AN EXPERIMENTAL STUDY INTO BEARING OF RIGID PILED RAFTS UNDER VERTICAL LOADS

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AN EXPERIMENTAL STUDY INTO BEARING OF RIGID PILED RAFTS UNDER VERTICAL LOADS

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ABSTRACT

AN EXPERIMENTAL STUDY INTO BEARING OF RIGID PILED RAFTS UNDER VERTICAL LOADS

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In this study, the load bearing behavior of piled raft foundations is investigated performing laboratory and field tests. Piled raft foundation of a multi storey building was also instrumented and monitored in order to study the load sharing mechanism of piled raft foundations.

A small reinforced concrete piled raft of 2.3 m square supported by four mini piles at the corners was loaded and contribution of the raft support up to 41 % of the total load was observed. The soil was stiff fissured Ankara clay with no ground water.

A building founded on a piled raft foundation was instrumented and monitored using earth pressure cells beneath the raft during its construction period. The foundation soil was a deep graywacke highly weathered at the upper 10 m with

no ground water. The proportion of load that was carried by the raft was 21 to 24 % of the total load near the edge and 44 to 56 % under the core.

In the laboratory tests, model aluminum piles with outer\inner diameters of 22\18 mm and a length of 200 mm were used. The raft was made of steel plate with plan dimensions of 176 mm x 176 mm and a thickness of 10 mm. The model piles were instrumented with strain gages to monitor pile loads. Model piled raft configurations with different number of piles were tested. The behavior of a single pile and the plain raft were also investigated. The soil in the model tests was half and half sand – kaolinite mixture.

It has been observed that when a piled raft is loaded gradually, piles take more load initially and after they reach their full capacity additional loads are carried by raft. The proportion of load that was carried by the raft decreases with the increasing number of piles and the load per pile is decreased. Center, edge and corner piles are not loaded equally under rafts. It has been found that rafts share foundation loads at such levels that should not be ignored.

Keywords: Piled Raft Foundation, Piled Raft Coefficient, Model Test, Field Instrumentation, Field Load Test

ÖZ

RİJİT KAZIKLI RADYELERİN DÜŞEY YÜKLER ALTINDA TAŞIMASI ÜZERİNE DENEYSEL BİR ÇALIŞMA

Türkmen, Haydar Kürşat
Doktora, İnşaat Mühendisliği Bölümü
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Mart 2008, 125 sayfa

Bu çalışmada, laboratuvar ve saha deneyleri yapılarak, kazıklı radye temellerin yük taşıma davranışı incelenmiştir. Ayrıca, kazıklı radye temellerin yük paylaşım mekanizmasını inceleyebilmek için çok katlı bir binanın kazıklı radye temeli gözlem aletleriyle donatılmış ve gözlemlenmiştir.

Köşelerinde dört mini kazıkla desteklenen, bir kenarı 2.3 m olan kare şeklinde küçük bir betonarme kazıklı radye yüklenmiş ve toplam yükün %41'ine radye desteğinin katkısı gözlenmiştir. Zemin fisürlü katı Ankara kilidir ve yeraltı suyu yoktur.

Kazıklı radye temel üzerine oturan bir bina, radye altında zemin basınç ölçerler kullanarak donatılmış ve inşaatı süresince gözlemlenmiştir. Temel zemini üstteki 10 m' de çok ayrışmış, derin grovaktan oluşmaktadır ve yeraltı suyu yoktur.

Radye tarafından taşınan yük oranı, kenarda toplam yükün %21-24'ü ve çekirdeğin altında ise %44-56'sı kadar olmuştur.

Laboratuvar deneylerinde, dış çapı 22 mm, iç çapı 18 mm ve uzunluğu 200 mm olan model aluminyum kazıklar kullanılmıştır. Plan boyutları 176 mm x 176 mm ve kalınlığı 10 mm olan radye, çelik plakadan imal edilmiştir. Model kazıklar, kazık yüklerini ölçebilmek için, birim deformasyon ölçerlerle donatılmıştır. Değişik sayıda kazıktan oluşan model kazıklı radye grupları test edilmiştir. Tek bir kazık ve tek radye davranışı da ayrıca incelenmiştir. Model deneylerde kullanılan zemin, yarı yarıya kum-kaolinit karışımıdır.

Kazıklı radye temel kademeli olarak yüklendiğinde, başlangıçta kazıkların daha fazla yük aldığı ve tam kapasitelerine ulaştıktan sonra ek yüklerin radye tarafından taşındığı gözlenmiştir. Radye tarafından taşınan yük oranı artan kazık sayısıyla azalmakta ve kazık başına düşen yük azalmaktadır. Radye altındaki merkez, kenar ve köşe kazıklar eşit olarak yüklenmemektedir. Radyelerin temel yüklerini göz ardı edilemeyecek seviyelerde paylaştığı bulunmuştur.

Anahtar Kelimeler: Kazıklı Radye Temel, Kazıklı Radye Katsayısı, Model Deney, Saha Aletsel Gözlemi, Saha Yükleme Deneyi

to my parents and sister . . .

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CHAPTER 1

INTRODUCTION

Piled foundations are extensively used to transfer heavy structural loads to the stronger subsoils, to reduce total and differential settlements and to avoid tilting of the high rise buildings. Conventional pile groups are designed so that all the loads of the structures are carried by piles. Generally contact of the pile cap to the ground is neglected and its contribution to the total load bearing capacity of the pile group is not considered. In reality the load carrying mechanism of a piled raft is very complex and the load is shared between the piles and the raft, if the raft is in contact with the ground. In recent years, the contribution of the raft to the total load bearing capacity is being considered in design approaches and in some local codes, which lead to considerable reduction in the pile construction costs.

In this study, the load bearing behavior of piled raft foundations is investigated performing laboratory and field tests. Model foundations were instrumented in laboratory and in the field, in order to investigate load-settlement behavior and load-sharing mechanism of piled raft foundations. In the field load test, a cap with 4 bored piles was tested under vertical load. Different configurations of piled raft foundation models were also tested in the laboratory. Their load sharing mechanism, the effect of settlements and foundation element stiffness to this mechanism were also investigated.

Foundation of a multi storey building was instrumented and monitored during the construction period of the building. Contact pressures were measured using earth pressure cells beneath the raft and load sharing mechanism of piled raft foundation was studied.

In Chapter 2 piled raft definitions, design concepts and selected applications are given with a literature review. A description of the field load test, instrumentation and monitoring of the building, presentation and discussion of the results related to field observations are given in Chapter 3. Laboratory tests are outlined in Chapter 4. Results of the laboratory tests are presented in Chapter 5. Discussion of the laboratory test results are given in Chapter 6. Finally, Chapter 7 includes the conclusions of the study.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

In spite of extensive research about piled raft foundations there are still uncertainties in predicting the behavior and design of such foundations. The previous researches about the concept of piled raft foundations can be divided into two broad categories: experimental and analytical researches. In this chapter analysis, design and application of piled raft foundations will be introduced with the available literature.

2.2 Piled Raft Foundation Concept and Definitions

Burland et al. (1977) have defined piled rafts as composite foundation constructions which use both piles and the raft as bearing elements in order to transfer structural loads into subsoil (Katzenbach and Moormann, 2001). Since, combination of the conventional piles with a raft foundation is used to transfer structural loads some researchers (e.g. Katzenbach et al. (2001, 2004, 2005)) have named this foundation type as a combined pile raft foundation (CPRF). Some others has called them as piled rafts or piled raft foundations. Throughout the thesis, the terms of piled rafts or piled raft foundations will be used to define them.

The load bearing mechanism and interaction effects of the soil, piles and the raft in a piled raft foundation system is illustrated in Figure 2.1 (Katzenbach et al., 2004).

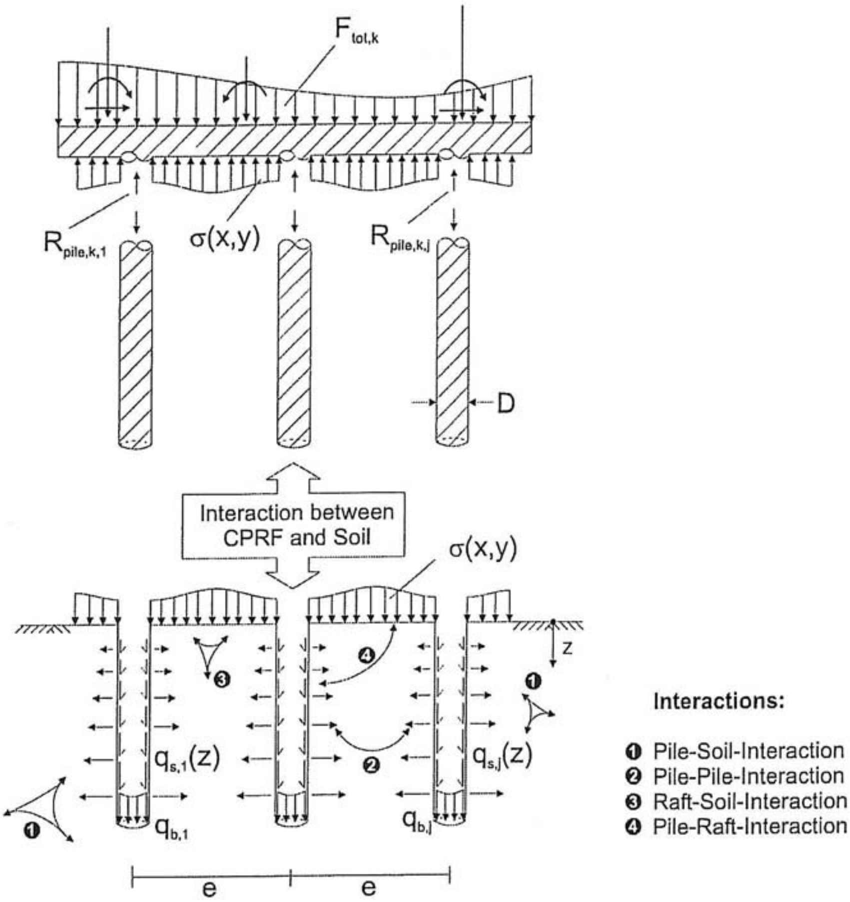

Figure 2.1 Soil-structure interaction of piled rafts (Katzenbach et al., 2004)

According to Katzenbach et al. (2004), at a settlement level of s, the characteristic value of the total resistance $R_{tot,k}(s)$ of the piled raft foundation consists of the summation of the characteristic pile resistances and the characteristic base resistance:

$$R_{tot,k}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) + R_{raft,k}(s) \tag{2.1}$$

where $R_{pile,k,j}(s)$ is the characteristic pile resistance and $R_{raft,k}(s)$ is the characteristic base resistance. The characteristic base resistance can be estimated from the integration of the settlement dependent contact pressure $\sigma(s,x,y)$ to plan area A of the raft foundation as follows:

$$R_{raft,k}(s) = \iint \sigma(s, x, y)dxdy \tag{2.2}$$

The bearing behavior of a piled raft foundation can be described by the piled raft coefficient, α_{pr}, which describes the load sharing between piles and the raft (Katzenbach and Moorman, 2001). The piled raft coefficient is defined by the ratio between the sum of the characteristic pile resistances and the characteristic value of the total resistance:

$$\alpha_{pr}(s) = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)} \tag{2.3}$$

A piled raft coefficient of $\alpha_{pr} = 0$ indicates the case of a shallow foundation and $\alpha_{pr} = 1$ indicates the case of a piled foundation without contact pressure beneath the raft, which means that conventional shallow and piled foundations are the limiting cases of a piled raft. Piled raft foundations cover the range $0 < \alpha_{pr} < 1$ (Katzenbach et al., 2000). For a large number of high-rise buildings which have been instrumented by the Institute and Laboratory of Geotechnics of Technische Universität Darmstadt, the observed piled raft coefficients and settlements are illustrated in Figure 2.2 (Katzenbach et al., 2001).

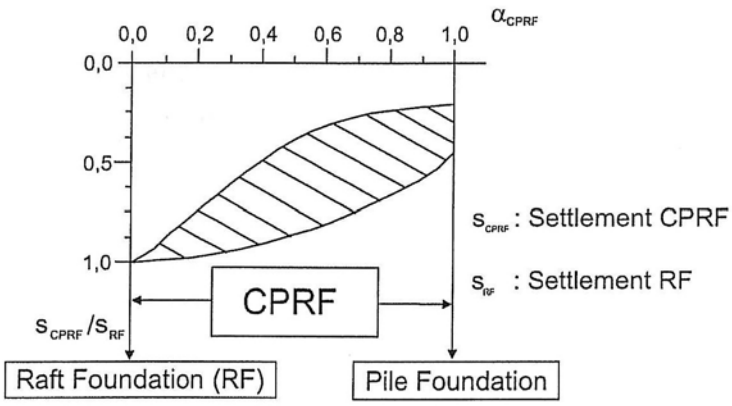

Figure 2.2 Foundation settlements as a function of piled raft coefficient (Katzenbach et al., 2005)

According to Randolph (1994), one of the principle benefits of casting a pile cap directly on the ground is to enforce a block type failure. If the pile cap acts directly on the soil surface, relative slip between pile and soil cannot occur at shallow depths, and the ultimate limit state must involve punching failure of the entire block of soil containing the piles (Randolph, 1994). He has defined three different design approaches for piled rafts:

1. Conventional Approach: In this approach the foundation is designed as a pile group, while making some allowance for the contribution of the pile cap to the load transmitted to the ground. The piles are distributed uniformly beneath the raft. As only 60-75 % of the total structural load is being carried by the piles, the principle benefit is the reduction in the total number of piles.

2. Creep Piling Approach: Creep piling has been proposed by Hansbo and Källström (1983) (Randolph, 1994). In this approach the piles are designed to operate at a working load at which significant creep starts to occur, typically at 70-80 % of its ultimate bearing capacity. Sufficient piles are included to reduce the net contact pressure between raft and soil to below the preconsolidation pressure of the soil. The foundation is designed as a raft foundation, but the total

settlement is reduced by uniformly distributed piles beneath the raft. The piles are allowed to move plastically relative to the surrounding soil.

3. Differential Settlement Control Approach: In this approach piles are located strategically in order to reduce differential settlements, without necessarily reducing the average settlement significantly. Figure 2.3 shows the principle behind the design of piles to reduce settlements (Randolph, 1994). According to Randolph (1994), assuming that the structural load is uniformly distributed over the foundation, adding a few piles over the central region of the foundation will reduce the tendency for an unpiled raft to dish in the center and thus the differential settlements will be minimized.

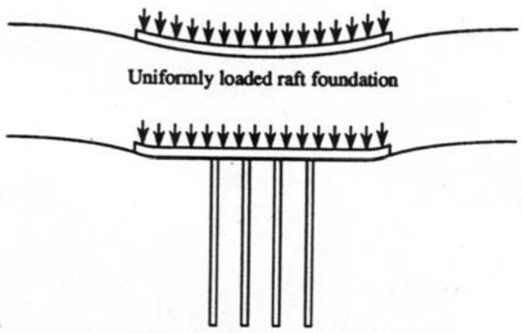

Figure 2.3 Central piles to reduce differential settlement (Randolph, 1994)

Randolph (1994) has stated that the required pile support may be estimated by consideration of the ideal contact pressure distribution that acts beneath a rigid raft, where the central pressure is approximately half of the average applied pressure. Designing the central piles to support 50-70 % of the average applied pressure, the contact stress distribution of a flexible raft will match the contact stress distribution of a rigid raft and thus differential settlements will be minimized. Randolph (1994) has noted that, since the piles will contribute some settlement, the piles should be designed to carry more than half the applied pressure.

Poulos (2000a) has defined a more extreme version of creep piling, in which the full load capacity of some or all of the piles is utilized. This defines the concept of using piles primarily as settlement reducers and also using piles in order to increase the ultimate load capacity of the foundation system.

The load-settlement behavior of piled rafts designed according to the first two strategies is illustrated in Figure 2.4 (Poulos, 2000a). Curve 0 shows the behavior of the raft alone and the settlements are excessive at the design load. Curve 1 represents the conventional design approach, in which the piles are designed as a pile group and piles carry the major part of the load. The behavior of the pile-raft system may be largely linear at the design load. Curve 2 represents the case of creep piling. In this case raft carries more load compared to the conventional design approach case, because there are fewer piles and the piles operate at a lower factor of safety. Curve 3 represents the concept of using piles as settlements reducers and utilizing the full capacity of the piles at the design load. The load-settlement relation may be non-linear at the design load.

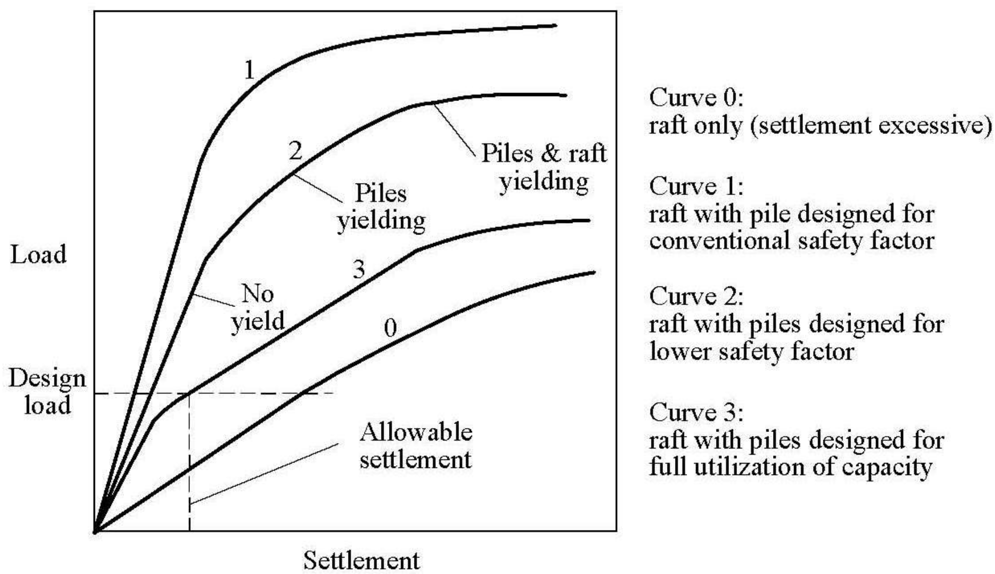

Figure 2.4 Load-settlement curves for piled rafts according to various design philosophies (Poulos, 2000a)

2.3 Methods of Analysis of Piled Rafts

Poulos et al. (1997) has classified the analysis methods of piled rafts in three groups:

1. Simplified analysis methods
2. Approximate computer methods
3. More rigorous computer methods

2.3.1 Simplified Analysis Methods

These methods involve some simplifications related to the modeling of the soil profile and loading conditions. Poulos and Davis (1980), Randolph (1983, 1994), van Impe and Clerq (1995), Burland (1995) and Poulos-Davis-Randolph Methods (Poulos 2001) are some of the simplified analysis methods of piled raft foundations (Poulos 2001).

Traditionally, the settlement of a pile group has been estimated by considering an equivalent raft which is assumed to be located at two-thirds of the lower part of the piles which penetrate into the bearing stratum for the floating piles or at the level of the pile bases for end bearing piles as indicated in Figure 2.5 (Randolph, 1994).

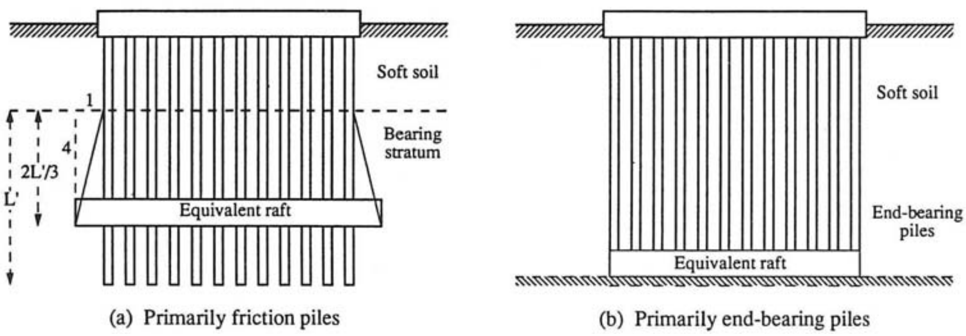

Figure 2.5 Equivalent raft approach for pile groups (Randolph, 1994)

The average settlement is calculated as the summation of the settlement of the equivalent raft and the elastic compression of the piles above the level of the equivalent raft. Although various approaches have been suggested for the equivalent raft method, a load spread of 1 in 4 is generally assumed in order to evaluate the size of the raft as shown in Figure 2.5 (Randolph, 1994).

Poulos and Davis (1980) have proposed the equivalent pier method for estimating the load-settlement behavior of a pile group. They have suggested replacing the pile groups by an equivalent single pier that settles an equal amount. The solutions of a single pile can be applied in order to estimate the load-settlement response of the equivalent pier. Poulos and Davis (1980) have made two approximations to be useful for different circumstances:

1. An equivalent single pier of the same circumscribed plan area as the pile group having an equivalent length, L_e.
2. An equivalent single pier of the same length as the piles having an equivalent diameter, d_e.

Randolph (1994) has suggested that the diameter of the equivalent pier can be estimated as:

$$d_{eq} = \sqrt{\frac{4}{\pi} A_g} \tag{2.4}$$

where d_{eq} is the diameter of the equivalent pier and A_g is the plan area of the pile group as a block. The Young's modulus of the equivalent pier can be taken as:

$$E_{eq} = E_s + (E_p - E_s)\left(\frac{A_p}{A_g}\right) \tag{2.5}$$

where E_{eq}, E_p and E_s is the Young's modulus of the equivalent pier, piles and the soil penetrated by the piles respectively and A_p is the total cross sectional area of the piles in the group.

Clancy and Randolph (1993) have defined a parameter to categorize pile groups:

$$R = \sqrt{\frac{ns}{L_p}} \tag{2.6}$$

where n is the number of piles, s the pile spacing and L_p is embedded length of the pile. They stated that for the values of R greater than 4, equivalent raft approach is more appropriate and if R values are less than 2, equivalent pier approach is more logical.

Randolph (1983) has combined the individual stiffness of pile group and raft using a single pile-raft unit in order to represent the piles and the raft. Load sharing between the piles and the raft can be calculated and the overall stiffness of a piled raft can be estimated. The overall stiffness (load/displacement response) of a piled raft can be calculated as follows:

$$k_{pr} = \frac{k_p + k_r(1 - 2\alpha_{rp})}{1 - (k_r / k_p)\alpha_{rp}^{\,2}} \tag{2.7}$$

where k_{pr} is the overall stiffness of a piled raft, k_p and k_r are the stiffness of pile group and the raft alone. k_p and k_r can be estimated from elastic theory. Load carried by the raft or pile group can be estimated using the following relation:

$$\frac{P_r}{P_r + P_p} = \frac{P_r}{P_t} = \frac{(1 - \alpha_{rp})k_r}{k_p + k_r(1 - 2\alpha_{rp})} = X \tag{2.8}$$

where P_p and P_r are the load carried by the pile group and the raft respectively, α_{rp} is an interaction factor. Interaction factor between raft and pile group α_{rp} can be calculated by:

$$\alpha_{rp} = 1 - \frac{\ln(r_c / r_o)}{\zeta} \tag{2.9}$$

where $\zeta = \ln(r_m / r_o)$ (2.10)

$r_m = 2.5\rho(1-\nu)L_p$ (2.11)

r_c = radius of the pile cap (calculated from the area of raft associated with each pile)

r_o = pile radius

ζ = load transfer parameter for pile shaft

r_m = maximum radius of influence of pile

ρ = parameter for relative homogeneity of soil modulus (varies from unity for homogeneous soil conditions to 0.5 where the stiffness is proportional to depth)

ν = Poisson's ratio of soil

L_p = embedded length of a pile

Poulos (2000a, 2001) has stated that a tri-linear load-settlement curve can be developed using the above equations as shown in Figure 2.6. Using Equation 2.7 the stiffness of the piled raft is computed. The pile capacity is reached at a total applied load of P_1 which is given by:

$$P_1 = \frac{P_{pu}}{1 - X} \tag{2.12}$$

where P_{pu} is the ultimate load capacity of the piles in the group and X is the proportion of load carried by the raft (Equation 2.8).

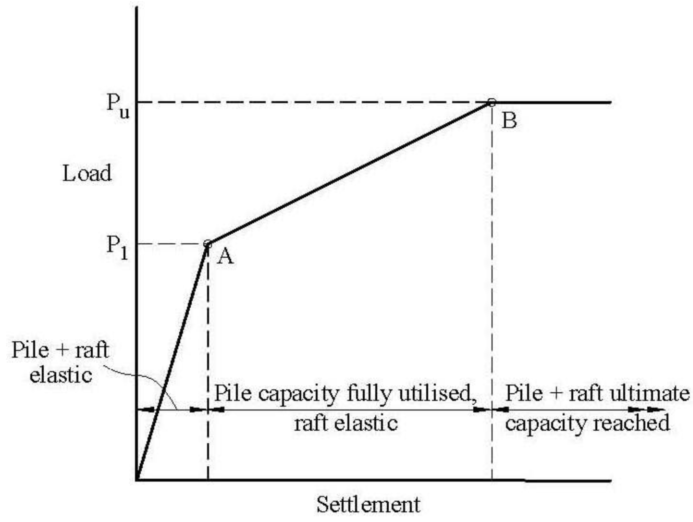

Figure 2.6 Simplified load-settlement curve (Poulos, 2000a, 2001)

The stiffness of the piled raft is in use up to the ultimate load capacity of the piles in the group (Point A in Figure 2.6). Beyond this stage, the stiffness of the foundation system is equal to the stiffness of the raft alone (k_r) until the ultimate piled raft foundation capacity is reached (Point B in Figure 2.6). After this stage load-settlement relationship becomes horizontal.

Burland (1995) has developed a simplified design method for the piles to design piles as settlement reducers. Piles full geotechnical capacities are developed at the design load. First, load-settlement relationship for the raft without piles is estimated (Figure 2.7).

At the design load P_o a settlement of S_o is obtained. P_1 is the load carried by the raft at an acceptable design settlement of S_a which should include a margin of safety. The excess load P_o - P_1 is assumed to be carried by settlement-reducing piles. Since the shaft resistance of these piles will be fully mobilized, no factor of safety will be applied. However, Burland has suggested applying a mobilization factor of 0.9 to the ultimate shaft capacity, P_{su}.

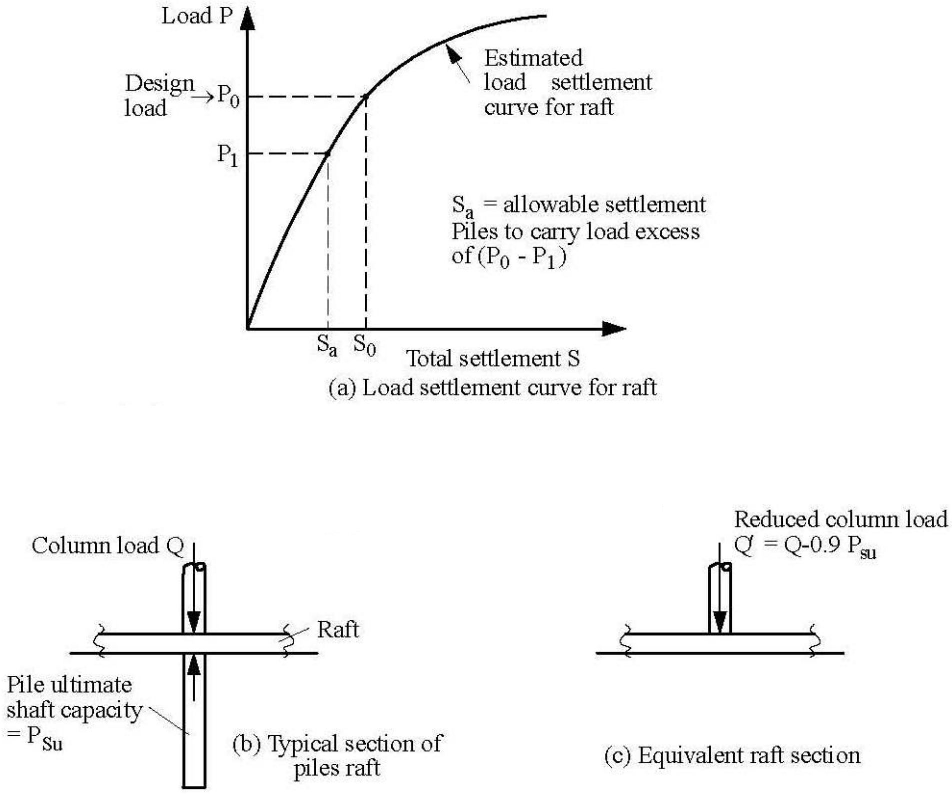

Figure 2.7 Burland's simplified design concept (Poulos, 2000a, 2001)

If the piles are located below columns which carry a load Q greater than P_{su}, the piled raft may be analyzed as a raft subjected to reduced column loads, Q_r, which is:

$$Q_r = Q - 0.9\, P_{su} \tag{2.13}$$

The bending moments in the raft can also be obtained by analyzing the piled raft as a raft with reduced loads Q_r.

2.3.2 Approximate Computer Methods

Strip on springs approach and plate on springs approach can be included in this category. Poulos (1991) has presented the strip on springs method in which a section the raft is represented by a strip and the piles are represented by springs. Raft-raft, pile-pile, raft-pile and pile-raft interactions are taken into account.

In the plate on springs method, the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modeled as interacting springs (Poulos, 2001).

2.3.3 More Rigorous Computer Methods

This category includes methods in which components of the piled raft system are modeled more detailed using the boundary element method, the finite element method and sometimes their combination (Poulos, 2000b). In many of the methods, special purpose software is used.

In boundary element methods, the full interface between soil, piles and raft is discretized and an appropriate Green's function (generally that due to Midlin (1936)) is used to relate the average displacement of each element to the traction on each element (Randolph, 1994). Butterfield and Banerjee (1971) have studied the behavior of a pile group with a rigid cap in contact with the surface with the use of boundary element method. Kuwabara (1989) has described an elastic boundary element analysis of square groups of compressible piles with rigid rafts. Free standing pile groups and groups of piles connected to a raft which is in contact with the ground have been analyzed. At normal pile spacing and under elastic conditions, it has been found that contribution of the raft to the load carrying capacity of the piled raft is small. Poulos (1993) has included the limiting values of contact pressures between raft and soil. Development of ultimate compression and tension loads in the piles has been also limited.

Hain and Lee (1978) have combined the finite element analysis and the boundary element analysis. They have represented the raft as thin plate finite elements and they used boundary element method to estimate pile behavior. Franke et al. (1994) has also described a technique combining finite element analyses for the raft and boundary element analyses for the raft. The non-linear behavior of the piles has been taken into account. Sinha (1997) has analyzed the piles using the boundary element method and the raft by thin plate finite elements in a homogeneous elastic soil medium. The non-linear behavior is considered by limiting the contact pressures between the raft and soil, the stresses beneath the pile tip and between the pile shaft and the soil.

