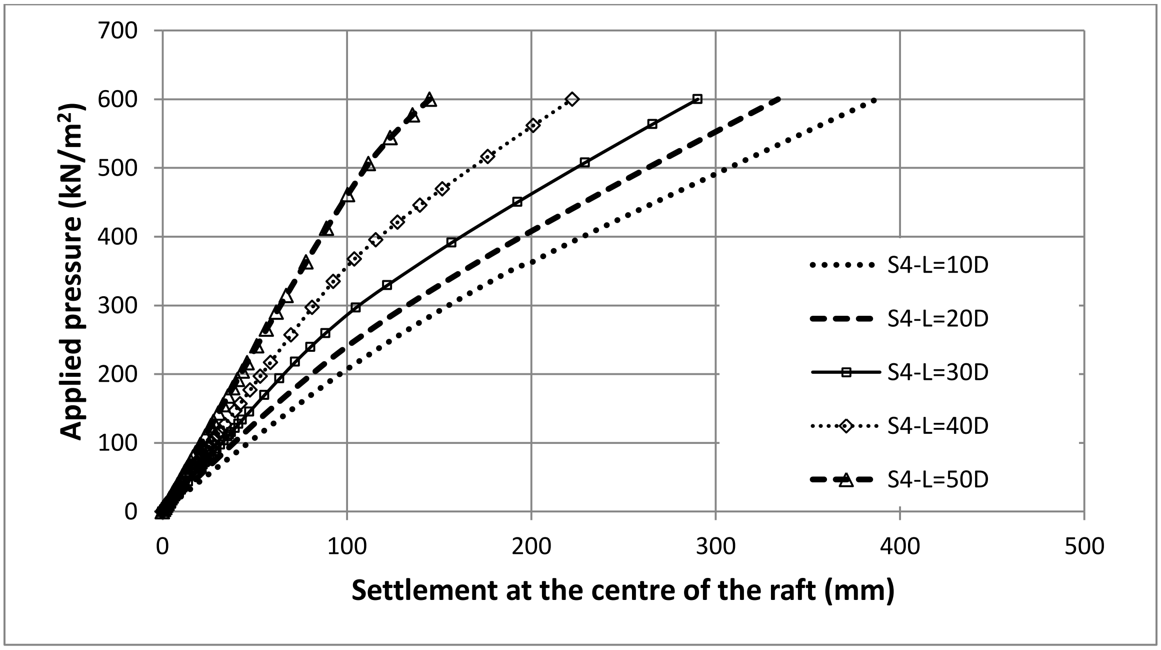

Fig. 3.28: Effect of pile length on the load-settlement relationship of piled-raft supported by 4×4 pile group

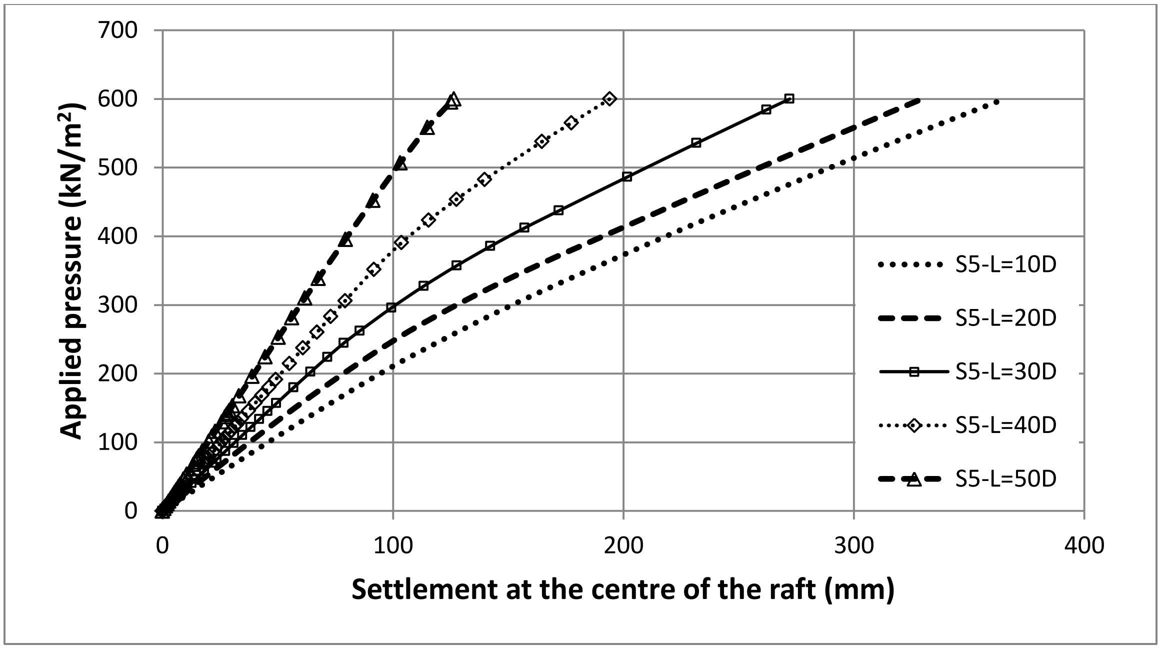

Fig. 3.29: Effect of pile length on the load-settlement relationship of piled-raft supported by 5×5 pile group

After the yielding point, the stiffness of the piled-raft foundation is not affected by the change in the pile length because it is equal to the stiffness of the raft alone. On the other hand, the bearing capacity of piled-raft foundations increases significantly with increasing the pile length before and after the yielding point. This observation is in agreement with observation from experimental studies. El Sawwaf (2010) reported that at the same settlement level, the bearing pressure of piled-raft foundations improves with increasing the pile length. Also, the load level at which the piled-raft system yields becomes higher for longer piles. This large effect of the pile length is a result of the enhancement in the shaft resistance of the piles when the pile length increases. The pile length has a significant effect on the load sharing between the raft and the piles as shown in Fig. 3.30.

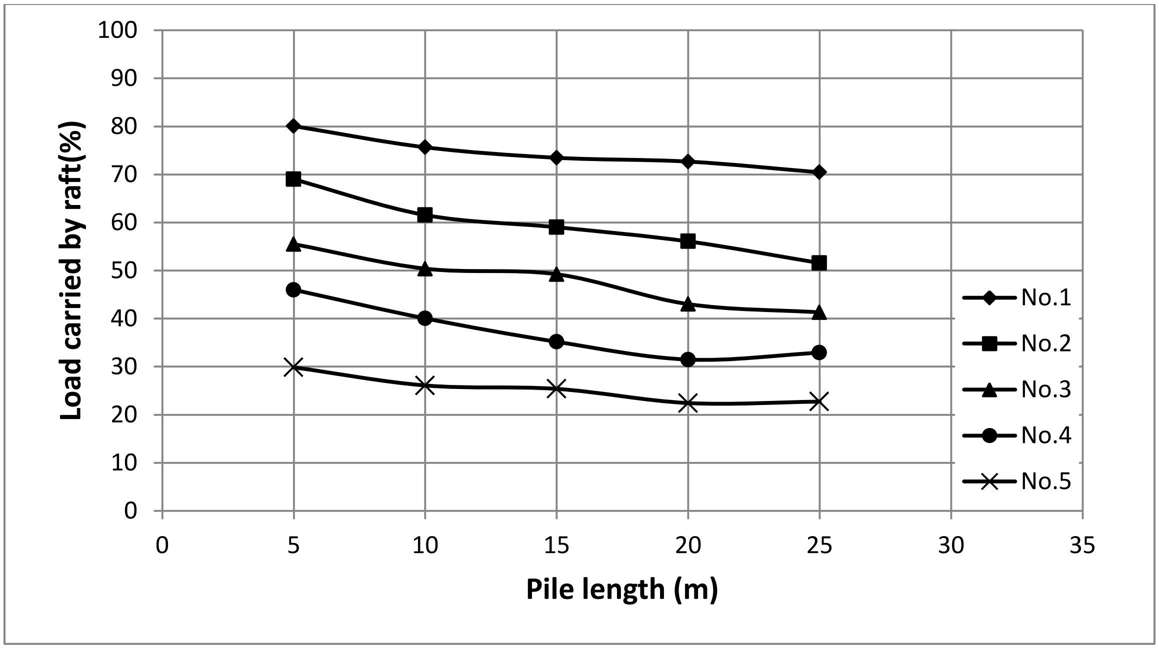

Fig. 3.30: Effect of pile length on the load sharing between the raft and piles

It can be seen that when the pile length and the number of the piles increase the load carried by the raft decreases. It should be noted here that as the pile length and the number of the piles decrease the settlement increases. This can be attributed to the increase in the stiffness of the pile group, which causes the contact pressure between the soil and the raft to reduce. Other researchers attribute the increase in the raft contribution to the increase in settlements. Comodromos et al. (2009) reported that as the settlement level increases the proportion of the load carried by the piles decreases due to the contribution of the raft. A similar observation regarding the effect of pile length on the load sharing was reported by other researchers. Rabiei (2009) observed that the proportion of the load carried by the piles increases as the length of the pile increases.

3.4.5 Effect of pile spacing

The pile spacing does not show any effect on the load-settlement relationship for piled-raft supported by a small number of piles. Figure. 3.31 shows that the pile spacing in the range from s=2D to s=6D has no effect on the load-settlement relationship of piled-raft supported by 2×2 pile group.

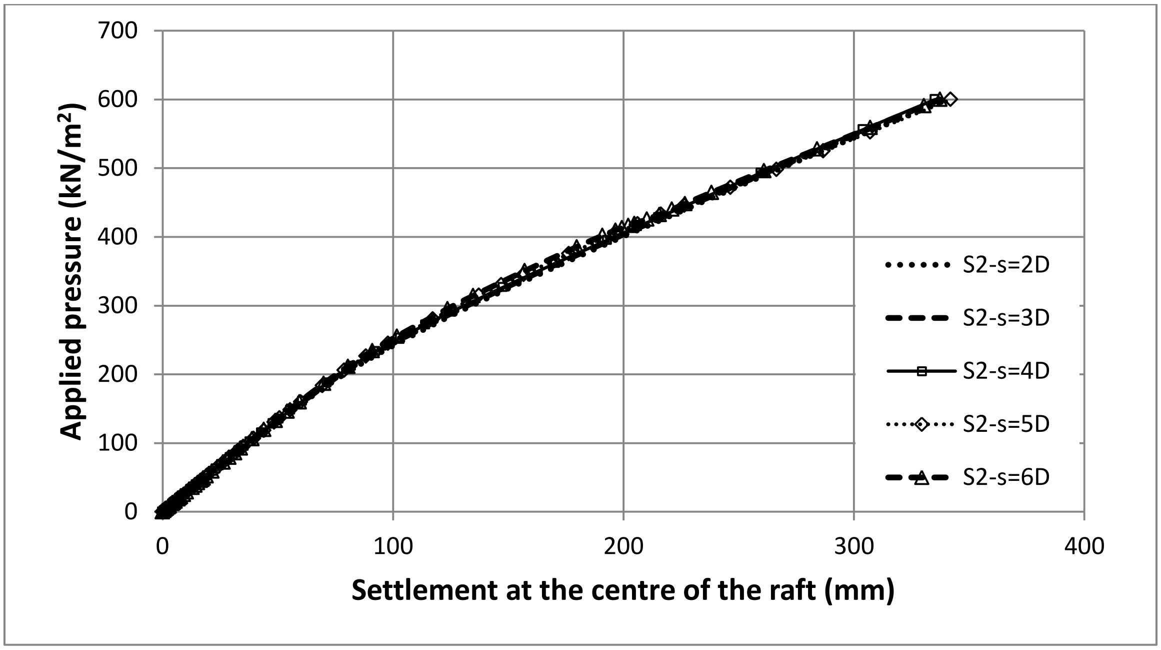

Fig. 3.31: Effect of pile spacing on the load-settlement relationship of piled-raft supported by 2×2 pile group

On the other hand, it can be seen from Figs. 3.32 to 3.34 that the spacing between the piles affects the load-settlement curve of piled-raft foundations supported by 3×3, 4×4, and 5×5 pile groups and its effect becomes more significant as the number of the piles supporting the raft increases. When the number of the piles supporting the raft increases and the pile spacing increases a better distribution of the piles under the raft will provide important enhancement to the performance of the piled-raft foundations.

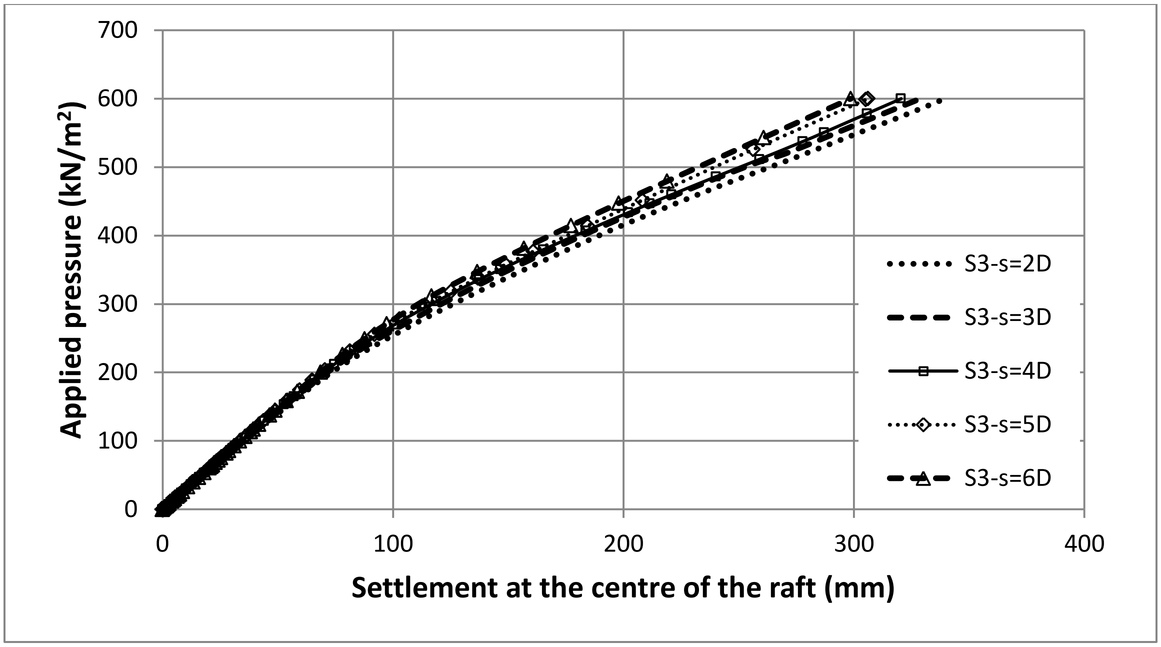

Fig. 3.32: Effect of pile spacing on the load-settlement relationship of piled-raft supported by 3×3 pile group

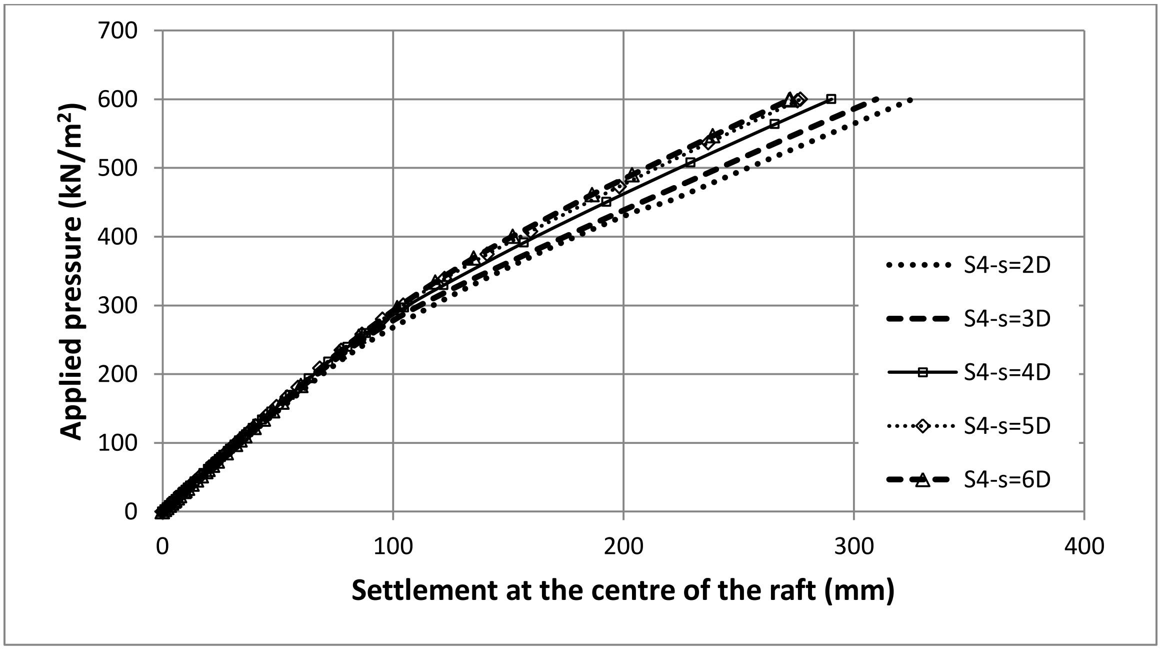

Fig. 3.33: Effect of pile spacing on the load-settlement relationship of piled-raft supported by 4×4 pile group

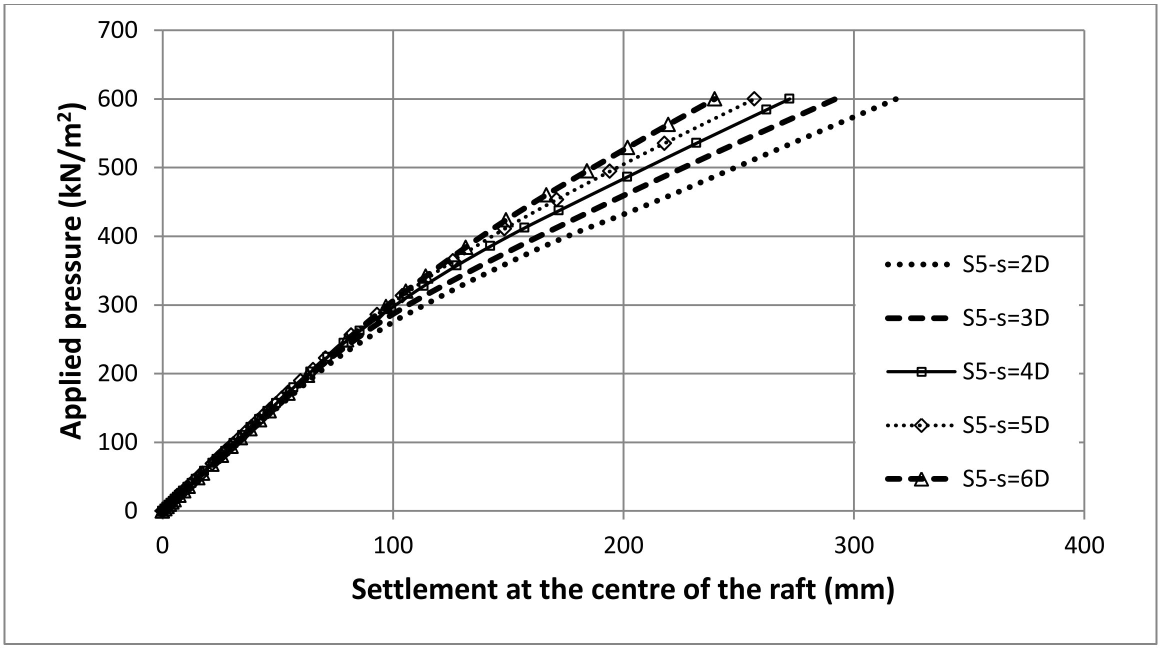

Fig. 3.34: Effect of pile spacing on the load-settlement relationship of piled-raft supported by 5×5 pile group

Before the yielding point of the system, the results showed that pile spacing had no effect on the stiffness of the piled-raft foundations. This may be attributed to the minor interaction effect between piles when the settlement is small. It should be noted that other studies reported a different trend for the effect of pile spacing at small settlements. Oh et al. (2008) reported that increasing pile spacing led to increasing settlement of piled-raft foundations. After the yielding point of the system, the effect of pile spacing on the stiffness of the foundations becomes large due to increasing pile capacity as pile spacing increase. Pile capacity increase is due to the reduction in the interaction effect among piles as pile spacing increase. Therefore, it can be stated that for piled-raft foundations on sand soil, pile spacing plays an important role only at large settlements whereas at working load conditions its effect is minor.

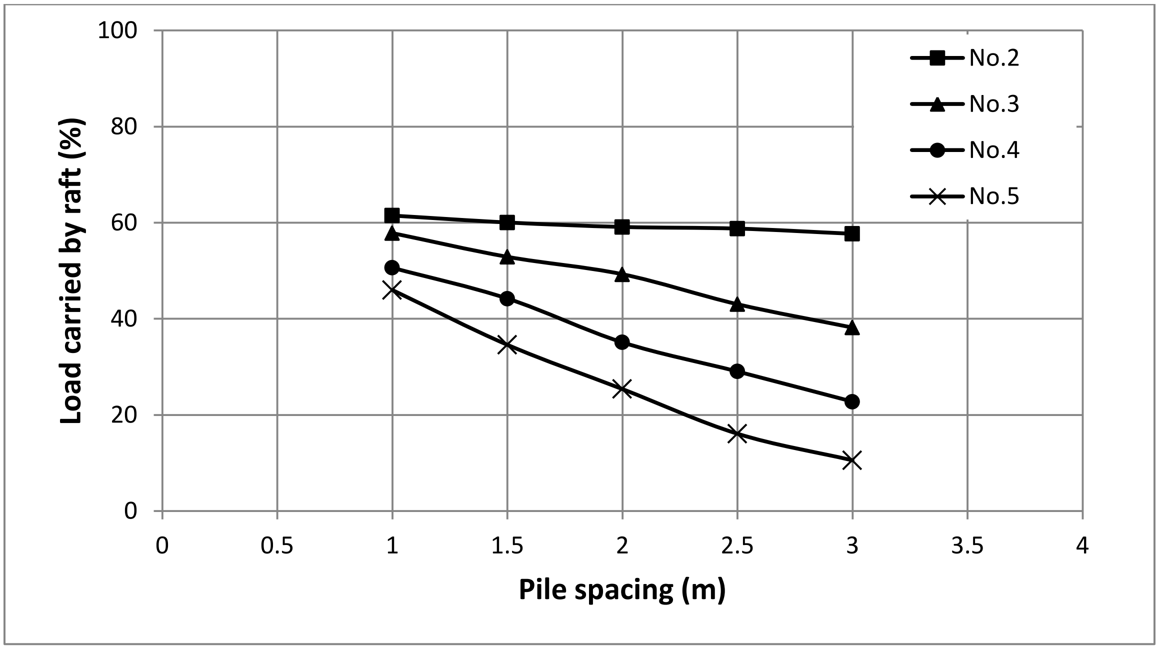

Fig. 3.35: Effect of pile spacing on the load sharing between the raft and piles

The effect of pile spacing on the load sharing between the piles and the raft is shown in Fig. 3.35. It can be seen that pile spacing does not affect the load sharing between piles and raft in case of piled-raft supported by 2×2 pile group whereas a great effect is observed on the cases of piled-raft supported by 3×3, 4×4 and 5×5 pile groups. Similar observation for the effect of pile spacing at small settlement levels was reported by other studies. Oh et al. (2008) observed that the pile spacing greatly affects the load sharing between the piles and the raft.

When the pile spacing is large, the stiffness of the pile group is large due to the reduction in the interaction between the piles as the pile spacing increases. In addition, good distribution of piles assists in reducing the differential settlement between the raft center and edge. However, when the pile spacing is small, all piles are located under the center of the raft. In this case, there will be a large difference between the settlement at the raft center and edge. The settlement at the raft edge will be large and hence the contact stress between the raft and the soil will be large as well. Other studies have shown that when the piles are close to the edge of the raft they take more load than the piles at the center of the raft. Singh and Singh (2008) observed that the contact pressure at the edge of the raft is larger than that at the center of the raft.

3.4.6 Effect of modulus of elasticity of piles

Figures 3.36 to 3.40 show that the modulus of elasticity of the piles has no effect on the load-settlement relationship of the piled-raft foundation for all cases at small or large settlement levels.