There are some others methods which can be classified as simplified finite element analyses. In these analyses the piled rafts are represented as a plain strain problem (Desai, 1974) or as an axisymmetric problem (Hooper, 1973) (Poulos, 2000b). Structural elements and soil are represented using the finite elements including non-linear behavior of soil and raft. Only regular loading patterns can be analyzed using these methods and torsional moments in the raft cannot be obtained. These are the main disadvantages of these methods.

Three-dimensional finite element methods are the most accurate and suitable methods of analysis to model the complex interactions of piled raft foundations. However, the computer time for preparing an analysis and running is considerable high. Also, assigning the appropriate parameters for the analysis is another problem. Ottaviani (1975) has presented a study using three-dimensional finite element method. Ta and Small (1996) have developed a method using finite elements. Katzenbach et al. (1998) has carried out three-dimensional finite element analyses of different piled raft configurations. Capabilities of different methods are summarized in Table 2.1 (Poulos, 2001)

Table 2.1 Summary of capabilities of various methods (Poulos, 2001)

Method	Response Characteristics					Problem Modelling			
	Settlement	Differential settlement	Pile loads	Raft bending moment	Torsional shear	Non-linear soil	Non-linear pile	Non-uniform soil	Raft flexibility
Poulos & Davis (1980)	✓						✓		
Randolph (1983)	✓		✓						
Van Impe & Clerq (1995)	✓	✓							
Equivalent Raft (Poulos, 1994)	✓	✓							
Brown & Wiesner (1975)	✓	✓	✓	✓					✓
Clancy & Randolph (1993)	✓	✓	✓	✓	✓			✓	✓
Poulos (1994)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kuwabara (1989)	✓		✓						
Hain & Lee (1978)	✓	✓	✓	✓	✓		✓		✓
Sinha (1997)	✓	✓	✓	✓	✓	✓	✓		✓
Franke et al (1994)	✓	✓	✓	✓	✓		✓		✓
Hooper (1973)	✓	✓	✓	✓		✓		✓	✓
Hewitt & Gue (1994)	✓	✓	✓	✓				✓	✓
Lee et al (1993)	✓	✓	✓	✓	✓			✓	✓
Ta & Small (1996)	✓	✓	✓	✓	✓			✓	✓
Wang (1995)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Katzenbach et al (1998)	✓	✓	✓	✓	✓	✓	✓	✓	✓

2.4 German Piled Raft Guideline

A group of geotechnical and constructional experts supported by the German Institute for Building Research Berlin (DIBt) has developed a guideline for design, computation and construction of piled rafts, based on the parametric studies with numerical models and extensive experiences gained by monitoring of various piled rafts (Katzenbach and Moormann, 2001). They have presented some of the main aspects of the recommendations of the guideline.

2.4.1 Requirements for Calculation Methods to Design Piled Rafts

An appropriate calculation method has to consider the relevant pile-soil-raft interactions and the model should be able to predict the following concepts (Katzenbach and Moormann, 2001):

- The load-settlement behavior of the piled raft system up to ultimate loads.
- The load sharing between the piles and the raft as a function of the settlement of the piled raft.
- The bearing behavior of the individual piles depending on their particular position inside the pile group.
- The internal forces and bending moments for the structural design of piles and raft.

The German Guideline requires that suitability of the chosen method has to be proven in a preliminary step by the back-analysis of the investigated load-settlement behavior of a single pile and by the back-analysis of the measured behavior of the existing foundations with similar conditions.

2.4.2 Design and Safety Concepts

The guideline follows the limit state design philosophy and a distinction is made between the external and internal bearing capacity (Katzenbach et al., 2002). Within the limit state design method, first a set of limits beyond which the structure fails to satisfy fundamental requirements are stated. Then the performance of the whole structure and its all parts are described with reference to those limits. The Eurocode distinguishes between ultimate limit state (ULS) and serviceability limit state (SLS).

Ultimate limit states involve the situations where there is a risk of danger to people and/or severe economic loss due to collapse, failure and excessive deformations prior to failure. The ultimate limit state is separated into two parts as shown in Figure 2.8 (Katzenbach et al., 2005). The external bearing capacity is the bearing capacity of subsoil and the internal bearing capacity is the structural bearing capacity of piles and the raft. Concerning external bearing capacity, it has to be proofed that the overall piled raft system has an adequate margin of safety. Proofing an individual pile external bearing capacity is not necessary and this is the main difference to the classical piled foundations. For geometrically regular configuration of the piled raft, homogeneous subsoil (no layering) and centrically loaded raft foundation, the external bearing capacity of the piled raft may also be calculated as the base failure of an equivalent shallow foundation neglecting the piles (Katzenbach and Moormann, 2001). For the proof of the internal bearing capacity of the piled raft foundation, the internal forces of the foundation system components have to be calculated under working loads. Then the internal forces have to be proofed according to the relevant standards.

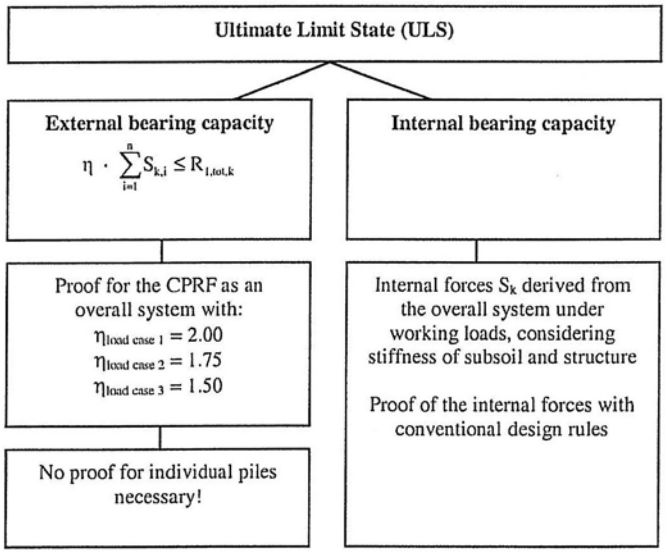

Figure 2.8 Ultimate Limit State (ULS) approach (Katzenbach et al., 2005)

The serviceability limit state (SLS) is illustrated in Figure 2.9. It is defined by the limiting values of deformations, settlements and vibrations, in normal use under working conditions, beyond which the serviceability of the structure is not guaranteed. The design value of action E has to be less than the limiting value of the deformation of the structure at the serviceability limit state. C is the resistance property for the serviceability limit state.

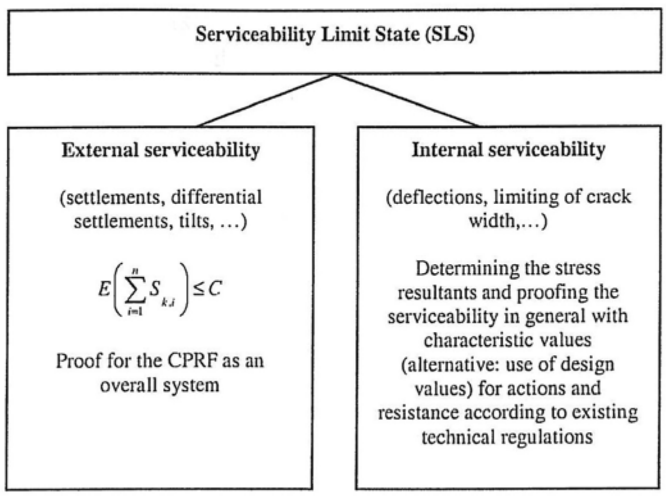

Figure 2.9 Serviceability Limit State (SLS) approach (Katzenbach et al., 2005)

The German Piled Raft Guideline has further requirements related to safety (Katzenbach and Moormann, 2001). The observational method described in Eurocode 7 has to be applied and the design of a piled raft has to be supervised and checked by an independent expert in the field of soil mechanics and foundation design. The integrity of the construction processes for piles and raft has to be guaranteed by a quality assurance concept.

2.5 Selected Case Histories of Projects with Piled Raft Foundations

2.5.1 Messe-Torhaus Building, Germany

Messe-Torhaus was the first application of a piled raft foundation in Germany (Katzenbach et al.,2000, 2005, Franke et.a l, 2000). The building constructed during 1983 to 1985 has 30-storey up to a length of 130 m (Figure 2.10).

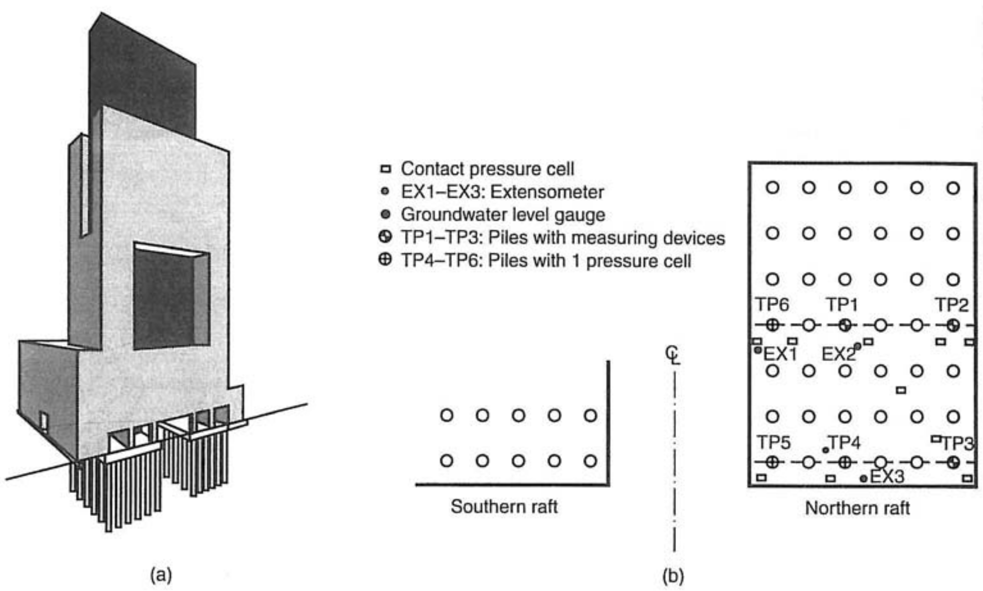

Figure 2.10 Messe-Torhaus building: a) isometric view,
b) plan of piled raft with measuring devices (Franke et al., 2000)

The foundation of the building consists of two separate rafts with dimensions of 17.5 m x 24.5 m in plan. 42 bored piles with a length of 20 m and a diameter of 0.9 m are used uniformly under each raft with a pile spacing of 3 to 3.5 times the pile diameter. Each raft is loaded by an effective structural load of 200 MN. The piled raft coefficient is about $\alpha_{pr} = 0.8$ which means that the contribution of the raft to the total load carrying capacity is small. The value of piled raft coefficient indicates that the design of the piled raft foundation is conservative and can be further optimized.

2.5.2 Messeturm Building, Germany

Messeturm building (Figure 2.11) which has a basement with two underground floors and a 60-storey concrete tower of 256 m was constructed from 1988 to 1991 (Katzenbach et al.,2000, 2005, Franke et al., 2000). The total load of the building was 1880 MN. The raft with a thickness of 3 m to 6 m is supported by 64 bored piles having a diameter of 1.3 and a spacing of 3.5 to 6 times the pile diameter. Piles were arranged in three concentric circles beneath the raft. The pile lengths are 26.9 m for the 28 piles of the outer circle, 30.9 m for the 20 piles of the middle circle and 34.9 m for the 16 piles of the inner circle. With the help of the extensive geotechnical monitoring method, the piled raft coefficient was found as 0.55. This result indicates that the contribution of the raft to the total bearing capacity is important and an optimized was obtained. The measured pile loads show that the mobilized skin friction is much higher than the determined skin friction for a single isolated pile.

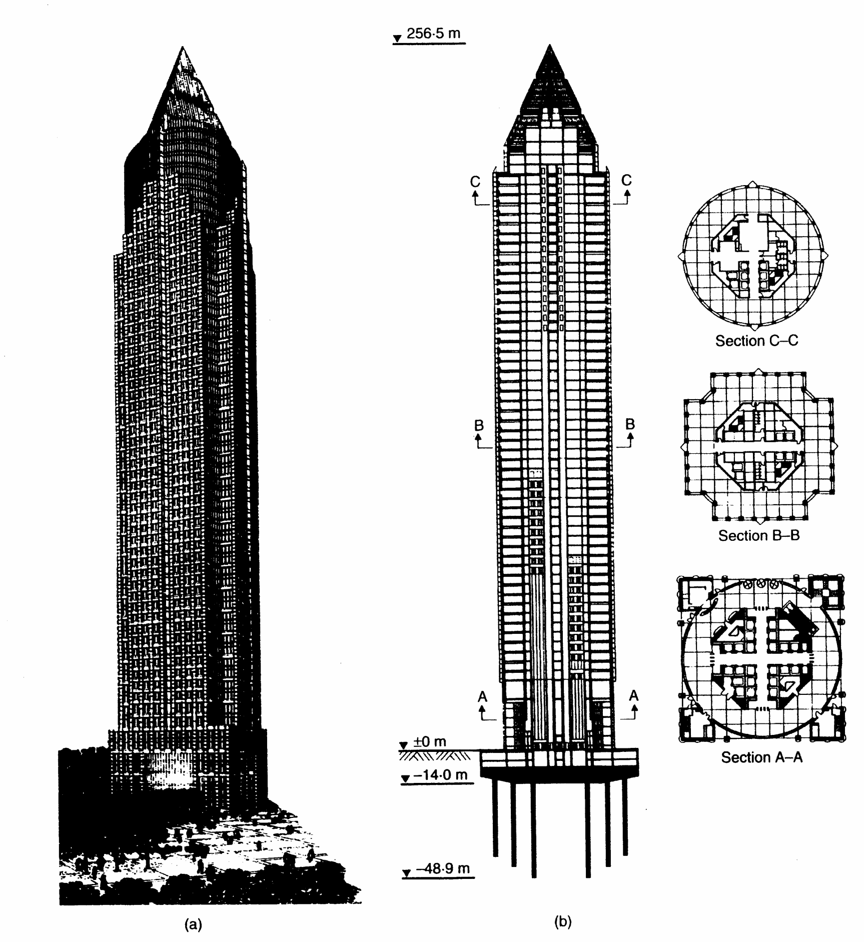

Figure 2.11 Messeturm building: a) elevation, b) cross-sections (Katzenbach et al., 2000)

2.5.3 DG-Bank (Westendstrasse 1) Building, Germany

The building complex of the DG-Bank (Figure 2.12) includes a 208 m 53-storey high office tower and a 12-storey apartment building surrounding the tower on two sides (Katzenbach et al., 2000). The tower with a total structural load of 1420 MN is founded on a piled raft and it is separated from the adjacent raft of the side building by a settlement joint. The determined piled raft coefficient was 0.5 which means that the raft and piles shared the total structural load equally.

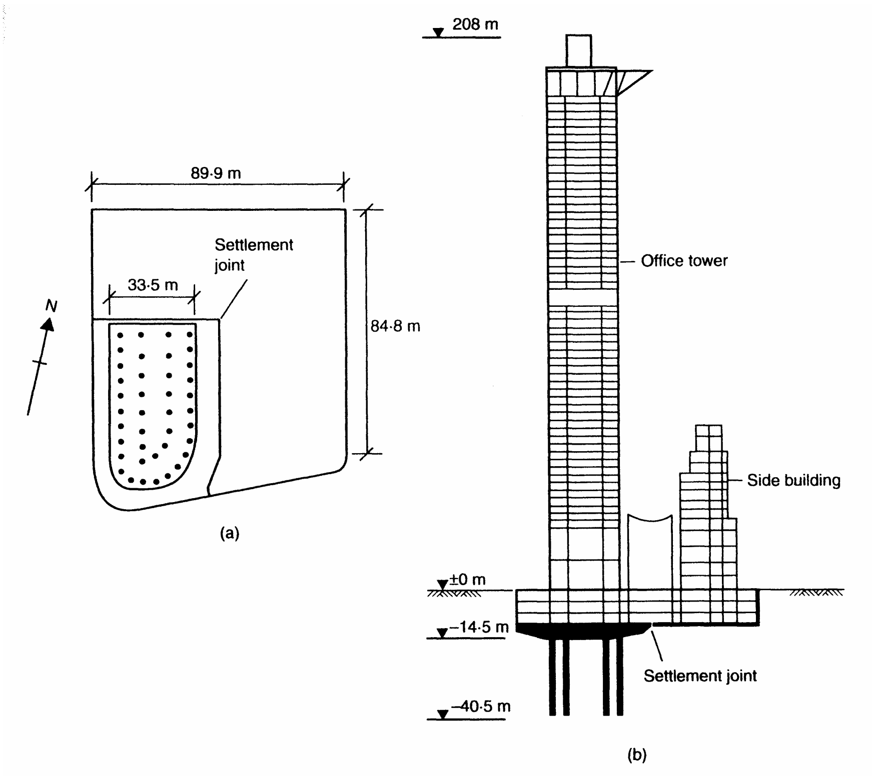

Figure 2.12 DG-Bank building: a) ground plan, b) sectional elevation (Katzenbach et al., 2000)

2.5.4 Taunustor-Japan-Centre Building, Germany

The building (Figure 2.13) has 4 basement floors and a 29-storey eccentrically placed tower with plan dimensions of 36.6 m x 36.6 m (Katzenbach et al., 2000).Total structural load is 1050 MN. 25 bored piles with a diameter of 1.3 m and length of 22 m are supporting the building. Due to the eccentricity in the building, piles are not uniformly distributed under the raft. The raft thickness is 3.0 m at the centre and 1.0 m at the edges. 60 % of the structural load is carried by the raft.

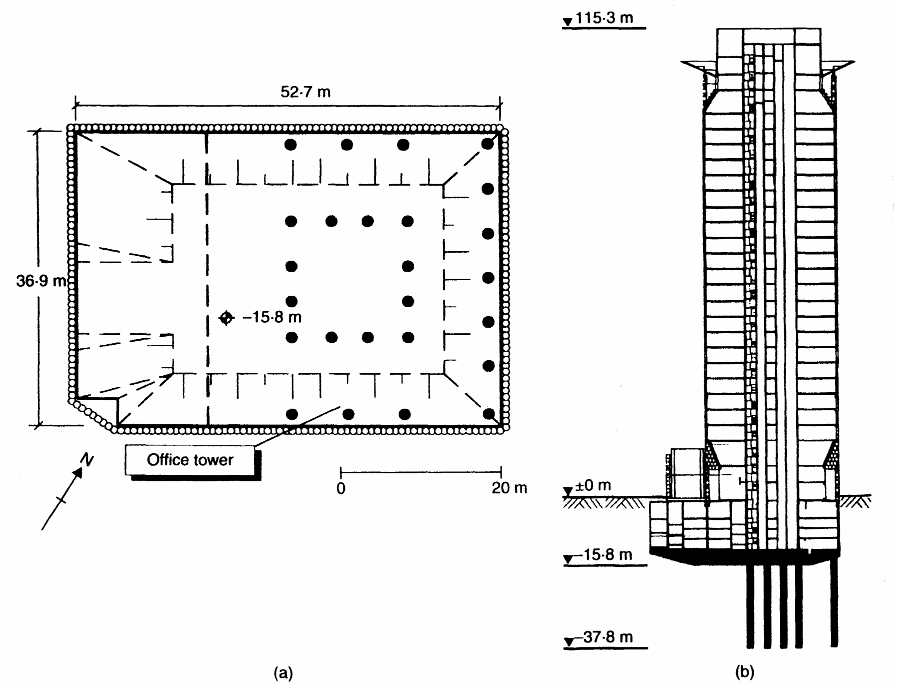

Figure 2.13 Japan-Centre building: a) ground plan b) sectional elevation (Katzenbach et al., 2005)

CHAPTER 3

FIELD LOAD TEST AND MONITORING

3.1 General

In this chapter, load test of a model piled raft foundation performed in the field and monitoring of a multi-storey building will be presented. Those observations were done in order to study the load sharing mechanism of piled raft foundations. Instrumentation used in both cases was mainly concerned with the load sharing mechanism of piled raft foundations. The settlement characteristics of the model piled raft foundation were also investigated.

3.2 Field Load Test of a Model Piled Raft Foundation

In order to observe the load sharing behavior of piles and the raft in a piled raft foundation system, a model piled raft foundation was constructed and loaded in the field. The model piled raft foundation was formed by a reinforced cap and 4 bored piles. The test area is located near the water treatment plant of Middle East Technical University. The soil was stiff fissured Ankara clay with no ground water.

3.2.1 Site Works and Model Test Setup

Model test setup consists of a piled raft foundation with 4 bored piles and a vertical reaction system. Before starting site works, the vegetative cover and other residuals at the area were cleaned. Then, reinforcement works of piles were started and the holes for the piles were drilled using a hydraulic boring machine. Reinforcing cages of the piles were placed in the drilled holes using the lifting jack apparatus of the hydraulic boring machine and then concreted (Figure 3.1). Reinforcement of the piles was extended in the raft to provide a fixed pile-raft connection.

Figure 3.1 Construction of bored piles

A total number of 8 piles were constructed. Bored piles constructed under the rafts had a diameter of 32 cm, length of 5 m and center to center pile spacing of 150 cm. In order to provide vertical reaction, 4 reaction piles were constructed with a length of 9 m and a diameter of 32 cm. To be able to fix reaction piles to the steel reaction beams, steel rods were placed in the reaction piles before concreting them. Length of the steel rods were chosen in order to provide a sufficient clearance between the steel reaction beams and the reinforced cap for the hydraulic jack, load cell and the base plate of the hydraulic jack.

After hardening of reinforced concrete piles and before commencing reinforcement works of raft, an earth pressure cell with a capacity of 200 kPa was placed at the interface between the base of raft and soil, in the mid point of the raft (Figure 3.2). The type of the soil pressure transducer (earth pressure cell) used for measuring pressure beneath the raft was KDB-200KPA and it was a product of Tokyo Sokki Kenkyujo Co., Ltd. The instrument has a diameter of 200 mm with a sensing area diameter of 166 mm. In order to protect the instrument, to minimize the measurement errors and to mount the earth pressure cell to the reinforced concrete raft, a steel apparatus was manufactured. The cable of the instrument was placed in a thick pipe to provide a mechanical protection.

Formwork was constructed using iron plates before the reinforcement works of the rafts were carried out (Figure 3.3). Then, the raft was concreted. The concrete was delivered to the site with ready mixed concrete trucks and poured. A vibrator was used to spread the concrete uniformly. The reinforced concrete raft has a dimension of 230 cm x 230 cm in plan with a thickness of 50 cm.

Figure 3.2 Installation of the earth pressure cell beneath the raft

Figure 3.3 Construction of model piled raft

Dimensions of the piles and the rafts were chosen to provide elastic behavior during the load tests. During 4 weeks before loading tests, the concrete surfaces were kept wet in order to prevent them from surface cracking.

Steel reaction beams were bolted to the reaction piles using a mobile crane to provide necessary reaction in vertical direction (Figure 3.4). Two steel beams with enough stiffness and strength, weighing approximately 2 tons were used. Vertical load was applied using a high capacity hydraulic cylinder and a hydraulic pump. A steel base plate was manufactured and placed under the hydraulic cylinder.

Figure 3.4 Replacement of steel reaction beams

Displacements were measured at the four corners of the model foundation using potentiometric displacement sensors. They were mounted on the steel reference beams having enough rigidity. The reference beams were supported using steel rods driven in ground. The settlements, load cell and earth pressure readings were recorded using a TDG AI8a Data Acquisition System and a notebook computer (Figure 3.5). Data Acquisition system converts electronic signals into binary data and this data is analyzed and stored with TDG Data Logging Software. A load cell with a capacity of 2000 kN was used to measure the applied vertical loads and it was calibrated in the Construction Materials Laboratory of Middle East Technical University before testing.

Figure 3.5 Loading and measurement systems

3.2.2 Presentation and Discussion of Field Test Results

Vertical loading sequence of the model piled raft foundation is presented in Figure 3.6. In the first cycle 200, 400 and 600 kN of load was applied. Then the load is decreased to 6.5 kN and then model piled raft foundation was loaded again with 400, 600 and 800 kN. At each increment load was kept constant for 15 minutes.

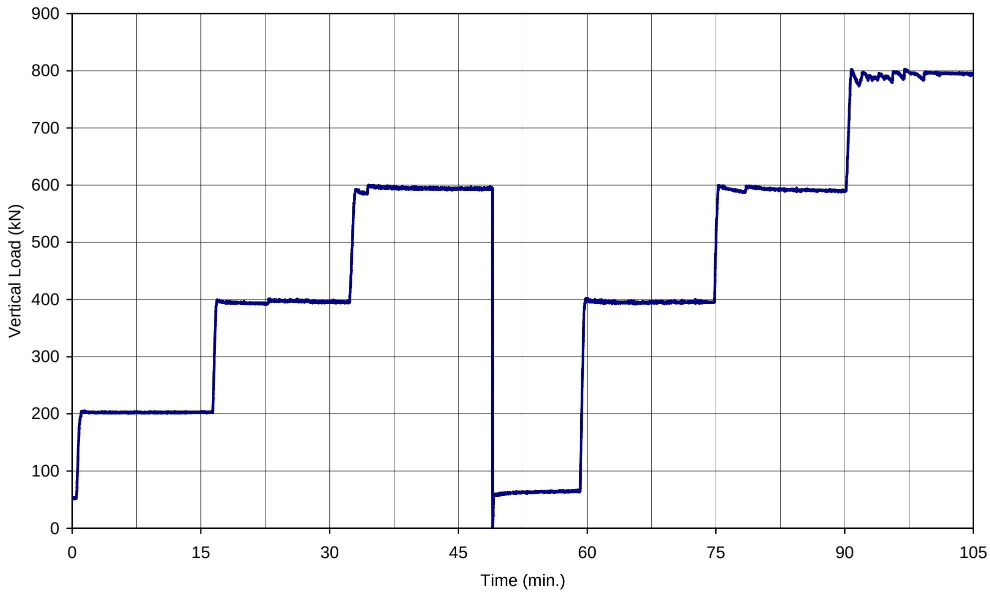

Figure 3.6 Vertical loading sequence of model piled raft foundation

Measured vertical displacement–time relationship of the model piled raft foundation is presented in Figure 3.7. It is seen that settlements die out in a relatively short time (i.e. mostly immediate settlement). Contact pressure-time relationship is given in Figure 3.8. Applied total pressure is found by dividing total applied load by the raft area. In Figure 3.8, the maximum raft load coefficient is 0.41, assuming that the pressure measured using the earth pressure cell is the average contact pressure between the raft and the subsoil. This means that the raft carries 41 % of the total vertical load. This shows that raft has a considerable contribution to the total load bearing capacity of a piled raft foundation for the specific piled raft configuration of four piles at the corners which was loaded centrally on stiff plastic clay. Theoretical pile load carrying capacity is much larger than the measured loads. Raft load coefficient changes at different load levels, as settlements vary under different load levels.

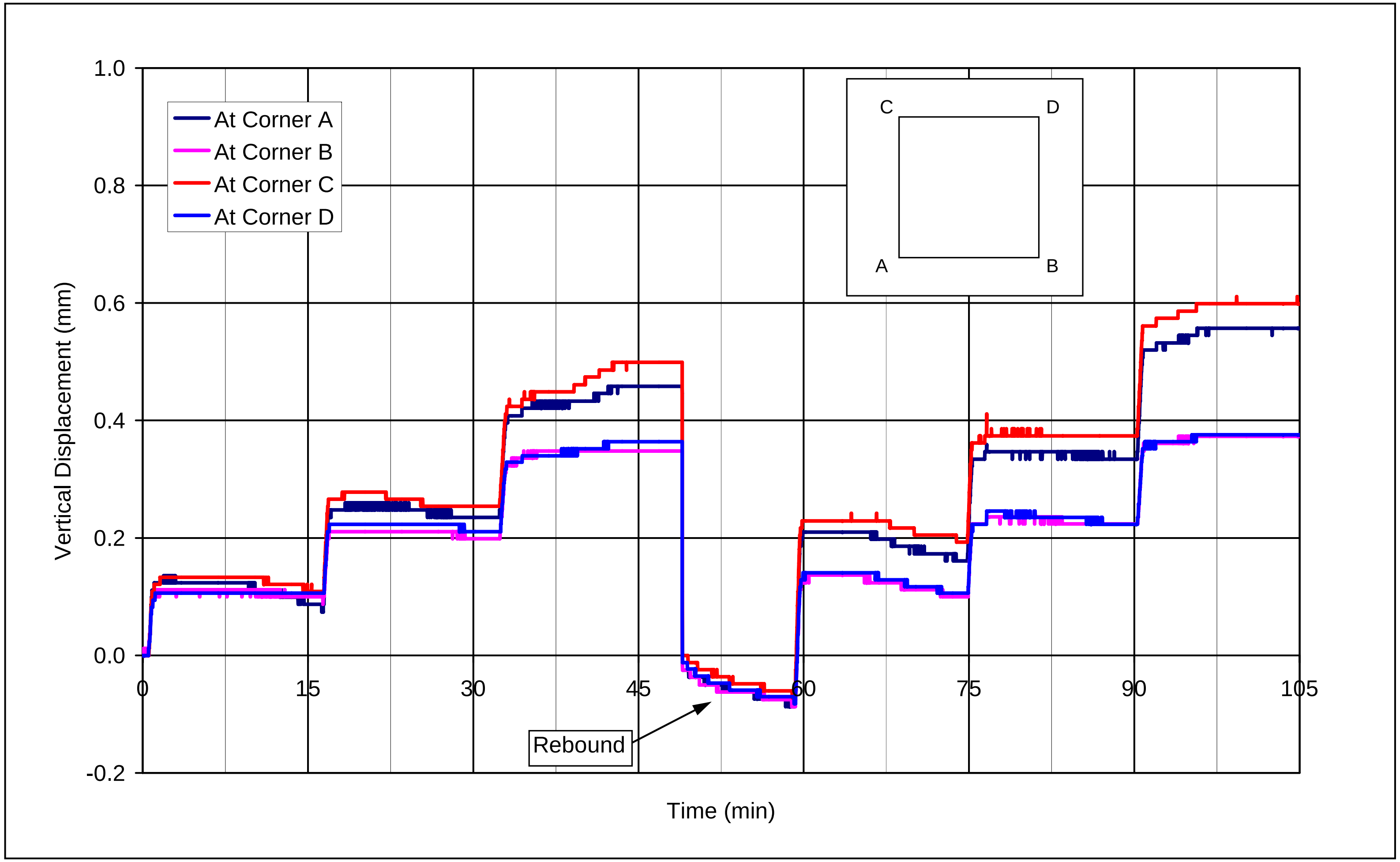

Figure 3.7 Vertical displacement – time relationship of the model piled raft foundation

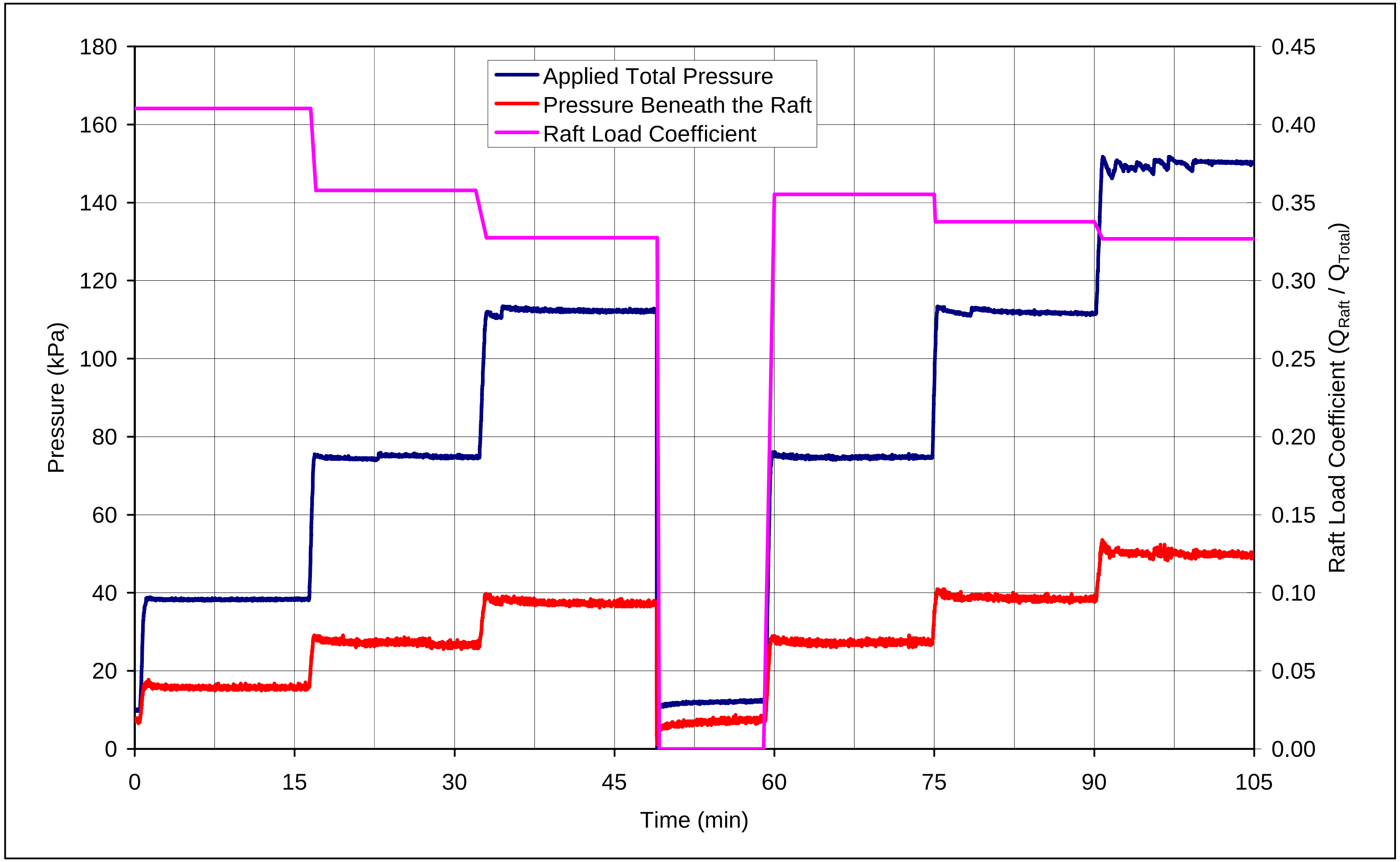

Figure 3.8 Contact pressure-time and raft load coefficient-time relationships of the model piled raft foundation

3.3 Monitoring of a Piled Raft Foundation of a Building in Parkvadi Project, Ankara

Piled raft foundation of a high-rise building in Parkvadi Project in Ankara was monitored during its construction period in order to observe the contribution of the raft to the load bearing capacity of the piled raft foundation. The monitored block has two basement floors and a 26- storey core shaft (Figures 3.9 and 3.10). The building core has a height of 78 m above the basement floors and its total estimated structural load is 421250 kN.

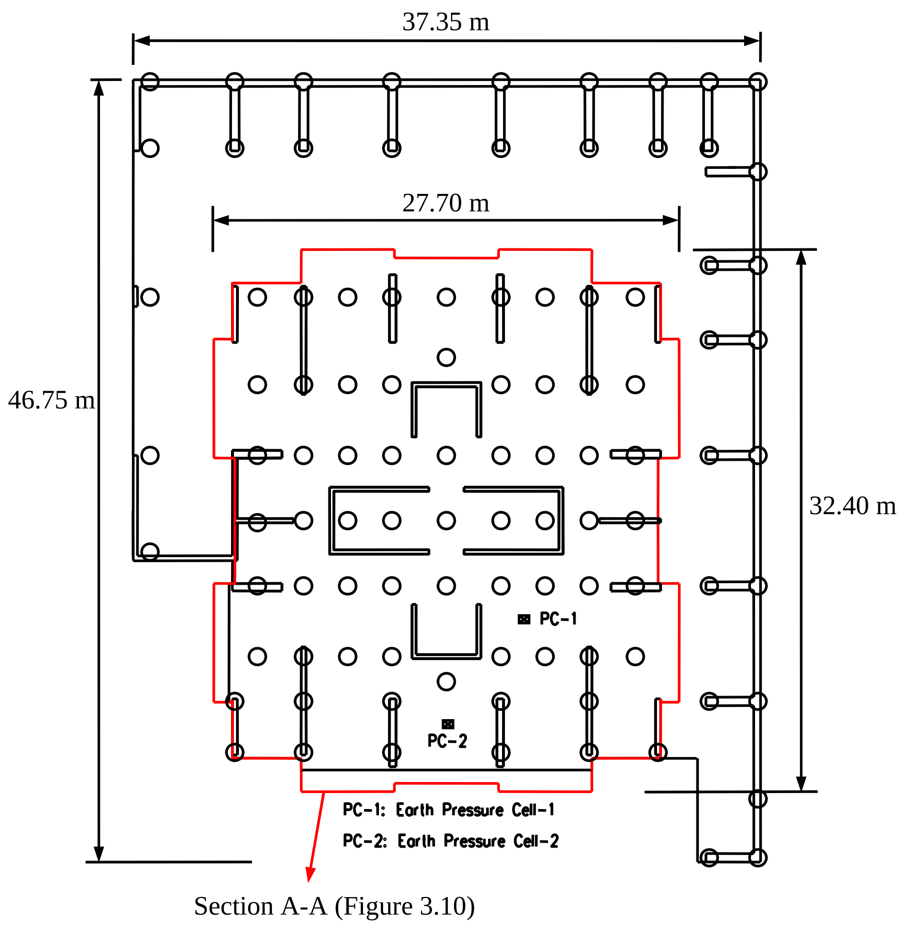

Figure 3.9 Plan view of the piled raft foundation of the building

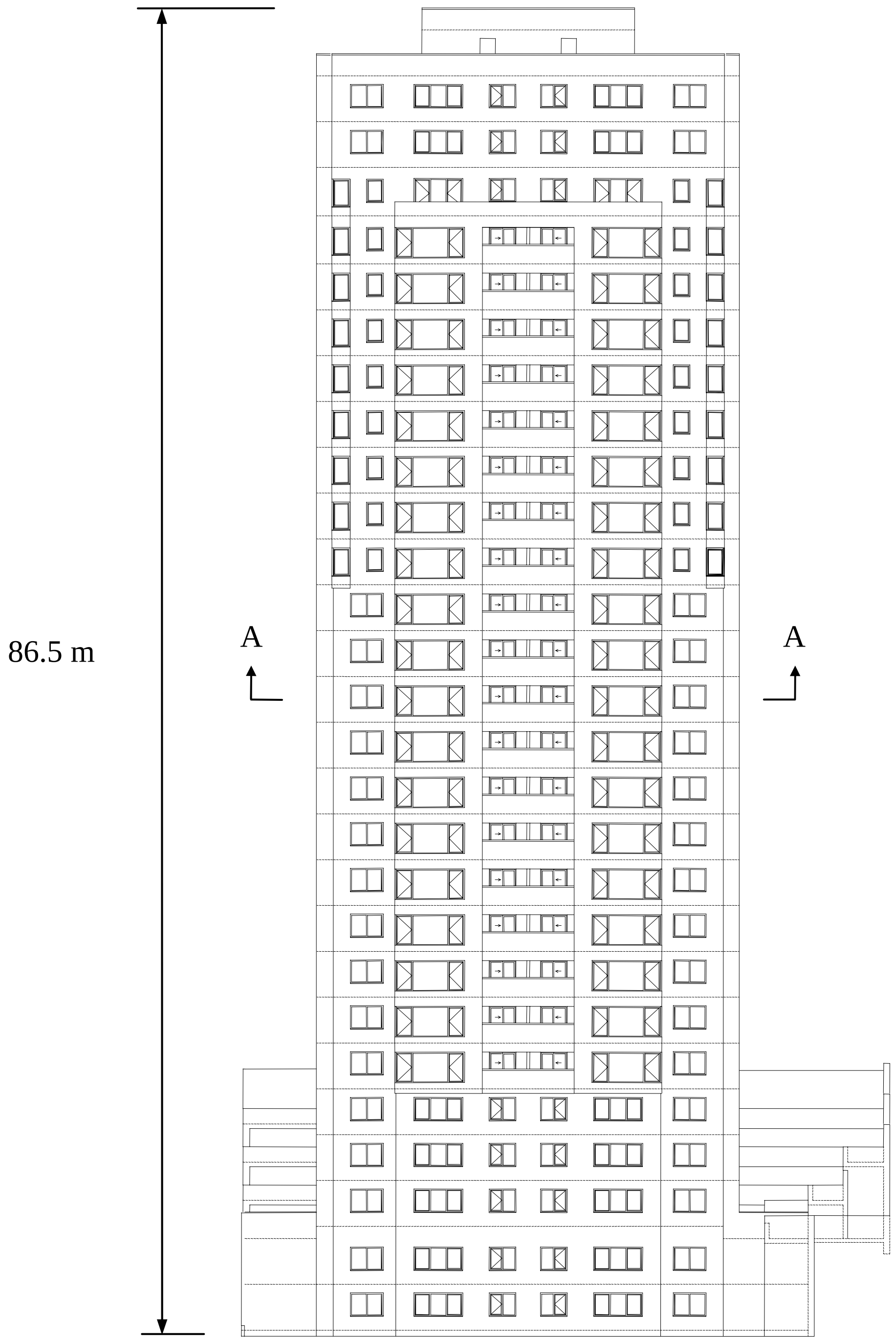

Figure 3.10 Elevation of the monitored building

The foundation soil is deep graywacke, which is highly weathered at the upper 10 m, with no ground water. The building is founded on a piled raft with an area of 1482 m^2 (Figure 3.9). The raft has a thickness of 1.60 m. 99 bored piles with a diameter of 1 m and a length of 11 m were used in order to minimize differential settlements and tilting of the building.

The piled raft was monitored during the construction period of the building. The main purpose of this monitoring was to observe the load-sharing behavior of the piled raft.

3.3.1 Installation of Earth Pressure Cells

Earth pressure cells were installed at two different locations as shown in Figure 3.9. One earth pressure cell (PC-1) was placed near the building core and the other earth pressure cell (PC-2) near the edge of the foundation. A view from the site before the installation of the earth pressure cells is given in Figure 3.11. First, a small hole with a diameter larger than the earth pressure cell diameter was excavated. The bottom of the hole was leveled and a sand layer was placed at the bottom. After leveling the sand layer the earth pressure cell was placed over the sand layer (Figure 3.12). Then, concrete was poured over the earth pressure cell with caution and the cables of the earth pressure cells were placed in a thick pipe for protection. After the earth pressure cells were placed and their holes were filled with concrete, the lean concrete was placed all over the area. After construction works of the foundation and the first basement was finished, a box was manufactured and installed at the first basement floor in order to provide a safe place for the connection of the earth pressure cell cables to the data acquisition system. Type of the earth pressure cells were the same as the one used in the field load test and described in the previous section. TDG Ai8b Data Acquisition System was used to monitor and record data.

Figure 3.11 A view from the site before installation of earth pressure cells

Figure 3.12 Placing and leveling of the earth pressure cell

3.3.2 Presentation and Discussion of the Results of Monitoring of Piled Raft Foundation

The first reading was taken on 4 September 2007 after the construction of two basements and 3 stories (Figure 3.13) and the last reading was taken on 27 January 2008 after the rest was completed (Figure 3.14).

Figure 3.13 Level of the construction at the first reading

At the first reading stage 30 % of the building weight and at the last reading stage 70 % of the building weight was applied as structural loading on the ground. During construction of the building, the raft load increased progressively and this increase is monitored by earth pressure cells.

Figure 3.14 Level of the construction at the last reading

In Figures 3.15 and 3.16, relation of the measured contact pressures beneath the raft and the applied foundation pressures are presented. Average foundation pressure is found by dividing the total applied load by the foundation area for the related construction stages. The difference between the contact pressures under the core and the edge may be explained by the stiffness (1.60 m thick) of the raft. The piled raft is highly loaded at the center and more settlement is expected under the central part of the 1.6 m thick raft.

Raft load coefficient is the ratio between the load carried by the raft and the total applied load. For the earth pressure cell near the core (PC-1), raft load coefficient of 0.44 to 0.56 is observed and for the earth pressure cell near the edge, raft load coefficient of 0.21 to 0.24 is observed (Figures 3.17 and 3.18). The results of monitoring indicate that raft has a noticeable contribution to the load bearing capacity.

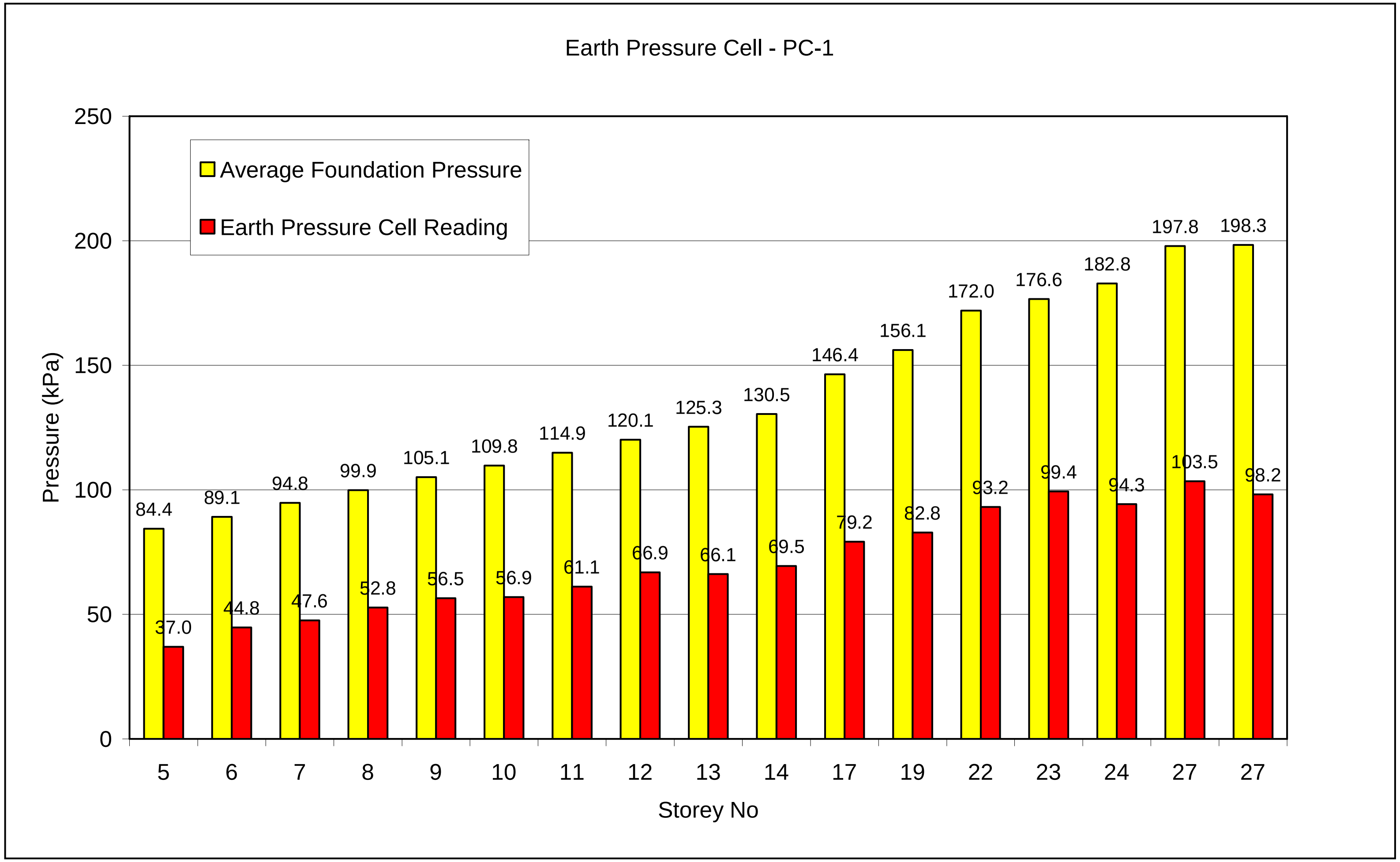

Figure 3.15 Total pressures and measured raft contact pressures by the earth pressure cell – PC 1

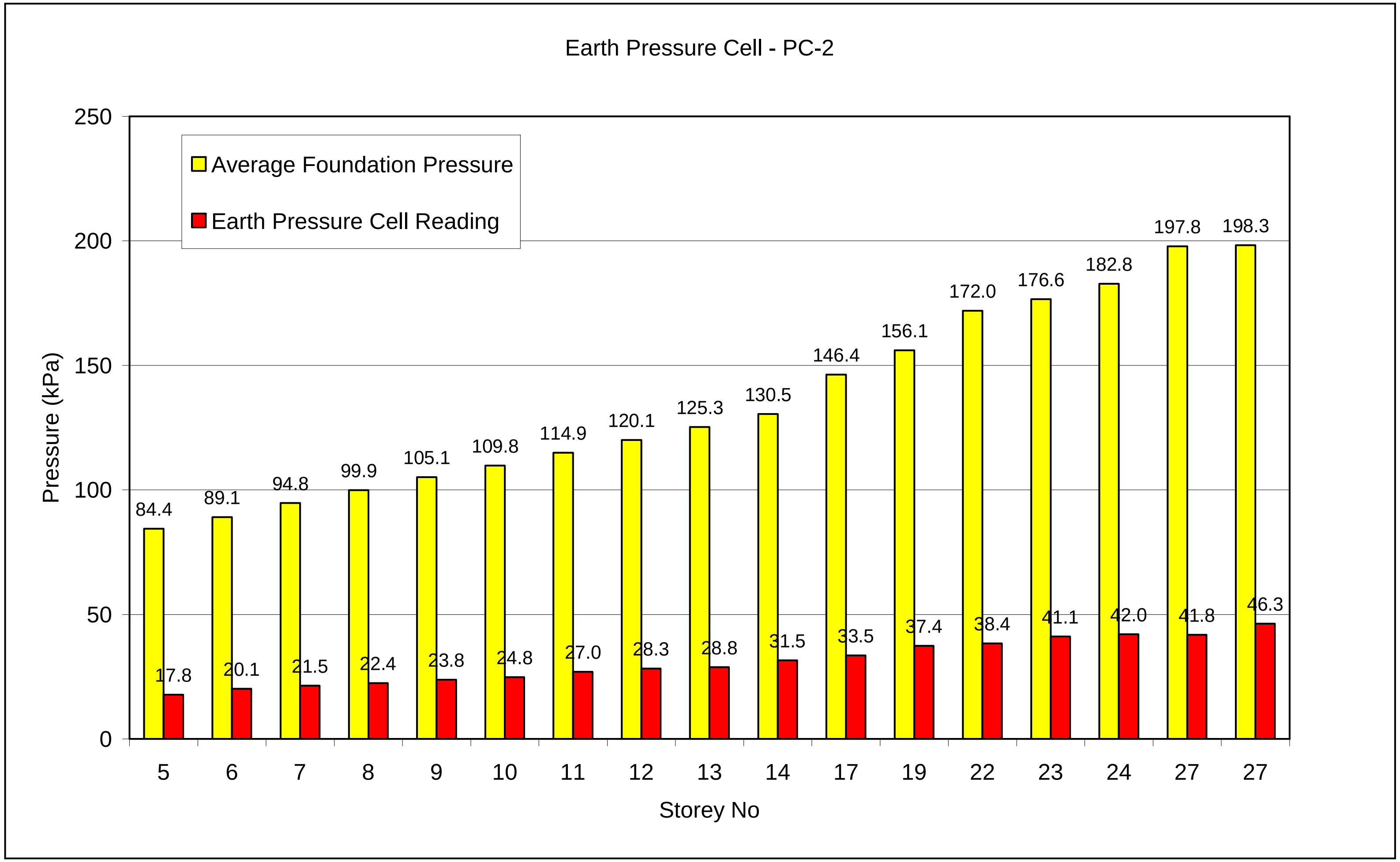

Figure 3.16 Total pressures and measured raft contact pressures by the earth pressure cell – PC 2

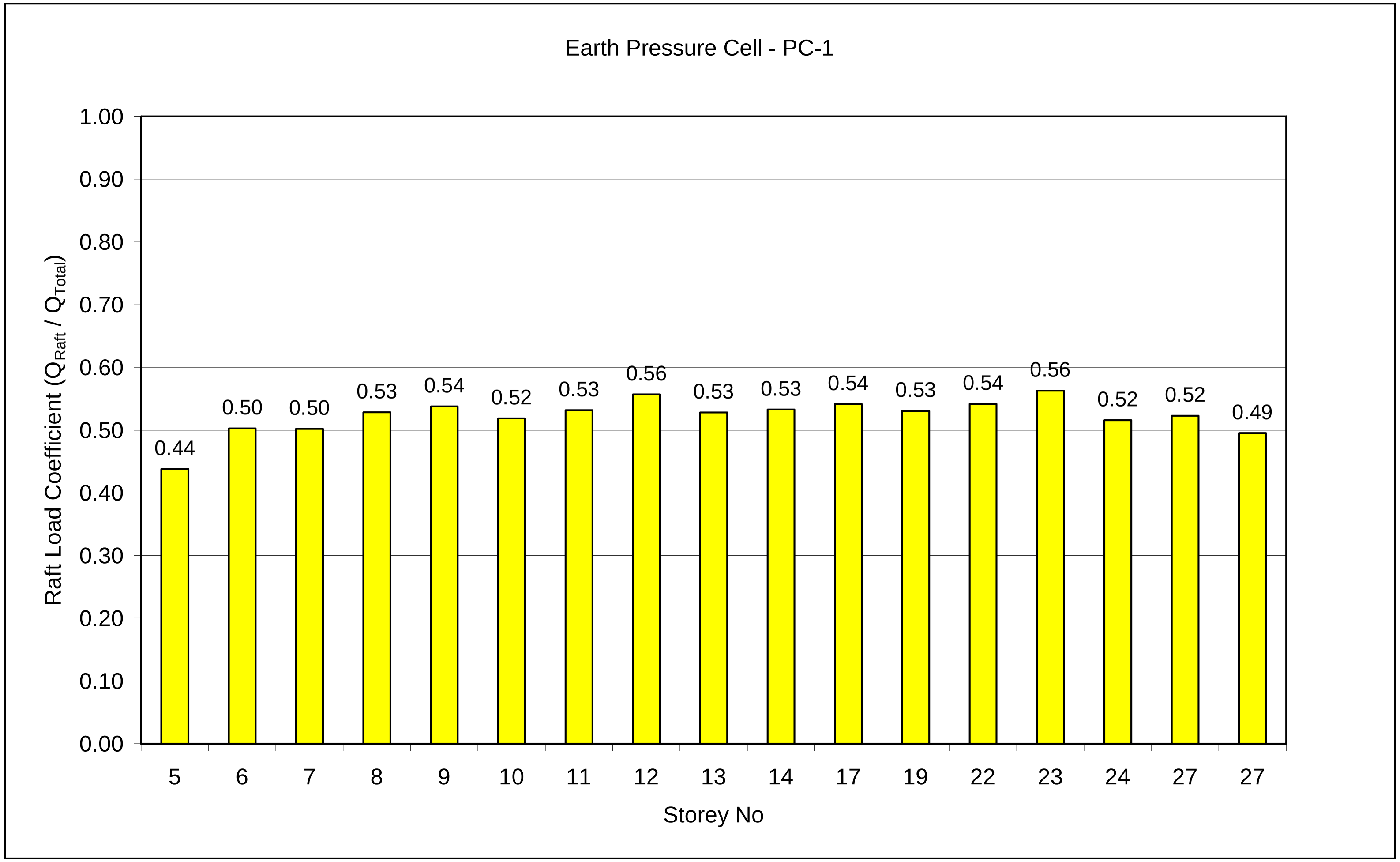

Figure 3.17 Raft load coefficient values observed at the location of earth pressure cell – PC 1

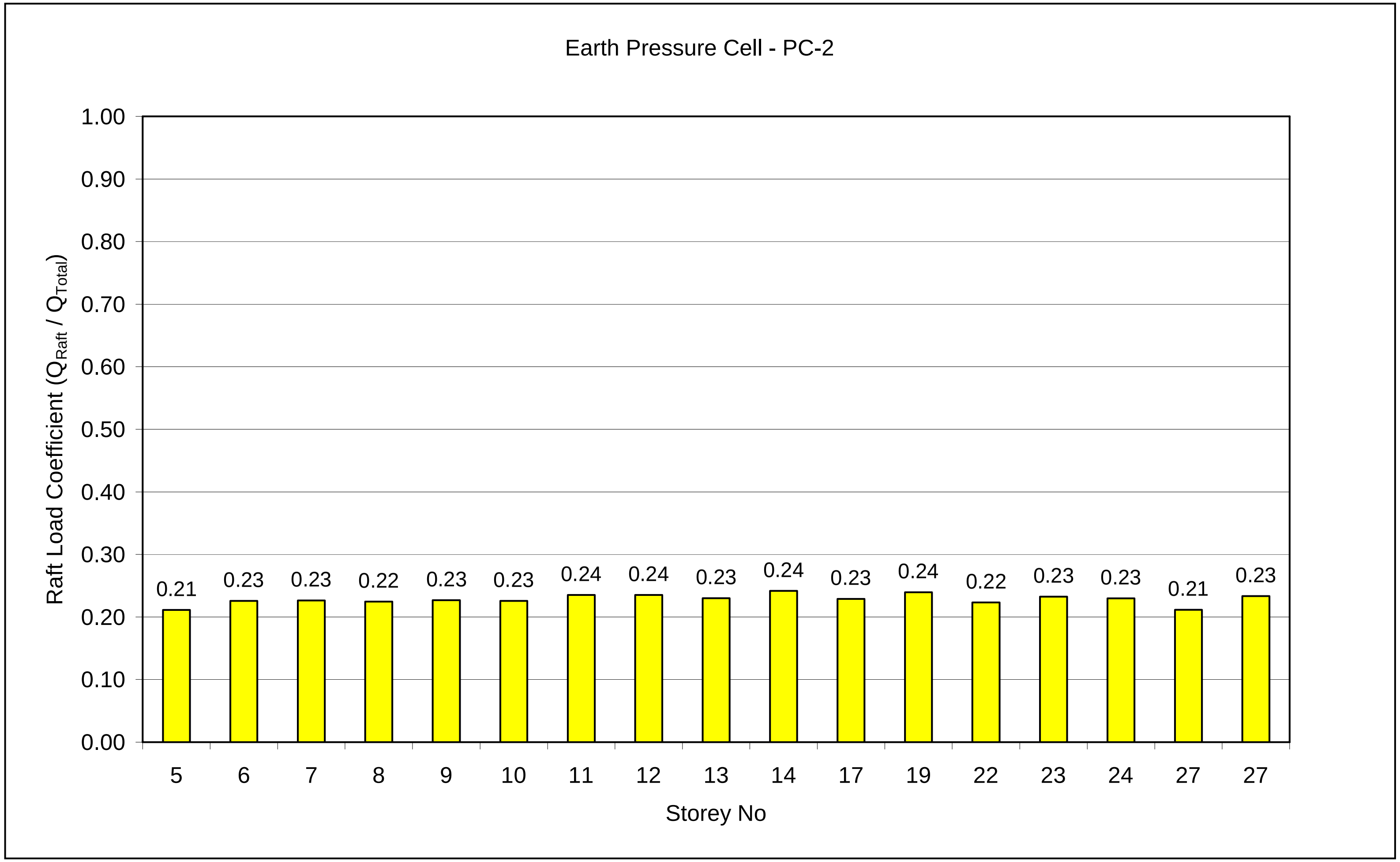

Figure 3.18 Raft load coefficient values observed at the location of earth pressure cell – PC 2

CHAPTER 4

LABORATORY MODEL TESTS

4.1 Introduction

In this chapter, laboratory model test setup and details of the testing procedure are presented. Model tests and their instrumentation were mainly concerned with the load sharing mechanism of piled raft foundations. The settlement characteristics of the piled raft foundations and distribution of loads on piles in different configurations of pile groups were also investigated. Tests were performed on models of piled rafts, plain raft and single pile. The number of piles was also changed in the piled raft tests.

4.2 Soil Properties and Preparation

4.2.1 Properties of Kaolinite Clay and Sand

The soil mixture used in the tests was composed of 50 % kaolinite clay and 50 % sand by weight. The kaolinite type remolded clay used in the model tests was obtained from the Ph.D. study conducted by Tekin (2005) and Kul (2003). It was ground to have a powdered form after drying in the oven. The Atterberg limits of kaolinite clay are given in Table 4.1 and the hydrometer test results are shown in Figure 4.1. Grain size distribution of the sand used in model tests is given in Figure 4.1. Materials retaining on 2.0 mm sieve was removed and the remaining part was used in the mixture. The powdered kaolinite clay was mixed with sand by means of a mixer to have uniform mixture and water was added in the mixture to have optimum water content (w=17 %). Then, the mixture was kept in the moisture room for five days to have homogeneous water content. The Atterberg limits of the mixture of kaolinite clay and sand are given in Table 4.2.

Table 4.1 Atterberg limits of kaolinite clay used in model tests (Tekin, 2005)

Liquid Limit LL (%)	**Plastic Limit PL (%)**	**Plasticity Index PI (%)**
51	29	22

Table 4.2 Atterberg limits of the mixture of kaolinite clay and sand

Liquid Limit LL (%)	**Plastic Limit PL (%)**	**Plasticity Index PI (%)**
27	18	9

4.2.2 Preparation of Soil

Tests were conducted in a steel circular container which has a diameter of 410 mm and a height of 380 mm. Six layers of soil mixture was placed in the container and each layer was compressed by a hydraulic jack. The applied pressure for compression was controlled by a load cell. In order to apply pressure and compress the placed layer of soil in the container easily, wooden blocks having a thickness of 56 mm were manufactured. Each layer had an equal weight of 15 kg and equal applied compressive force of 4800 kg.