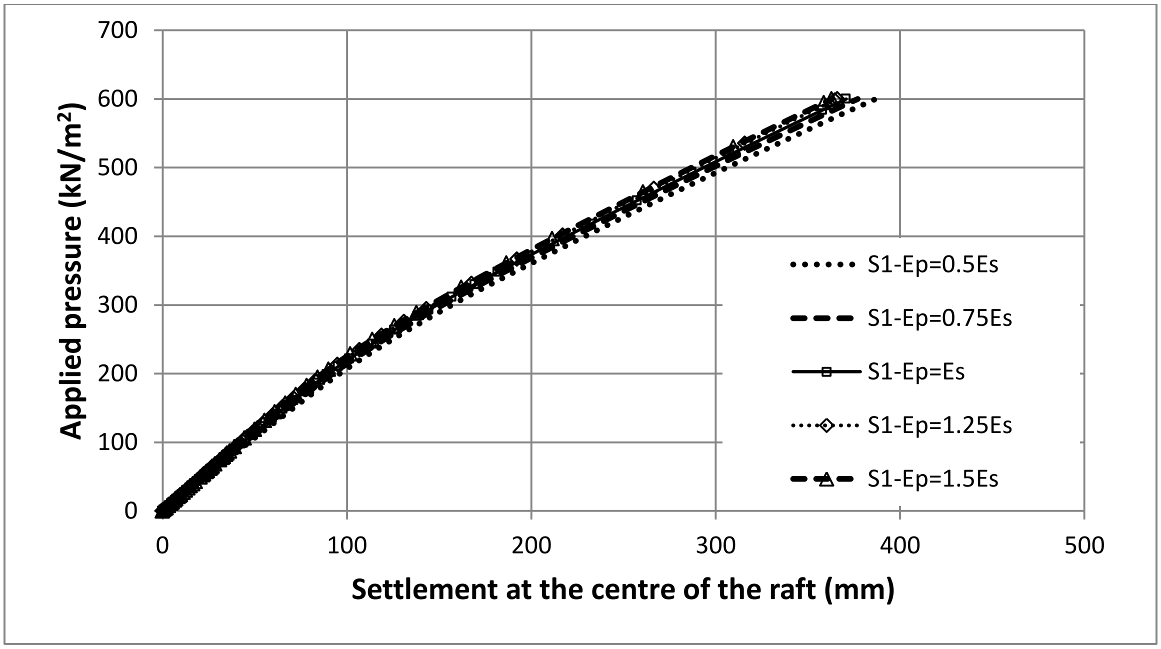

Fig. 3.36: Effect of the modulus of elasticity of the piles on the load-settlement relationship of piled-raft supported by single pile

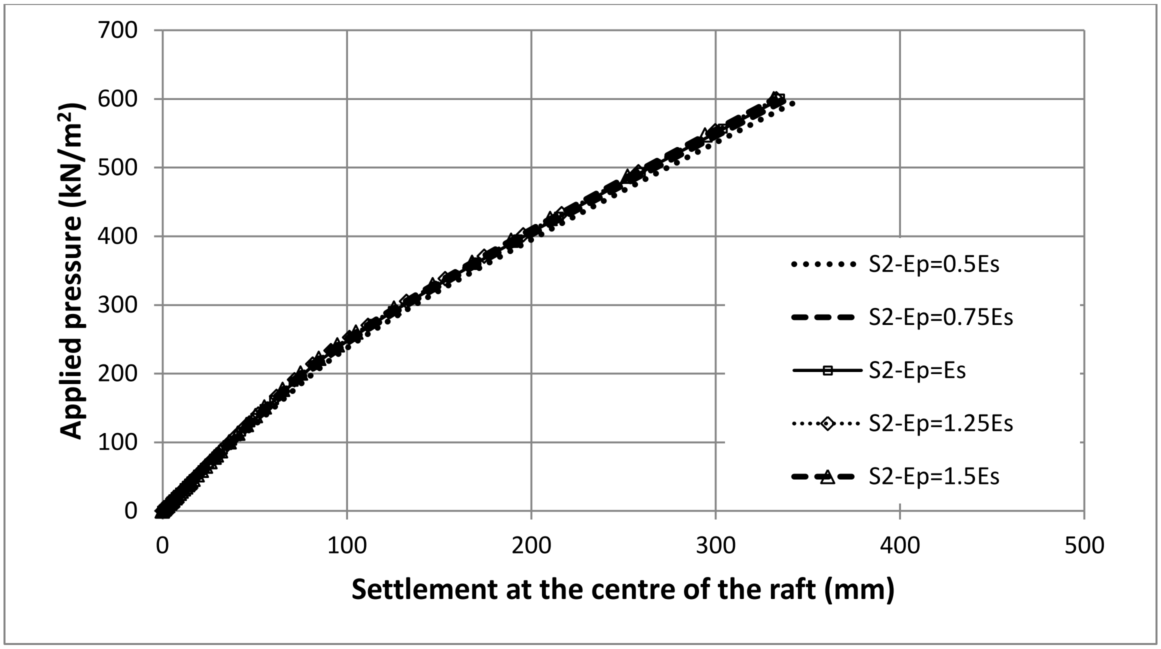

Fig. 3.37: Effect of the modulus of elasticity of the piles on the load-settlement relationship of piled-raft supported by 2×2 pile group

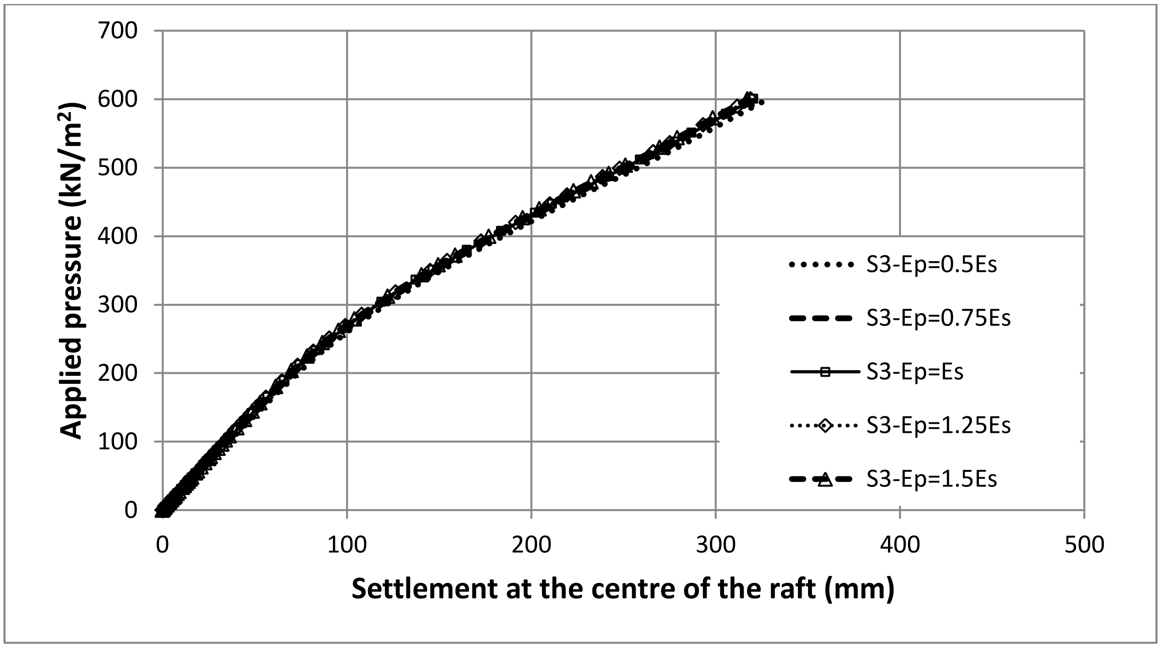

Fig. 3.38: Effect of the modulus of elasticity of the piles on the load-settlement relationship of piled-raft supported by 3×3 pile group

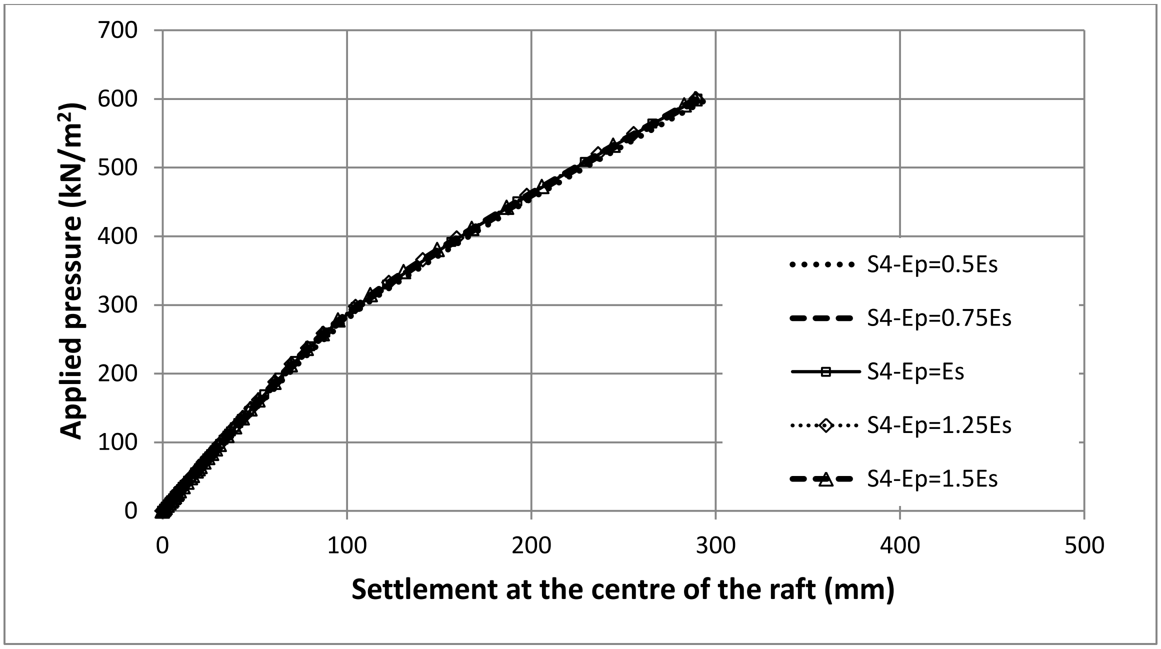

Fig. 3.39: Effect of the modulus of elasticity of the piles on the load-settlement relationship of piled-raft supported by 4×4 pile group

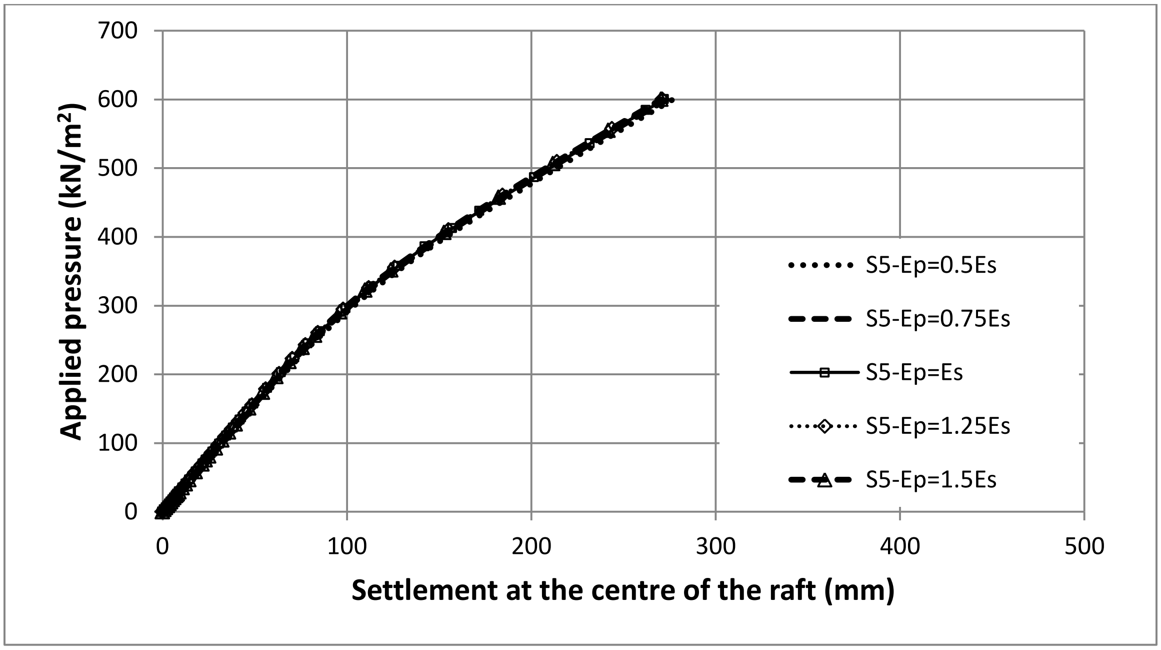

Fig. 3.40: Effect of the modulus of elasticity of the piles on the load-settlement relationship of piled-raft supported by 5×5 pile group

The modulus of elasticity of the piles showed a small effect on the load sharing between the piles and the raft for the piled-raft supported by 2×2 pile group whereas its effect diminishes as the number of the piles supporting the raft increases as can be seen from Fig. 3.41. However, with the increase in the number of the piles supporting the raft the load carried by the raft decreases significantly. It can be argued that because the modulus of elasticity of the piles has no effect on the load transfer in the piled-raft foundation, its effect on the load-settlement curve and load sharing between the raft and the piles is not important.

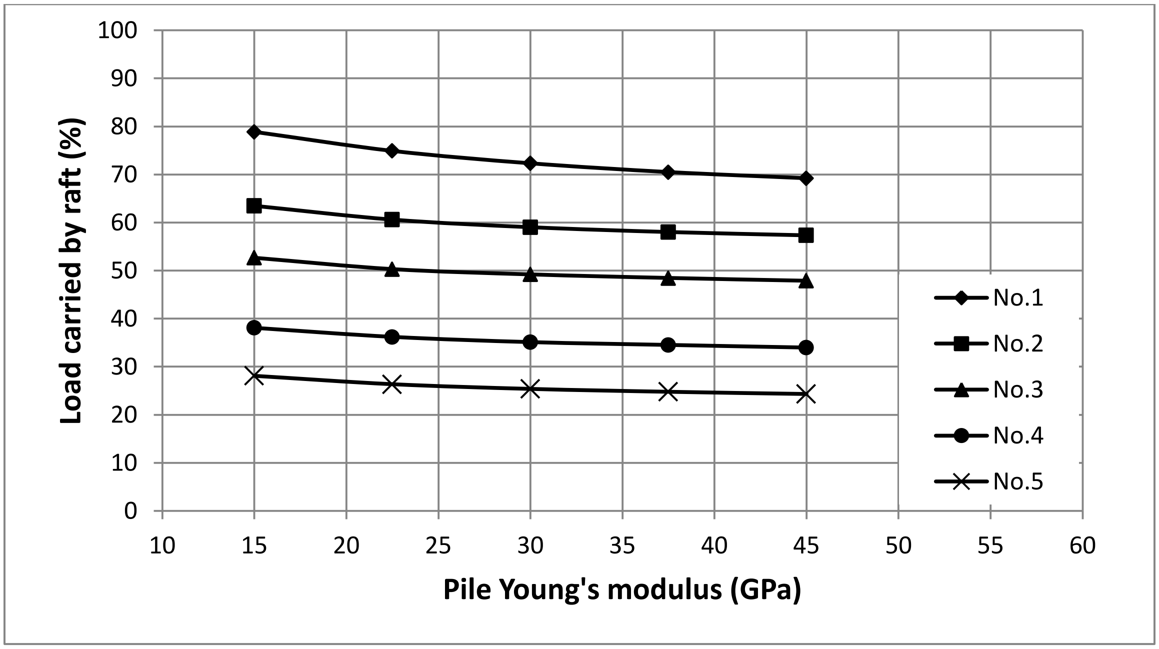

Fig. 3.41: Effect of the modulus of elasticity of the piles on the load sharing between the raft and piles

3.4.7 Effect of the reduction factor of the strength of the pile-soil interface

The effect of reducing the strength of the pile-soil interface region by using reduction factor, *r*, for reducing the soil strength and stiffness parameters at the pile soil interface region on the load-settlement relationship is shown in Figs. 3.42 to 3.46. It can be seen that the reduction factor of the strength of the pile-soil interface region has no effect on the load-settlement relationship of the piled-raft foundation for all cases. In addition, Fig. 3.47 shows that the reduction factor of the strength of the pile-soil interface has no effect on the load sharing between the piles and the raft. Similar trends for the effect of the strength of the pile-soil interface region were observed for piled-rafts supported by a single pile or pile groups of different sizes.

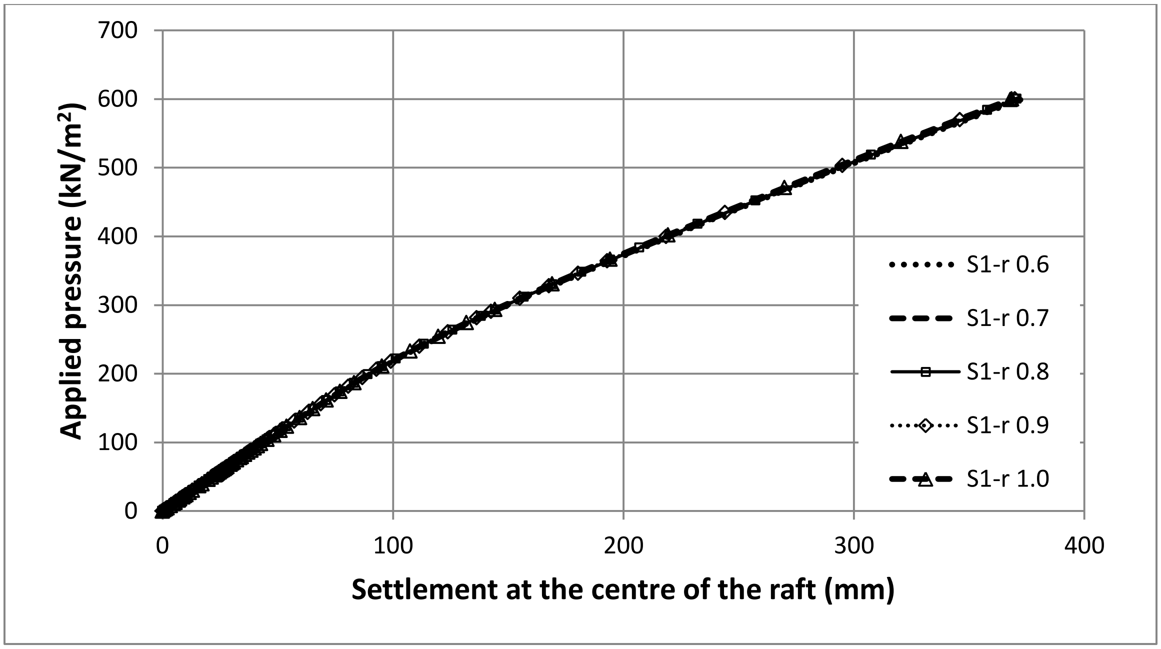

Fig. 3.42: Effect of the reduction factor of the pile-soil interface strength on the load-settlement relationship of piled-raft supported by single pile

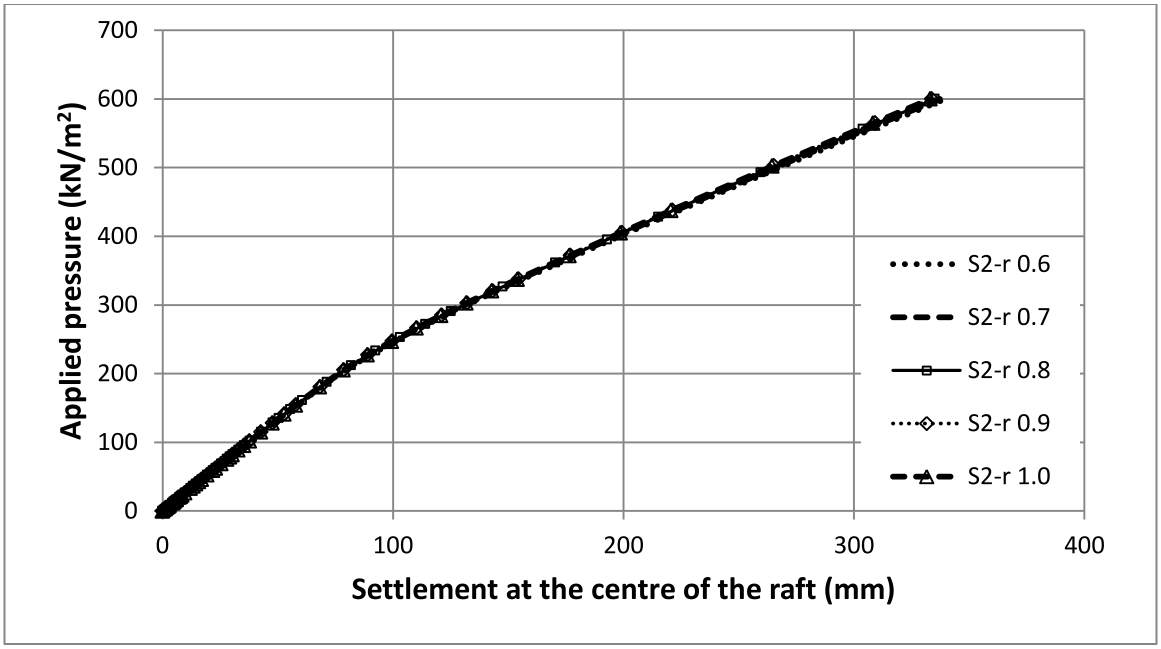

Fig. 3.43: Effect of the reduction factor of the pile-soil interface strength on the load-settlement relationship of piled-raft supported by 2×2 pile group

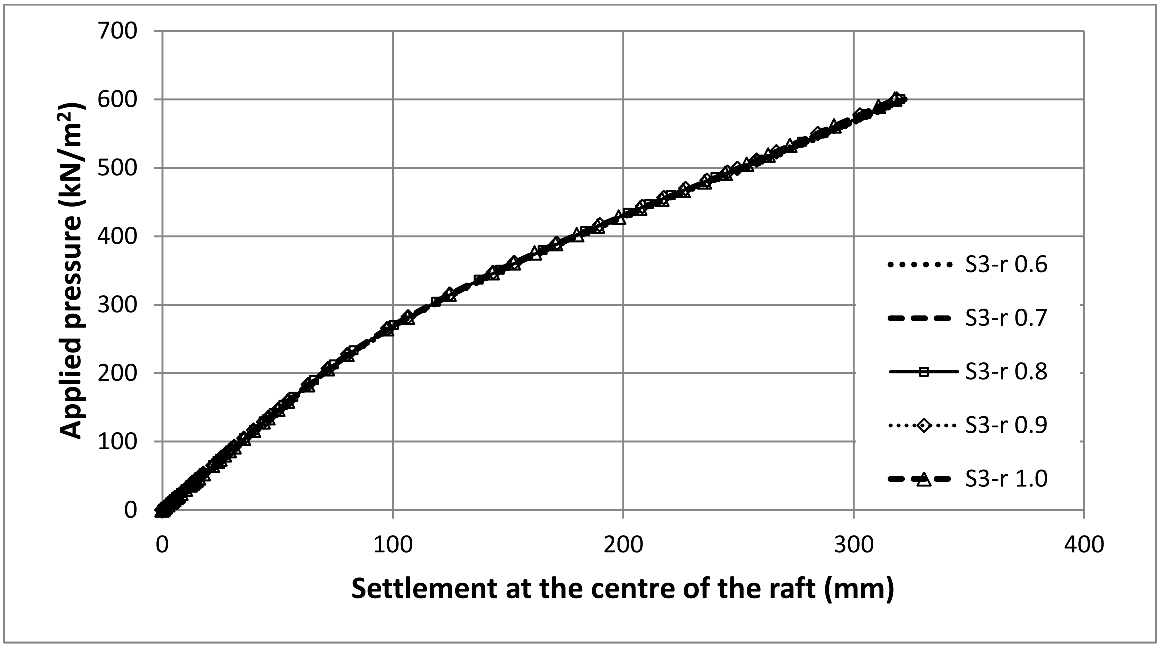

Fig. 3.44: Effect of the reduction factor of the pile-soil interface strength on the load-settlement relationship of piled-raft supported by 3×3 pile group

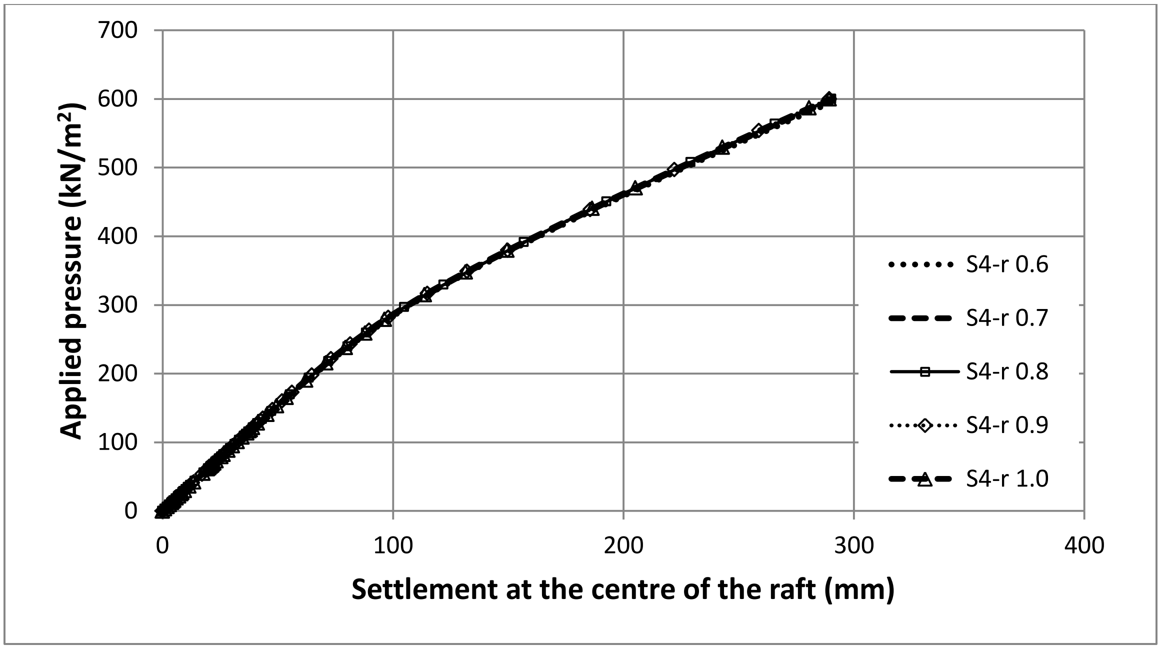

Fig. 3.45: Effect of the reduction factor of the pile-soil interface strength on the load-settlement relationship of piled-raft supported by 4×4 pile group

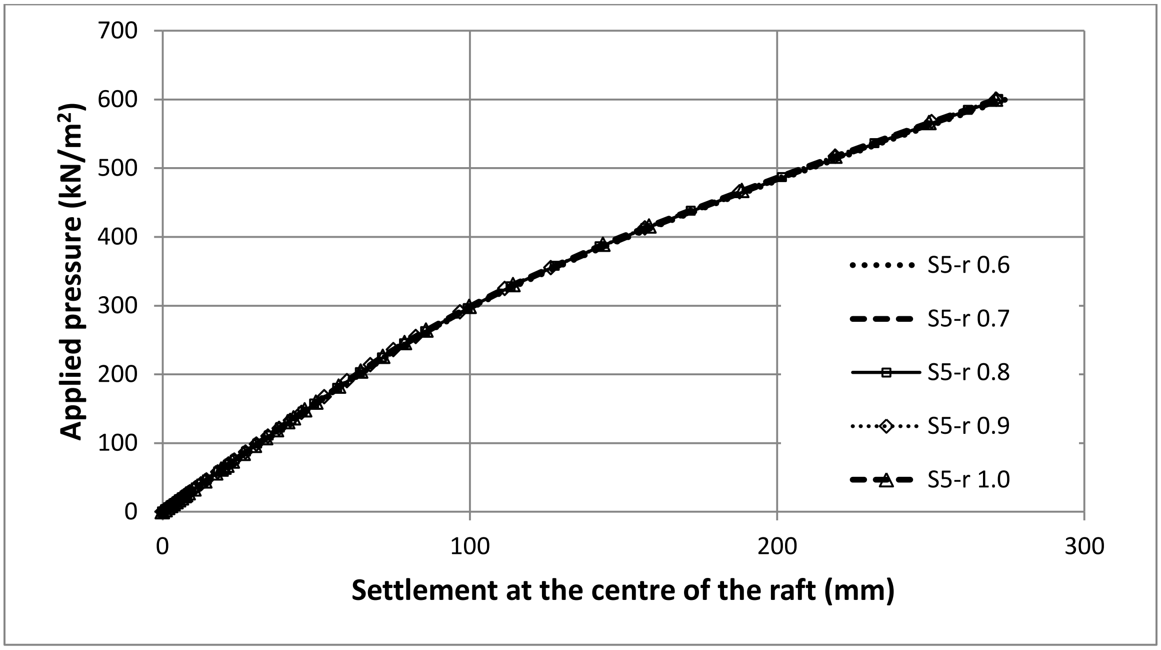

Fig. 3.46: Effect of the reduction factor of the pile-soil interface strength on the load-settlement relationship of piled-raft supported by 5×5 pile group

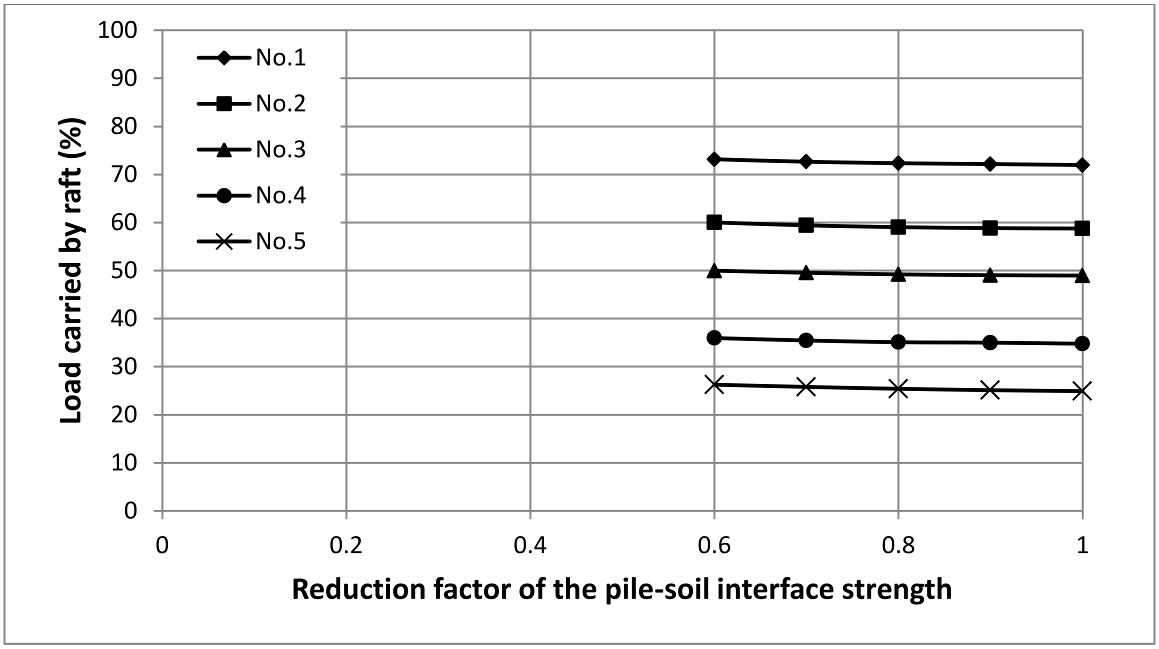

Fig. 3.47: Effect of the reduction factor of the pile-soil interface strength on the load sharing between the raft and piles

3.4.8 Effect of the modulus of elasticity of the soil

The modulus of elasticity of soil has a significant effect on the load-settlement relationship of piled-raft foundations on sand soil before and after the yielding point of the system as shown in Fig. 3.48 for piled-raft supported by a single pile. It can be seen that with the increase in the modulus of elasticity of the soil, the stiffness of the piled-raft system increases.