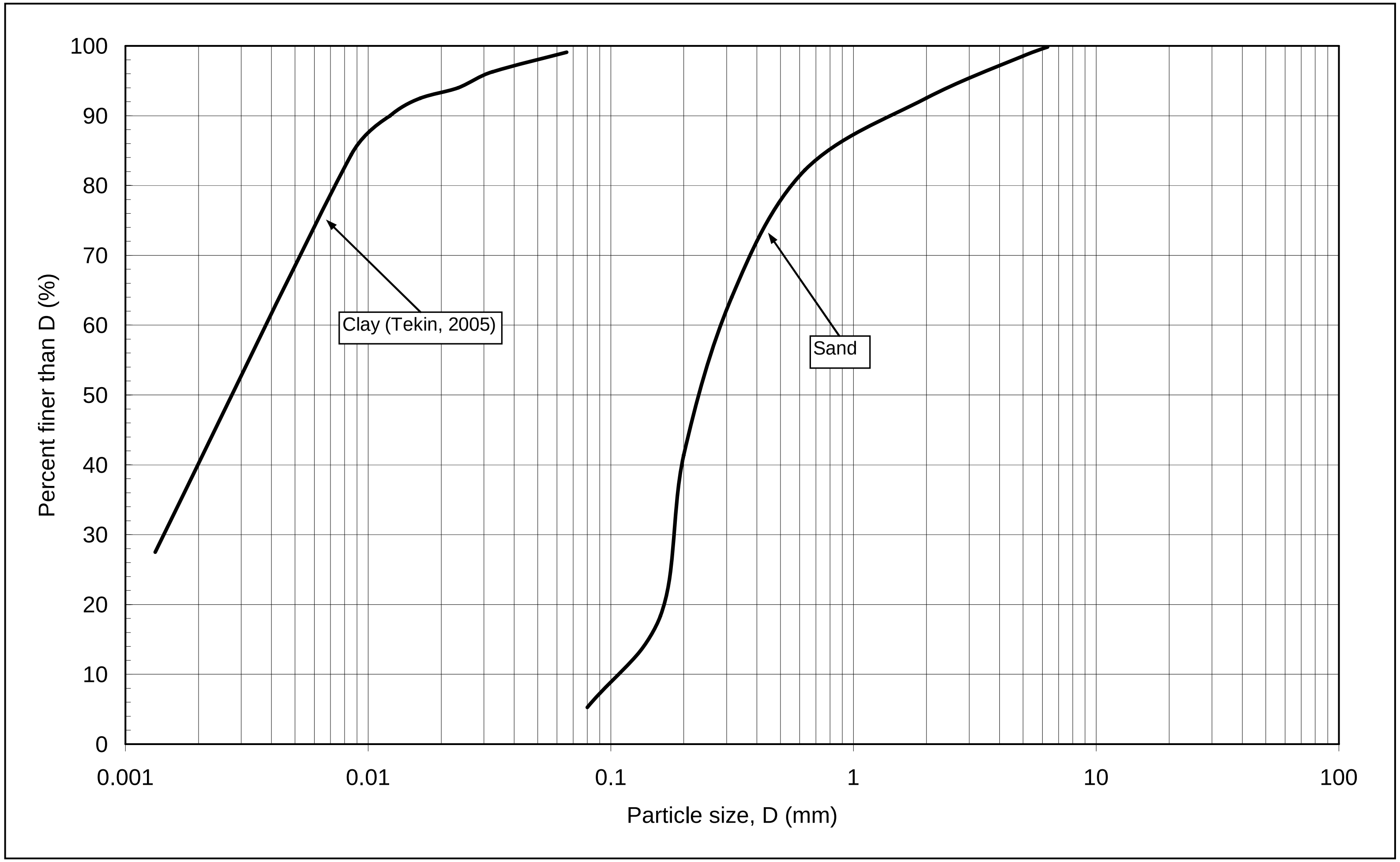

Figure 4.1 Particle size distributions of clay and sand used in model tests

A placing and compressing procedure was decided after a few number of trials. The placing and compressing procedure is as follows:

1. The soil was weighed and 15 kg of soil mixture was placed in the container. Then, its surface was leveled with the help of a steel plate.

2. After the soil was leveled, enough number of wooden blocks was placed on the soil up to the top of the container. The level was checked again.

3. The hydraulic jack and the load cell were placed on the top wooden block and the soil was compressed under 4800 kg of force (Figure 4.2).

4. After the initial settlements had occurred the pressure remained constant for 5 minutes in order to allow further settlements.

5. After this period, surface of soil was scratched with a steel rod (Figure 4.3).

6. After all these steps, a new layer was prepared following the same procedure. Six layers were formed in this way and the container was filled up to a certain level, which is 56 mm below from the top of the container.

7. After placing the final layer of soil mixture, the same pressure was sustained for an hour to allow further settlements to occur. This time period was found sufficient due to the observation of no additional displacements.

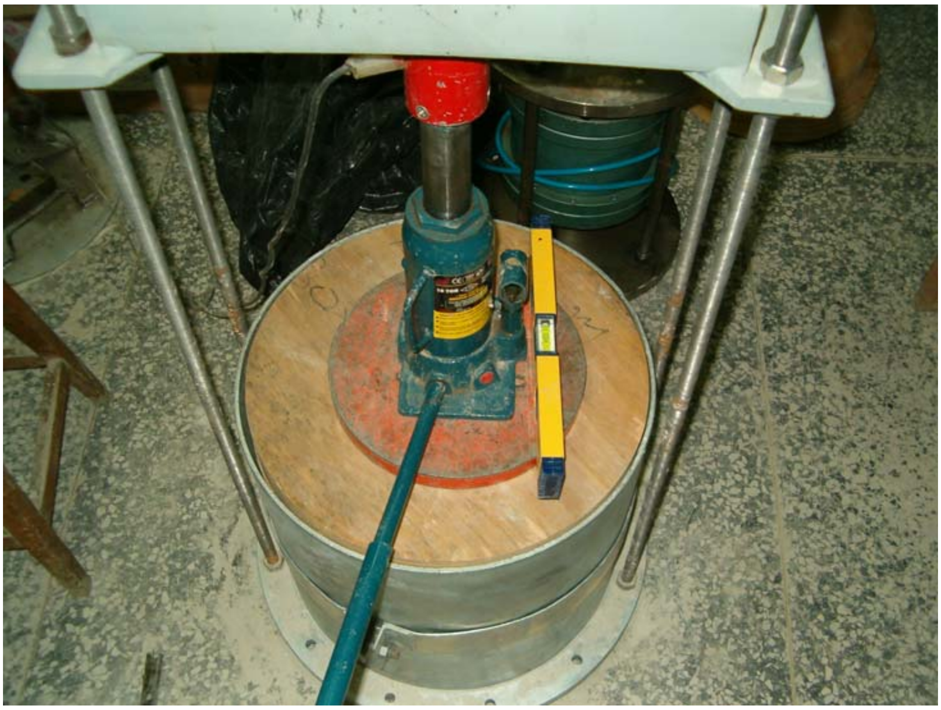

Figure 4.2 Compressing of the soil layers

Figure 4.3 Scratching of the soil layer surface

4.3 Model Test Setup, Instrumentation and Test Procedure

4.3.1 Model Piles

Model piles were made of aluminum having an outer diameter of 22 mm and an inner diameter of 18 mm as shown in Figure 4.4. The length of the pile below the soil surface was 200 mm. The smooth surface of the aluminum model piles were roughened with lathe and the tips of them were closed.

Figure 4.4 Model pile, cover plate and fixing element

The piles were instrumented with strain gages at the upper section, below the raft level, in order to measure the load transferred from the raft to the piles. That part of the model pile was processed with lathe and a suitable place for the strain gages and their terminals were manufactured. 4 foil strain gages and their terminals were used for each pile. The type of the strain gage was TML FLA-5-11 with a gage resistance of 120 Ohms. The strain gages were covered with special waterproofing compounds. Specially manufactured aluminum cover ring plates were used for mechanical protection. These plates were also roughened as the other parts of the pile. Strain gage wires were taken to upper tip of the piles through small holes at each strain gage location. Full bridge configuration was used for the connection of the strain gages. That bridge configuration is insensitive to the bending loads, but they are sensitive to the axial loads. Pile loads were monitored and recorded with TDG Ai8b Data Acquisition System. Instrumented model piles were calibrated in the laboratory using a mechanical press with known loads (Figure 4.5).

Figure 4.5 Calibration of a model pile in the mechanical press

4.3.2 Model Raft

The raft was made of steel with a length and width of 176 mm and a thickness of 10 mm (Figure 4.6). The raft had 9 holes to fix the piles. The piles were fixed to the raft with manufactured fixing elements.

Figure 4.6 Model piled raft

4.3.3 Loading System and Dial Gages

Load was applied by a pneumatic air cylinder as shown in Figure 4.7. The cylinder was a single action air cylinder and powered by an air compressor. The pressure applied was controlled with a valve. Load applied to the model foundation was measured by a load cell and recorded using the data acquisition system.

Figure 4.7 Pneumatic air cylinder and the loading system

Settlements were measured using mechanical dial gages. They were placed at two sides of the raft as shown in Figure 4.7 and displacements were observed and recorded during the test.

4.3.4 Test Procedure

Test procedure is as follows:

1. After placing and compressing the soil for an hour, the pressure was released and the holes having a diameter of 16 mm and a depth of 215 mm were drilled. These holes were the guide holes for the piles and they simulated the bored pile process. These holes were drilled using a steel template as shown in Figure 4.8, to provide enough accuracy in

the location of piles. In order to minimize the negative effects of the lateral earth pressure, the holes had a diameter equal to the model pile diameter, at the part where the strain gages were installed. The holes were drilled with two different hand augers and soil samples were taken from different depths of the holes in order to determine the water content of the soil mixture.

Figure 4.8 Drilling of the holes

2. After drilling the holes the piles were fixed to the raft and the model piled raft was placed on the holes. The hydraulic jack was placed on the piled raft foundation which was pushed into the soil using the hydraulic jack as shown in Figure 4.9. The level of the raft was controlled at different levels of penetration. After the raft had been in contact with the soil, the penetration was stopped and the hydraulic jack was removed from the system.

Figure 4.9 Placement of the model piled raft in the container

3. After assembling the load cell and the pneumatic air cylinder to the system, the load cell and strain gage cables were plugged to the data acquisition system. Dial gages were placed on the raft and load was applied at the center of the model piled raft foundation. Load was kept constant for 5 minutes at every increment of load and three settlement readings were recorded during this period. The waiting period to take readings was considered sufficient, because the displacements did not increase with time for this 50 % sand and 50 % clay mixture.

4. After tests were completed, the steel container was emptied using a spatula carefully, in order not to damage instrumented piles (Figure 4.10). Soil was crumbled in big tray and stored in plastic bags in the moisture room (Figure 4.11).

Figure 4.10 Emptying the container after the test

Figure 4.11 Crumbling of the soil after the test

CHAPTER 5

PRESENTATION OF LABORATORY MODEL TEST RESULTS

5.1 Introduction

In this chapter, laboratory model test results will be presented. 16 load tests were conducted in the laboratory. These tests were performed on models of piled rafts, plain raft and single pile. The number of piles varied in the piled raft tests. Every test was repeated two to four times (Table 5.1). Model piled raft configurations are presented in Figure 5.1.

Table 5.1 Laboratory model test series

Test Explanation	**Number of Tests Performed**
Plain Raft	2
Single Pile	2
Piled Raft with 2 piles	3
Piled Raft with 4 piles	3
Piled Raft with 7 piles	2
Piled Raft with 9 piles	4

Settlements (s) and applied loads (Q_{Total}) were measured for every test. Settlements were measured at two points and the average of those values is given as total settlement. For tests with piles, the forces at the upper section of the piles were also measured. The difference of the total applied loads (Q_{Total}) and the total pile forces (Q_{Pile}) is equal to the load carried by the raft (Q_{Raft}).

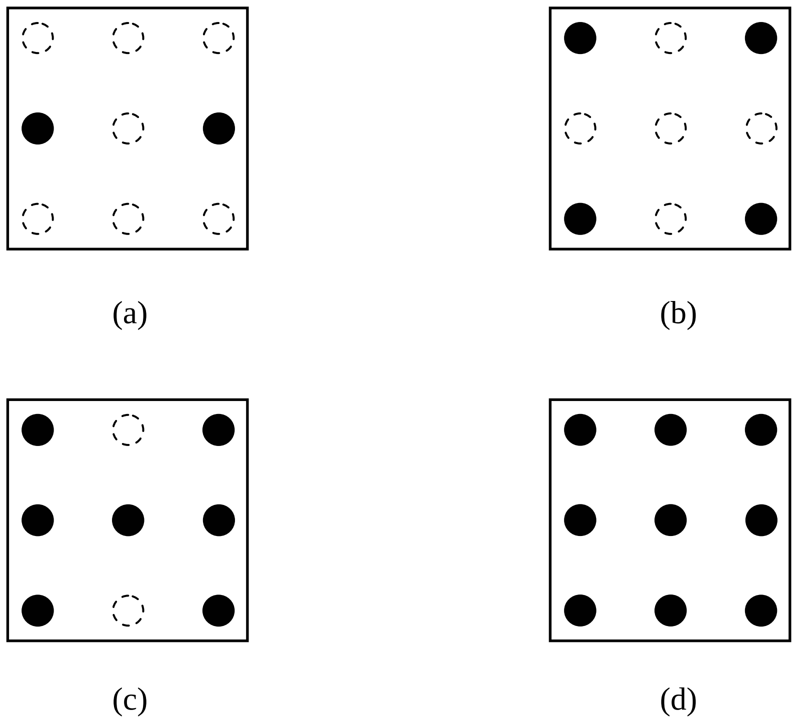

Figure 5.1 Model piled raft configurations: a) piled raft with 2 piles, b) piled raft with 4 piles, c) piled raft with 7 piles, d) piled raft with 9 piles

In the following sections piled raft coefficient term will be used. Piled raft coefficient is the ratio between the summation of pile loads (Q_{Pile}) and total applied load (Q_{Total}). Settlements will be presented in a dimensionless form by dividing them by the width of the footing (B). Water content (w) of each test is given in load-settlement graphs of them.

5.2 Laboratory Model Test Results of Plain Raft

A model raft was loaded and its load-settlement characteristics were observed to compare with the piled raft models. Two tests (Test 3, Test 13) were performed with plain raft. Model plain raft was loaded, displacements and pile forces were measured in order to investigate plain raft behavior under vertical loading (Figure 5.2).

Figure 5.2 Plain raft test setup

Loading sequence of a test with plain raft is shown in Figure 5.3. Settlements were measured at two points as shown in Figure 5.2 and the average of those values is given as total settlement. Load-settlement behavior is shown in Figure 5.4.

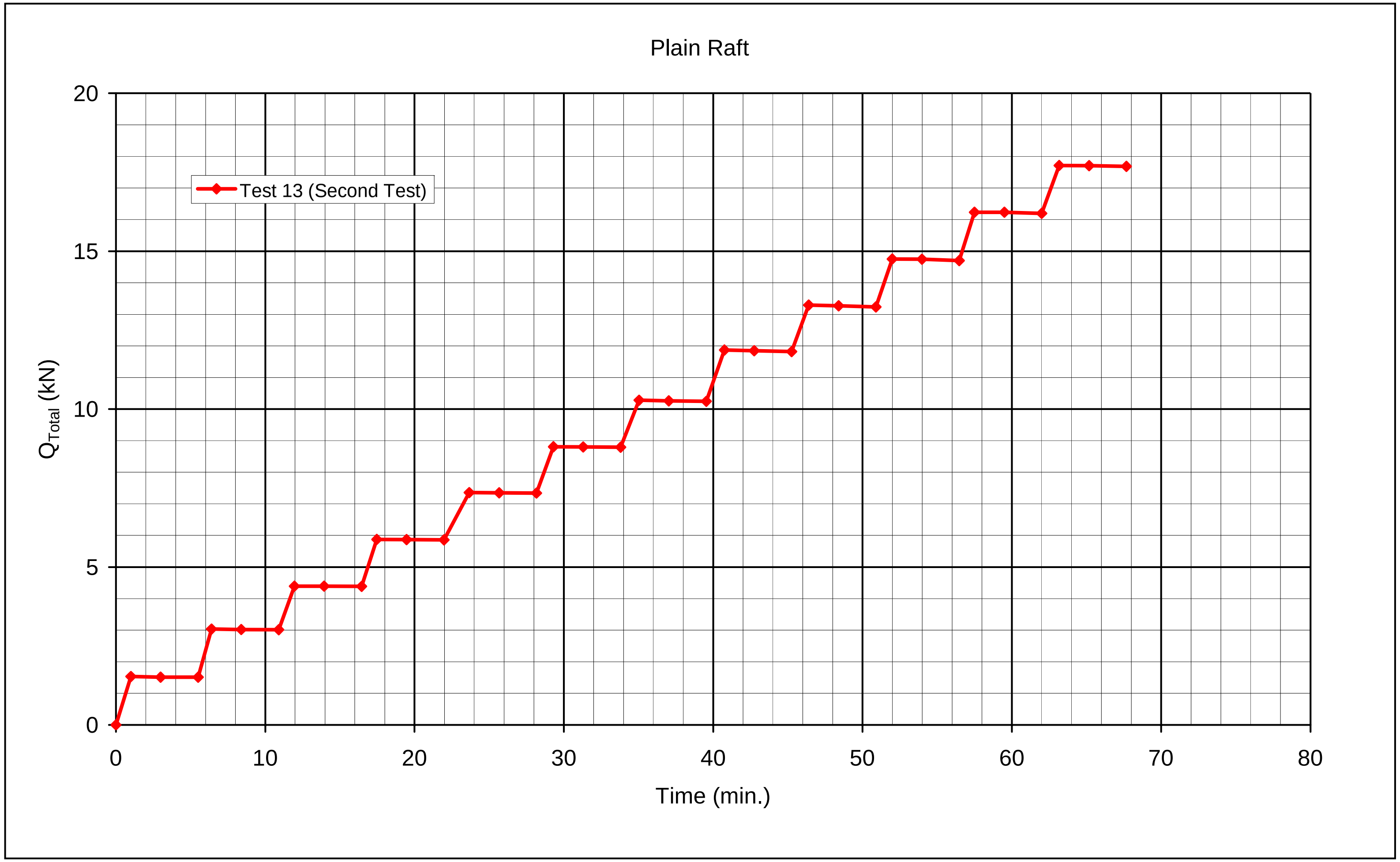

Figure 5.3 Loading sequence of plain raft

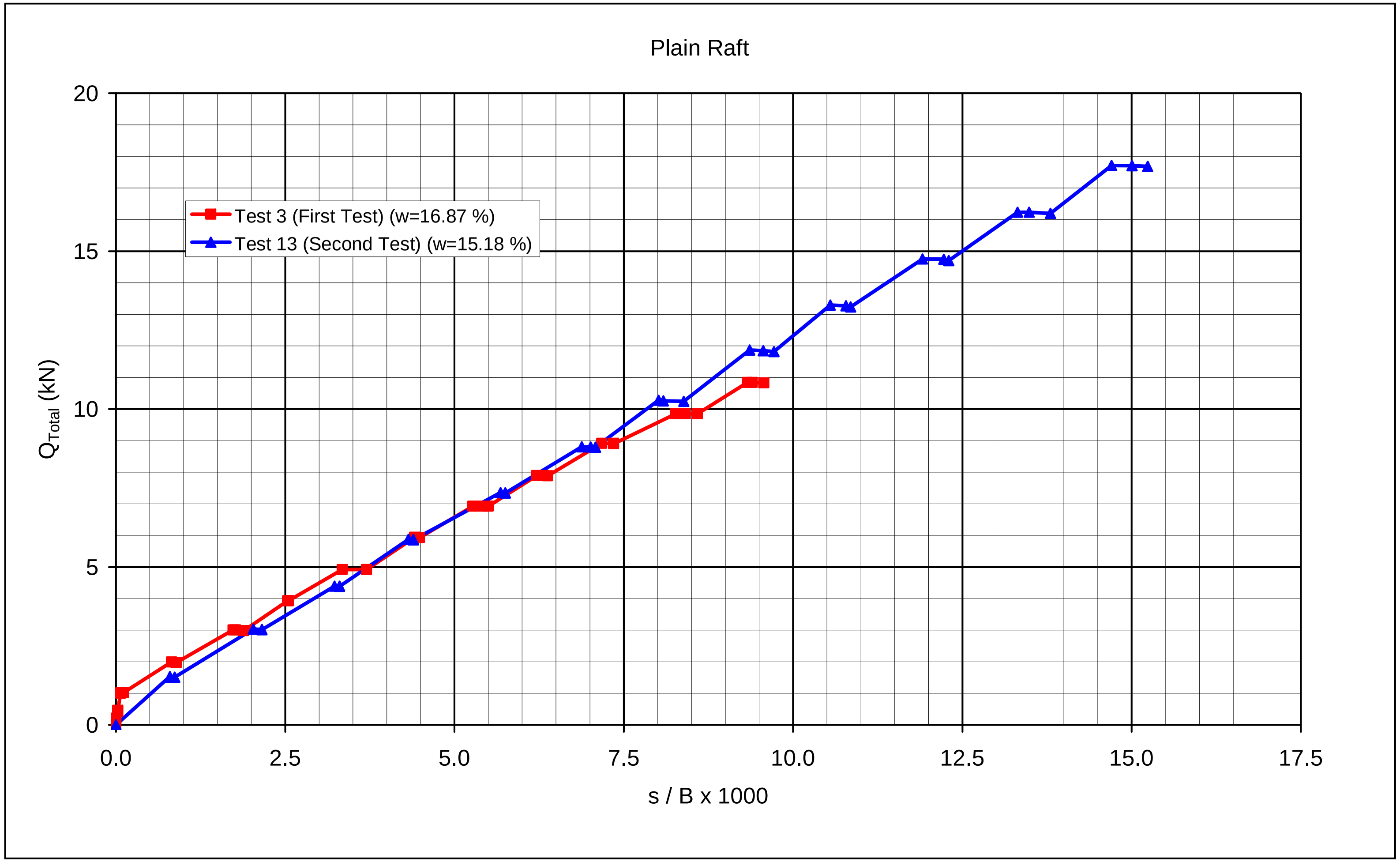

Figure 5.4 Load–settlement relationship of plain raft

5.3 Laboratory Model Test Results of Single Pile

In order to understand single pile load–settlement behavior, a single pile was loaded up to failure (Figure 5.5). Two tests (Test 4, Test 10) were performed with single isolated pile.

Figure 5.5 Single pile test setup

Loading sequence of a test with single pile is shown in Figure 5.6. The load applied to the pile was measured using the load cell attached to the pile head with a manufactured steel apparatus. Forces at the top of the pile were also measured by pile itself, since the pile was instrumented. These two records were plotted in Figure 5.6. This figure shows that both load cell and pile recordings are well-matched. Settlements were measured at two points as shown in Figure 5.5. Load-settlement behavior is shown in Figure 5.7. The measured loads by strain gages at yielding displacements represent total pile loads (skin friction + tip resistance).

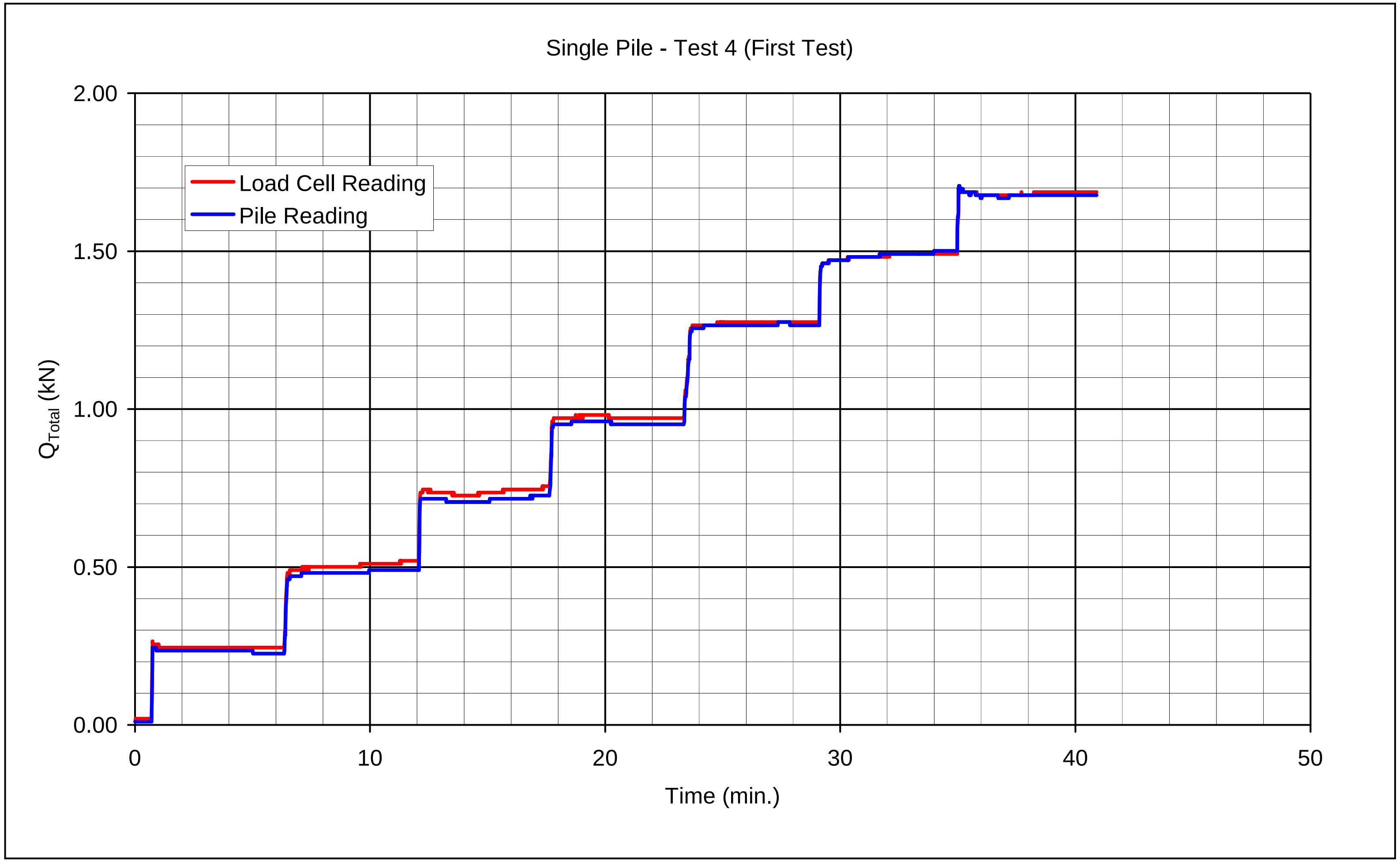

Figure 5.6 Loading sequence of single pile

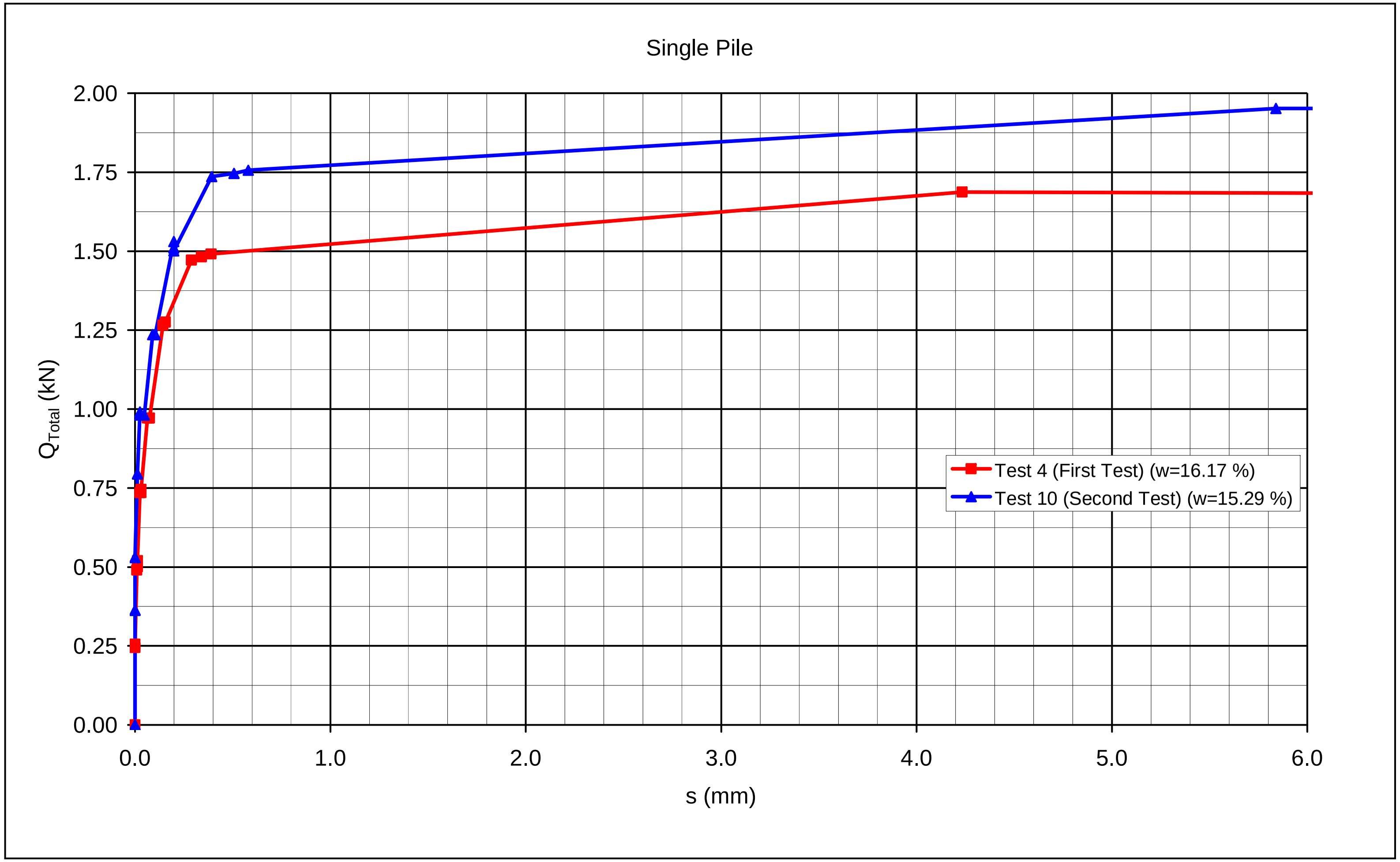

Figure 5.7 Load–settlement relationship of single pile

5.4 Laboratory Model Test Results of Piled Raft with 2 Piles

The first step of the piled raft series was the piled raft model with 2 piles (Figure 5.8). Model piled raft was loaded, displacements and pile forces were measured in order to investigate piled raft behavior under vertical loading. The test was performed three times (Test 14, Test 15 and Test 16).