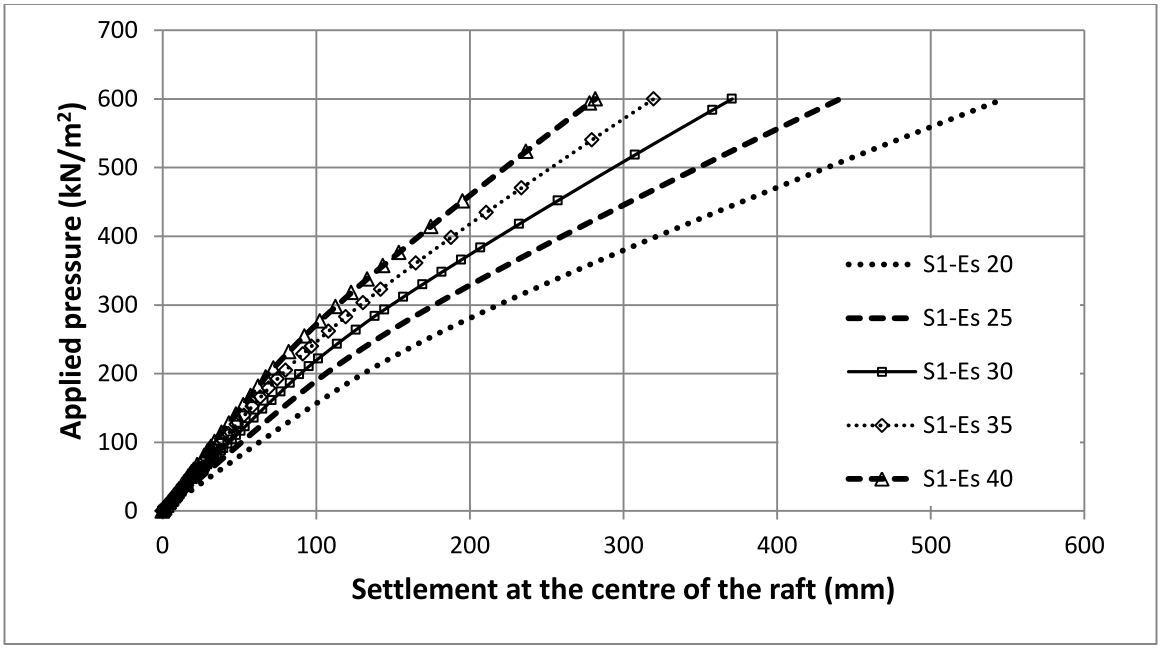

Fig. 3.48: Effect of the modulus of elasticity of the soil on the load-settlement relationship of piled-raft supported by single pile

Similar trends for the effect of the modulus of elasticity of soil were observed for the raft supported by pile group supports as shown in Figs. 3.49 to 3.52. The stiffness of the piled-raft system improved with increasing the modulus of elasticity of soil because increasing the modulus of elasticity of soil causes the stiffness of both the raft and the pile group to increase.

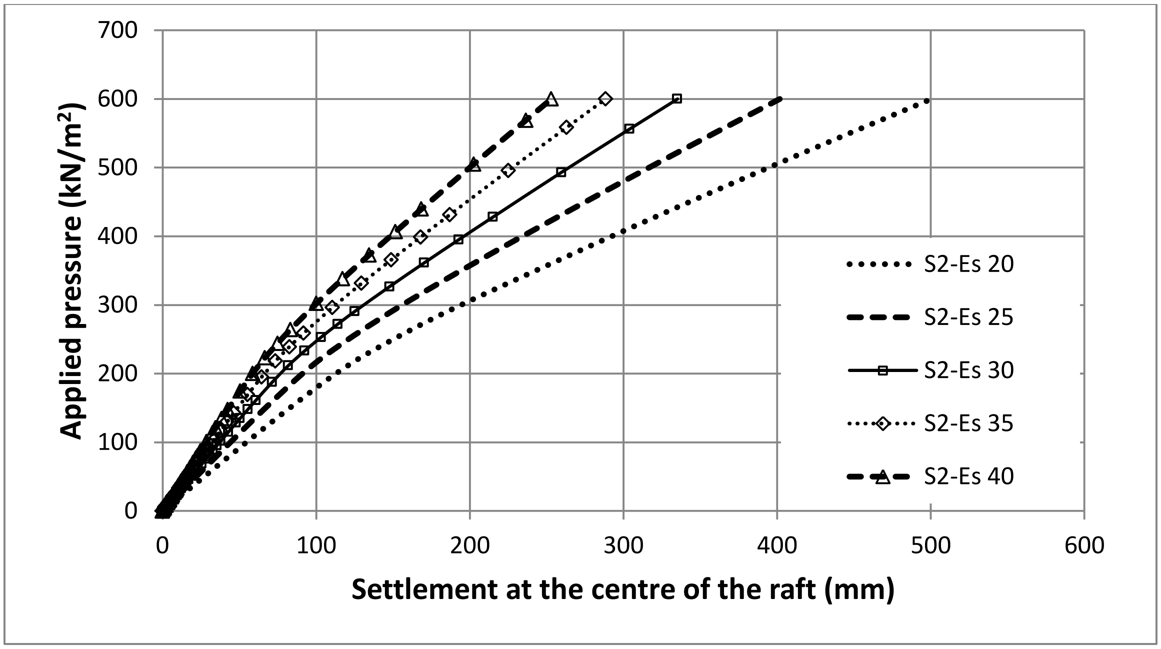

Fig. 3.49: Effect of the modulus of elasticity of the soil on the load-settlement relationship of piled-raft supported by 2×2 pile group

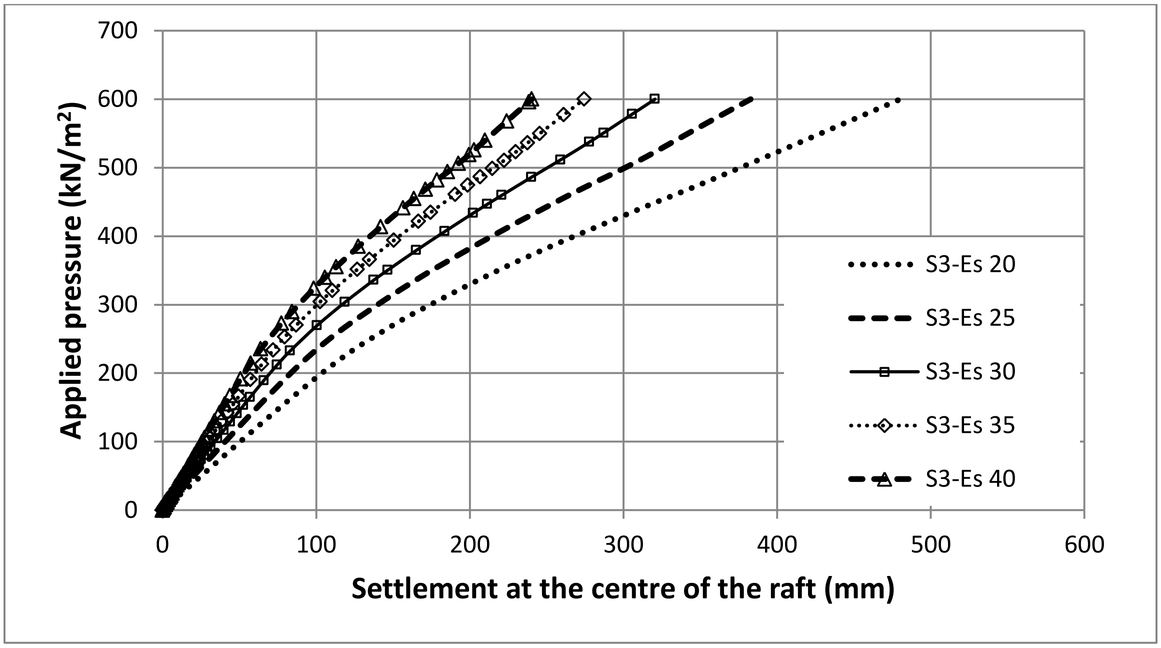

Fig. 3.50: Effect of the modulus of elasticity of the soil on the load-settlement relationship of piled-raft supported by 3×3 pile group

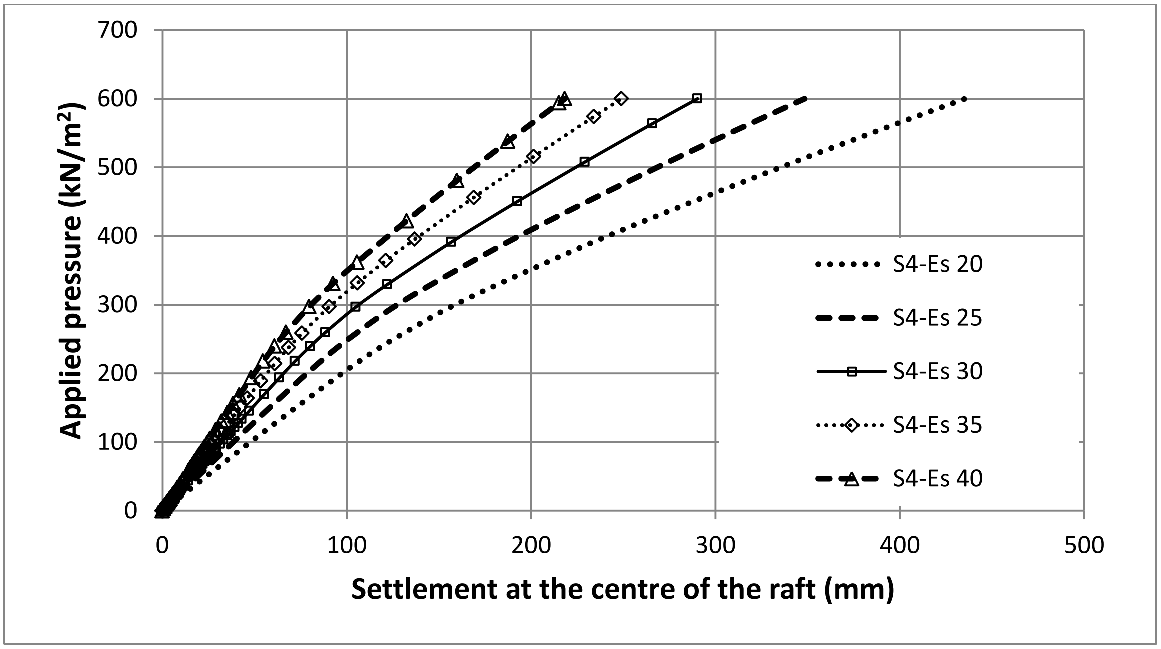

Fig. 3.51: Effect of the modulus of elasticity of the soil on the load-settlement relationship of piled-raft supported by 4×4 pile group

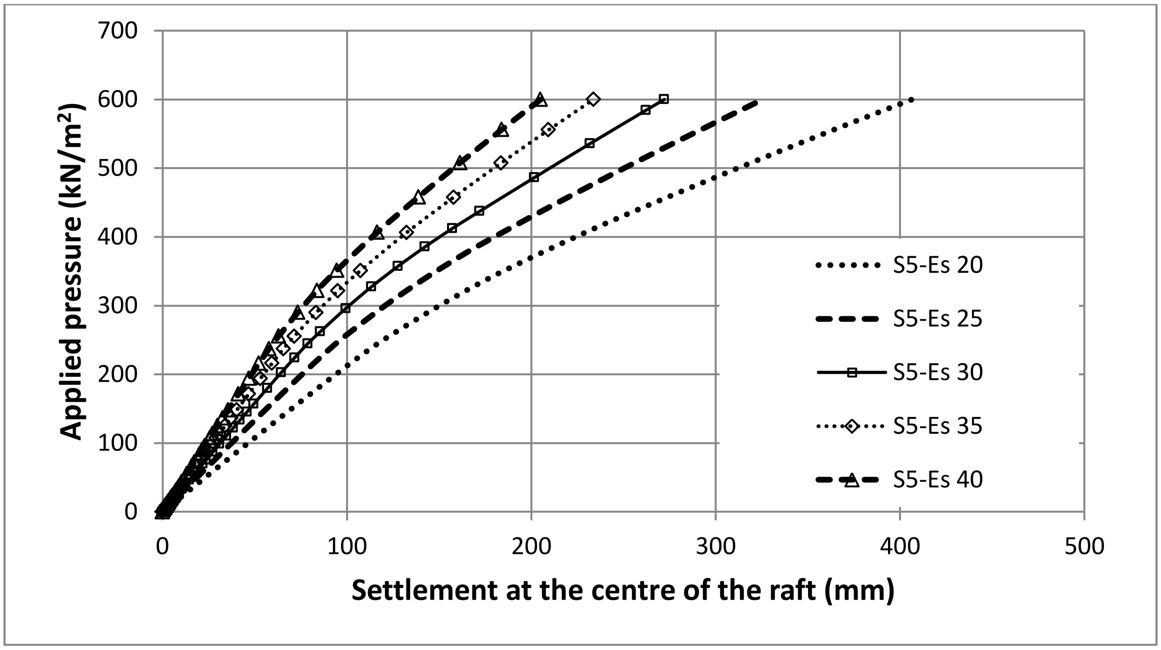

Fig. 3.52: Effect of the modulus of elasticity of the soil on the load-settlement relationship of piled-raft supported by 5×5 pile group

The stiffness of the piled-raft system improved with increasing the number of pile supporting the raft because as the number of the pile increases, the stiffness of the pile group increases accordingly. Other studies reported a similar observation regarding the effect of soil modulus of elasticity on the capacity of piled-raft foundations in clay soil. Singh and Singh (2008) observed from finite element analysis of piled raft foundations on clay soil that addition of even a small number of piles enhanced the capacity of the raft foundation and this enhancement effect is greater as the soil stiffness increases.

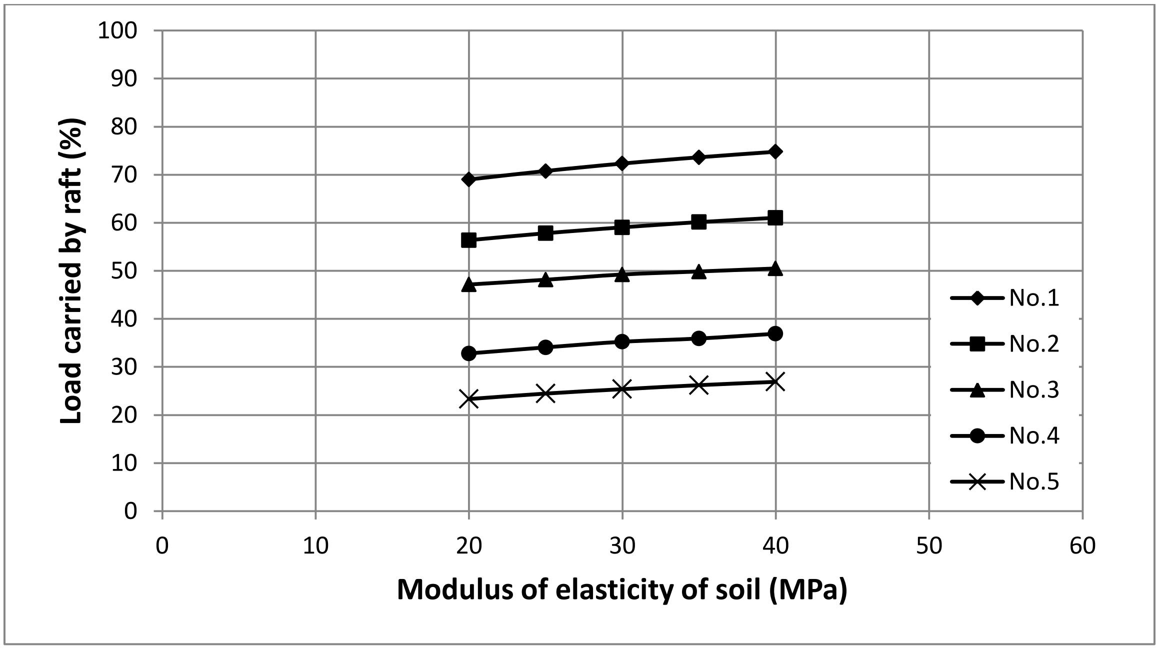

Fig. 3.53: Effect of the modulus of elasticity of the soil on the load sharing between the raft and piles

The effect of changing the modulus of elasticity of soil on the load sharing between the raft and the piles is shown in Fig. 3.53. The load carried by the raft increases slightly with the increase in the modulus of elasticity of soil. The load carried by the raft increases because for the same amount of settlement increasing the modulus of elasticity of soil causes the contact stresses below the raft to increase. The load carried by the raft decreases with the increase in the number of the piles supporting the raft because the stiffness of the pile group increases as the number of the piles increases. As a result, the contact pressure between the raft and soil decreases.

3.4.9 Effect of Poisson's ratio of the soil

Figures 3.54 to 3.58 show that the stiffness of the piled-raft foundations increases with the increase in the Poisson's ratio of the soil. It was observed that the effect of Poisson's ratio is significant at large settlements of the system whereas small effect can be seen at small settlements. It seems that the effect of Poisson's ratio on the stiffness of the system increases gradually with the increase of the settlement. Similar trends were observed whether a single pile or pile group support the raft.

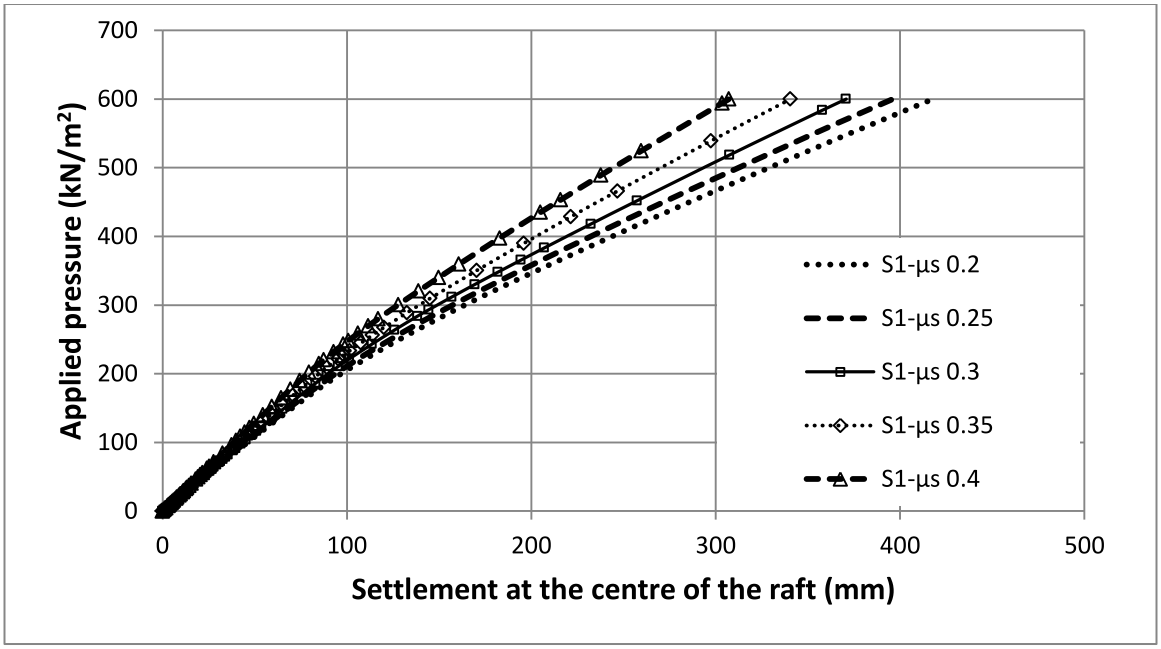

Fig. 3.54: Effect of Poisson's ratio of the soil on the load-settlement relationship of piled-raft supported by single pile

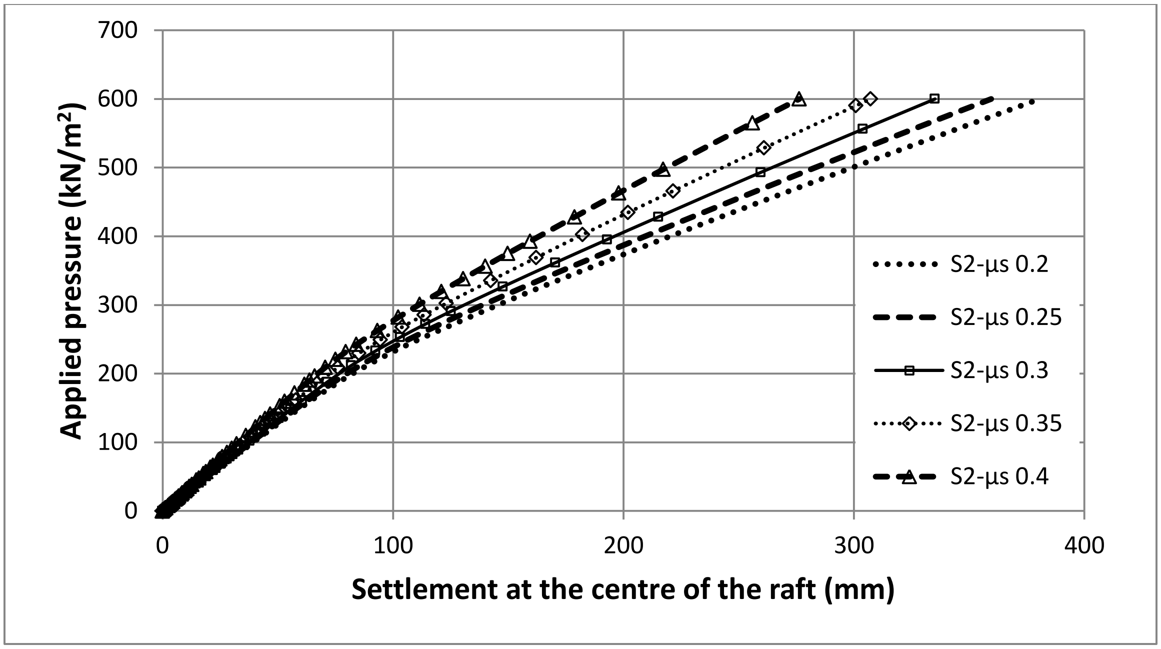

Fig. 3.55: Effect of Poisson's ratio of the soil on the load-settlement relationship of piled-raft supported by 2×2 pile group