Figure 5.8 Model piled raft with 2 piles

Loading sequence of a piled raft with 2 piles is shown in Figure 5.9. Load-settlement behavior is shown in Figure 5.10 for the tests. Piled raft coefficient-settlement relation is given in Figure 5.11 and load sharing behavior between piles and the raft is illustrated in Figure 5.12.

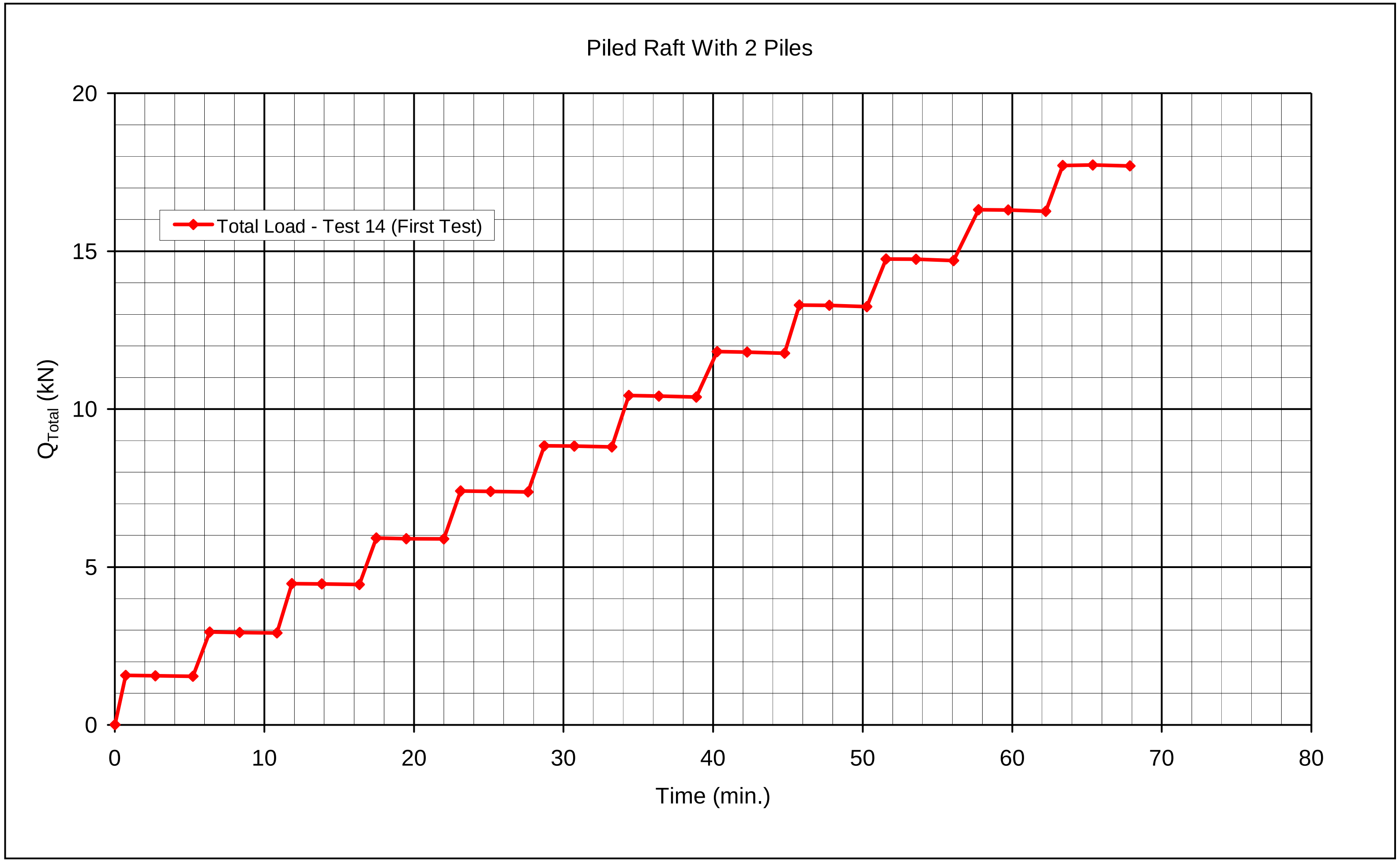

Figure 5.9 Loading sequence of the piled raft with 2 piles

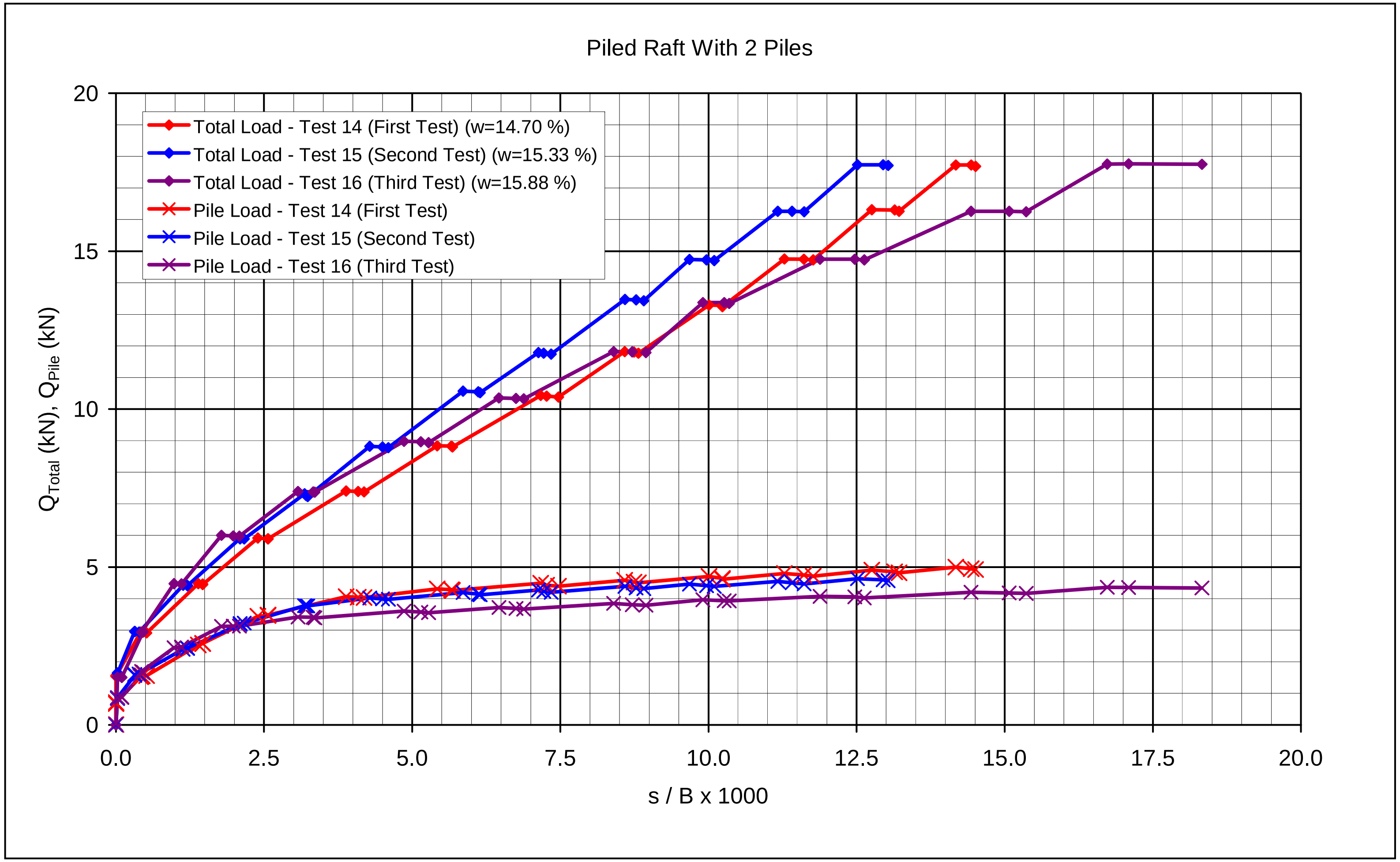

Figure 5.10 Load–settlement relationship of piled raft with 2 piles

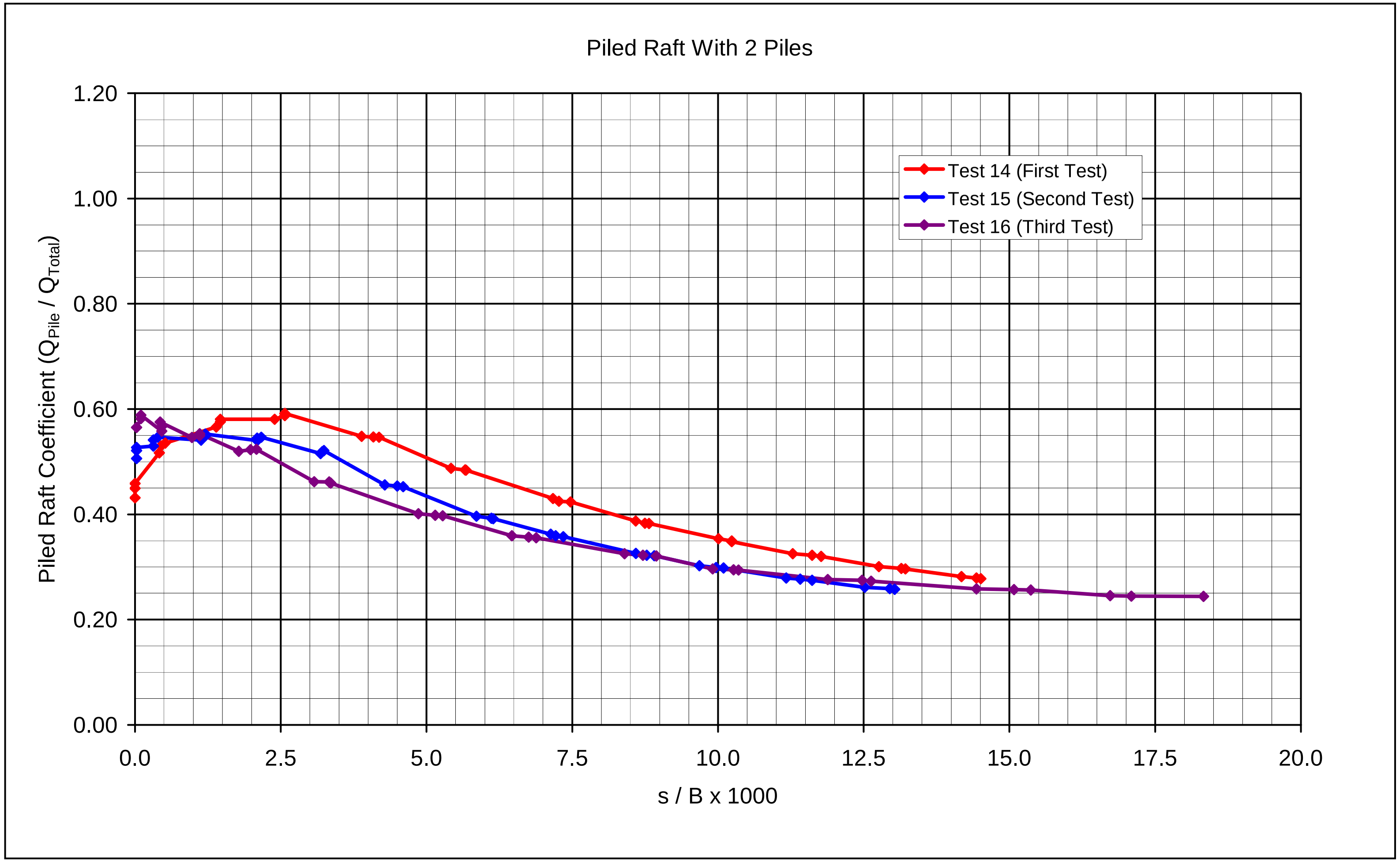

Figure 5.11 Piled raft coefficient–settlement relationship of piled raft with 2 piles

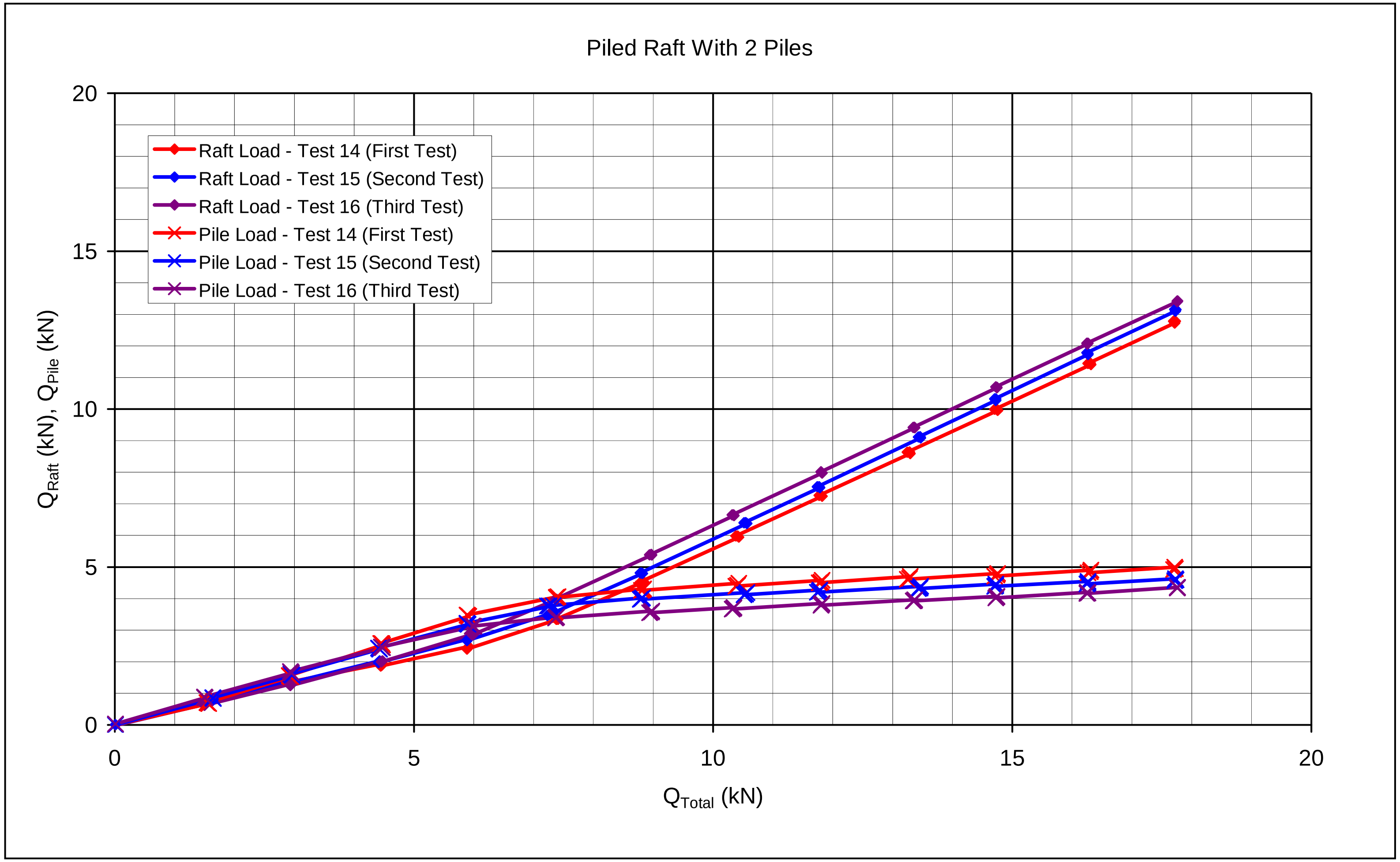

Figure 5.12 Load sharing between piles and the raft for the piled raft with 2 piles

5.5 Laboratory Model Test Results of Piled Raft with 4 Piles

Model piled raft (Figure 5.13) with 4 piles was loaded, displacements and pile forces were measured in order to investigate piled raft behavior under vertical loading. Three tests (Test 6, Test 7 and Test 9) were performed with piled raft with 4 piles.

Figure 5.13 Model piled raft with 4 piles

Loading sequence of a piled raft with 4 piles is shown in Figure 5.14 and related load-settlement behavior is shown in Figure 5.15 for the tests. In addition, piled raft coefficient-settlement relation is given in Figure 5.16. Finally, the load shared between piles and the raft is also shown in Figure 5.17.

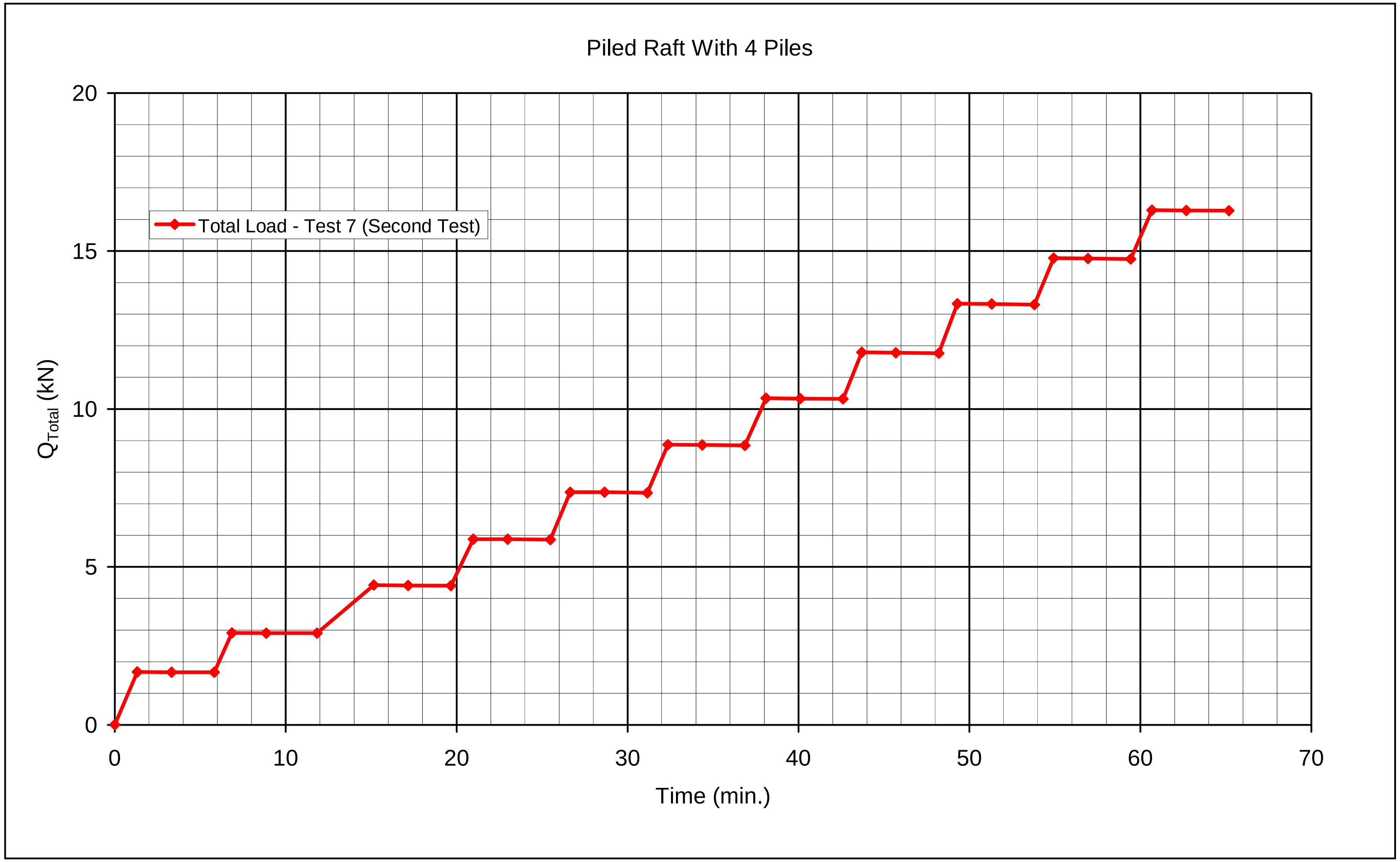

Figure 5.14 Loading sequence of the piled raft with 4 piles

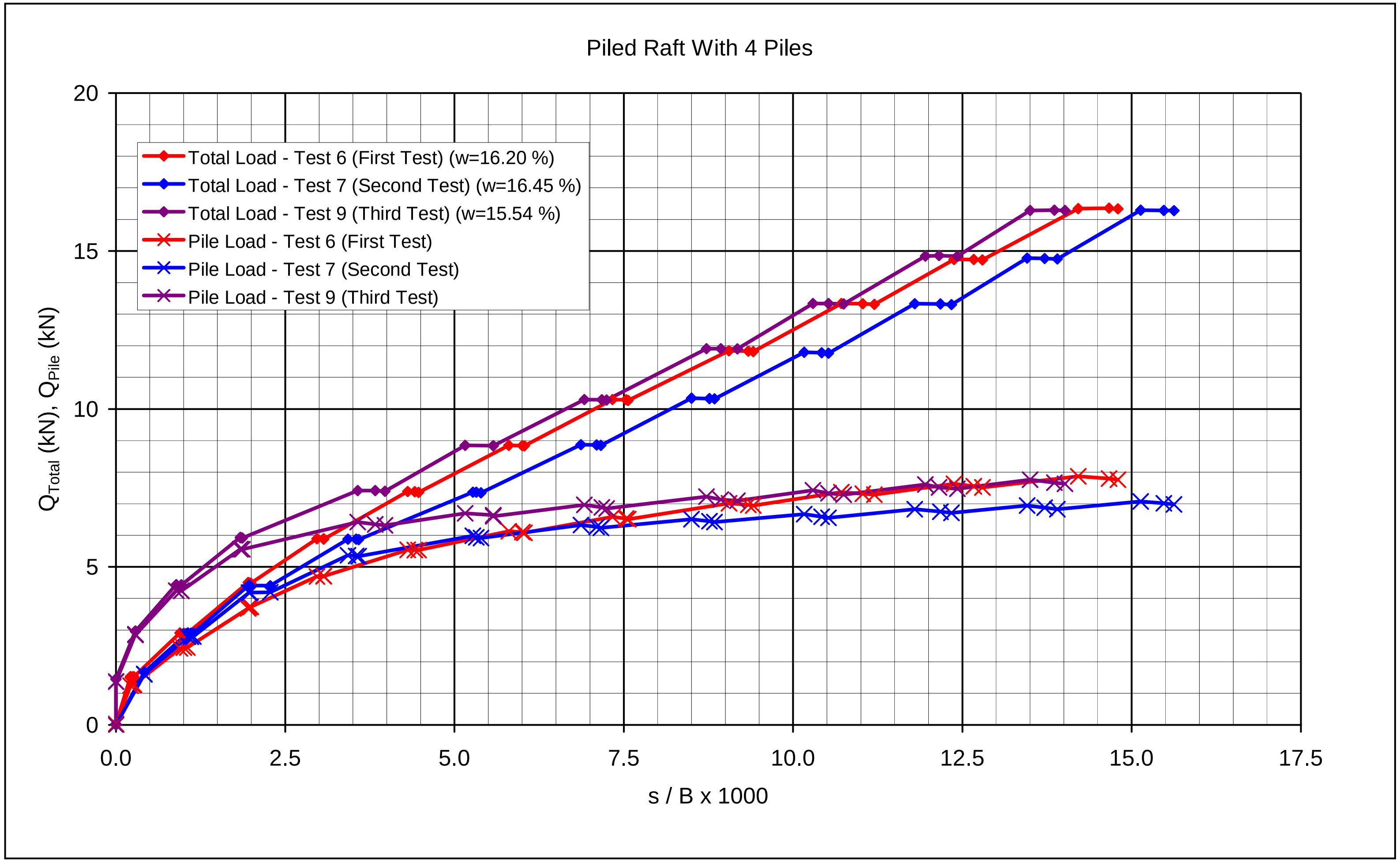

Figure 5.15 Load–settlement relationship of piled raft with 4 piles

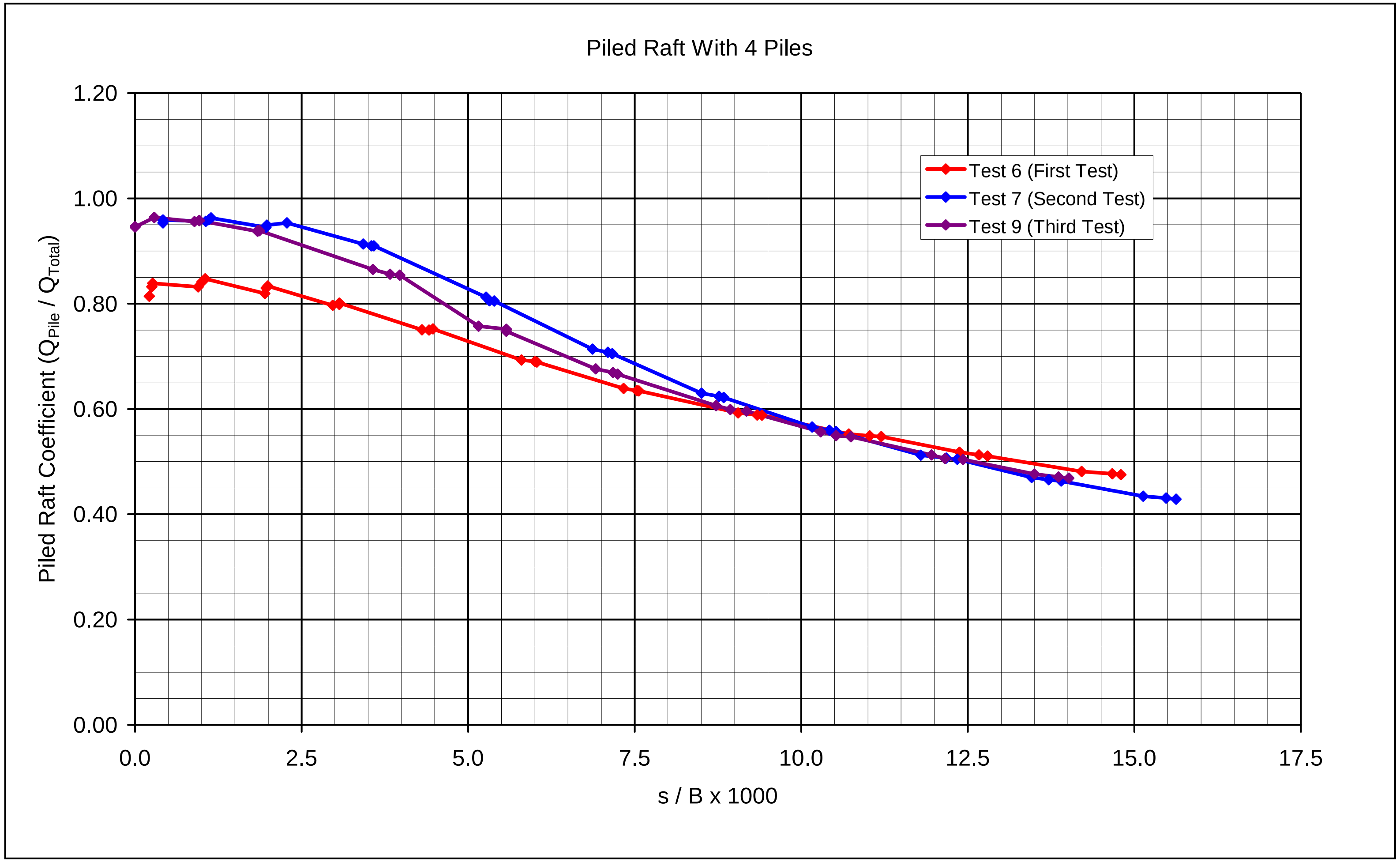

Figure 5.16 Piled raft coefficient–settlement relationship of piled raft with 4 piles

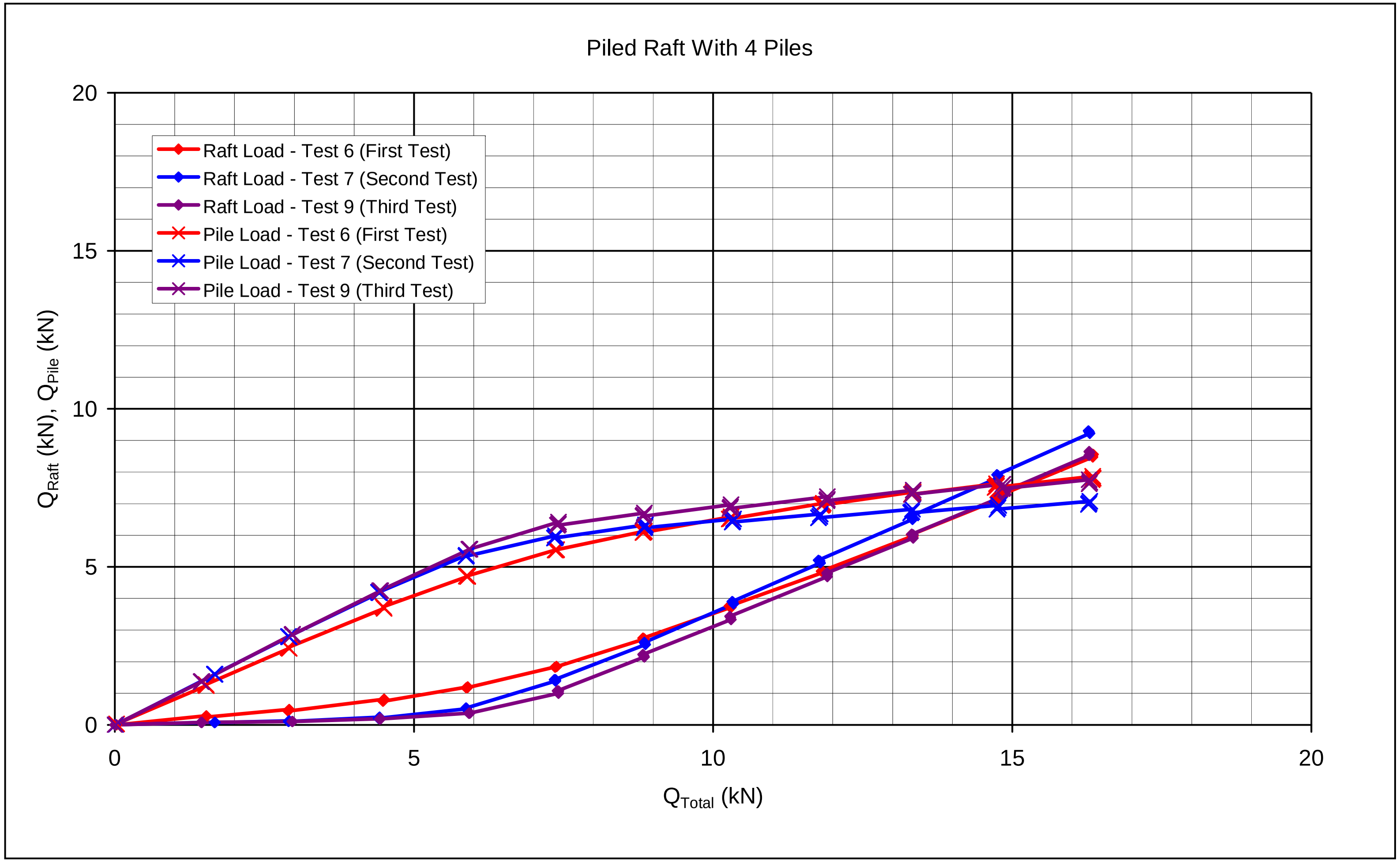

Figure 5.17 Load sharing between piles and the raft for the piled raft with 4 piles

5.6 Laboratory Model Test Results of Piled Raft with 7 Piles

Model piled raft with 7 piles was loaded (Figure 5.18) in vertical direction. Two tests (Test 2, Test 8) were performed with piled raft with 7 piles. Loading sequence of a model piled raft with 7 piles is given in Figure 5.19. Total vertical load–settlement and pile load–settlement relations are shown in Figure 5.20 and piled raft coefficient–settlement relation is shown in Figure 5.21. Load carried by piles and the raft is shown in Figure 5.22. Pile loads at different locations of the raft are presented in Figure 5.23 for Test 2 and in Figure 5.24 for Test 8.

Figure 5.18 Model piled raft with 7 piles

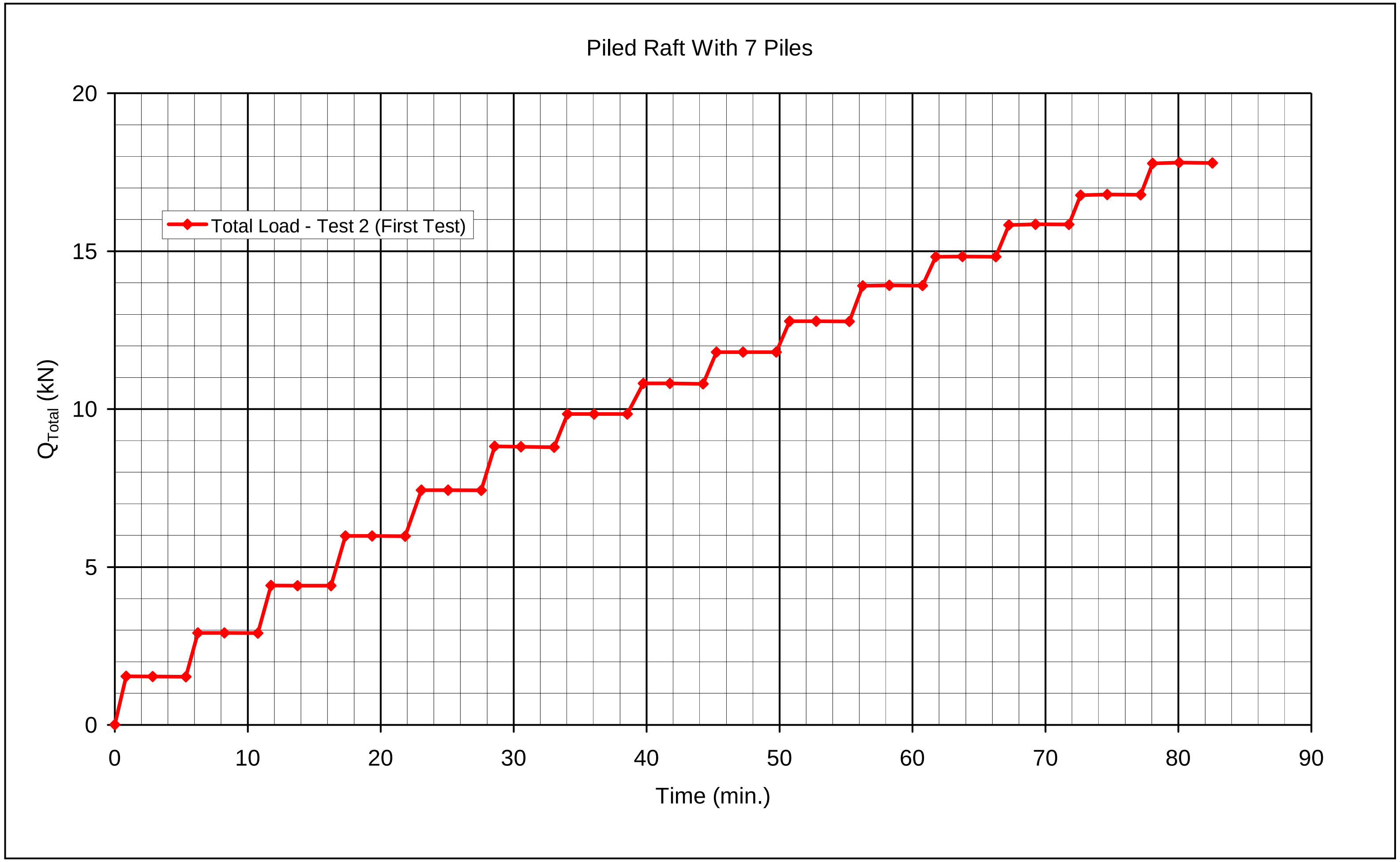

Figure 5.19 Loading sequence of the piled raft with 7 piles

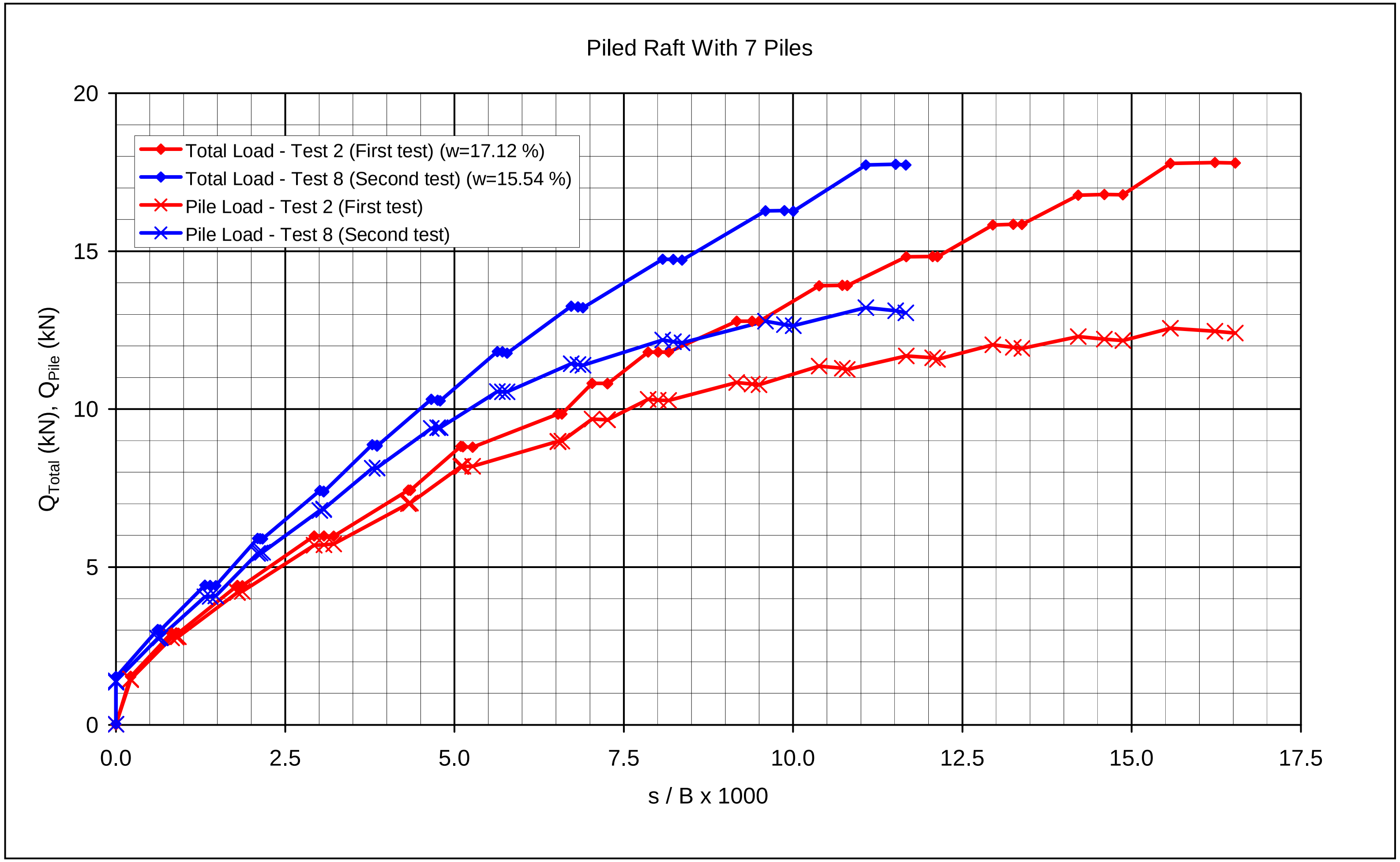

Figure 5.20 Load–settlement relationship of piled raft with 7 piles

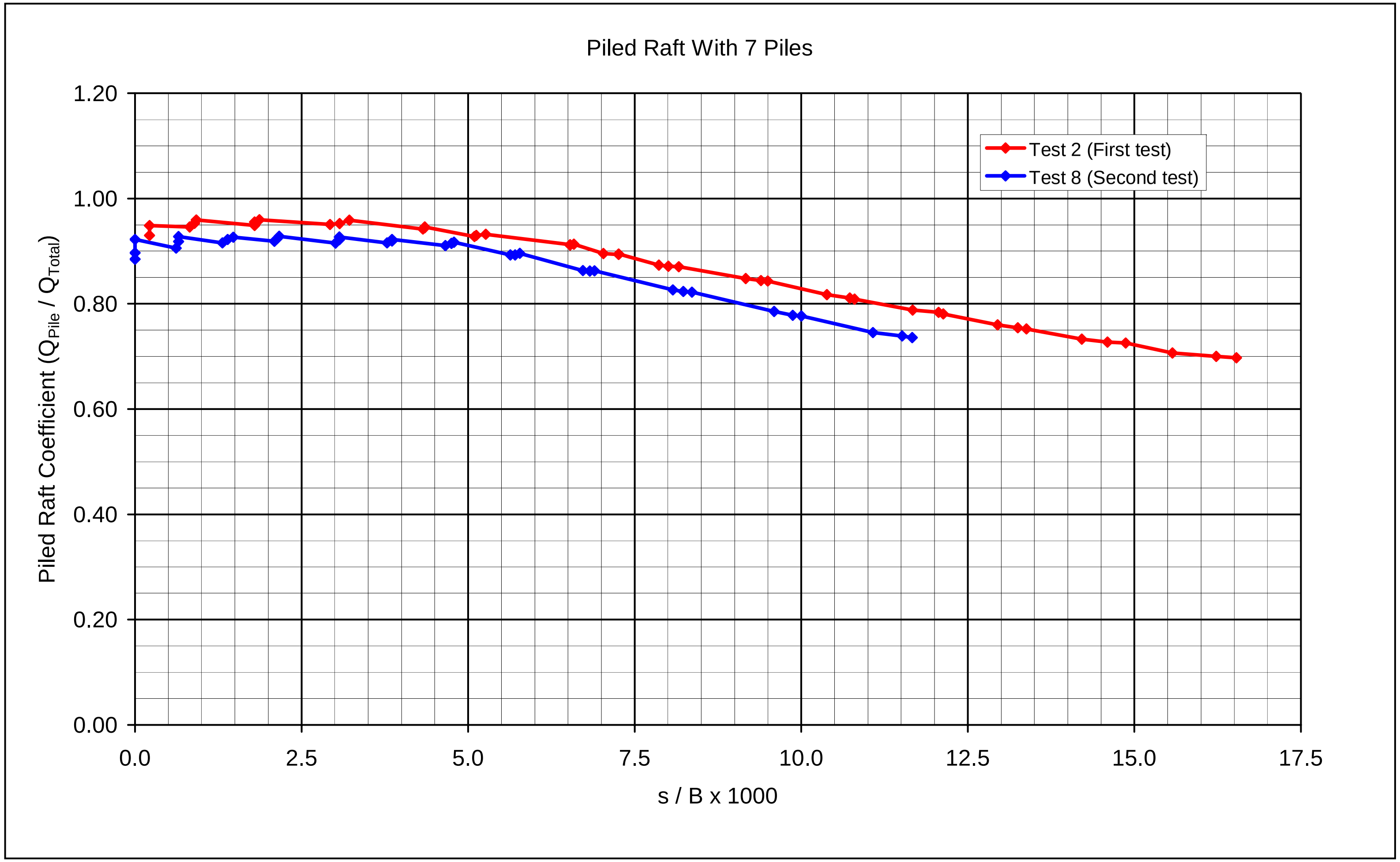

Figure 5.21 Piled raft coefficient–settlement relationship of piled raft with 7 piles

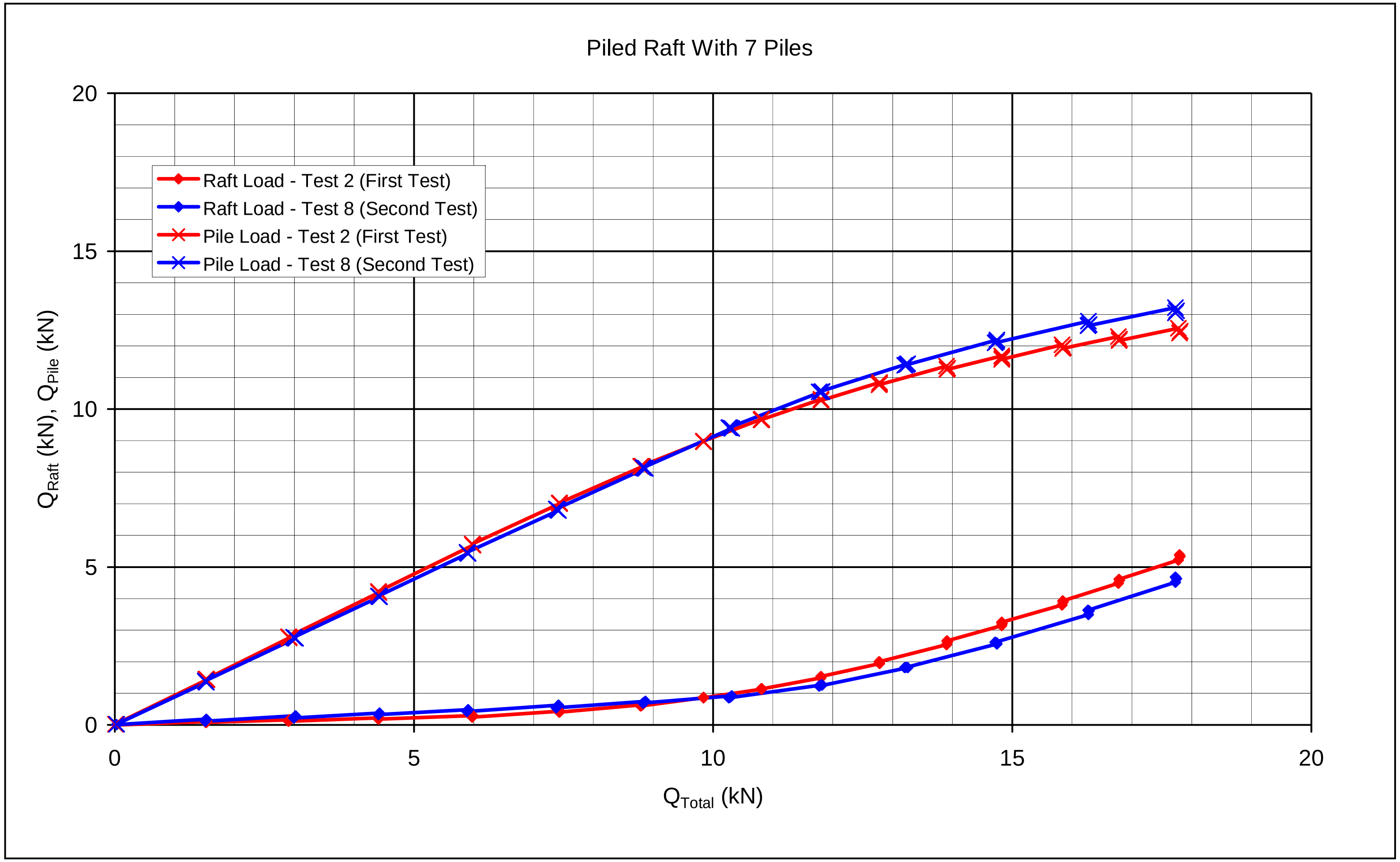

Figure 5.22 Load sharing between piles and the raft for the piled raft with 7 piles

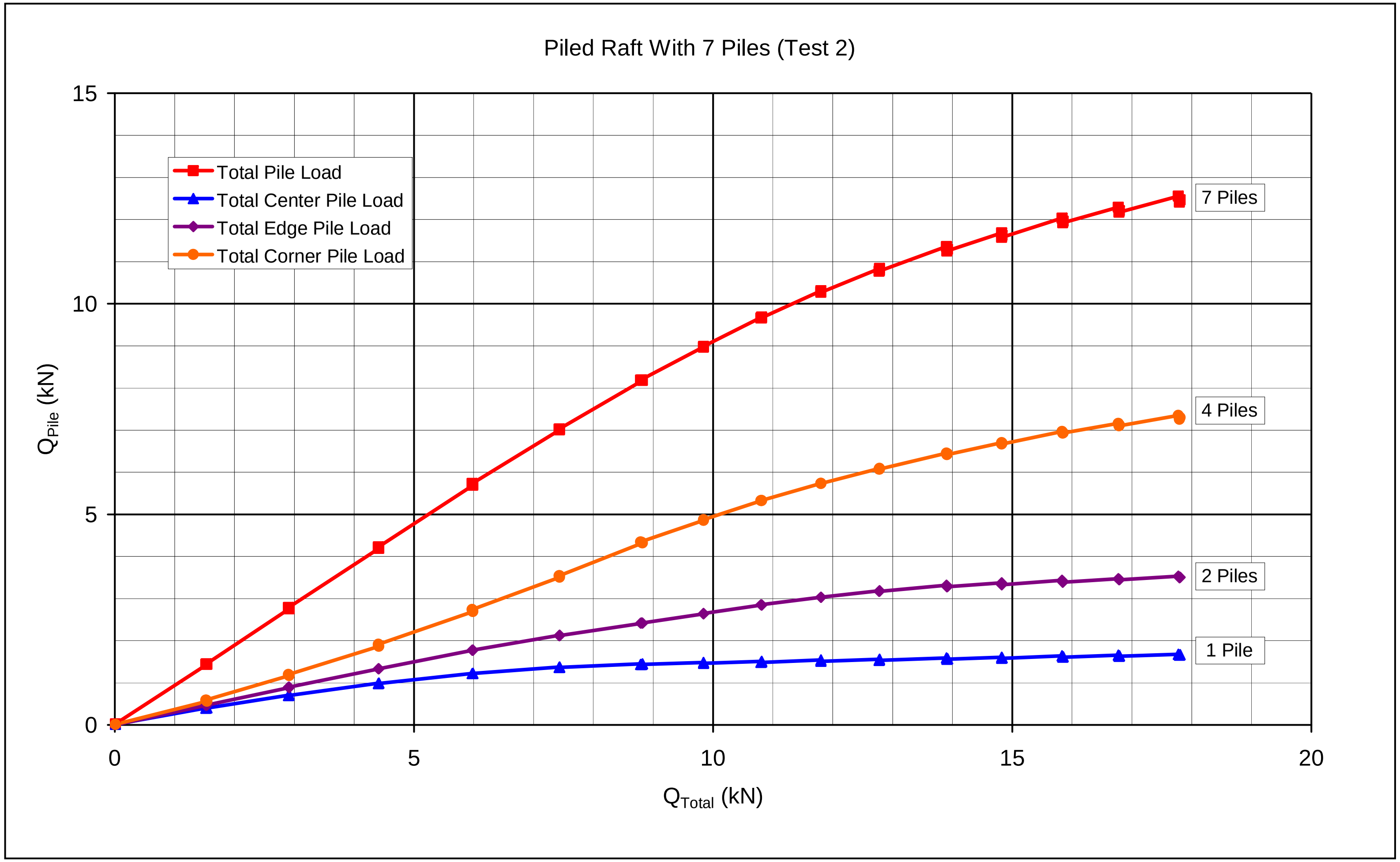

Figure 5.23 Measured pile loads for the piled raft with 7 piles in Test 2

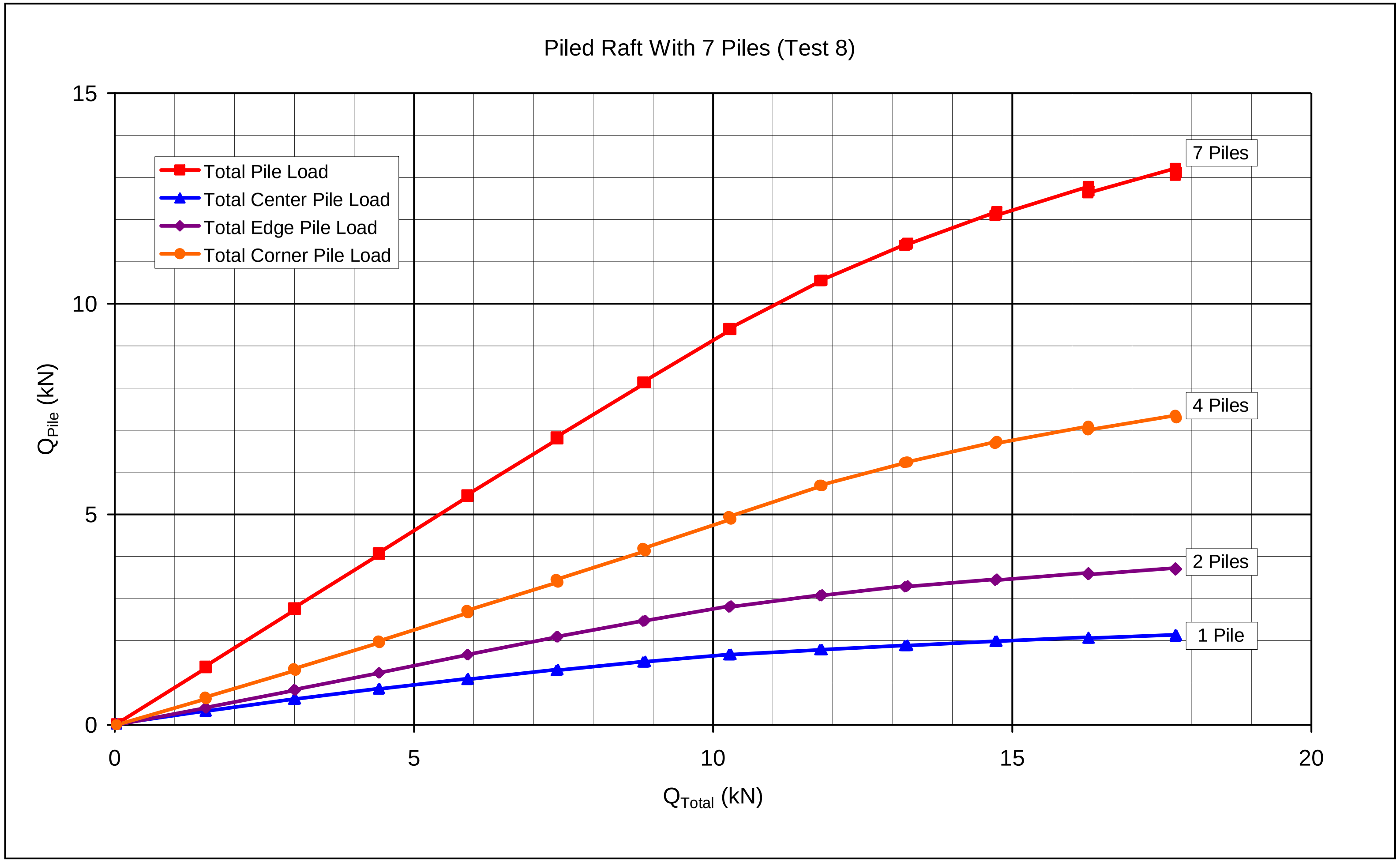

Figure 5.24 Measured pile loads for the piled raft with 7 piles in Test 8

5.7 Laboratory Model Test Results of Piled Raft with 9 Piles

Model piled raft with 9 piles was loaded, displacements and pile forces were measured in order to investigate piled raft behavior under vertical loading (Figure 5.25). Four tests (Test 1, Test 5, Test 11 and Test 12) were performed with piled raft with 9 piles. Loading sequence of a piled raft with 9 piles is shown in Figure 5.26. Total vertical load-settlement and pile load–settlement relations are shown in Figure 5.27.

Figure 5.25 Model piled raft with 9 piles

In Test 1, some problems occurred during test preparation and at the loading stage. Those problems may be the cause of differences of piled raft behavior in Test 1 compared to the other tests. In Test 1, after soil is compressed and some of the holes were drilled, a problem occurred in the drilling equipment. Repairing of the equipment took a few days and the soil in the tank remained without pressure on it and expanded a little bit during this period. Since the subsoil is expanded, the piled raft in Test 1 settled more than the piled rafts in other tests in the same series at the same load level. The second problem was related to measuring of pile loads in Test 1. Load of the center pile could not be measured due to a problem which occurred during the test. Load carried by the center pile was assumed to be equal to the average of the loads carried by other piles. The related diagrams of Test 1 were produced based on this assumption.

Piled raft coefficient–settlement relation is shown in Figure 5.28. Load sharing behavior of piled raft is shown in Figure 5.29. Pile loads for Test 1, Test 5, Test 11 and Test 12 is given in Figures 5.30 – 5.33 for different locations of the piled raft.