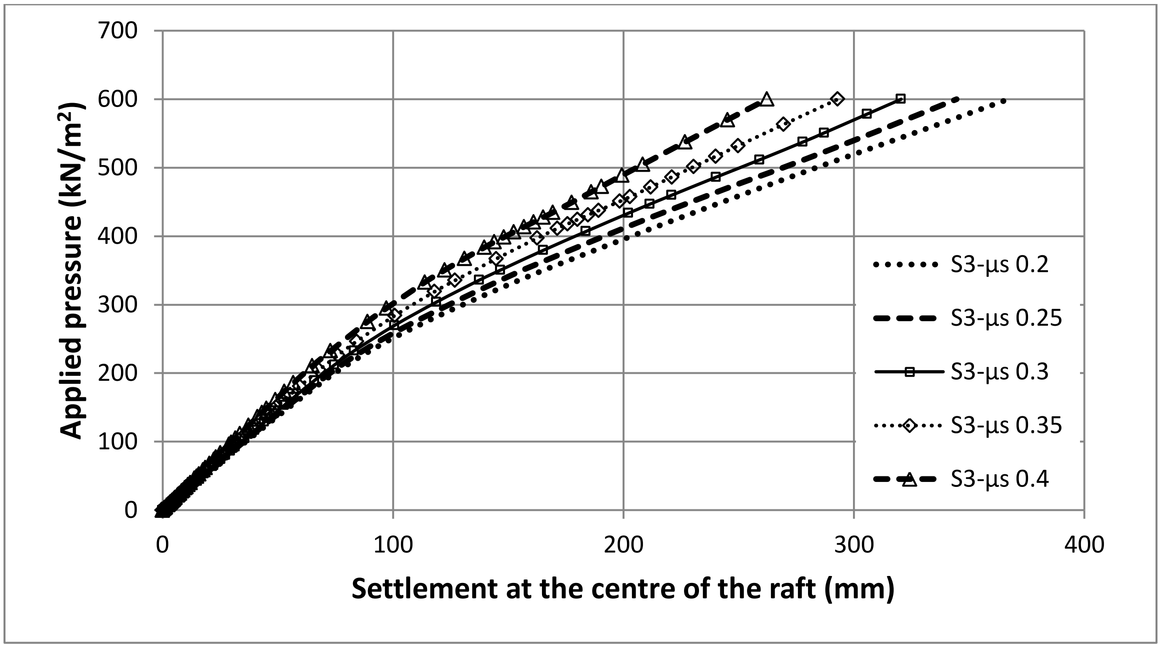

Fig. 3.56: Effect of Poisson's ratio of the soil on the load-settlement relationship of piled-raft supported by 3×3 pile group

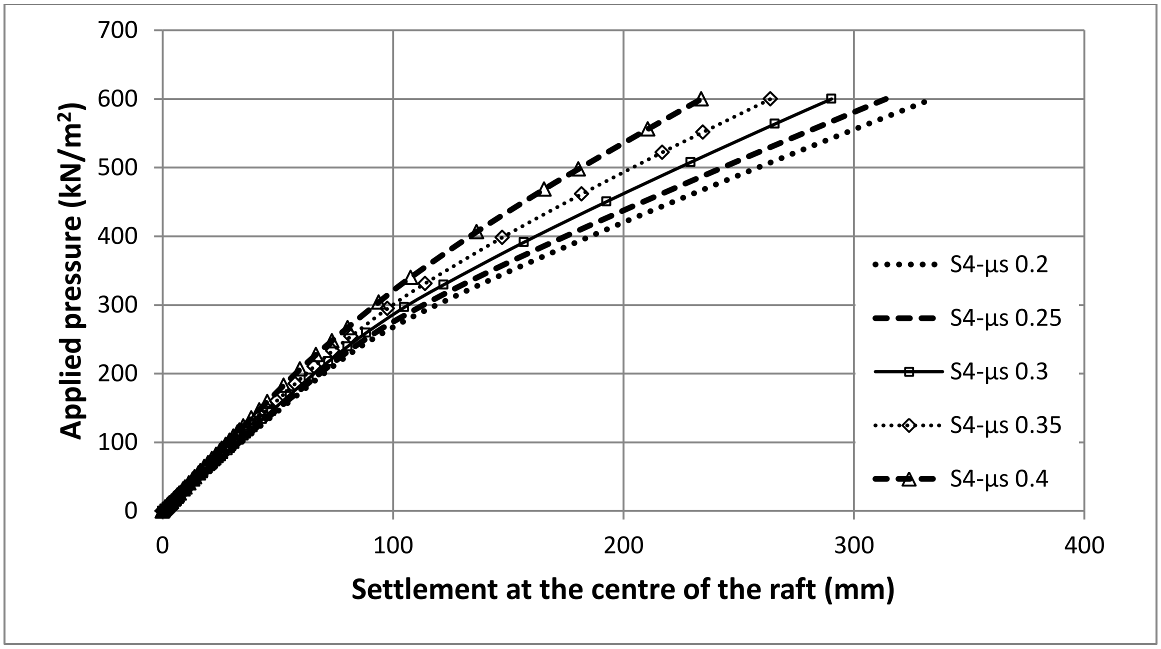

Fig. 3.57: Effect of Poisson's ratio of the soil on the load-settlement relationship of piled-raft supported by 4×4 pile group

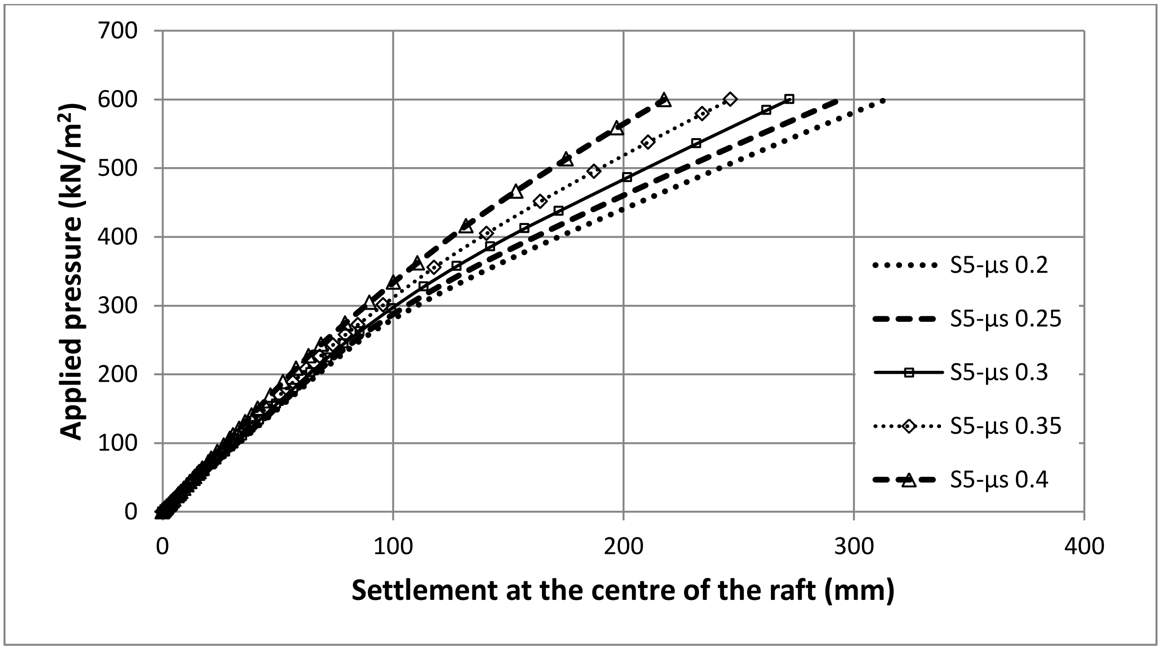

Fig. 3.58: Effect of Poisson's ratio of the soil on the load-settlement relationship of piled-raft supported by 5×5 pile group

The effect of the Poisson's ratio of the soil on the load sharing between the raft and the soil is shown in Fig. 3.59. It can be seen that the load carried by the raft increases slightly as the Poisson's ratio of the soil increases.

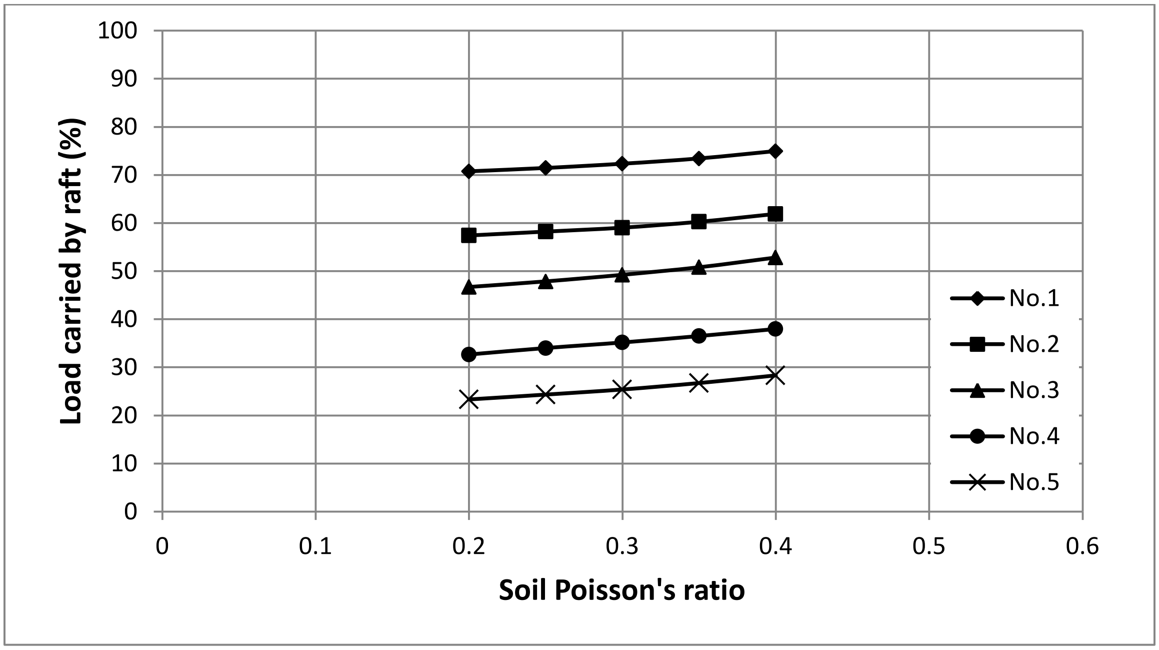

Fig. 3.59: Effect of Poisson's ratio of the soil on the load sharing between the raft and piles

3.4.10 Effect of the angle of internal friction of the soil

Figures 3.60 to 3.64 show that the angle of internal friction of soil does not affect the load-settlement curve at small settlements whereas it has significant effect at large settlements. It can be seen from that the stiffness of the piled-raft foundations after the yielding point increases significantly with increasing the friction angle of the soil. Increasing the number of the piles supporting the raft improves the stiffness of the piled-raft foundations because as the number of the piles increases, the stiffness of the pile group increases.

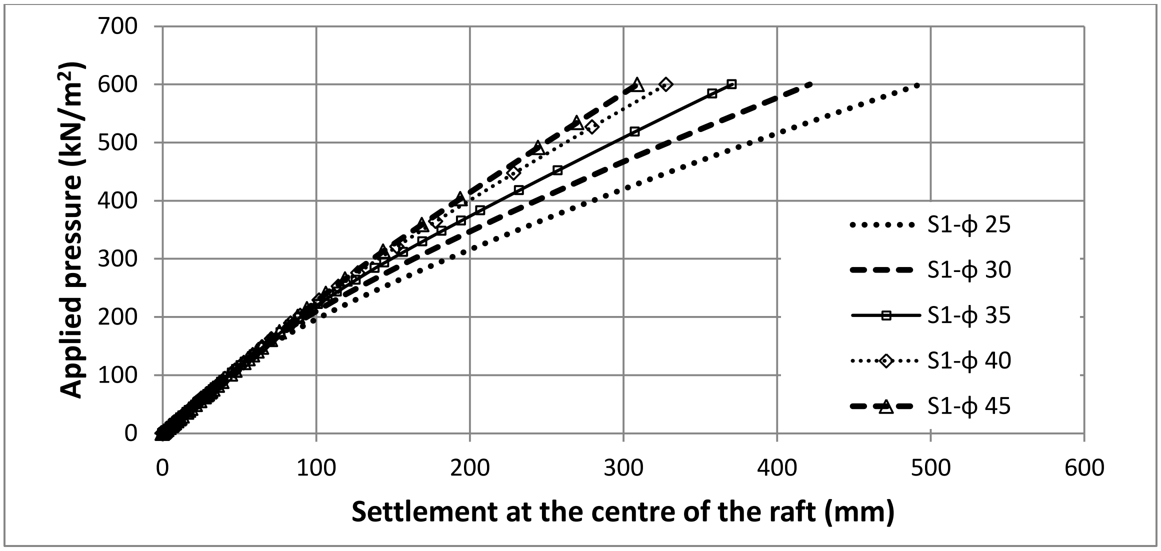

Fig. 3.60: Effect of the angle of internal friction of the soil on the load-settlement relationship of piled-raft supported by single pile

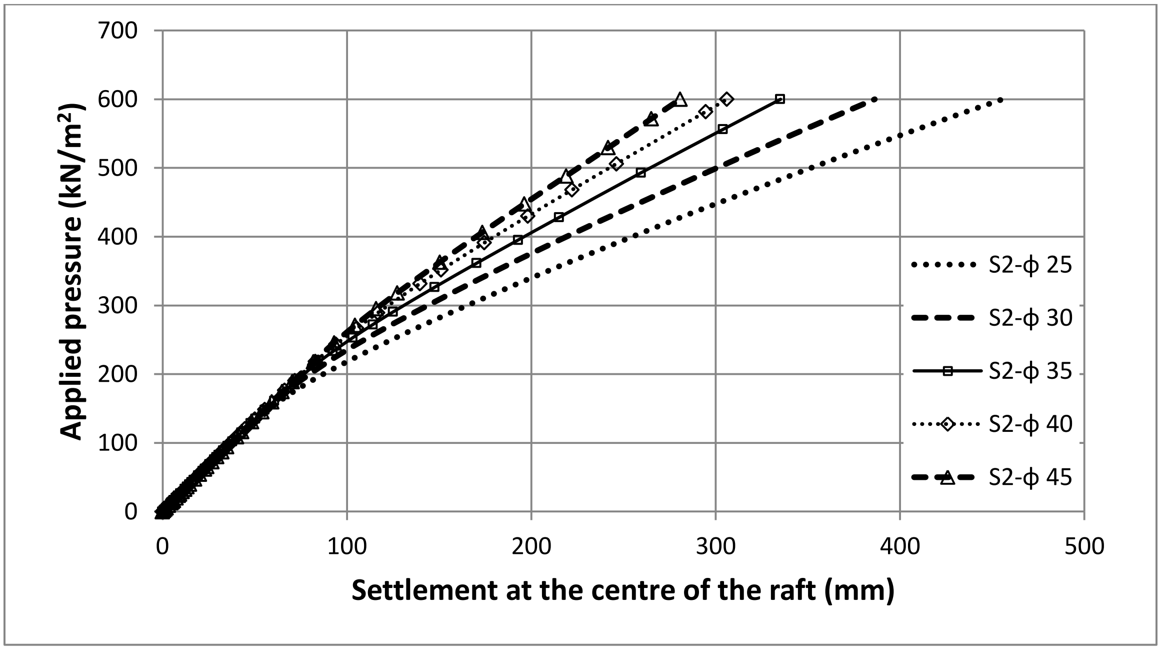

Fig. 3.61: Effect of the angle of internal friction of the soil on the load-settlement relationship of piled-raft supported by 2×2 pile group

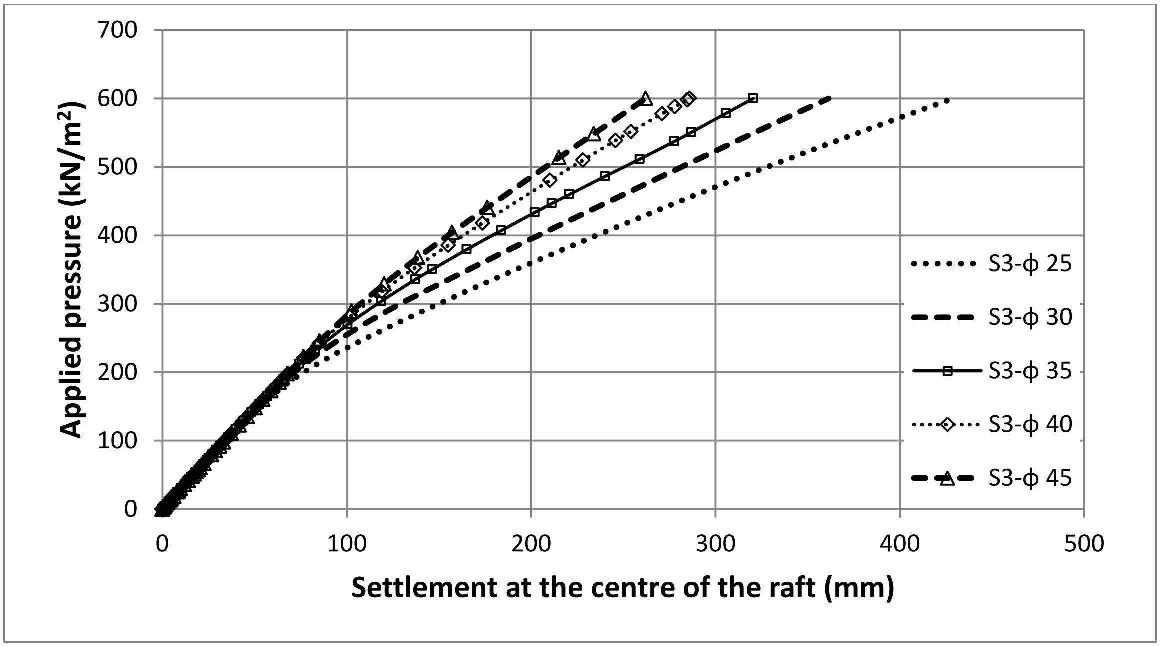

Fig. 3.62: Effect of the angle of internal friction of the soil on the load-settlement relationship of piled-raft supported by 3×3 pile group

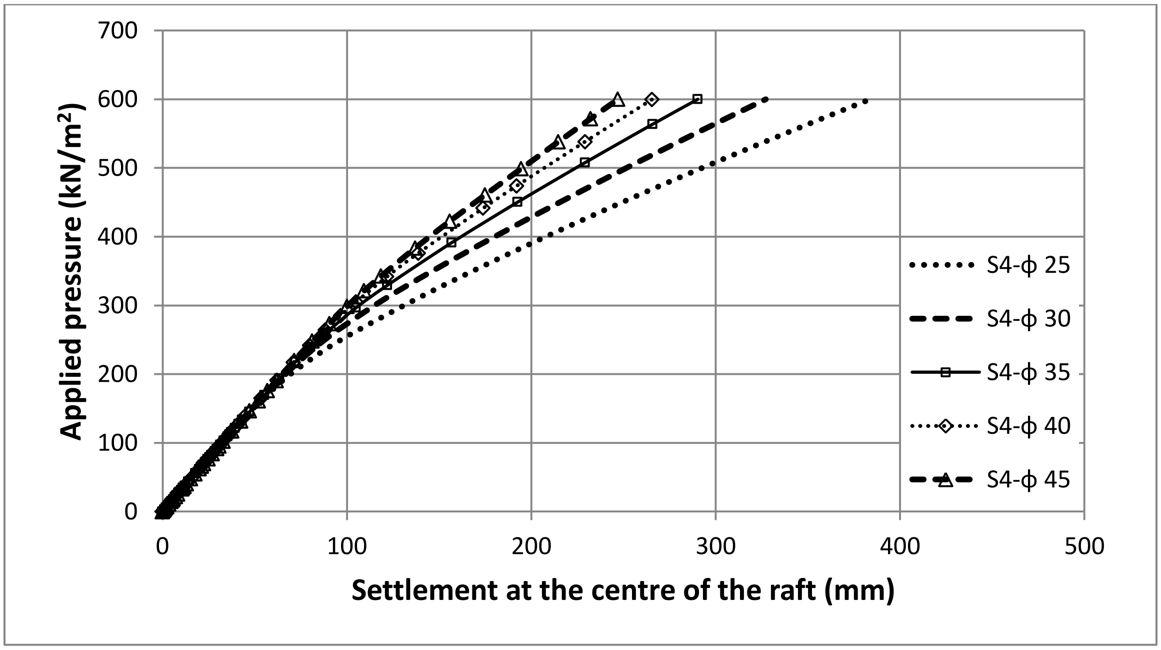

Fig. 3.63: Effect of the angle of internal friction of the soil on the load-settlement relationship of piled-raft supported by 4×4 pile group

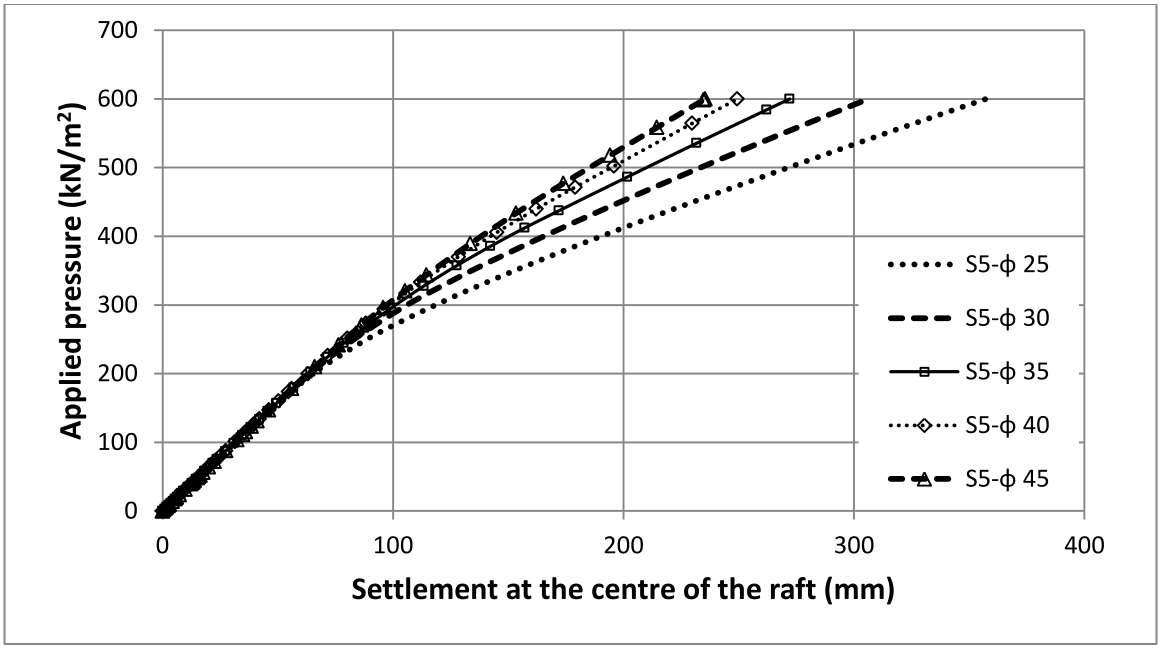

Fig. 3.64: Effect of the angle of internal friction of the soil on the load-settlement relationship of piled-raft supported by 5×5 pile group

The effect of changing the angle of internal friction on the load sharing between the raft and the piles is shown in Fig. 3.65. It was observed that the change in the friction angle of the soil does not affect the load sharing between the piles and the raft for rafts supported by single pile or pile group of small size. On the other hand, for rafts supported by pile groups of 3×3 or more, it can be seen that the friction angle smaller than 35° has a significant effect on the load sharing between the raft and the piles. However, for friction angle more than 35° the effect of soil friction angle becomes negligible regardless of the number of the piles supporting the raft. For the soil friction angle less than 35°, the load carried by the raft increases with the increase of soil friction angle. The contribution of the raft increases with the increase of the soil friction angle because the strength of the soil below the raft improves when the friction angle of the soil increases.

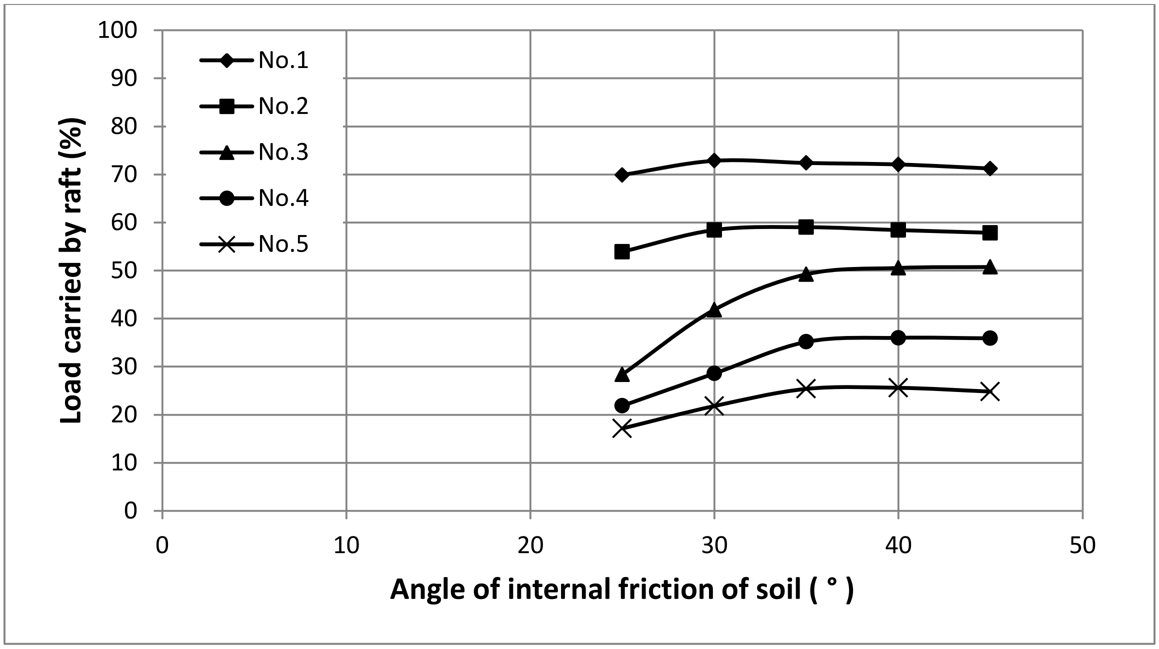

Fig. 3.65: Effect of the angle of internal friction of the soil on the load sharing between the raft and piles

However, it seems that the increase in the soil strength beyond a certain level does not improve the contribution of the raft as shown from Fig. 3.65. It can be argued that piled-raft foundations are not efficient in soils with angles of internal friction less that 35° because the contribution of the raft to the load carrying capacity reduces significantly with the reduction of the angle of internal friction of the soil. It seems that improving the soil strength under the raft using some soil improvement techniques such as compaction may enhance the contribution of the raft to the load carrying capacity in piled-raft foundations.

3.4.11 Effect of dilatancy angle of the soil

The effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft foundations is shown in Figs. 3.66 to 3.70. The dilatancy angle showed no effect on the load-settlement curves at small settlements of the foundations whereas it showed significant effect at large settlements. The stiffness of the piled-raft foundations increases with the increase of the dilatancy angle only at large settlements. The dilatancy angle has the same effect regardless of the number of piles supporting the raft. The change in the dilatancy angle of the soil does not affect the load carried by the raft for all cases as shown in Fig. 3.71. It seems that dilatancy angle is not an important parameter for the design of piled-raft foundations since it has no effect on the load sharing between the piles and the raft.

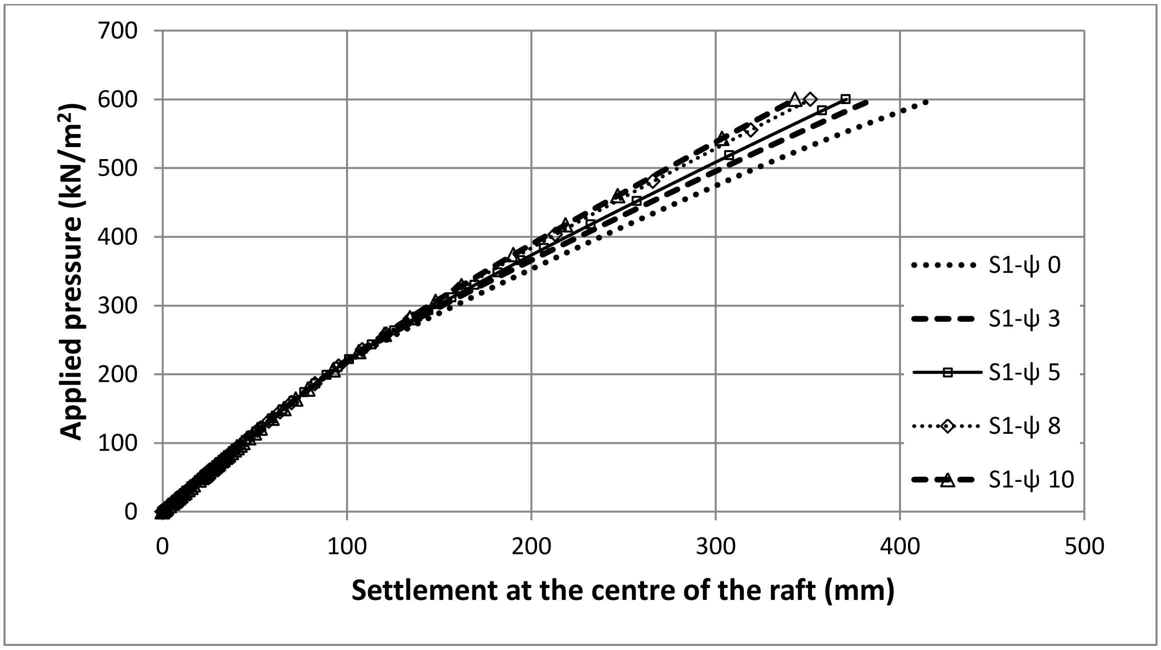

Fig. 3.66: Effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft supported by single pile

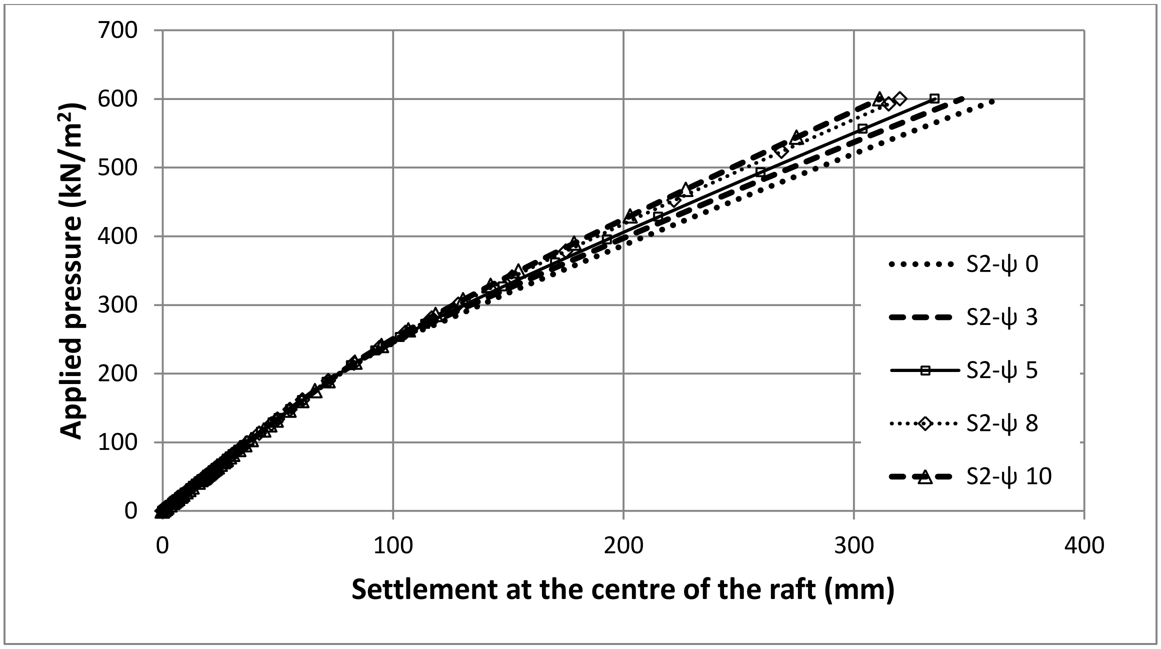

Fig. 3.67: Effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft supported by 2×2 pile group

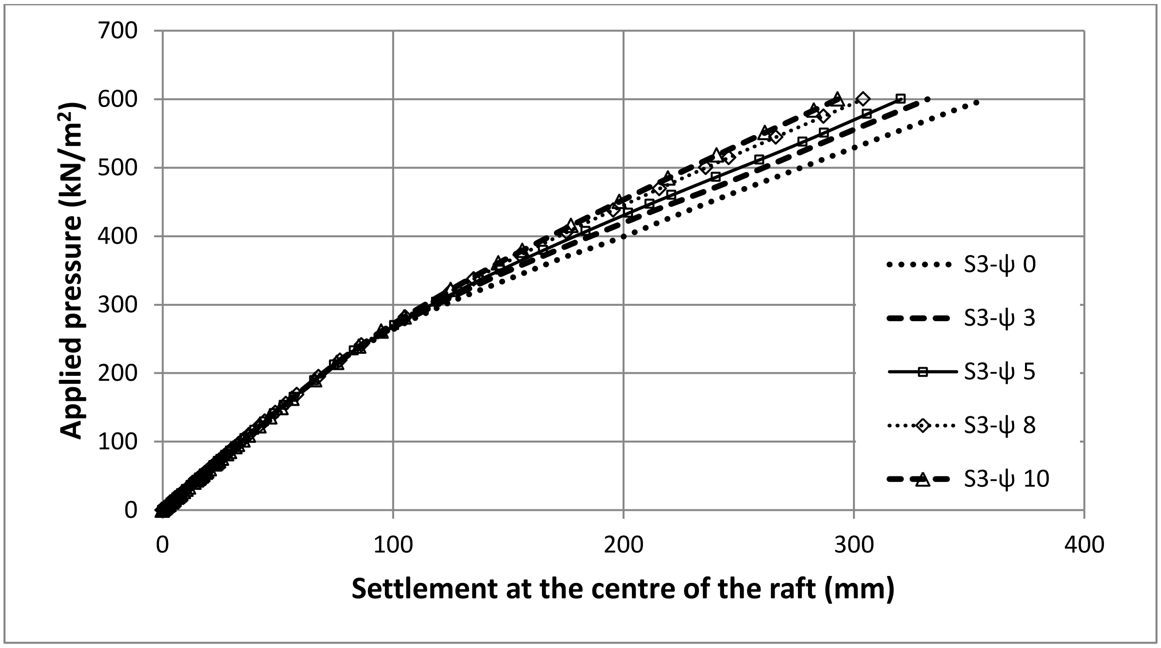

Fig. 3.68: Effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft supported by 3×3 pile group

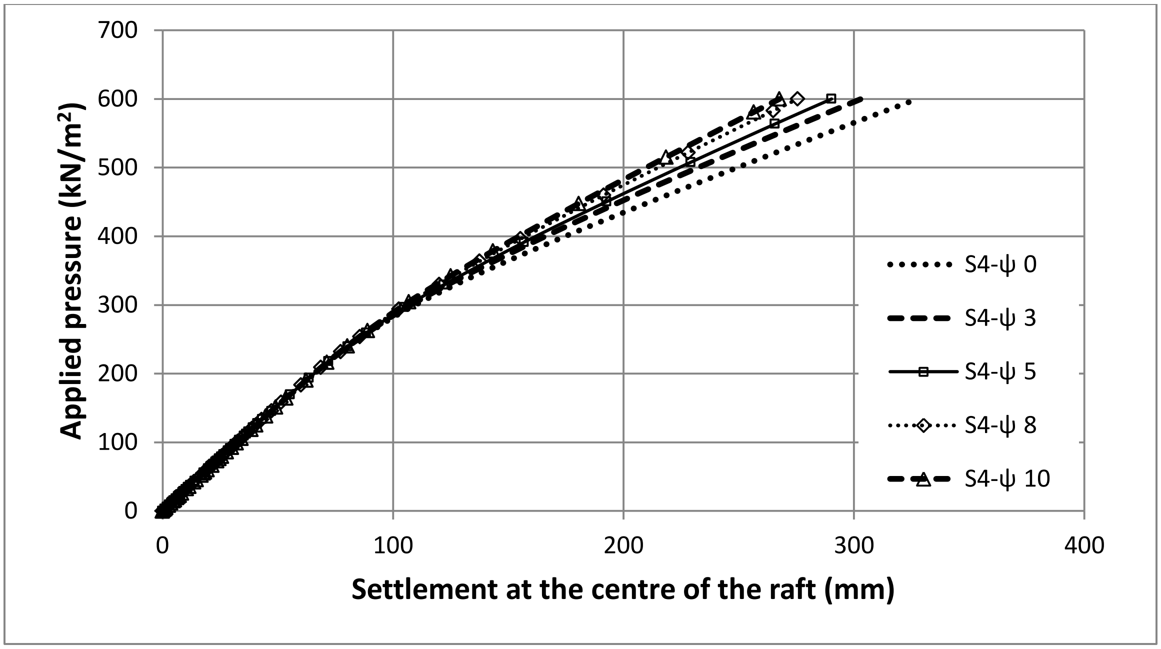

Fig. 3.69: Effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft supported by 4×4 pile group

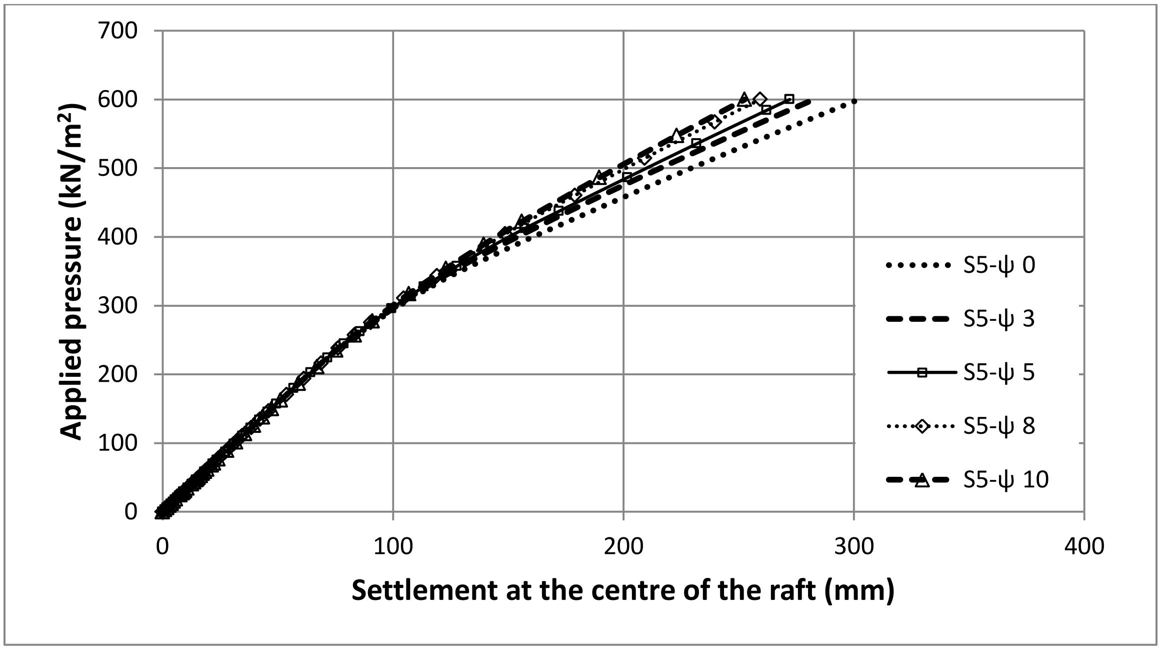

Fig. 3.70: Effect of the dilatancy angle of the soil on the load-settlement relationship of piled-raft supported by 5×5 pile group

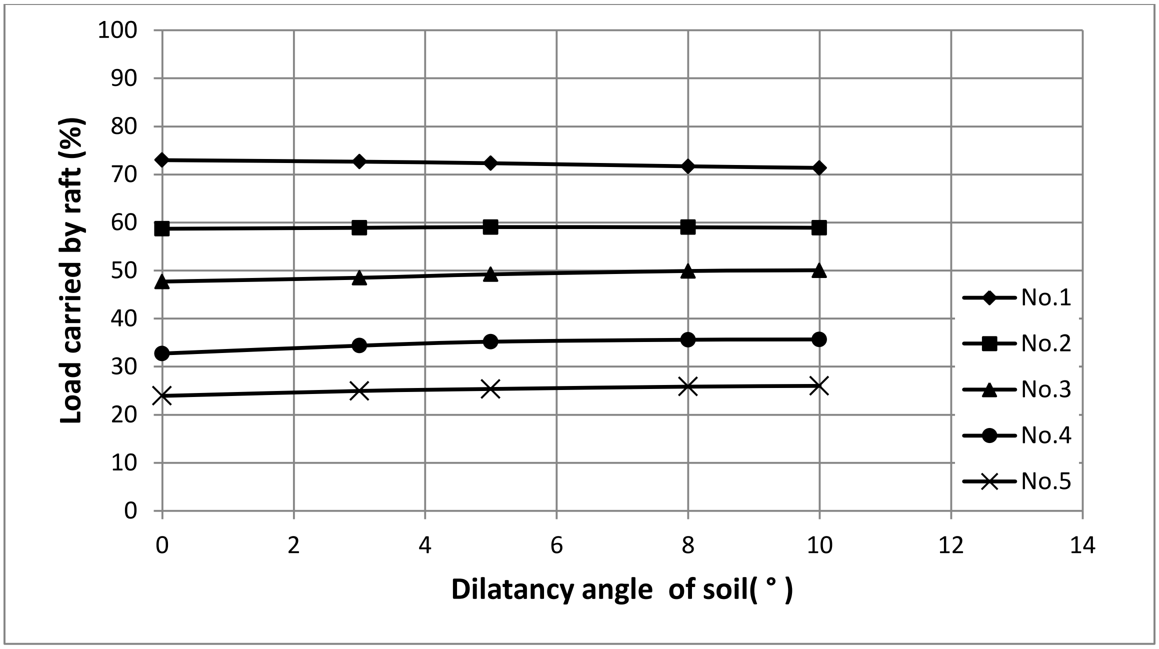

Fig. 3.71: Effect of the dilatancy angle of the soil on the load sharing between the raft and piles

3.4.12 Effect of the unit weight of soil

As shown in Figs. 3.72 to 3.76, the unit weight of soil does not affect the load-settlement curves at small settlements of the foundations whereas it has only a small effect at large settlements. The load carried by the raft is not affected by the change in the unit weight of soil as shown in Fig.3.77. It should be noted that in this study the piles were assumed to be bored piles. Therefore, it can be stated that changing the unit weight of the soil has no effect because there is no densification of the soil around the pile shaft in case of bored piles, and hence, the shaft friction resistance of the piles is not affected. However, the unit weight of soil may show an effect if the piles were driven piles, which due to densification of the soil during the pile's installation.

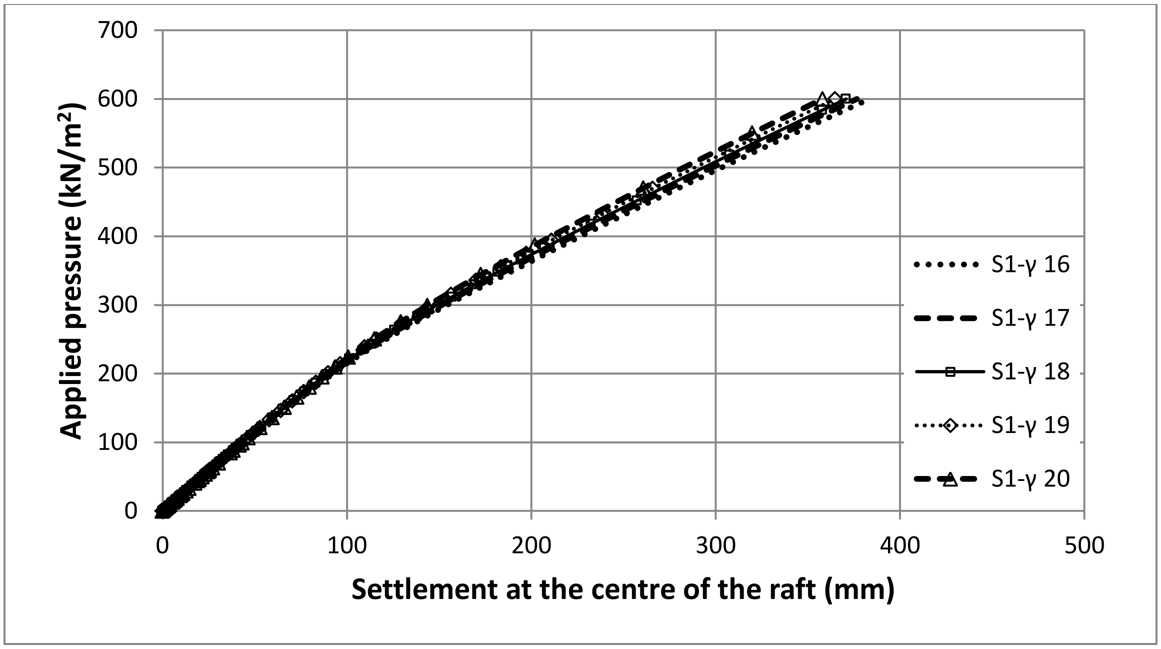

Fig. 3.72: Effect of the unit weight of the soil on the load-settlement relationship of piled-raft supported by single pile

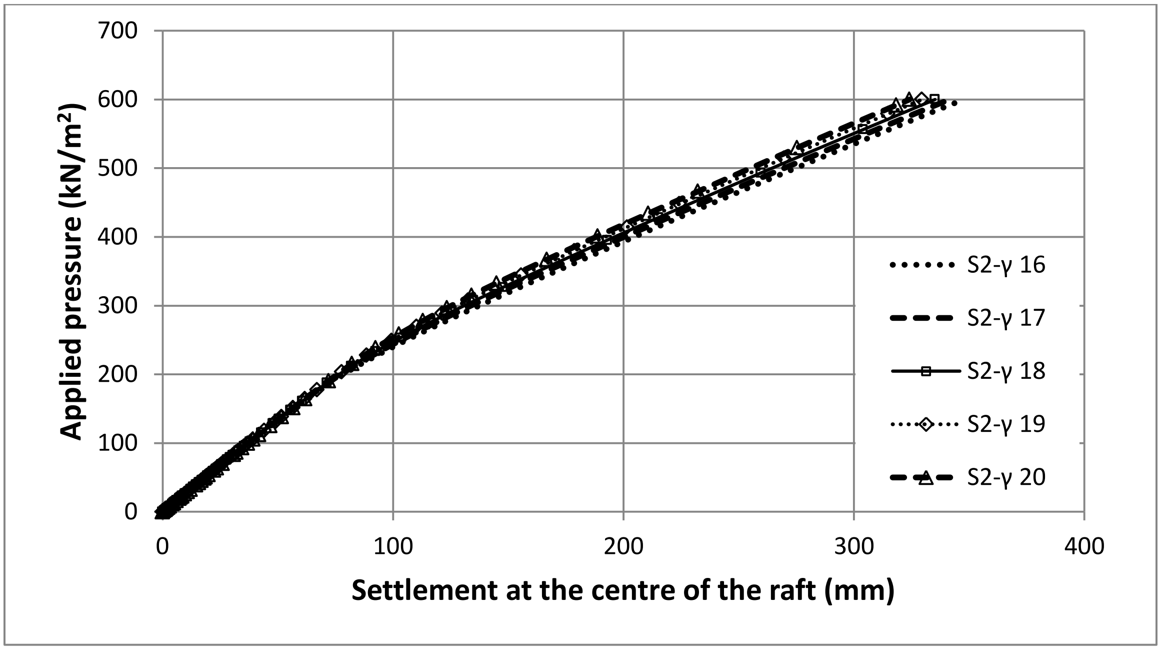

Fig. 3.73: Effect of the unit weight of the soil on the load-settlement relationship of piled-raft supported by 2×2 pile group

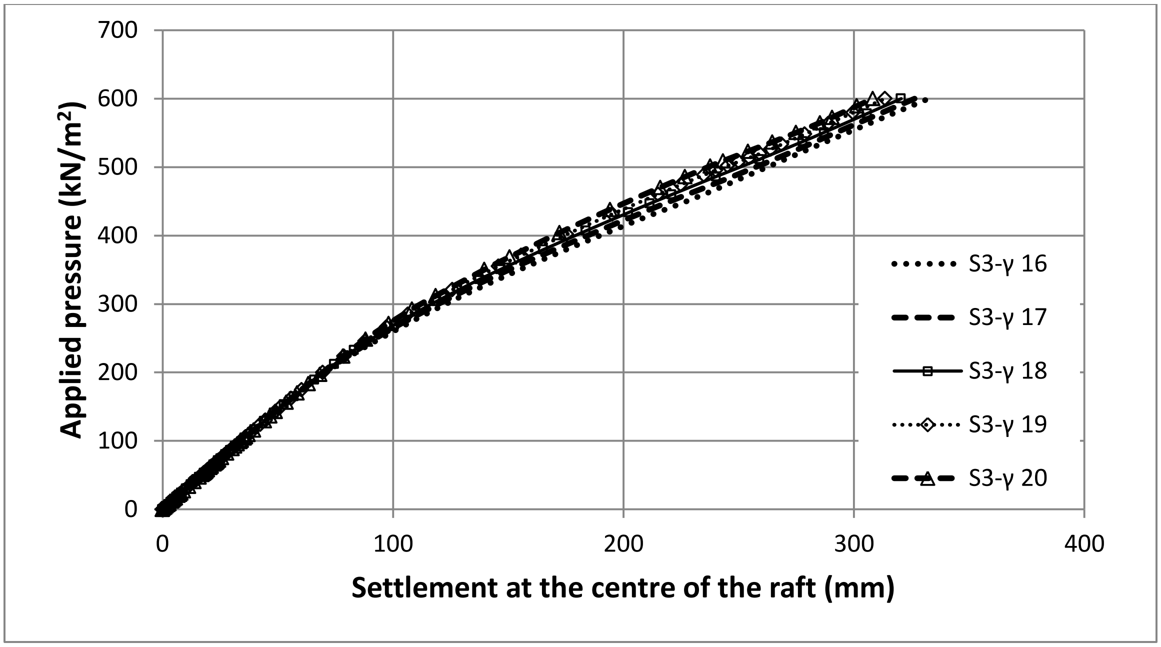

Fig. 3.74: Effect of the unit weight of the soil on the load-settlement relationship of piled-raft supported by 3×3 pile group

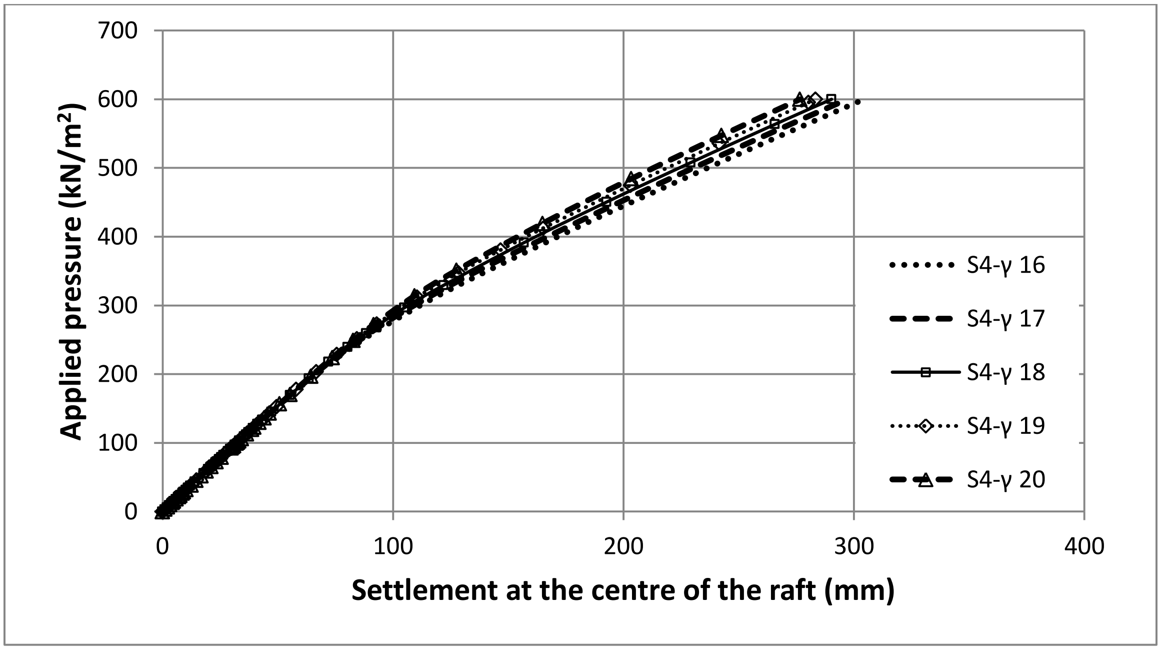

Fig. 3.75: Effect of the unit weight of the soil on the load-settlement relationship of piled-raft supported by 4×4 pile group