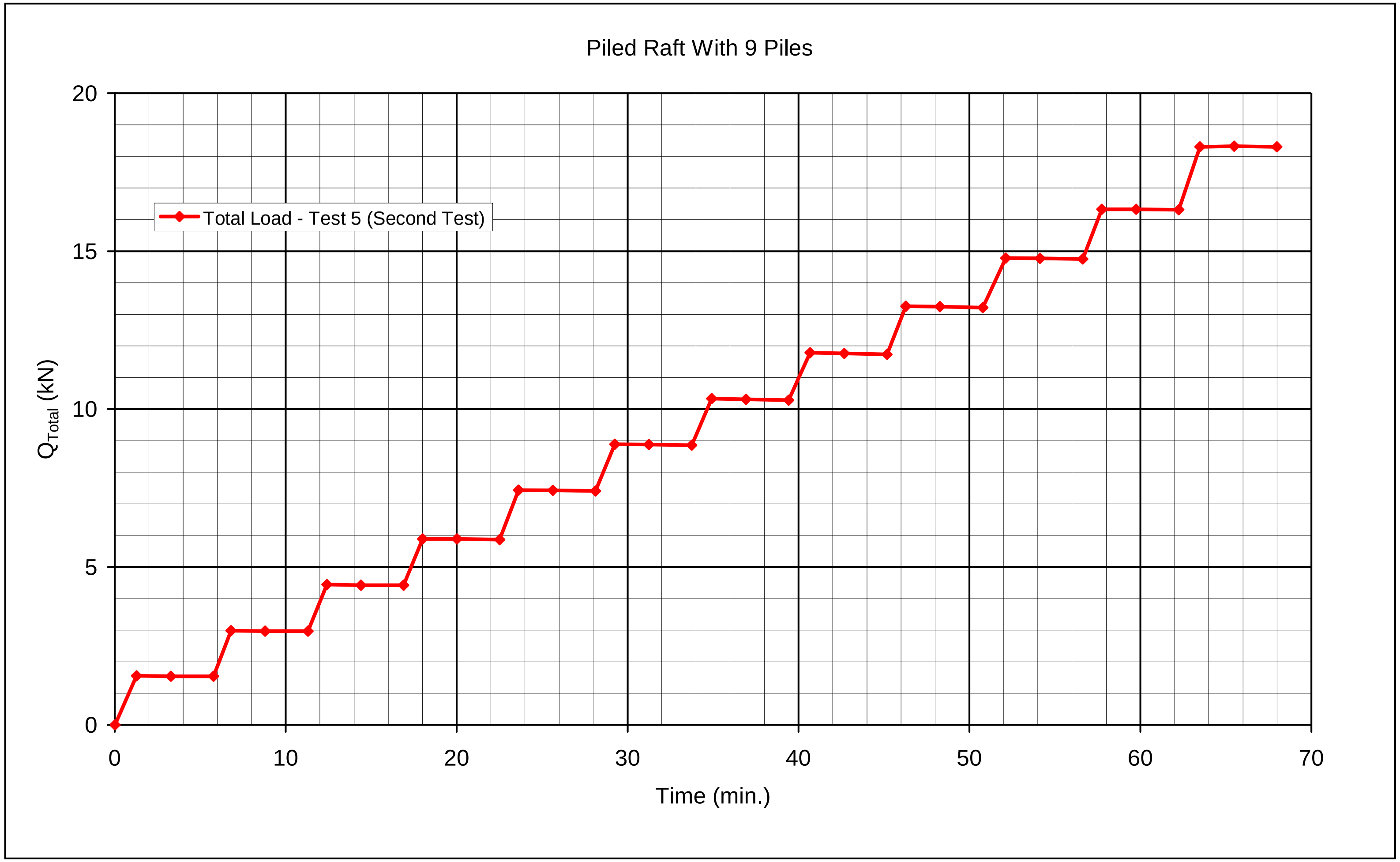

Figure 5.26 Loading sequence of the piled raft with 9 piles

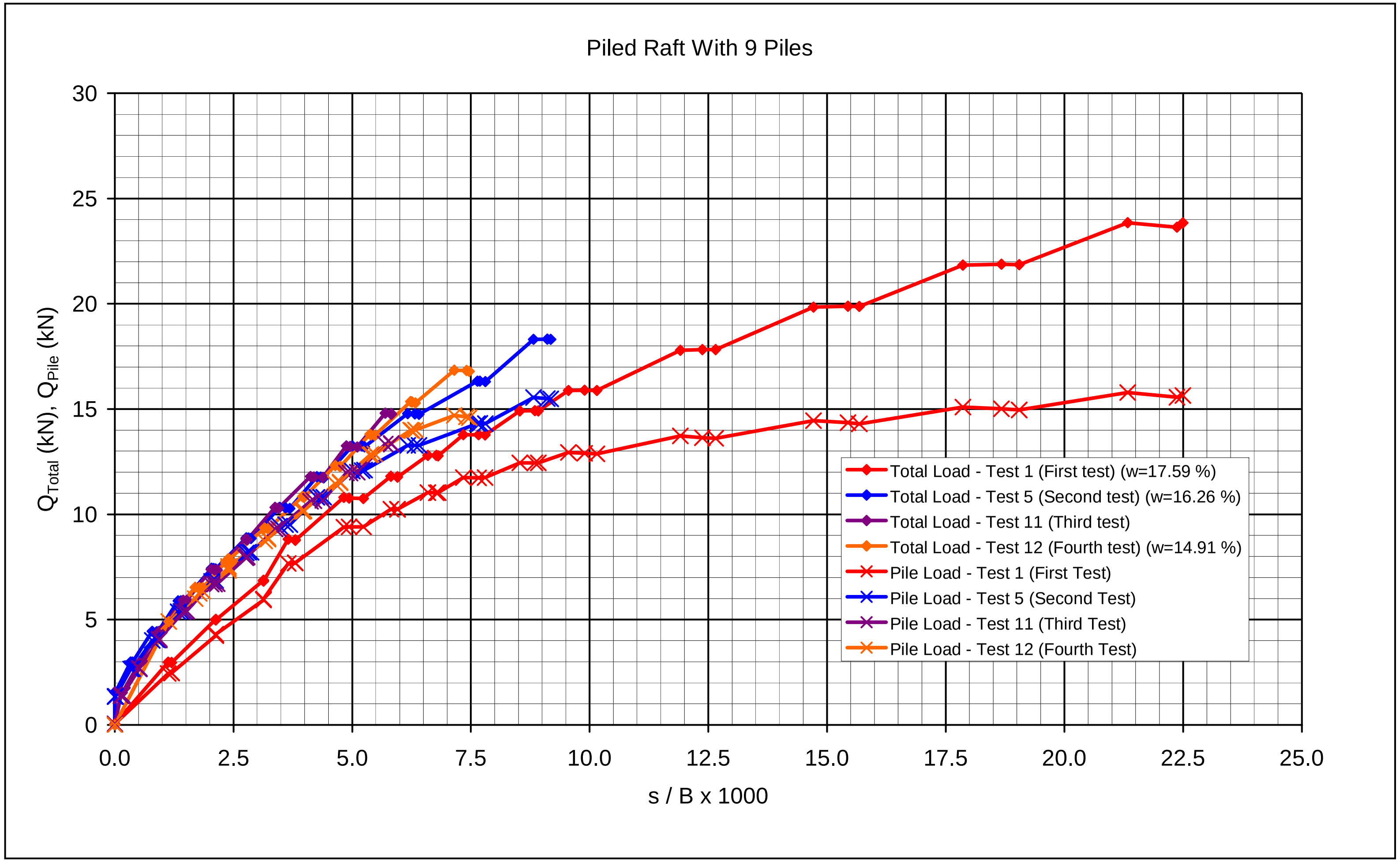

Figure 5.27 Load–settlement relationship of piled raft with 9 piles

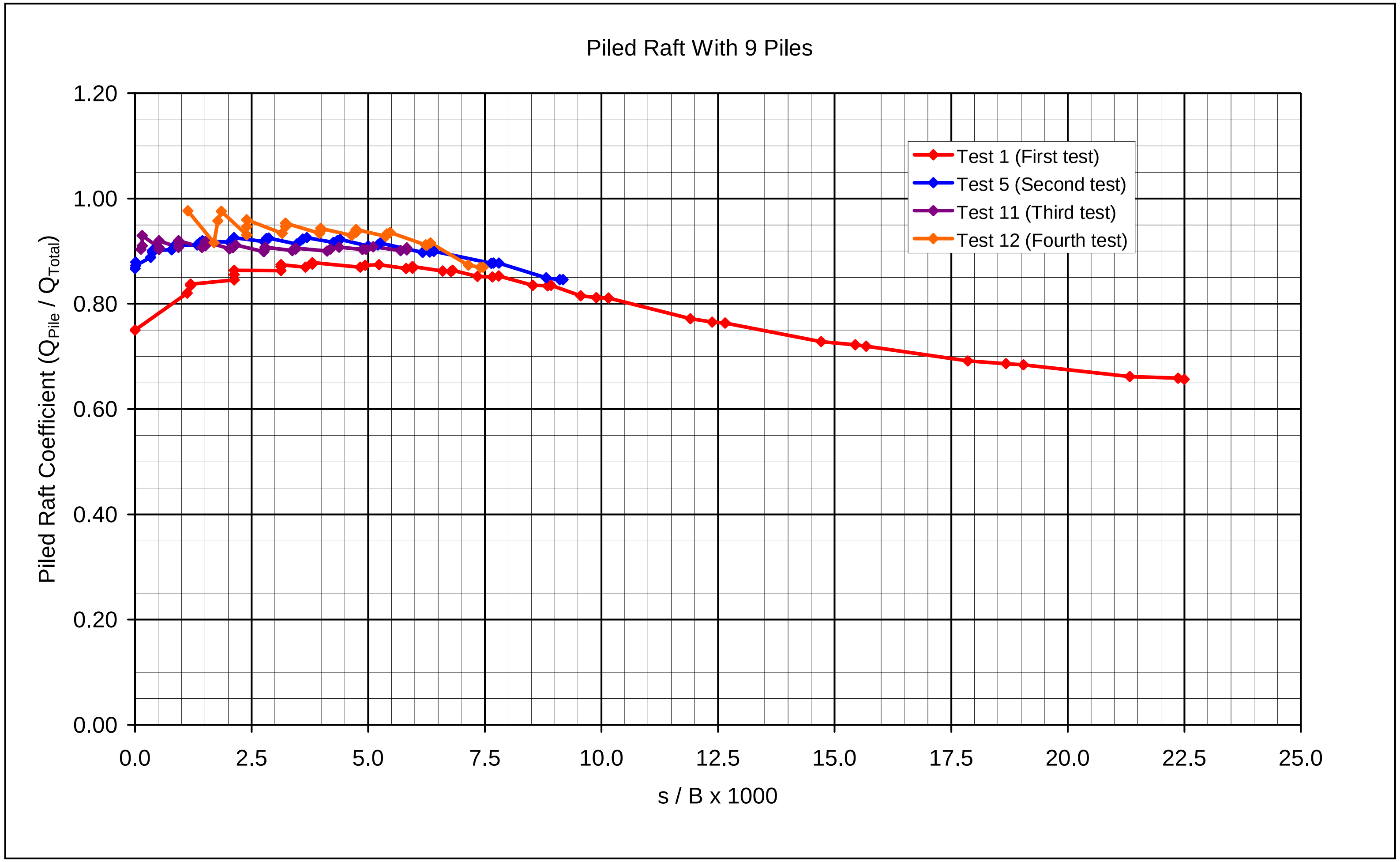

Figure 5.28 Piled raft coefficient–settlement relationship of piled raft with 9 piles

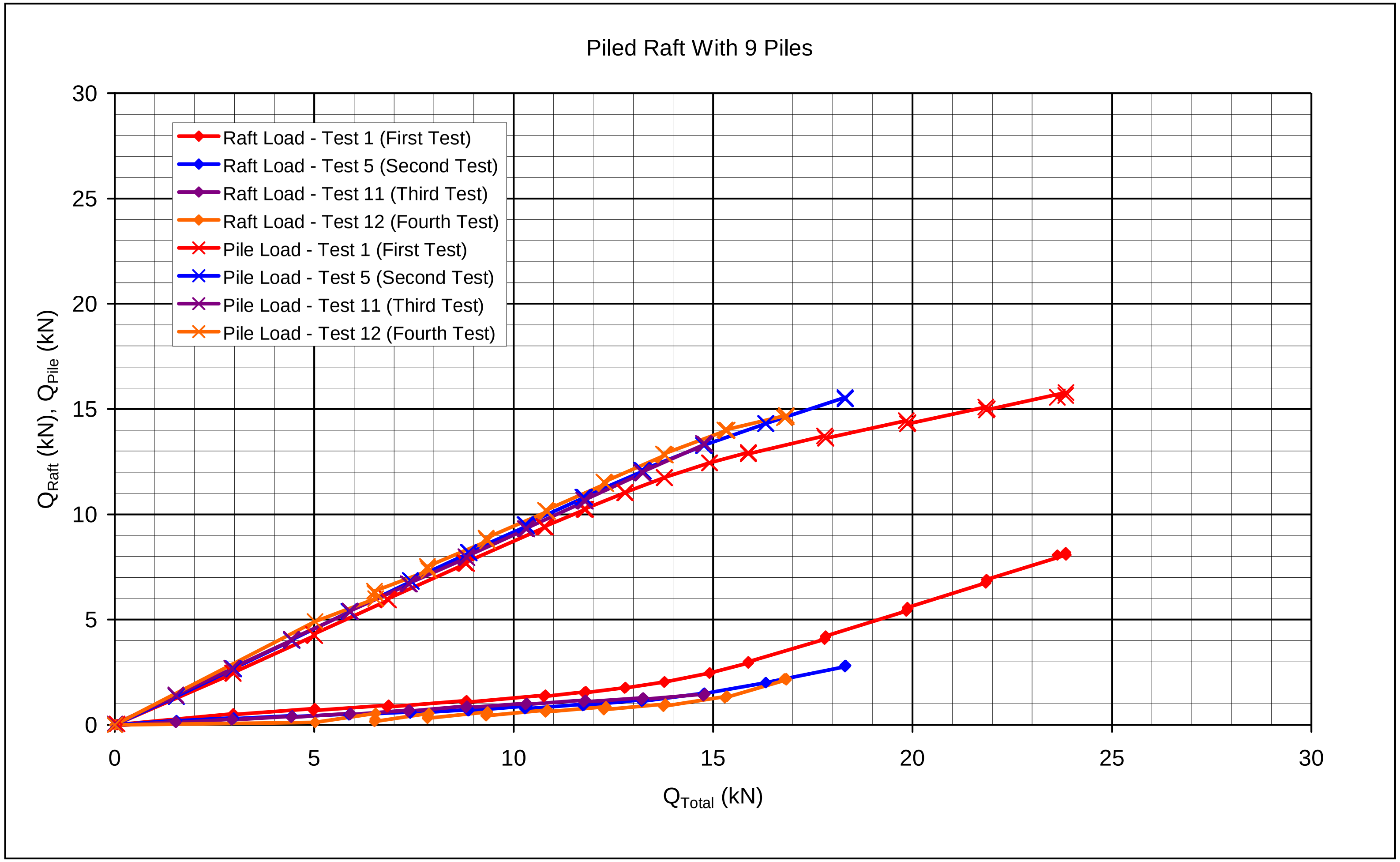

Figure 5.29 Load sharing between piles and the raft for the piled raft with 9 piles

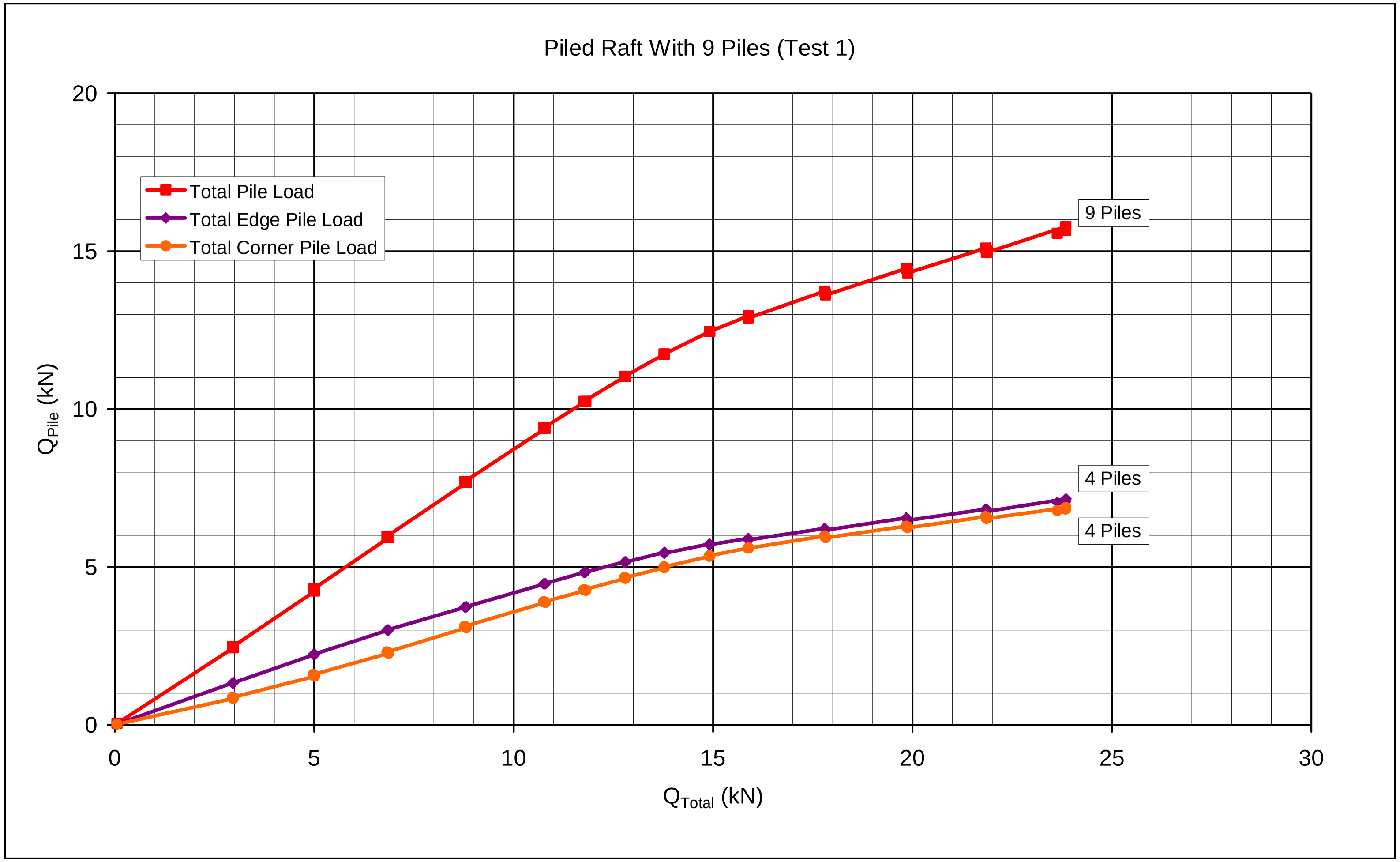

Figure 5.30 Measured pile loads for the piled raft with 9 piles in Test 1

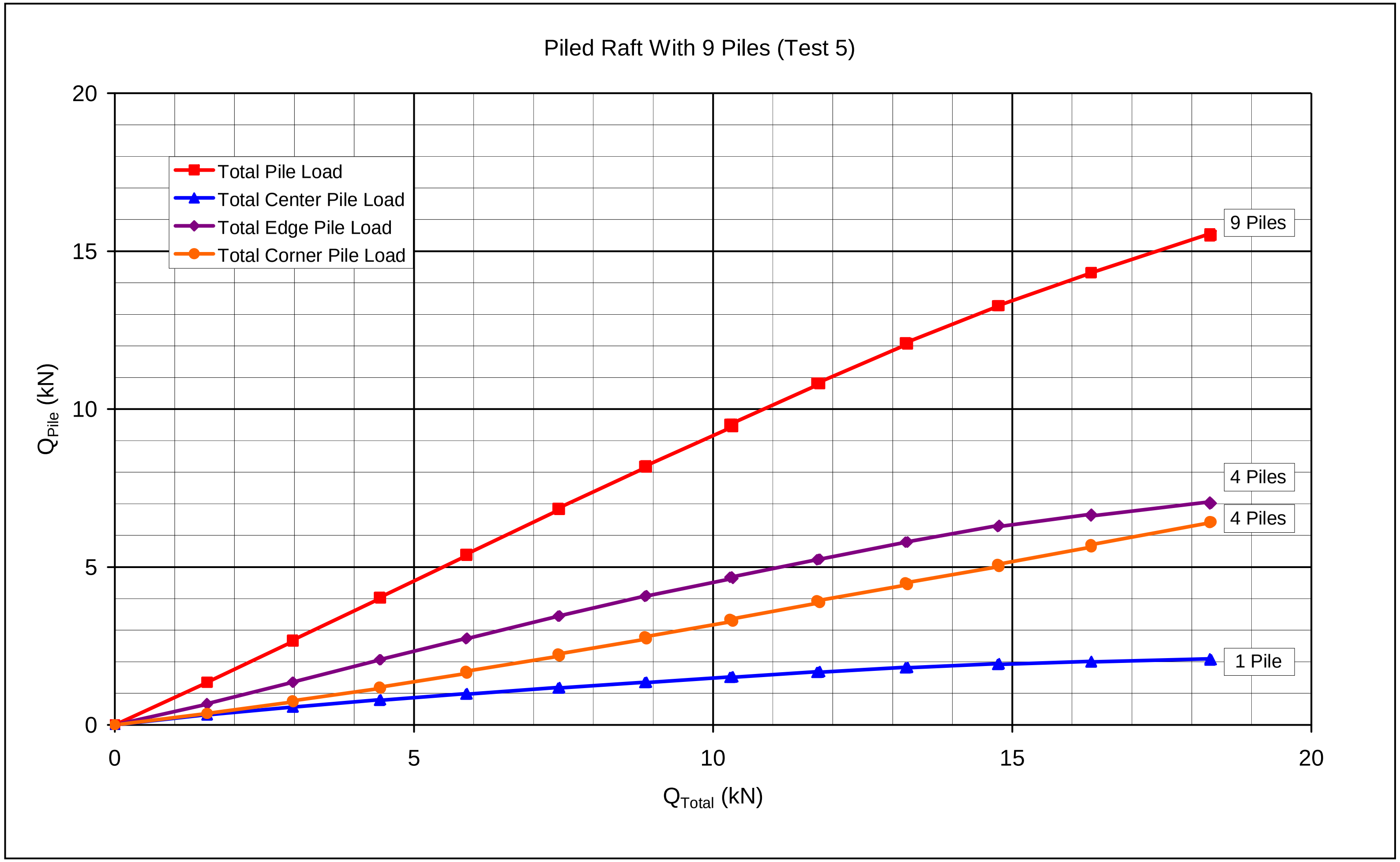

Figure 5.31 Measured pile loads for the piled raft with 9 piles in Test 5

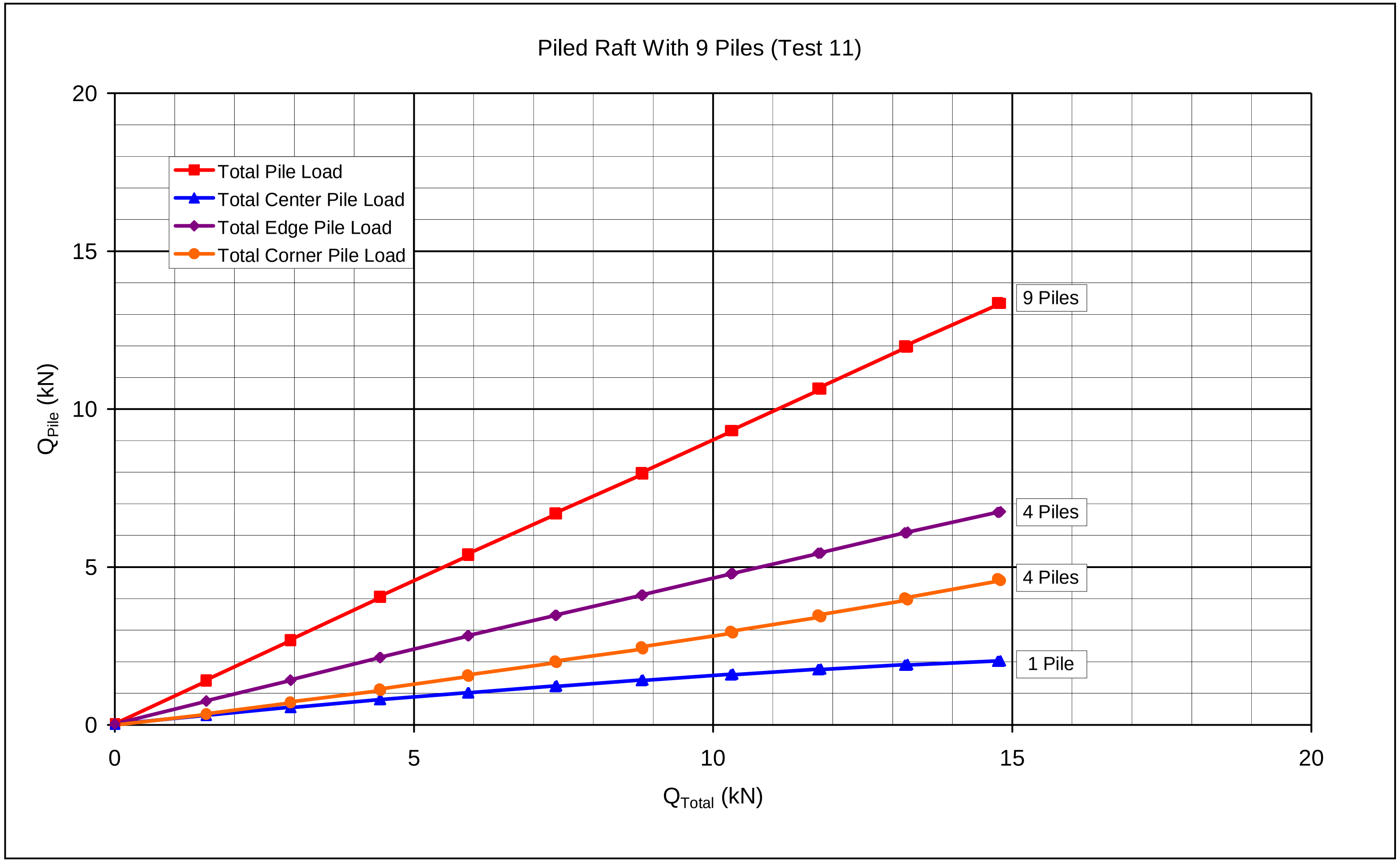

Figure 5.32 Measured pile loads for the piled raft with 9 piles in Test 11

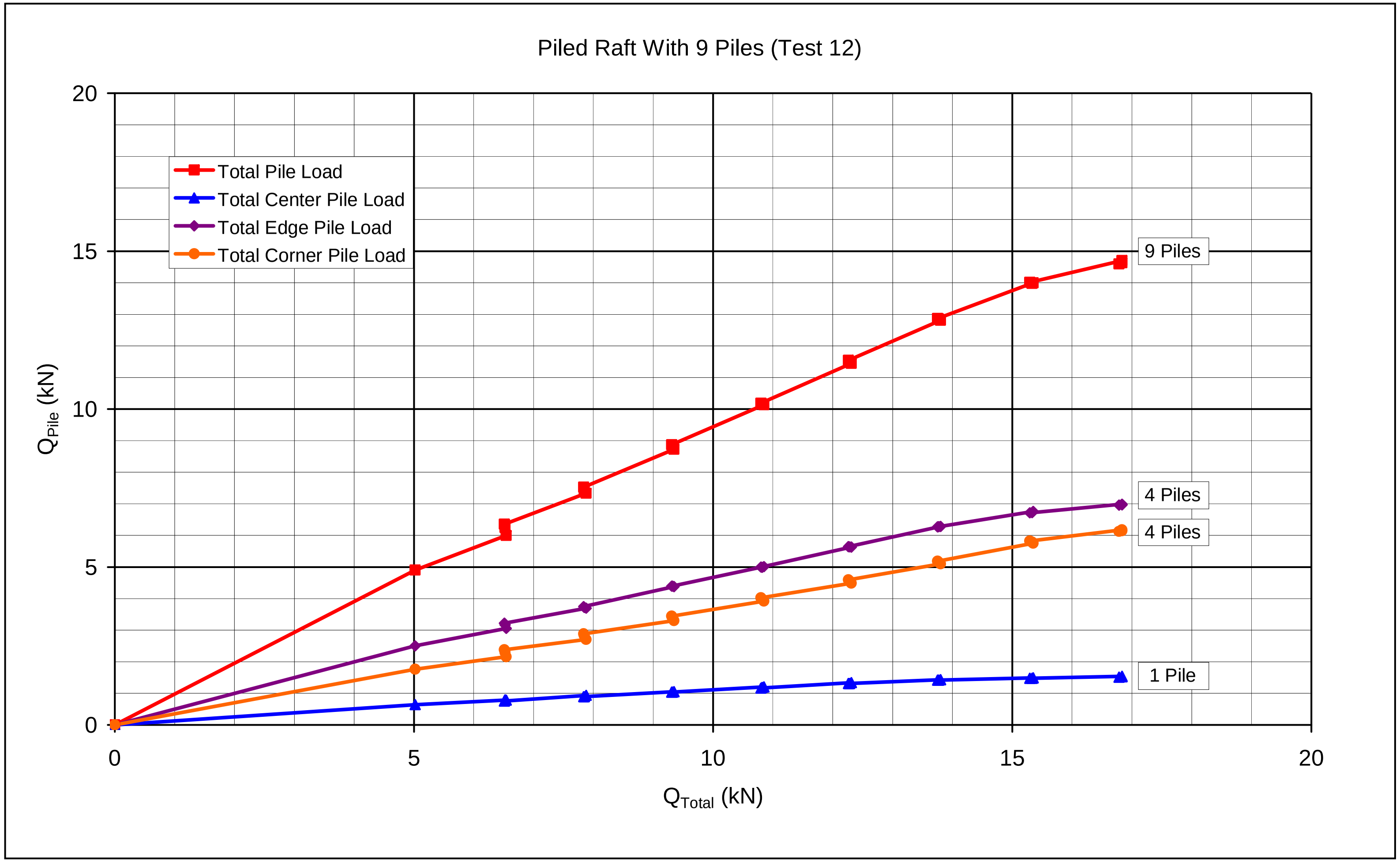

Figure 5.33 Measured pile loads for the piled raft with 9 piles in Test 12

CHAPTER 6

DISCUSSION OF LABORATORY MODEL TEST RESULTS

6.1 Introduction

In this chapter, laboratory model test results will be discussed. The discussion will be presented mainly in five parts: repeatability of the tests, distribution of loads on piles in a piled raft, load sharing mechanism of piled raft foundations, settlement behavior of piled raft foundations and design and safety approaches of piled raft foundations.

6.2 Repeatability of the Tests

In order to verify the repeatability of the tests, the tests were performed at least two times and for some cases up to four times. Before deciding the testing procedure 9 preliminary tests were conducted in order to see the problems that can be faced and decide the final test setup. With the experience gained during those preliminary tests, the main tests were conducted.

There are some differences between the test results as shown in the previous chapter. These differences may be due to the changes in homogeneity, compression characteristics and water content (w) of the prepared soil samples. Water content is the dominant parameter affecting the test results, because settlement characteristics are directly related to the water content. In the tests clay (50 % by weight) and sand (50 % by weight) mixture was used as foundation soil. Water content of the soil decreases due to the processes of preparing soil mass and temperature increase during the tests. In order to keep the water content constant for all tests, water content was checked at every test and, if necessary, water was added. The minimum and the maximum water contents were 14.70 % and 17.59 % respectively. Water content values related to each test were given in the load-settlement curves in the previous chapter. If those values and related load-settlement behavior is analyzed, it can be seen that the soil gets stiffer with the decreasing water content.

In Figure 6.1, the effect of water content to the load-settlement characteristics of the piled raft with 4 piles is clearly seen. For this piled raft configuration, 4 tests were conducted in order to be sure about the repeatability of the tests. Water content values for the tests are different and also their load-settlement behavior is slightly different. Total load required for a settlement of 1.50 mm is 11.8 kN for the test with water content of 15.54 %, 11.4 kN for the test with water content of 16.20 % and 10.3 kN for the test with water content of 16.45 %. This shows that with the decreasing water content, the soil tends to be stiffer and this affects the load-settlement characteristics.

Another reason for the differences in the test results may be the tilting of the loading frame and model foundations under high loads after displacements starts. This also causes small variations in the results.

In some of the tests with the same number of piles, it is observed that the load carried by the raft at the initial stages of loading differs. This may be due to the unavoidable variations in the placement of the model piled rafts, although the same procedure is used for every test. Variations in initial load sharing are considered to be insignificant, since these variations have no effect on load sharing at higher loads.

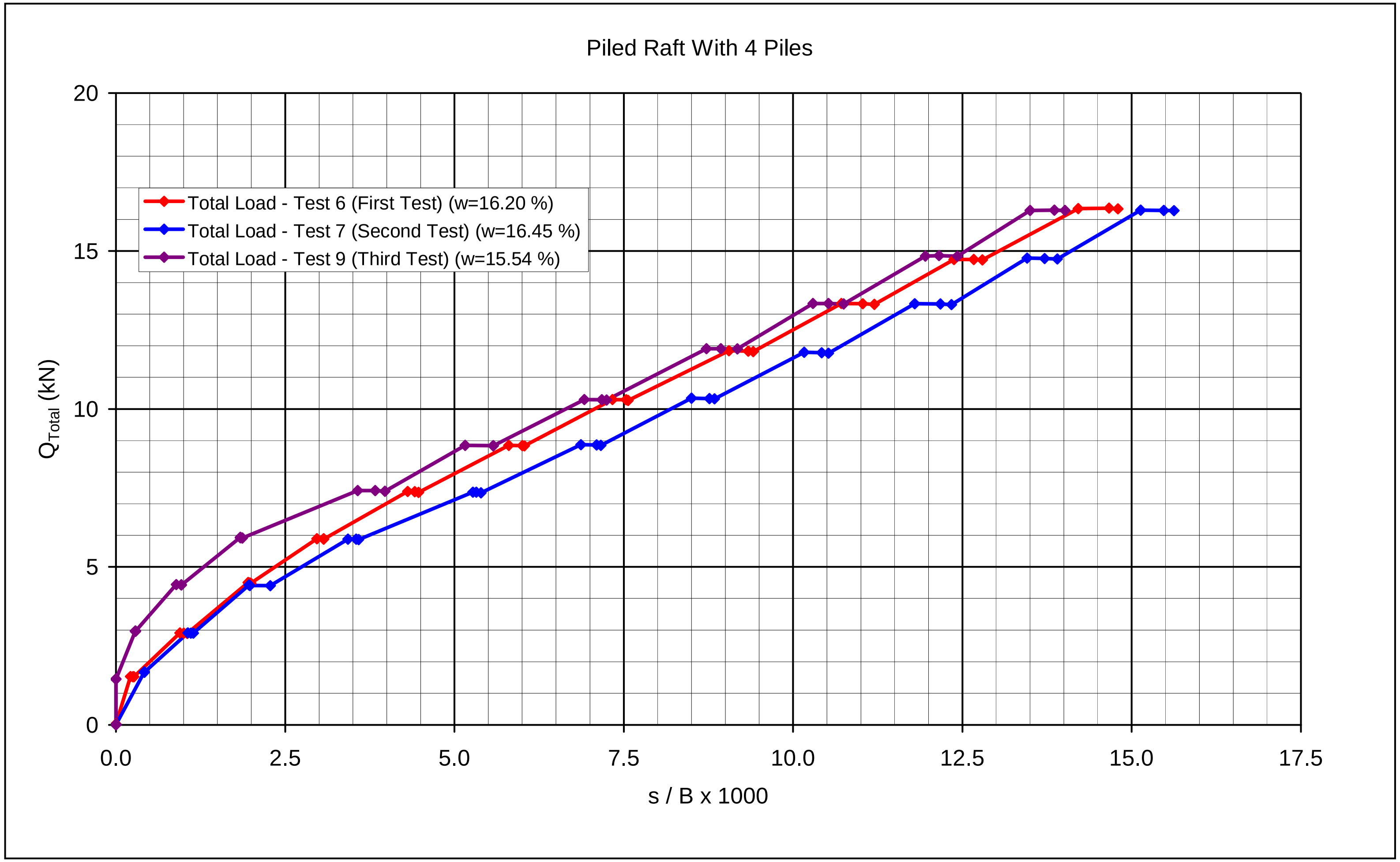

Figure 6.1 Load–settlement relationship of the piled raft with 4 piles

6.3 Distribution of Loads on Piles in a Piled Raft

In this section distribution of pile loads in a pile group will be discussed. Tests with 7 and 9 piles will be used for comparison and discussion. Pile loads at different locations of the raft are presented in Figures 5.23 and 5.24 for piled raft with 7 piles and in Figures 5.30 – 5.33 for piled raft with 9 piles.