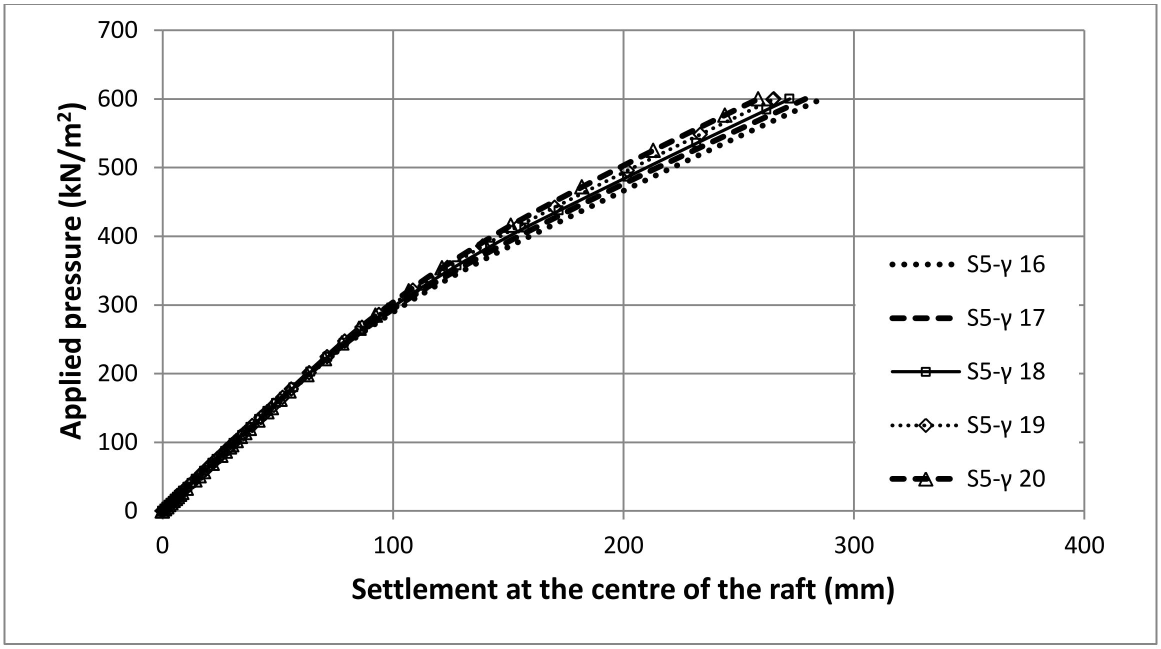

Fig. 3.76: Effect of the unit weight of the soil on the load-settlement relationship of piled-raft supported by 5×5 pile group

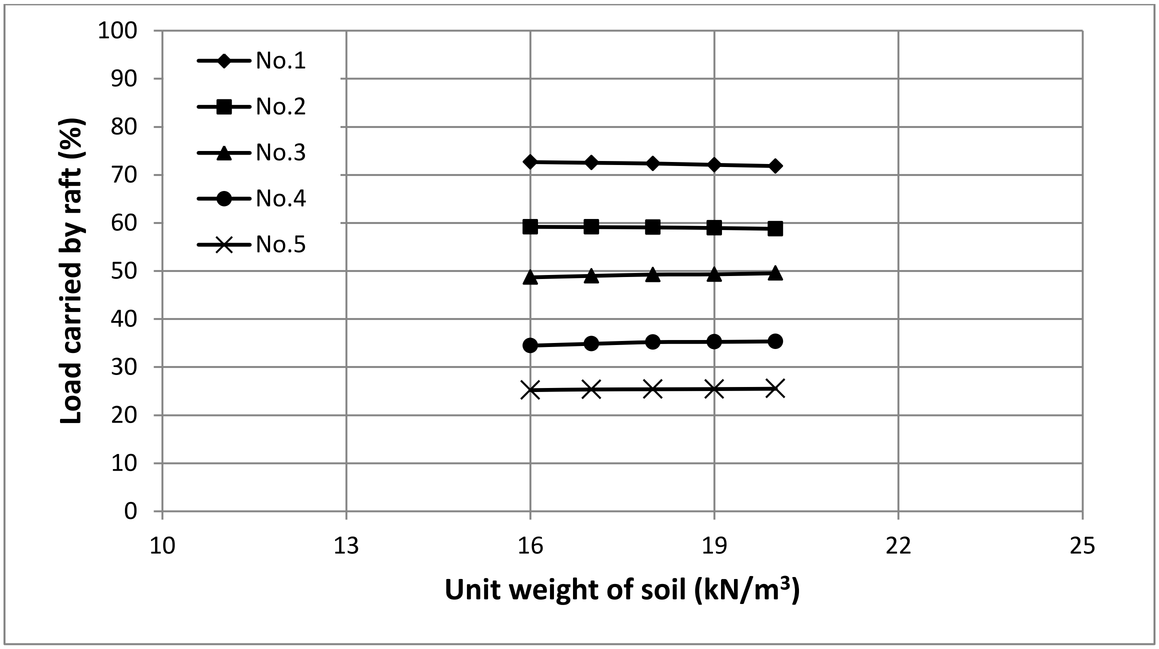

Fig. 3.77: Effect of the unit weight of the soil on the load sharing between the raft and piles

3.4.13 Effect of the raft thickness

Within the range of raft thicknesses (0.3 to 0.7 m) considered in this study it was found that the raft thickness has no effect on the load settlement relationship of piled-raft foundations either at small settlement or at large settlement levels as shown in Figs. 3.78 to 3.82. Other researchers reported similar observations regarding the effect of raft thickness at small settlement levels. Oh et al (2008) reported that raft thickness has little effect on the maximum settlement of piled-raft foundations on sand soil. Singh and Singh (2008) reported that finite element analyses of piled-raft foundations showed that the raft thickness has little effect on maximum settlement in soft cohesive soils. It can be stated that the effect of raft thickness on load-settlement relationship of piled-raft foundations is the same at small or large settlement levels.

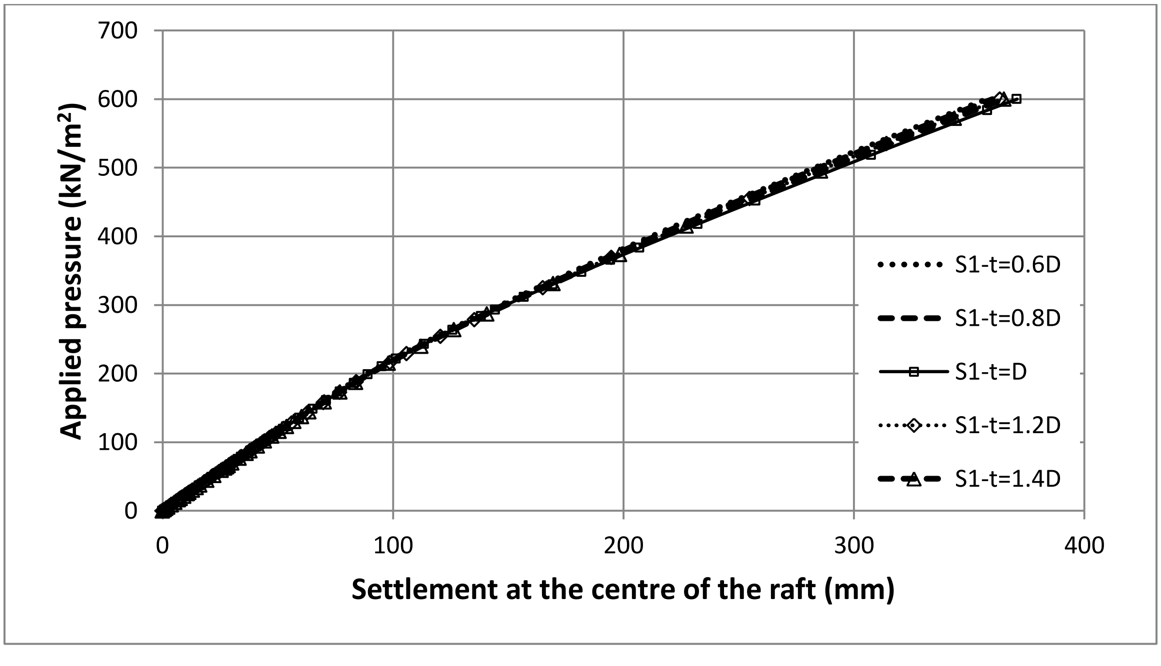

Fig. 3.78: Effect of raft thickness on the load-settlement relationship of piled-raft supported by single pile

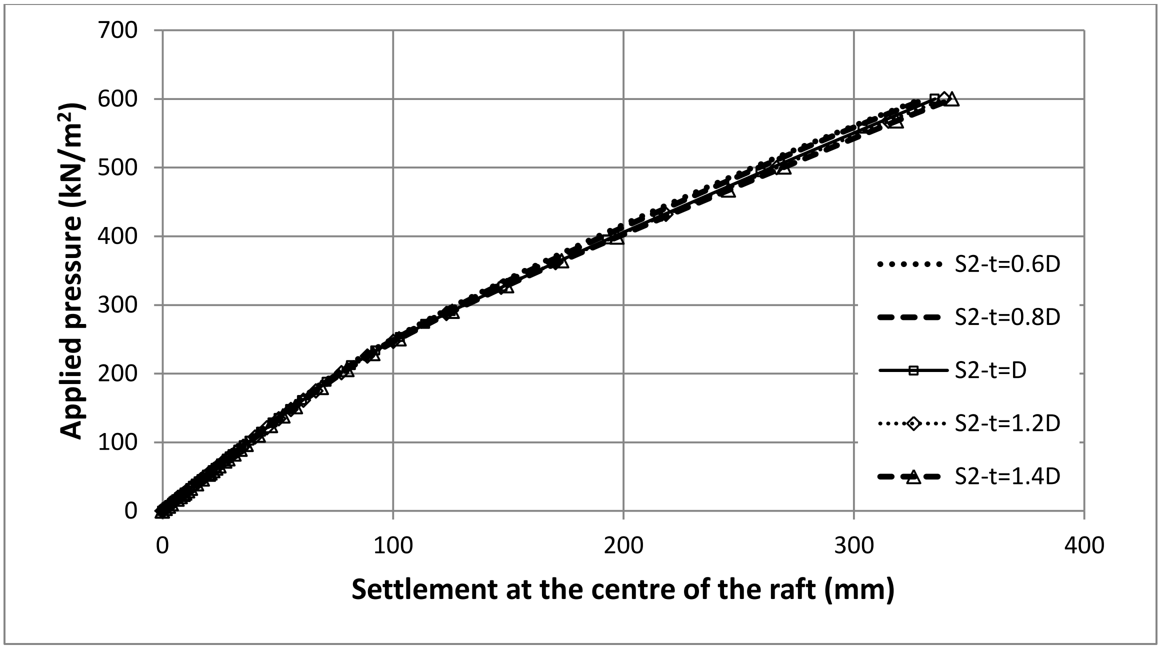

Fig. 3.79: Effect of raft thickness on the load-settlement relationship of piled-raft supported by 2×2 pile group

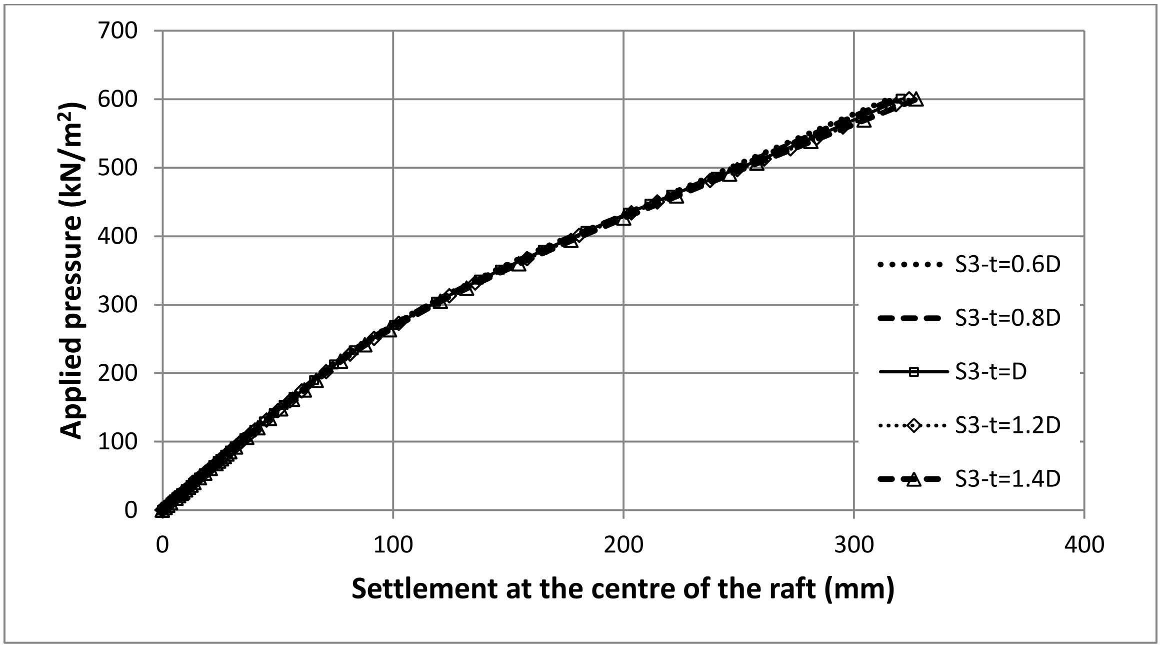

Fig. 3.80: Effect of raft thickness on the load-settlement relationship of piled-raft supported by 3×3 pile group

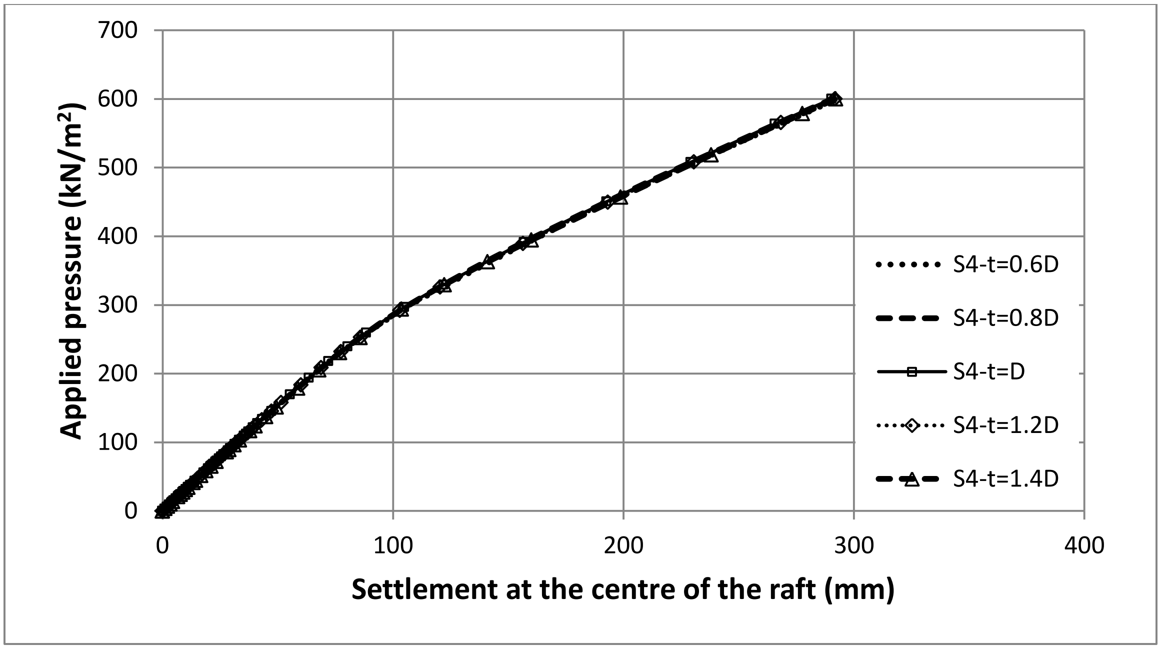

Fig. 3.81: Effect of raft thickness on the load-settlement relationship of piled-raft supported by 4×4 pile group

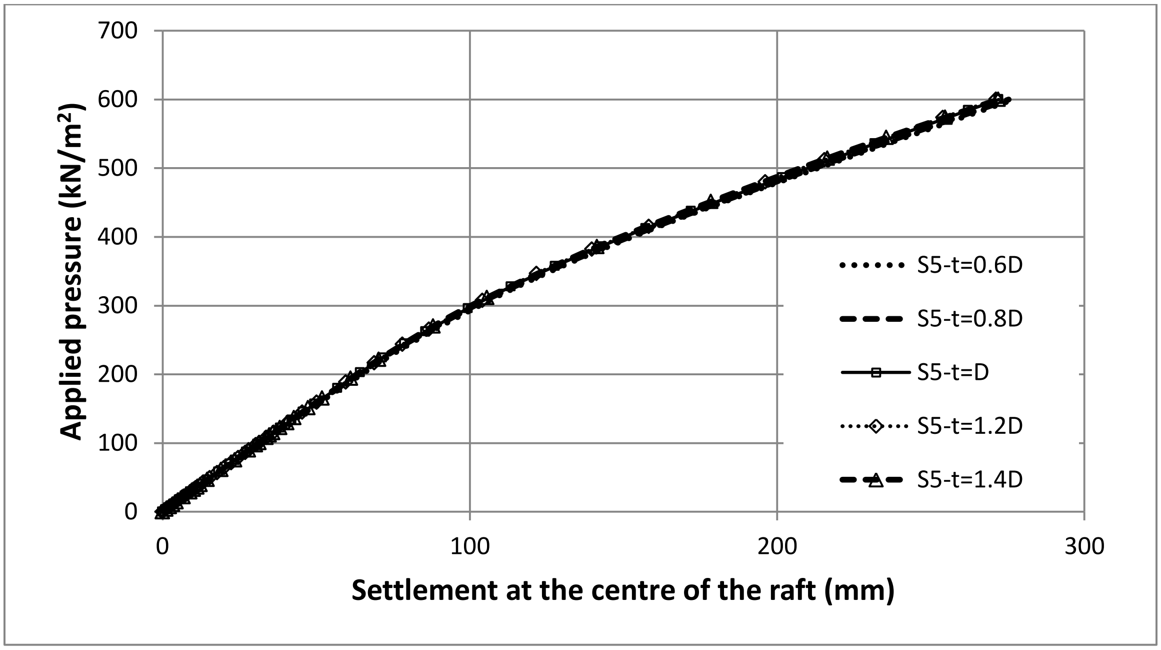

Fig. 3.82: Effect of raft thickness on the load-settlement relationship of piled-raft supported by 5×5 pile group

The raft thickness has very small effect on the load carried by the raft as shown in Fig. 3.83. Other researchers reported similar observations regarding the effect of raft thickness on the load sharing at small settlement levels. Oh et al (2008) reported that raft thickness has little effect on the load sharing of piled-raft foundations on sand soil. Therefore, raft thickness can be considered not an important parameter for estimating the settlement and the load sharing.

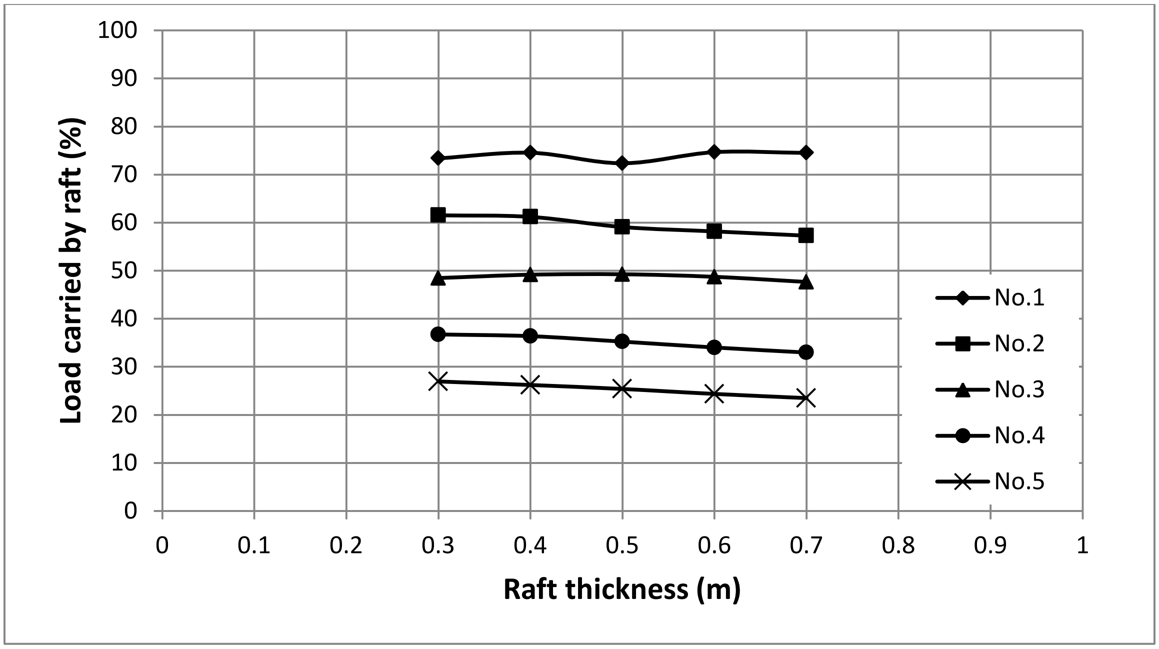

Fig. 3.83: Effect of raft thickness on the load sharing between the raft and piles

3.4.14 Effect of the modulus of elasticity of the raft

The modulus of elasticity of the raft did not show an effect on the load settlement relationship of piled-raft foundations as shown in Figs. 3.85 to 3.88 and on the load carried by the raft as shown in Fig. 3.89. The change in the modulus of elasticity of the raft means that the rigidity of the raft is changing. Similarly, as discussed in the above section, the change in the raft rigidity by changing the raft thickness shows no effect on the load-settlement curves and load sharing between the raft and piles. Therefore, it can be stated that the modulus of elasticity of the raft is not an important parameter for estimating the settlement and the load sharing between the raft and piles in piled-raft foundations.

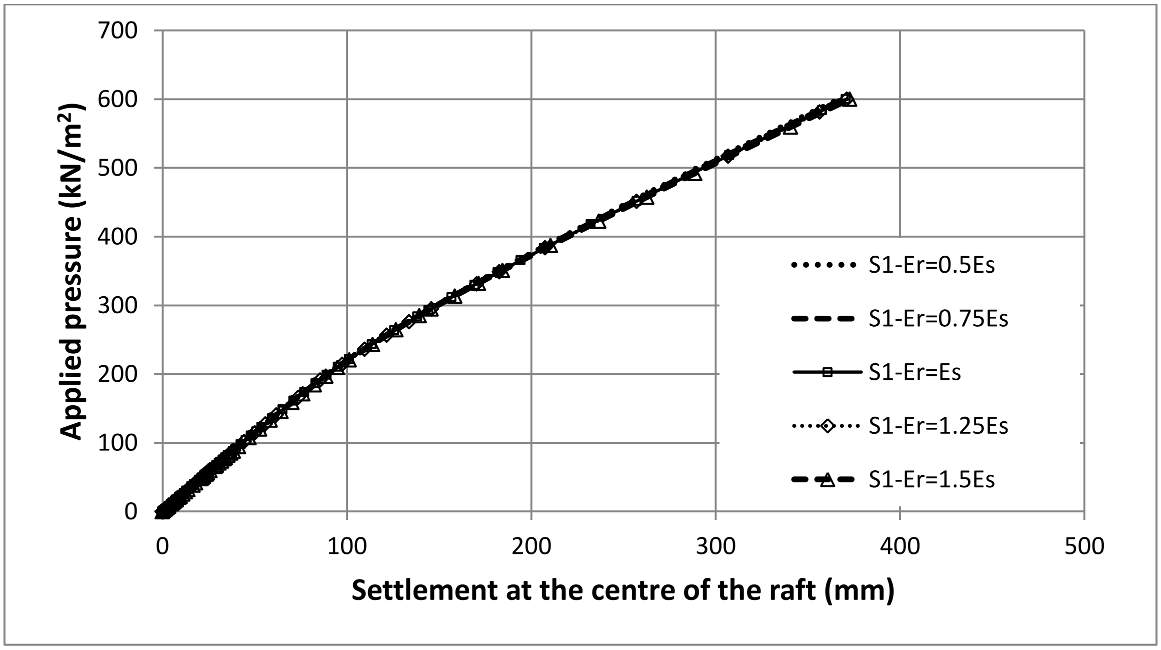

Fig. 3.84: Effect of the modulus of elasticity of the raft on the load-settlement relationship of piled-raft supported by single pile

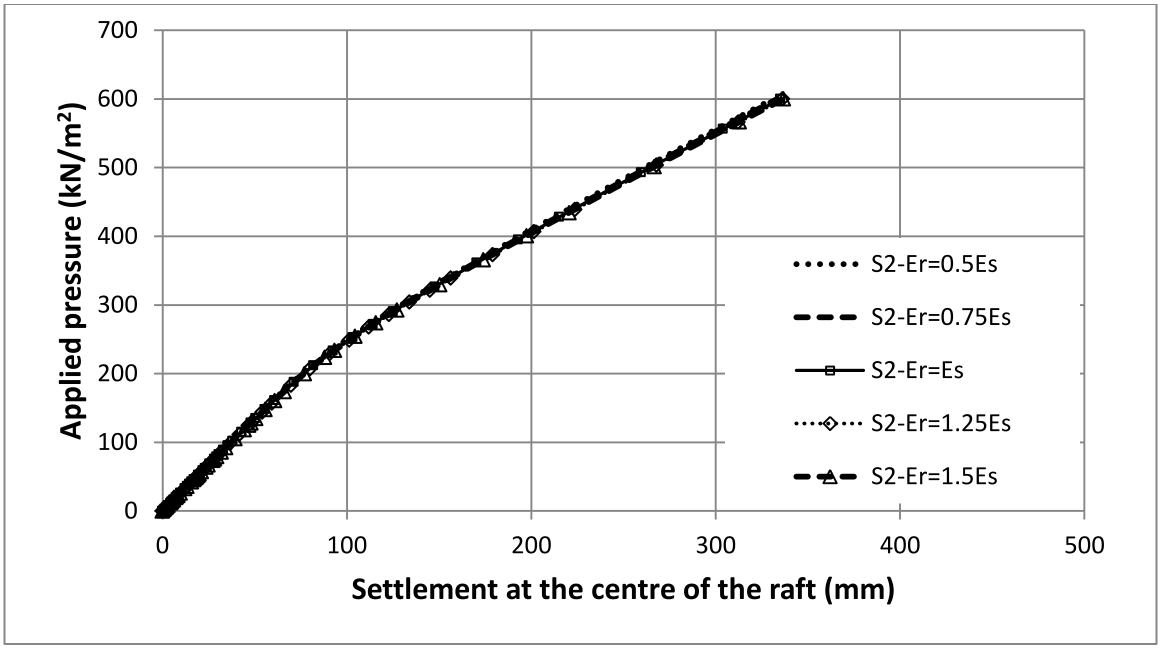

Fig. 3.85: Effect of the modulus of elasticity of the raft on the load-settlement relationship of piled-raft supported by 2×2 pile group

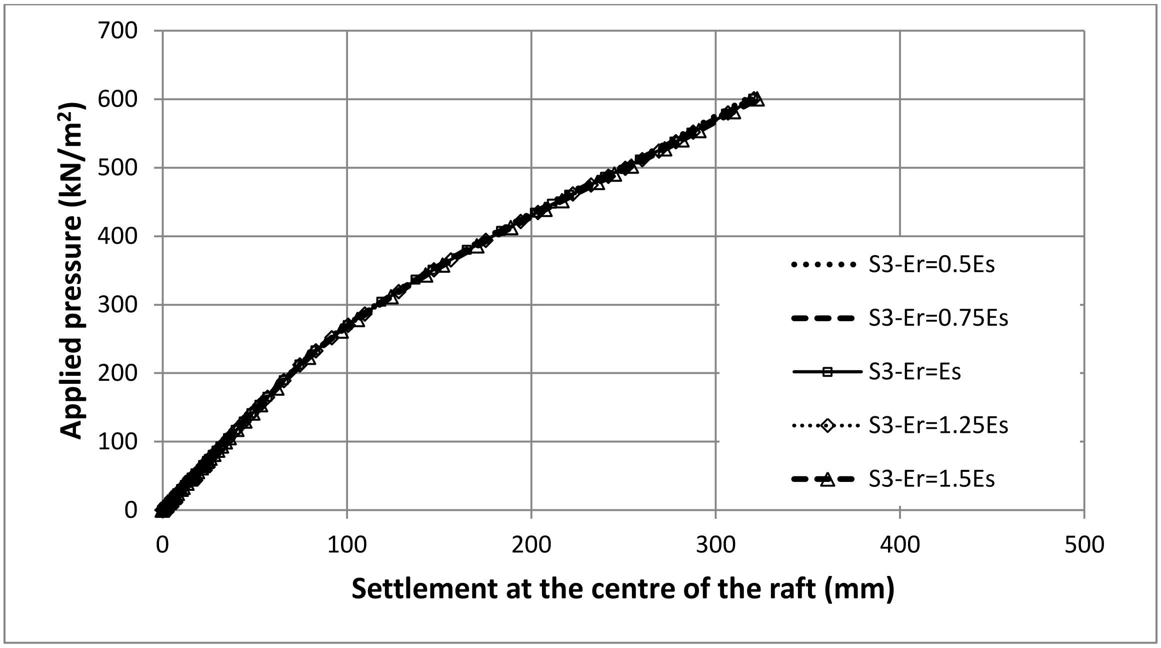

Fig. 3.86: Effect of the modulus of elasticity of the raft on the load-settlement relationship of piled-raft supported by 3×3 pile group

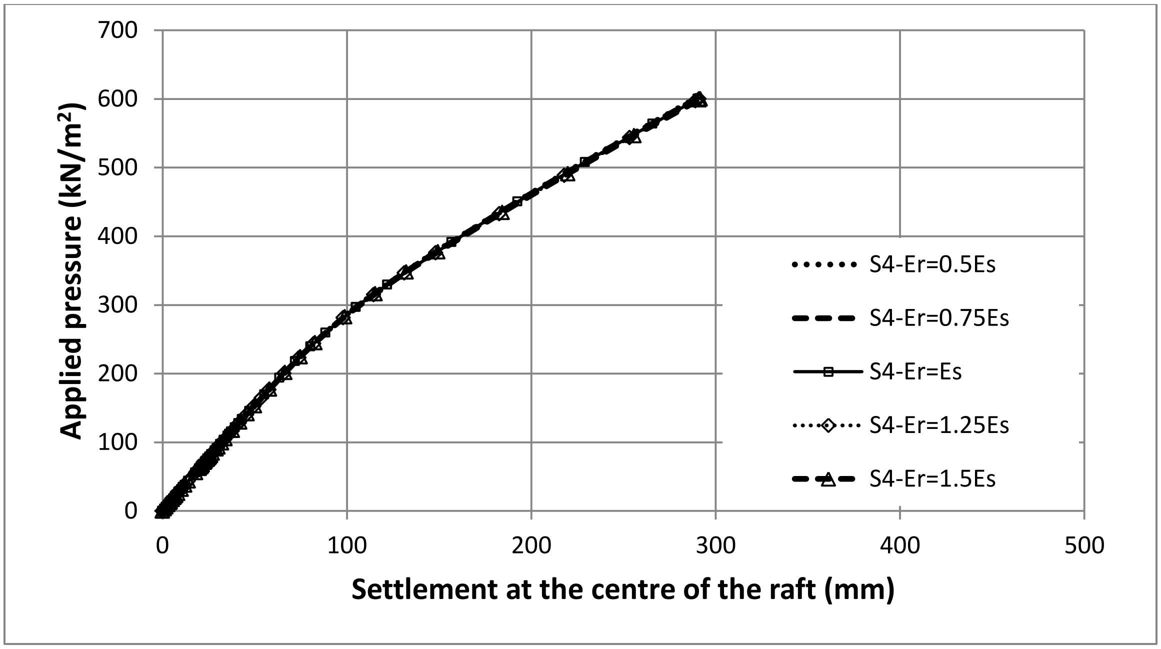

Fig. 3.87: Effect of the modulus of elasticity of the raft on the load-settlement relationship of piled-raft supported by 4×4 pile group

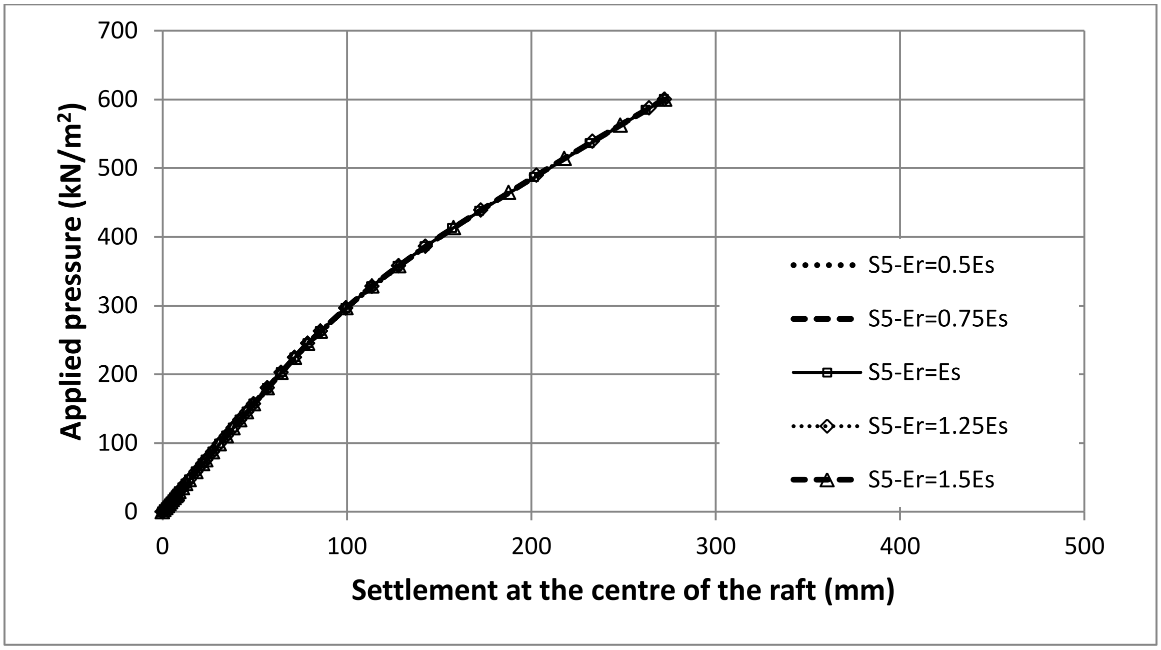

Fig. 3.88: Effect of the modulus of elasticity of the raft on the load-settlement relationship of piled-raft supported by 5×5 pile group

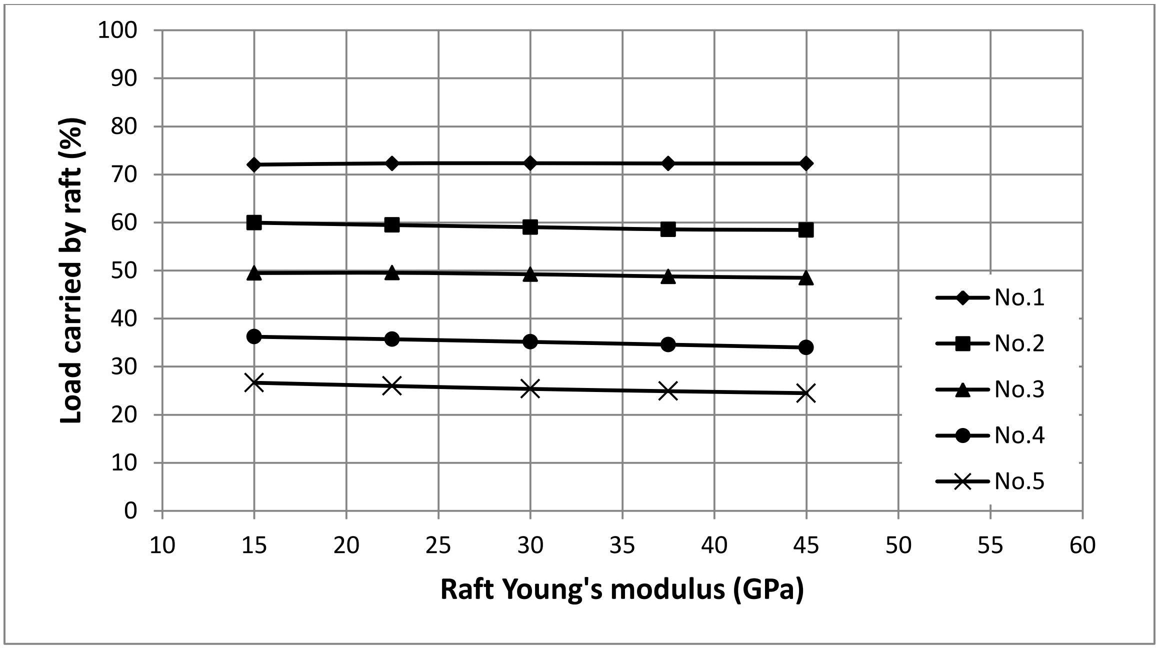

Fig. 3.89: Effect of the modulus of elasticity of the raft on the load sharing between the raft and piles

3.4.15 Effect of the raft width

The effect of changing the raft width on the load-settlement relationship of piled-raft foundations is shown in Figs. 3.90 to 3.94. It can be seen that the raft width has no effect on the load-settlement curve at small settlements of the system. The effect of the raft width occurs at larger settlements only. At large settlements, and at the same load level, the increase in the raft width causes the stiffness of the piled-raft foundations to increase. However, with the increase in the numbers of piles supporting the raft the increase in the stiffness with the increase in the raft width becomes less important.

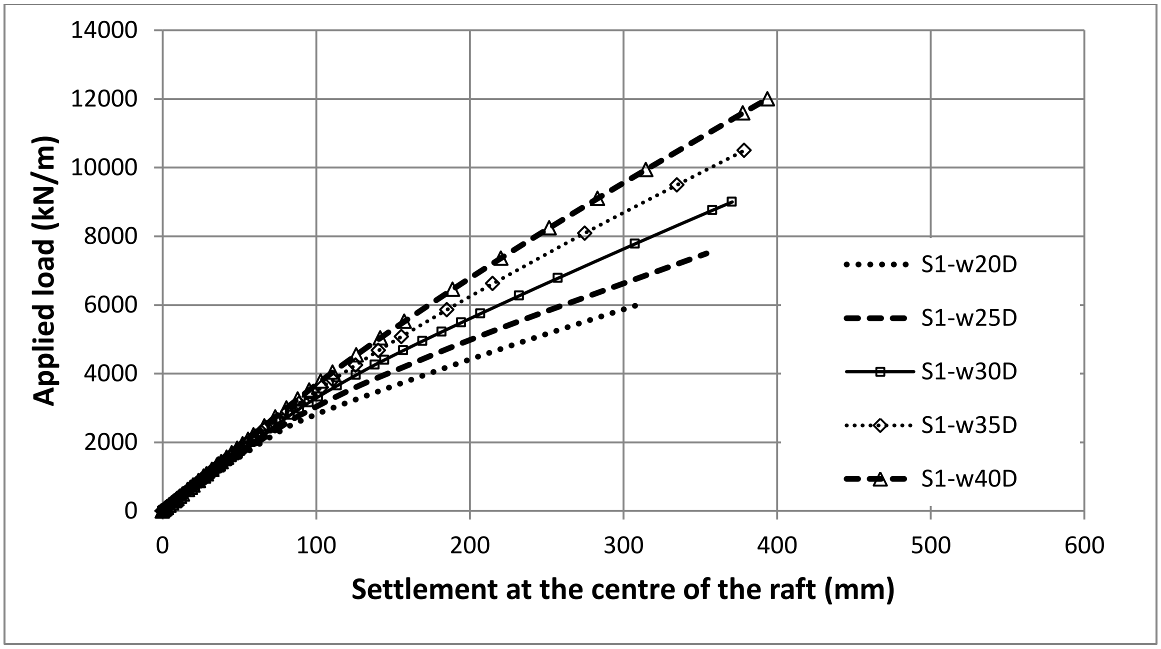

Fig. 3.90: Effect of raft width on the load-settlement relationship of piled-raft supported by single pile

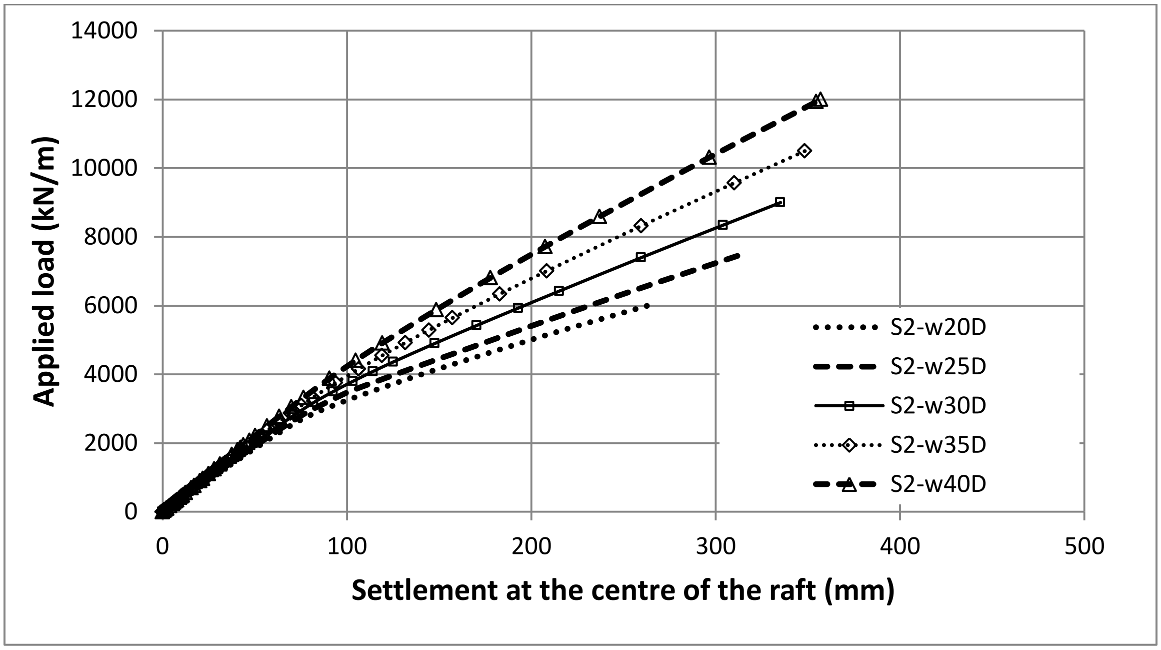

Fig. 3.91: Effect of raft width on the load-settlement relationship of piled-raft supported by 2×2 pile group

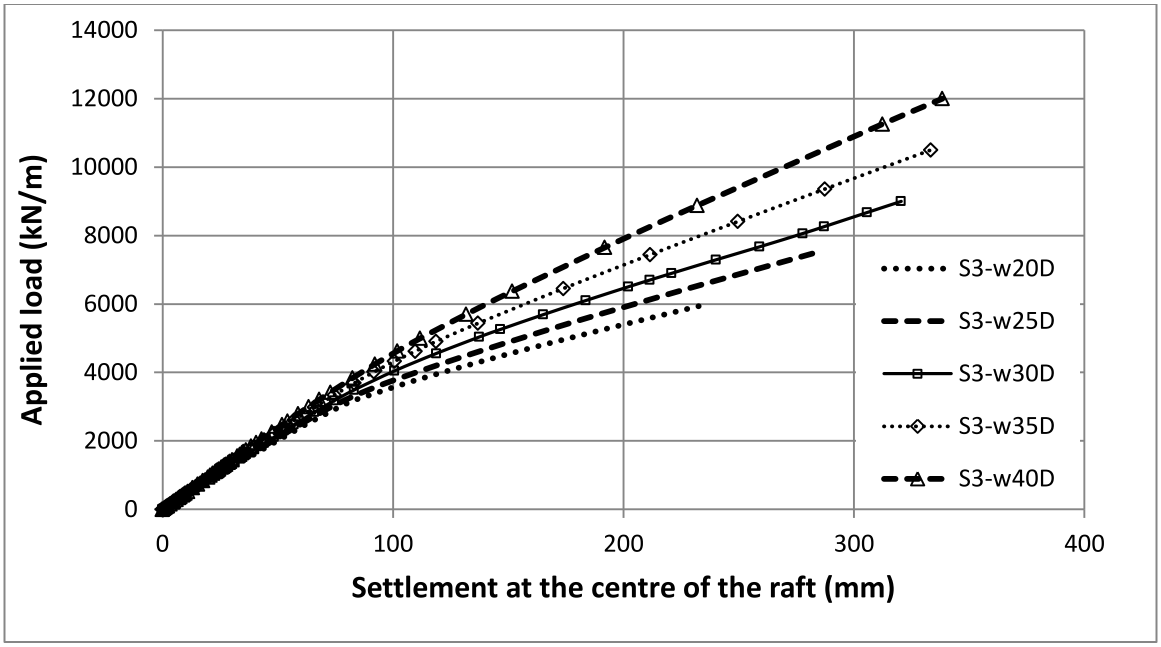

Fig. 3.92: Effect of raft width on the load-settlement relationship of piled-raft supported by 3×3 pile group

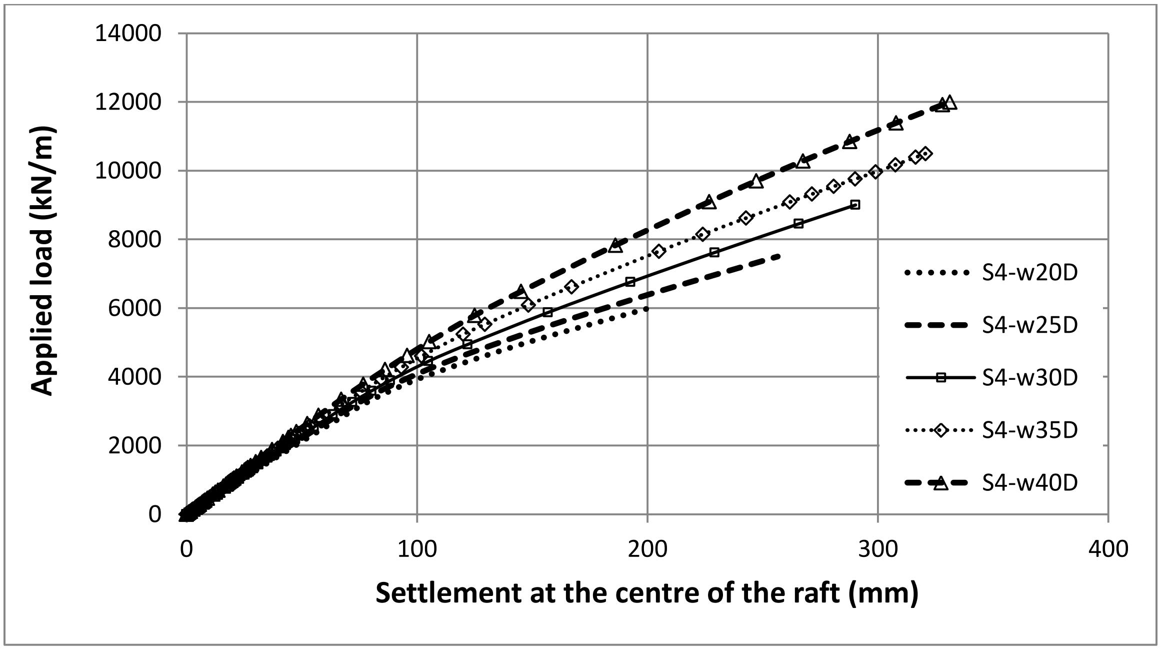

Fig. 3.93: Effect of raft width on the load-settlement relationship of piled-raft supported by 4×4 pile group

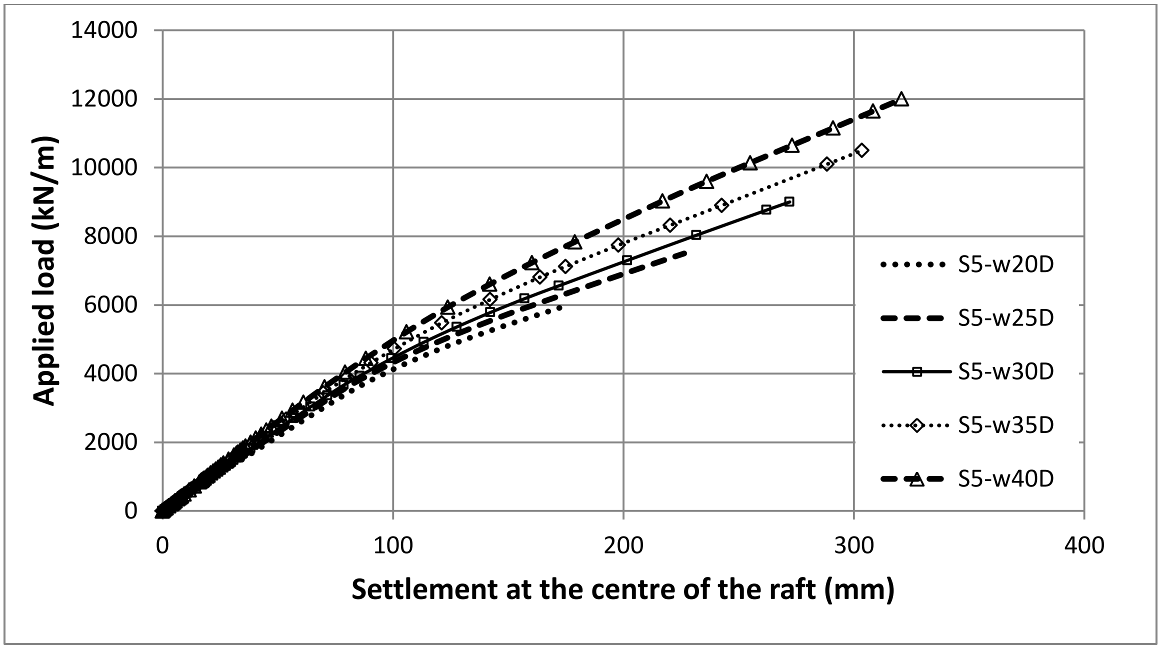

Fig. 3.94: Effect of raft width on the load-settlement relationship of piled-raft supported by 5×5 pile group

The effect of raft width on the load sharing between the raft and the pile is shown in Fig. 3.95. For the raft supported by a single pile the trend was different from that for rafts supported by pile groups. It was observed that the load carried by the raft reduced slightly by increasing the raft width from 12.5 m to 15 m. For rafts supported by pile groups, it can be seen that the contribution of the raft to the load carrying capacity increases significantly when the width of the raft increases. In fact, increasing the width of the raft leads to an increase in the stiffness of the raft. In these tests, the stiffness of the piles was not changed when studying the effect of raft width. Therefore, increasing the width of the raft causes the ratio of the stiffness of the pile to the stiffness of the raft to decrease. It can be argued that the ratio of the stiffness of the pile to the stiffness of the raft has a significant effect on the load sharing between the piles and the raft. As this ratio decreases, the load carried by the raft increases.

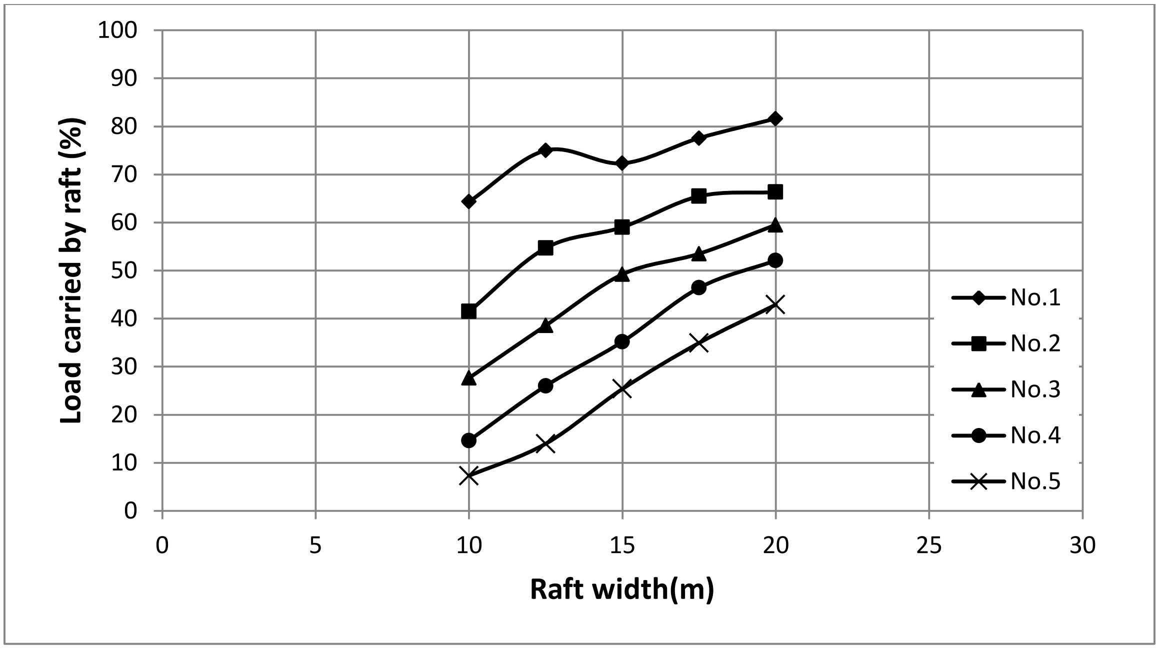

Fig. 3.95: Effect of raft width on the load sharing between the raft and piles

3.5 Summary and Discussion

In the above discussion it was assumed that the change in settlement more than 5% of pile diameter as significant effect otherwise it assumed minor effect. The effect of some important parameters on the load-settlement relationship and load sharing was studied. The results of this parametric study showed that some parameters have no effect on the load-settlement relationship of piled-raft foundations at small settlements or at large settlements of the system, such as the modulus of elasticity of the piles, the reduction factor of the pile-soil interface strength, the modulus of elasticity of the raft and the raft thickness. Some parameters have negligible effect on the load-settlement relationship of piled-raft foundations at small settlements whereas they have significant effect at large settlements, such as the pile diameter, pile spacing, raft width, Poisson’s ratio of the soil, angle of internal friction of the soil, dilatancy angle of the soil and unit weight of soil. It was found that the most important parameters, which have significant effect on the load-settlement relationship of piled-raft foundations at small and large settlements, are the pile length and modulus of elasticity of soil.

In piled-raft foundations, piles reduce the settlement of the raft and the contact pressure between the soil and the raft. In this study it is shown that a number of parameters can affect the reduction in the contact pressure. For the load sharing between the raft and piles, the effect of the investigated parameters can be categorized either as significant effect, small effect, or no effect. Parameters, which show significant effect on the load carried by the raft, are pile diameter, pile length, pile spacing, raft width, and angle of internal friction of soil. Parameters, which show only small effect on the load carried by the raft, are the raft thickness, modulus of elasticity of soil, Poisson's ratio of the soil and the modulus of elasticity of the piles. Parameters, which have no effect on the load carried by the raft, are dilatancy angle of the soil, unit weight of soil, the reduction factor of the pile-soil interface strength and the modulus of elasticity of the raft.

By changing the pile spacing it was observed that the location and arrangement of the piles under the raft significantly affect the load sharing between the piles and the raft because they affect the differential settlement of the raft. The raft contribution decreases as the number of piles supporting the raft increases because the stiffness of the pile group affected the performance of the system. It was concluded that the ratio of the stiffness of the pile group to the stiffness of the raft governs the load sharing between the piles and the raft.

3.6 Design Method

3.6.1 Introduction

The current design methods of piled-raft foundations produce conservative and uneconomic design due to ignoring the contribution of the raft. Developing simple, practical and reliable design methods is needed to avoid complicated numerical analysis and to enable practicing engineers to design piled-raft foundations. Moreover, developing simple design procedure will contribute to establishing design guidelines for design codes and manuals of foundation structures. More economical design can be attained by developing design methods that account for the contribution of the raft to the bearing capacity of the piled-raft foundations. Moreover, research in this field is justified since the increasing use of piled-raft foundations is well recognized. Complex numerical analysis can be used to carry out detailed parametric studies in order to identify the relationship between the most important design parameters and consequently developing simplified design models.

In this study, a simple model was developed for predicting the settlement and the load sharing between the raft and piles for piled-raft foundations. This model can provide valuable assistance to foundation engineers to design piled-raft foundations especially in the preliminary stage of the design process and to conduct feasibility studies to compare possible alternatives. Using this model engineers can save a lot of time and effort comparing with using a complicated numerical analysis which needs special software.

3.6.2 Load Sharing Model

This is due to the fact that the stiffness ratio of the foundation elements plays an important role in the performance of the piled-raft foundations; it was assumed that an approximate solution for such a system could be obtained based on the stiffness ratio of the foundation elements. Therefore, a simple model was developed to predict the stiffness of piled-raft foundations and the load sharing between the piles and the raft. This model accounts for the interaction between the raft and the piles by using efficiency factors for estimating the stiffness of the raft and the stiffness of the piles when combined together in the piled-raft foundations.

Piled-raft foundations are a combination between two types of foundations, which are a raft, and piles. When the load is applied, the raft and the piles share that load. Estimating the load sharing is an important issue for designing piled-raft foundations. From the parametric study it was found that the settlement of the foundations plays the most important role in distributing the load between the foundations elements (e.g. raft and the piles). It was found that the load share taken by the raft or by the piles depends mainly on the amount of the settlement foundations undergo. For example, the load carried by the raft can increase with the increase in the settlement of any particular piled-raft system. Therefore, predicting the settlement of piled-raft foundations is the first step to determine the load sharing between the piles and the raft.

It was assumed that since the piled-raft foundations is a combination between a raft and piles foundations, the stiffness of piled-raft foundations, *Kpr* should be also a combination between the stiffness of the raft, *Kr* and the stiffness of the piles , *Kp,* as given by equation (3.3):

$$Kpr = Kr + Kp \qquad (3.3)$$

This assumption was adopted from Fioravante (2011) statement regarding the estimation of the stiffness of piled-raft foundations. Fioravante (2011) reported that the piled-raft stiffness modulus before the yielding point could be roughly estimated by adding up the stiffness of the piles and the stiffness of the raft. However, due to the interaction between the raft and the pile, the pile affects the stiffness of the raft and the raft affects the stiffness of the pile. Consequently, equation (3.3) cannot accurately model the stiffness of piled-raft foundations system. Therefore, to account for the effect of the interaction between the raft and the piles, equation (3.3) has been modified to equation (3.4). In this equation, new factors named raft stiffness and piles stiffness efficiency factors have been suggested.

$$Kpr = \alpha r * Kr + \alpha p * Kp \qquad (3.4)$$

The load sharing between the raft and the piles can be determined from equations (3.5) and (3.6):

$$Raft\ load\ \% = 100 * (\alpha r * Kr) / Kpr \qquad (3.5)$$

$$Pile\ load\ \% = 100 - Raft\ load\ \% \qquad (3.6)$$

where αr, represents the efficiency factor to modify the stiffness of the raft due to the effect of the pile and αp, represents the efficiency factor to modify the stiffness of the piles due to the effect of the raft. *Kr* and *Kp* can be estimated by conventional methods available in the literature.

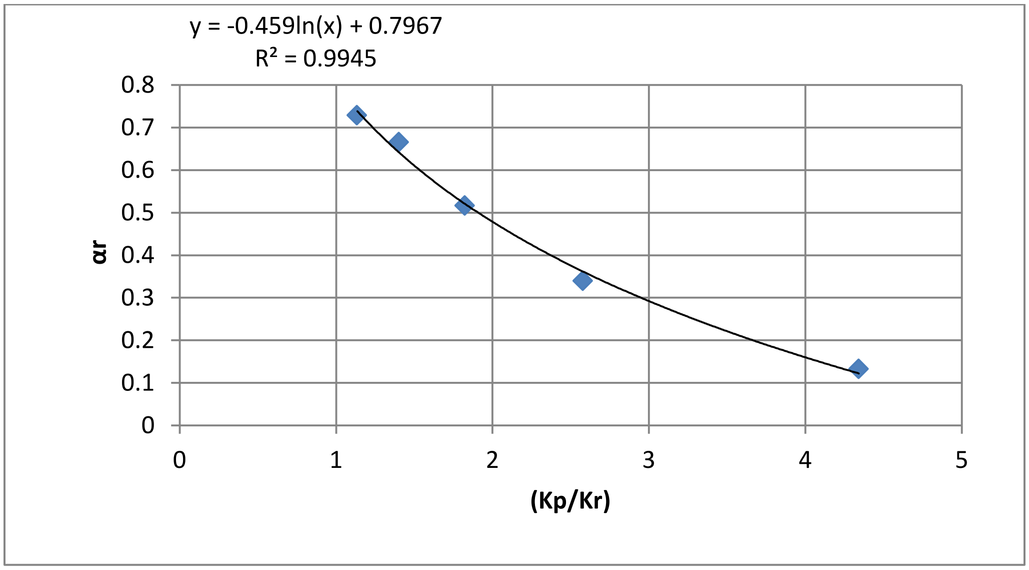

Fig. 3.96: Effect of pile-raft stiffness ratio on the raft efficiency factor, *αr*

To determine the value of the interaction factor, *αr,* and number of cases of piled-rafts supported by single pile having varied pile-raft stiffness ratios were analyzed using the developed model PLAXIS 2-D. Raft load, *Kp*, *Kr* and *Kpr* were determined for each case. Then for each case, *αr* was calculated from equation (3.5). Then the value of *αp* was obtained by substituting the value of *αr* in equation (3.4). The interaction factors, *αr* and *αp,* were found to vary with the stiffness ratio of the piles to that of the raft, *Kp/Kr* as shown in Figs. 3.96 and 3.97. Equations (3.7) and (3.8) were obtained graphically to estimate the interaction factors, *αr* and *αp*.

$$\alpha r = -0.459 \ln(Kp/Kr) + 0.7967 \quad (3.7)$$

$$\alpha p = 0.1818 * \ln(Kp/Kr) + 0.7563 \quad (3.8)$$

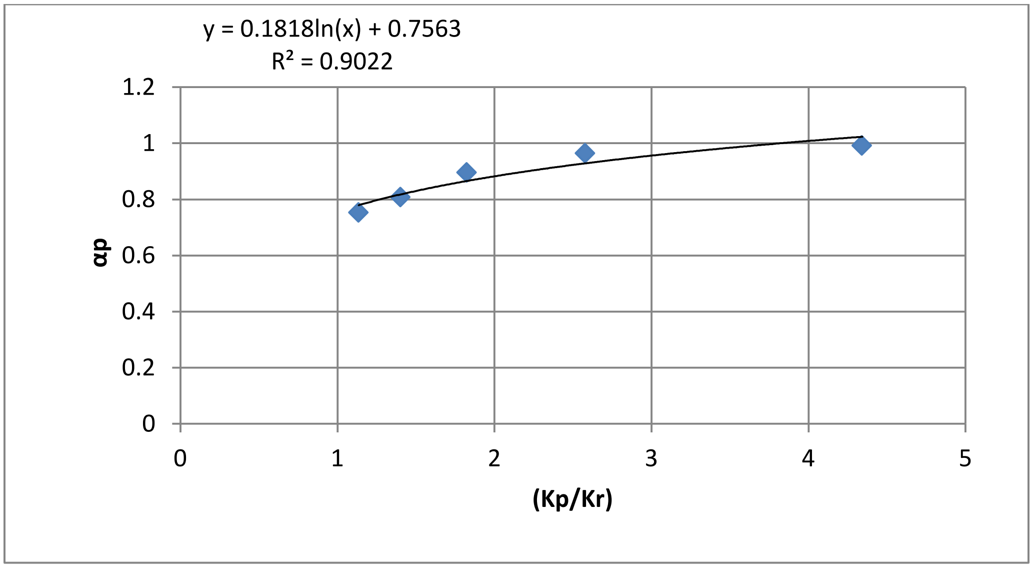

Fig. 3.97: Effect of pile-raft stiffness ratio on the pile efficiency factor, *αp*

The load sharing between the raft and the piles can be estimated by the ratio between the load carried by the raft to the load carried by the piled-raft at the same amount of settlement as given by equation (3.5). The load carried by the piles can be estimated from equation (3.6).

To examine the results of the proposed model, its predictions of the piled-raft stiffness and load carried by the raft for four cases of piled-rafts supported by different sizes of pile groups were compared with the prediction of PDR-Method developed by Randolph (1983).

Case 1: Randolph (1983) reported a case of piled-raft foundation which consists of a raft of overall dimension 20.1 m × 43.3 m supported by pile group of 350 piles. The foundations are subjected to a load of about 156000 kN. Randolph (1983) estimated the raft stiffness, *Kr* and pile group stiffness, *Kp* by 3250 kN/mm and 5300 kN/mm, respectively. To predict the piled-raft stiffness and the load carried by the raft using the proposed model, equations (3.4), and (3.5) can be used, respectively. The results of the proposed model are compared with the results of PDR-Method for as shown in Table 3.8.

Table 3.8: Comparison between the results of the proposed model and PDR-Method for Case 1

	PDR-Method	Proposed Model
Piled-raft stiffness, kN/mm	5720	6339
Settlement, mm	27	24
Raft Load %	24	29

Case 2: For case 1 mentioned above Randolph (1983) used a pile group consisting of 171 piles and predicted the stiffness of this pile group as, using *Kp* = 4700 kN/mm and *Kr* = 3250 kN/mm. The foundations are subjected to a load of about 156000 kN. To predict the piled-raft stiffness and the load carried by the raft using the proposed model, equations (3.4), and (3.5) can be used, respectively. Table 3.9 shows a comparison between the results of the proposed model and PDR-Method.

Table 3.9: Comparison between the results of the proposed model and PDR-Method for Case 2

	PDR-Method	Proposed Model
Piled-raft stiffness, kN/mm	5334	5909
Settlement, mm	29	26
Raft Load %	31	35

Case 3: For case 1 mentioned above, Fleming et al, (2009) reported that Horikoshi and Randolph (1999) suggested using a pile group of 18 piles only and predicted the pile group stiffness, *Kp* to be 3000 kN/mm and they use the same raft stiffness of case 1, namely, *Kr* = 3250 kN/mm (Fleming et al. 2009). The foundations are subjected to a load

of about 156600 kN. To predict the piled-raft stiffness and the load carried by the raft using the proposed model, equations (3.4), and (3.5) were used, respectively. Table 3.10 shows a comparison between the results of the proposed model and PDR-Method.

Table 3.10: Comparison between the results of the proposed model and PDR-Method for Case 3

	PDR-Method	Proposed Model
Piled-raft stiffness, kN/mm	3710	4933
Settlement, mm	42	32
Raft Load %	56	55

Case 4: Randolph (1994) reported a case of piled-raft foundation which consists of a raft of overall dimension 36 m × 36 m supported by a 9×9 pile group. Randolph (1994) estimated the raft stiffness, *Kr* and pile group stiffness, *Kp* to be 13500 kN/mm and 16200 kN/mm, respectively. The foundations are subjected to a total load of about 780000 kN. To predict the piled-raft stiffness and the load carried by the raft using the proposed model, equations (3.4), and (3.5) were used, respectively. Table 3.11 shows a comparison between the results of the proposed model and PDR-Method.

Table 3.11: Comparison between the results of the proposed model and PDR-Methods for Case 4

	PDR-Method	Proposed Model
Piled-raft stiffness, Kpr (kN/mm)	17400	22414
Settlement, (mm)	44	35
Raft Load %	33	43

It can be seen from Tables 3.8, 3.9, 3.10 and 3.11 that the prediction of the proposed model is close to the prediction of PDR-Method. The results of the proposed model are approximate. Giving the simplicity of the proposed model, this model can be used for the preliminary design stage to evaluate different alternatives. It can be observed from case #1 and #2 that increase number of piles under the raft has a minor effect in improving the piled-raft stiffness. This trend can be attributed to the interaction effect among piles when the number of the piles increases. Therefore, it can be argue that using a small number of the piles in piled raft foundations is more efficient than using a large number of piles.

3.6.3 Design Procedure for Piled-raft Foundations

In some cases, a raft foundation can provide the required bearing capacity but it cannot satisfy the settlement requirements. In such cases, it is recommended to consider a piled-raft foundation to reduce the settlement. For designing piled-raft foundations, especially in the preliminary design stage, the settlement of the foundation and the load sharing between the raft and piles are the most important criteria to obtain an efficient and economical design. Yamashita et al. (2011) suggested that the piled-rafts work more effectively if the raft carries out at least 30% of the load. Therefore, a design procedure based on these two criteria is proposed. The following steps are suggested to carry out a preliminary design of piled-raft foundations to obtain the most efficient and economical design. A flow chart of this procedure is shown in Fig.3.98:

1) Determine the stiffness of the raft foundation alone, *Kr*.
2) To reduce the settlement of the raft, consider a number of pile groups with different number of piles, pile length, pile diameter and pile spacing.
3) Determine the stiffness of the pile group without the raft, *Kp* for each case.
4) For each case, determine the settlement of the piled-raft foundations by using the stiffness of piled-raft foundations, *Kpr* has given by equation (3.4).

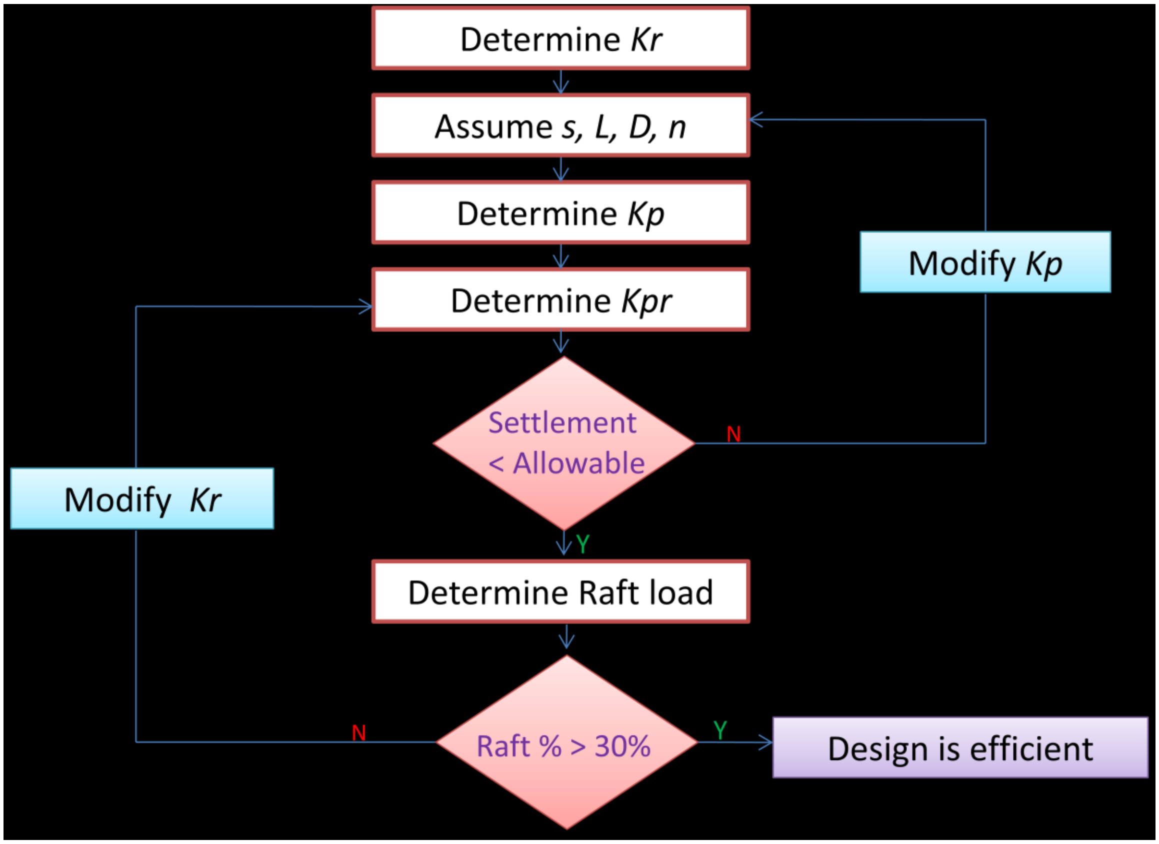

Fig. 3.98: Procedure for preliminary design of piled-raft foundations

5) If the estimated settlement is larger than the allowable settlement of the structure then modify, *Kp* and go back to step 2.
6) For the cases, which satisfy the settlement requirements, estimate the load sharing between the piles and the raft by using equation (3.5).
7) If load carried by raft is less than 30% then modify, *Kr* and go back to step 4.
8) Repeat the procedure until both settlement and load carried by the raft requirements are satisfied.

CHAPTER 4

CONCLUSIONS

4.1 Conclusion

In this study a numerical model was developed using the software PLAXIS to analyze piled-raft foundations as two dimensional problems. This model account for the effect of interaction factors among pile, raft and soil by employing very accurate element, namely, 15-node triangular element. The model was validated by comparing its results with the results of tests and other numerical models available in the literature. The results of the developed numerical model were found in reasonable agreement with the results of experimental data and other numerical models based on three dimensional analyses. The developed model provides improvement in the accuracy of 2D-finite element models and less computation time comparing with 3D-finite element models. The numerical model was used to carry out a parametric study to investigate the effect of some important parameters on the performance of piled-raft foundations in sand soil at small and large settlements. The numerical model was also used to develop a simple model for predicting the settlement and the load sharing between the piles and the raft.

The effect of some important design parameters on the performance of piled-raft foundations such as pile diameter, pile length, pile spacing, pile stiffness, raft width, raft thickness and raft stiffness was studied. The effect of some important soil properties which are not well studied in the literature such as the modulus of elasticity, Poisson's ratio, the friction angle, the dilatancy angle and the unit weight, was also investigated. The effect of these parameters was studied in terms of their influence on the load-settlement relationship at small and large settlements and on the load sharing between the piles and the raft. The effect of the selected parameters on the load-settlement relationship at small settlement was compared with those at large settlements.

The results of this study showed that some parameters have an effect on the load-settlement relationship at small settlements different from their effect at large settlements. The most important observations regarding the effect of the investigated parameters on the load-settlement relationship of piled-raft foundations can be summarized as follows:

1) Some parameters have no effect on the load-settlement relationship of piled-raft foundations at small or large settlements of the system. These are the modulus of elasticity of the piles, the reduction factor of the pile-soil interface strength, modulus of elasticity of the raft and raft thickness.
2) Some parameters have a negligible effect on the load-settlement relationship of piled-raft foundations at small settlements whereas they have a significant effect at large settlements. These are the pile diameter, pile spacing, raft width, Poisson's ratio of the soil, and angle of internal friction of the soil, dilatancy angle of the soil and unit weight of soil.
3) Some parameters have a significant effect on the load-settlement relationship of piled-raft foundations at small and large settlements. These are pile length and modulus of elasticity of soil.

In this study, it was found that the effect of the investigated parameters on the load sharing between the raft and piles can be categorized significant effect, a small effect, or no effect as follows:

1) Parameters, which show significant effect on the load carried by the raft, are pile diameter, pile length, pile spacing, raft width, and angle of internal friction of soil.
2) Some parameters show only small effect on the load carried by the raft such as raft thickness, modulus of elasticity of soil, Poisson’s ratio of the soil and the modulus of elasticity of the piles.
3) Parameters, which have no effect on the load carried by the raft, are dilatancy angle of the soil, unit weight of soil, the reduction factor of the pile-soil interface strength and modulus of elasticity of the raft.

Some important observations which can assist in conducting an efficient design of piled-raft foundations are described as follows:

1) By changing the pile spacing it was observed that the location and arrangement of the piles under the raft significantly affect the load sharing between the piles and the raft.
2) The raft contribution decreases as the number of piles supporting the raft increases.
3) The load carried by the raft increases significantly when the settlement of the raft increases.
4) The load sharing between the raft and the piles depends not only on the ratio of the stiffness of the piles to that of the raft but also on the settlement level of the foundations.
5) Piled-raft foundations are not efficient in sand soils with angles of internal friction less that 35°.

6) The stiffness of piled-raft foundations depends mainly on the ratio of the stiffness of the piles to that of the raft.

An approximate solution for the piled-raft system was obtained. Based on this approximate solution a simple model for predicting the stiffness of piled-raft foundations and load sharing between the piles and raft was developed in this study. To account for the interaction between the raft and piles two efficiency factors, namely, raft efficiency factor and piles efficiency factor were introduced in this model. Design procedure based on two design criteria, namely, settlement and load sharing between the raft and the piles, was proposed. The proposed design method is recommended for the preliminary design of piled-raft foundations.

4.2 Recommendations for Future Research

1) In this study, the analysis was carried out assuming that the piled-raft foundation is a two-dimensional problem. It is recommended to extend this study by carrying out the analysis of piled-raft foundations using three-dimensional analysis. It is recommended to use the software PLAXIS 3D to carry out such analysis.
2) It was assumed in the analysis that the soil stiffness is constant throughout the whole depth of the soil layer. It is recommended to extend this study by considering that the stiffness of the soil increases with the depth of the soil.
3) In this study it was assumed that water table is very deep from the soil surface. It is recommended to extend this study to investigate the effect of changing water table on the performance of piled-raft in terms of load sharing and load-settlement relationship.

4) It is recommended to investigate the performance of piled-raft foundations supported by different types of piles. For example, using tapered piles may have some effect on the performance of piled-raft foundations in terms of foundation stiffness or the load sharing between the raft and the piles.
5) In this study the piles used to support the raft were assumed to be non-displacement piles. It is recommended to extend this study by considering displacement piles.
6) It is recommended to investigate the effect of applying concentrated loads on the performance of piled-raft foundations.
7) In this study sand soil was considered to support the foundations. It is recommended to investigate the performance of piled-raft foundations in other types of soils.
8) It is recommended to study the effect of time factor on the load sharing of piled-raft foundations. It is expected that in some types of soil such as clay the load sharing may change with time.
9) It recommended considering developing sophisticated experimental set up to monitor and measuring load transfer mechanism in piled-raft foundations between the piles and the raft.

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