For the piled raft with 7 piles, it can be seen that much of the total load is carried by the corner piles (i.e. summation of loads carried by 4 corner piles) and the least amount of load is carried by the center pile (Figures 5.23 and 5.24). For the 9 piled case, much of the total load is transferred to the edge piles (i.e. summation of loads carried by 4 edge piles) and again center pile carries the least amount (Figures 5.30 – 5.33).

If we consider the average pile loads shown in Figures 6.2 - 6.7, much of the load is carried by center piles and the least amount of load by the corner pile. This shows that position of the pile in a group is an important factor in the distribution of loads on piles. Based on this, design of piled raft foundations may be optimized using different length of piles at different locations beneath the raft. In the model tests the load is applied at the center of the raft and center piles are loaded more than other. From this observation it can be concluded that, piles which are under heavily loaded areas are loaded more than the other piles and this will cause an increase in differential settlement. In order to minimize differential settlements and get a uniform pressure beneath the footing, increasing the number of piles or lengthening the piles under heavily loaded areas may a preferable option.

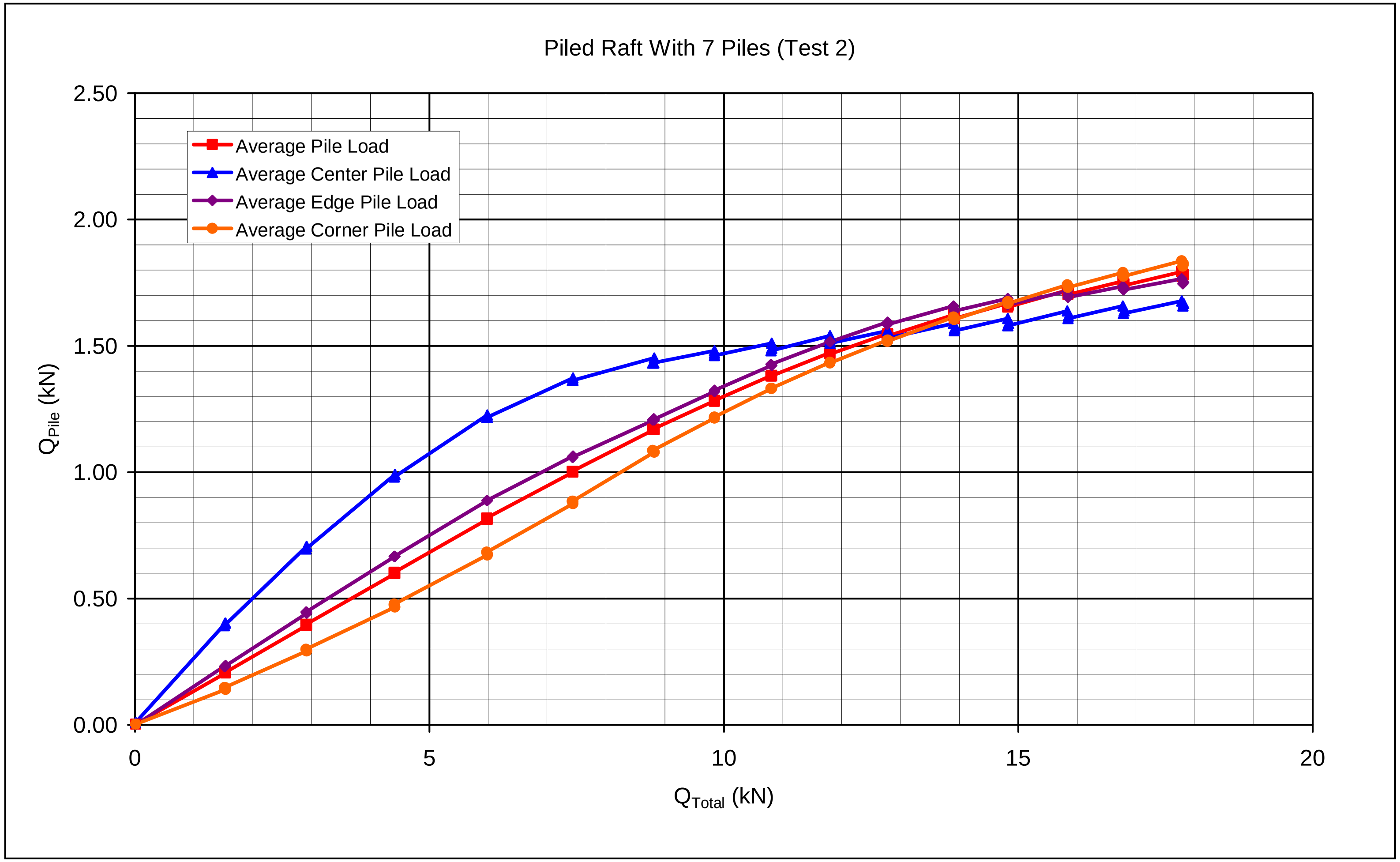

Figure 6.2 Average single pile loads for different locations of piles in the piled raft with 7 piles (Test 2)

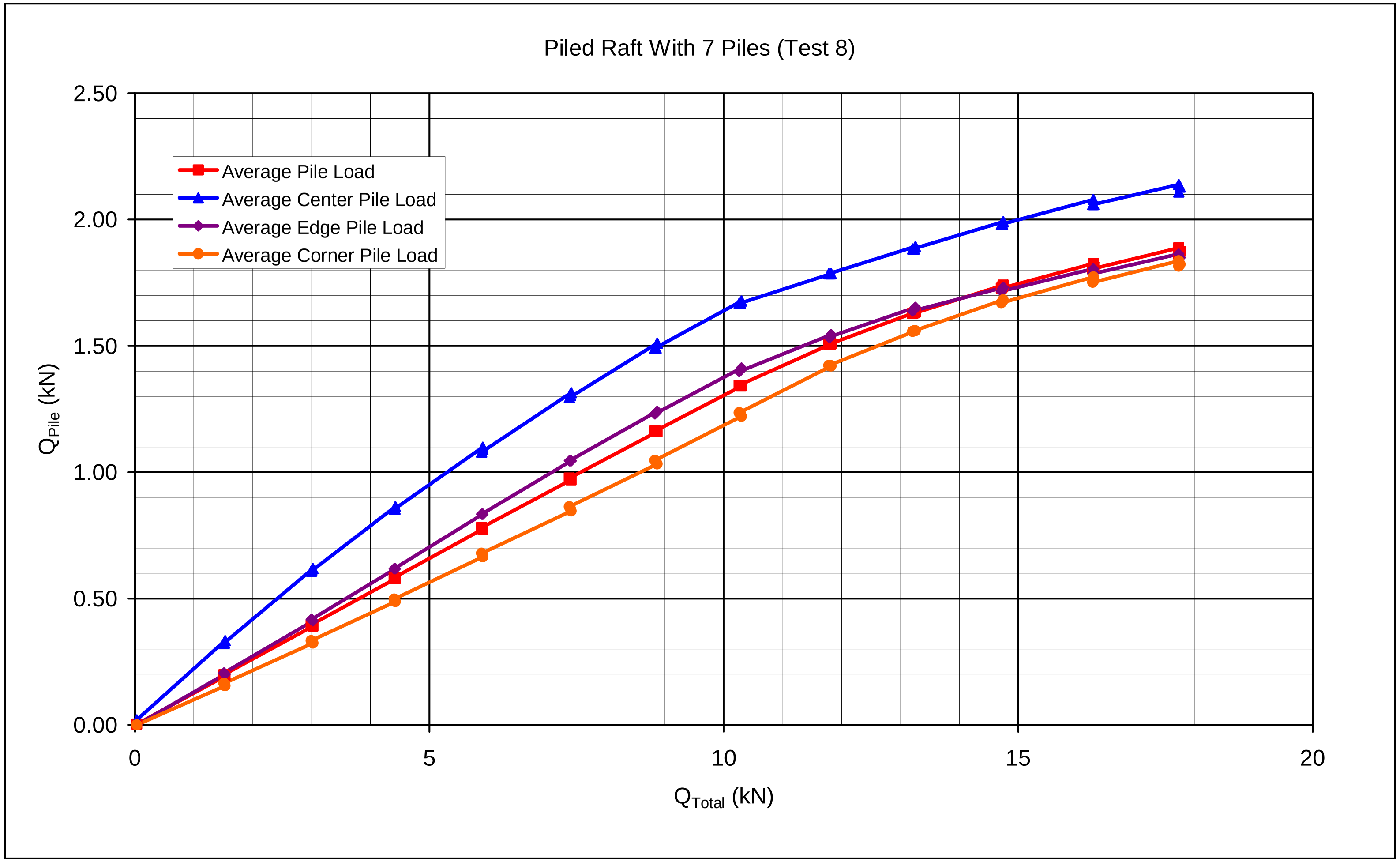

Figure 6.3 Average single pile loads for different locations of piles in the piled raft with 7 piles (Test 8)

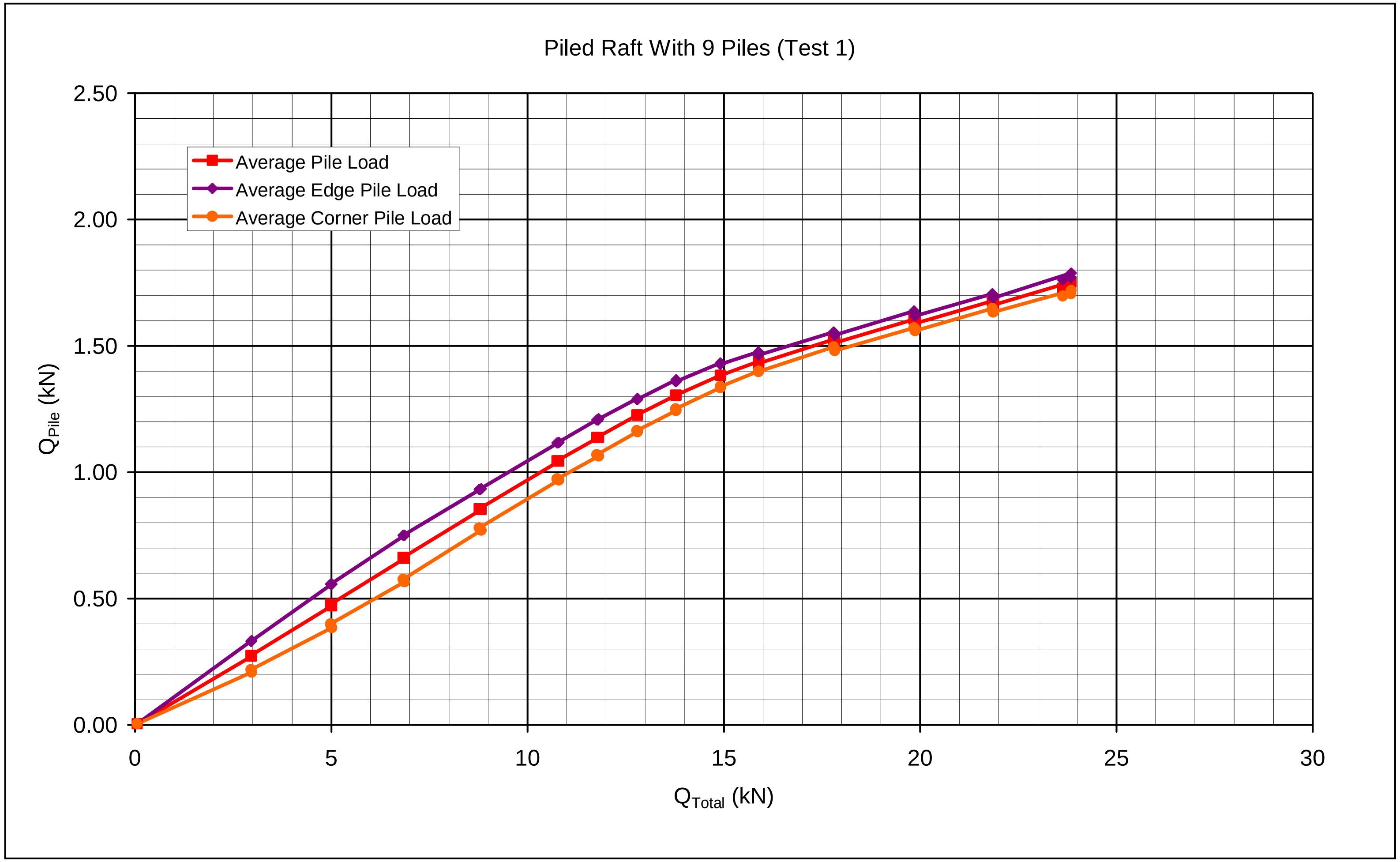

Figure 6.4 Average single pile loads for different locations of piles in the piled raft with 9 piles (Test 1)

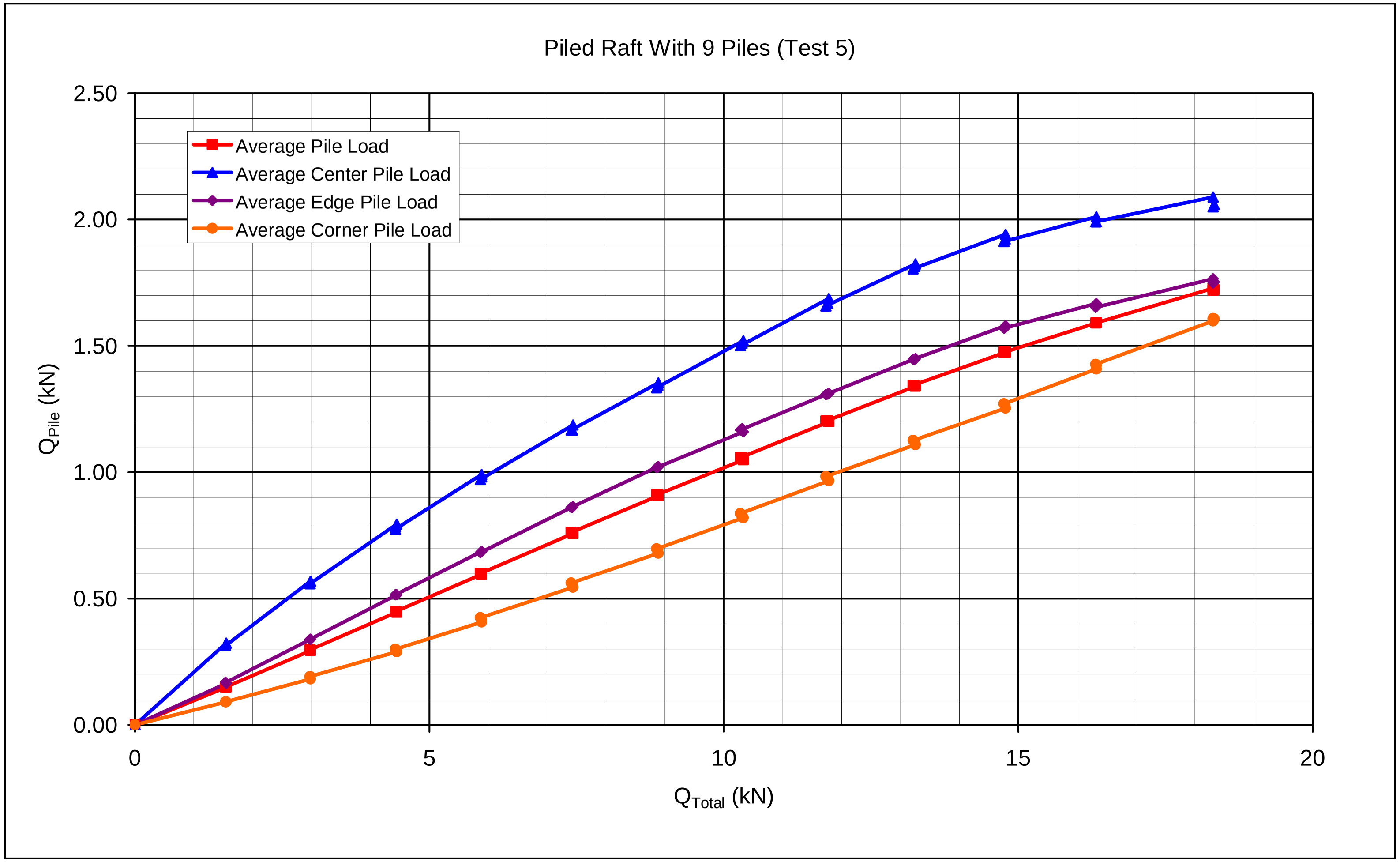

Figure 6.5 Average single pile loads for different locations of piles in the piled raft with 9 piles (Test 5)

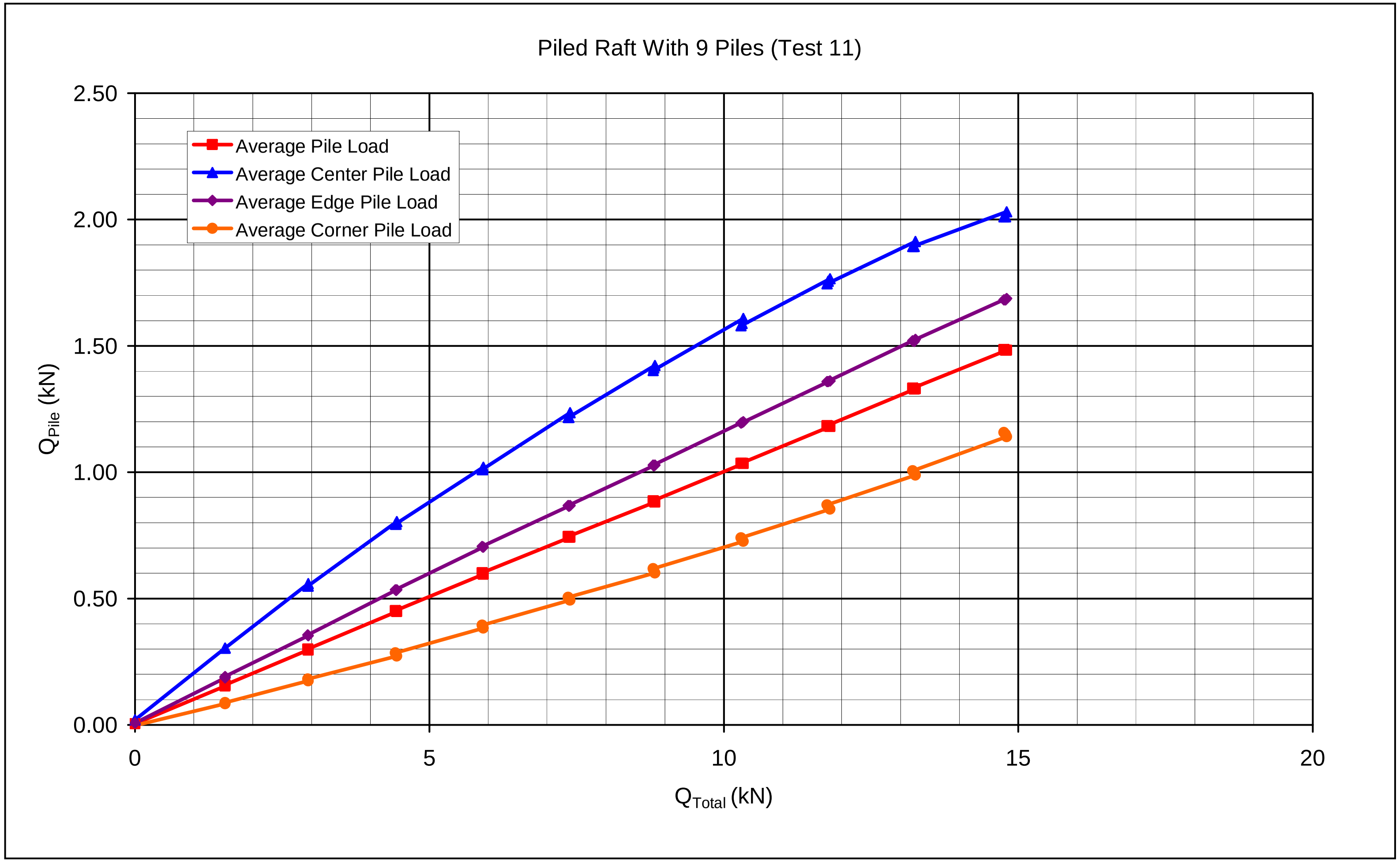

Figure 6.6 Average single pile loads for different locations of piles in the piled raft with 9 piles (Test 11)

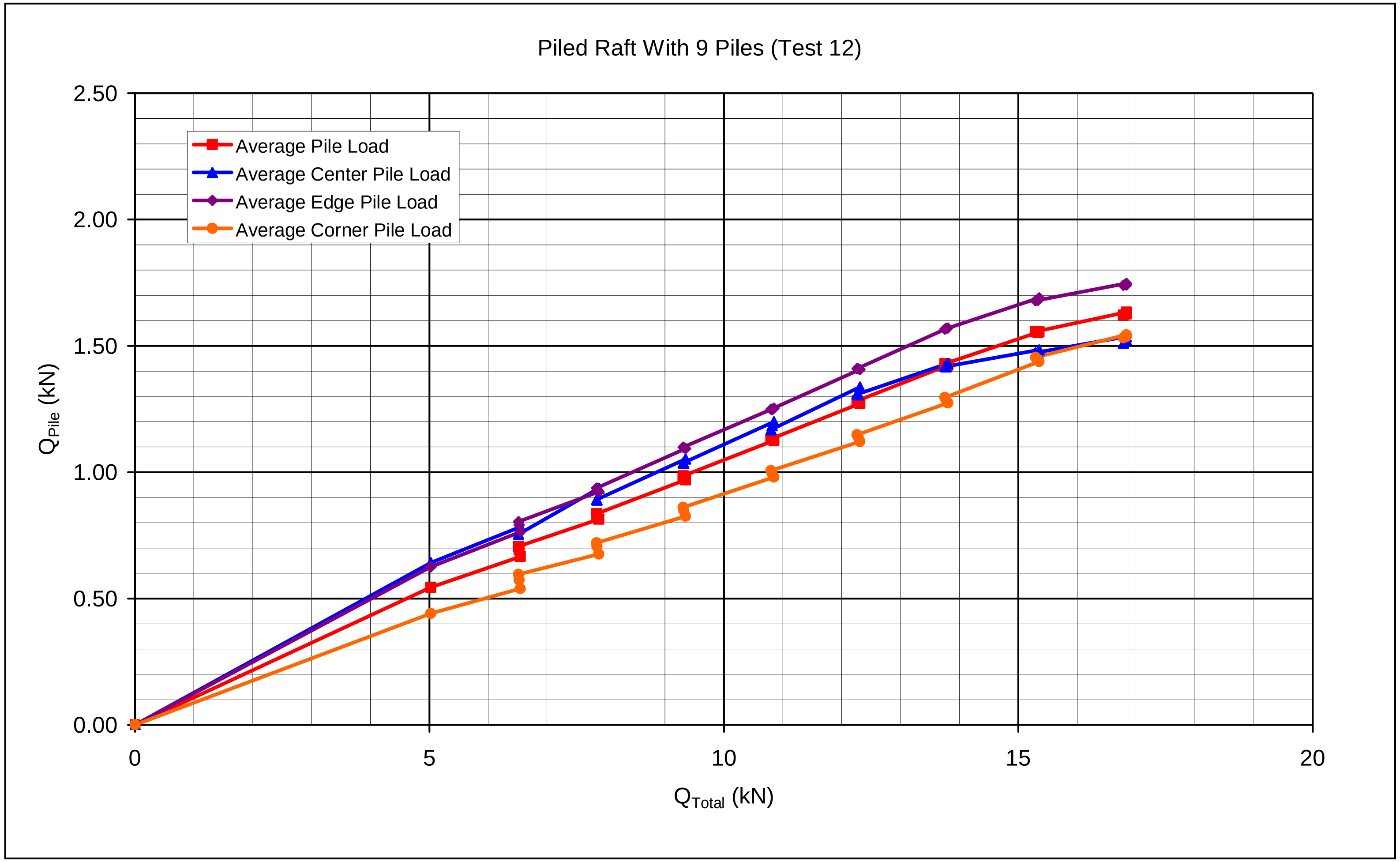

Figure 6.7 Average single pile loads for different locations of piles in the piled raft with 9 piles (Test 12)

6.4 Load Sharing Mechanism of Piled Raft Foundations

The load-settlement behavior of the piled raft with 7 piles is shown in Figure 6.8. Pile and raft loads with respect to raft settlements are also presented in Figure 6.8. At the initial stages of loading nearly the entire applied vertical load is carried with piles for piled raft with 7 piles.

After some displacement occurs, piles start to carry more load. Up to a certain point, load carried by the raft remains nearly constant. As settlements increase, the full capacities of piles are mobilized and raft shares more load. After piles reach their full capacity, the load carried by piles remains nearly constant and additional loads are carried by raft. Raft load coefficient is the ratio between the raft load (Q_{Raft}) and the total vertical load (Q_{Total}). Figure 6.9 shows variation of the raft load coefficient with settlement. Raft load coefficient of 0 indicates the case of a piled foundation with no contact between the raft and soil mass and all load is carried by piles. On the other hand, raft load coefficient of 1 indicates the case of a plain raft without any piles. At the initial stages of loading, raft load coefficient remains constant. With increasing displacements, raft load coefficient increases.

The load-settlement behavior of the piled raft with 2 piles is shown in Figure 6.10. Contrary to the previous case, at the initial stages of loading, piles and raft are sharing the load nearly equal. Piles reach their full capacity at a lower load and settlement level compared to the case with 7 piles. Figure 6.11 shows the variation of the raft load coefficient with settlement. Contribution of the raft to the total bearing capacity is much more than the previous case with 7 piles.

Tt was observed that initial load sharing proportion depends on the number and capacity of piles (Figures 5.11, 5.16, 5.21 and 5.28). Initial raft load coefficient of the piled raft with 2 piles is higher than the piled raft with 7 piles.

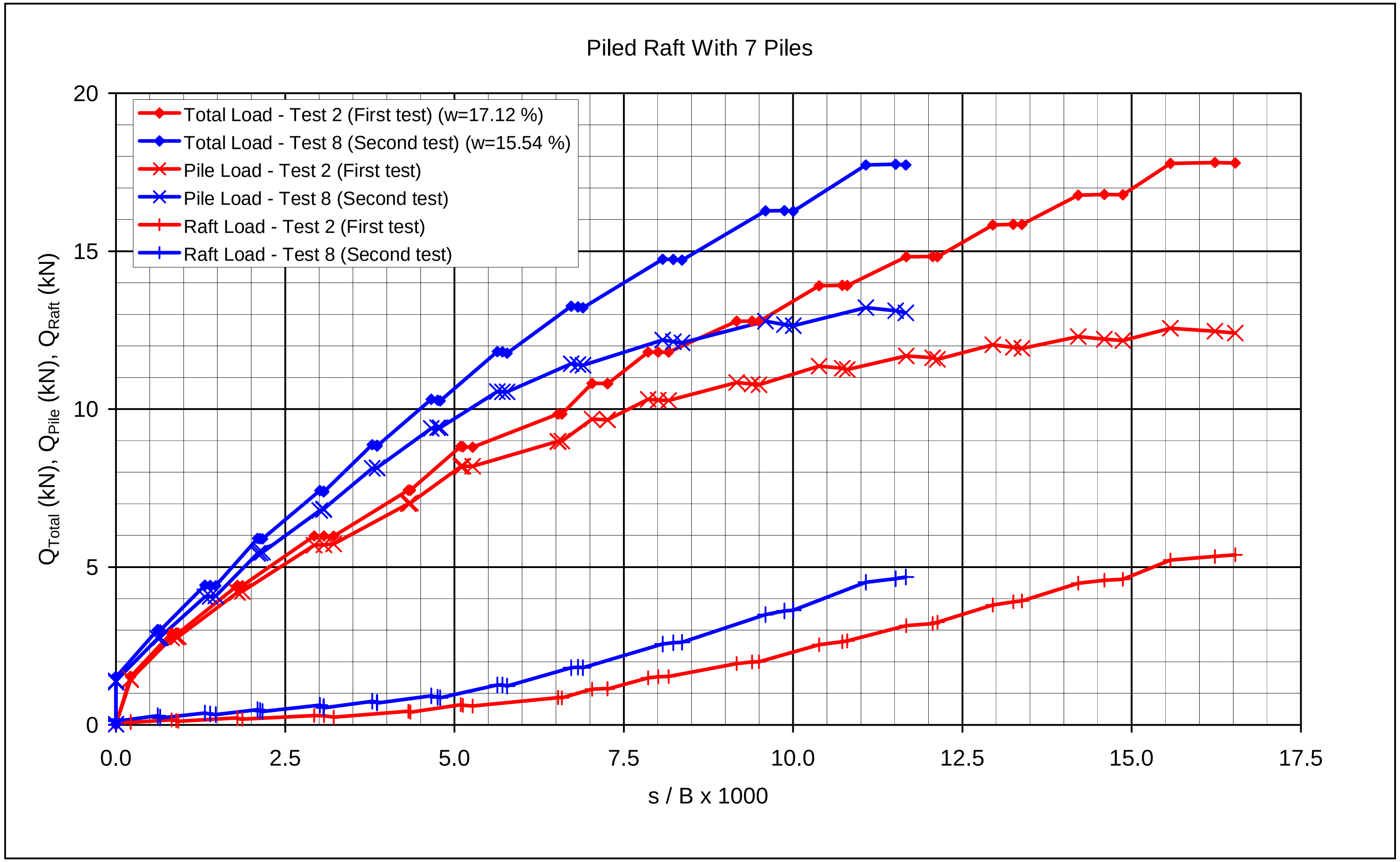

Figure 6.8 Load–settlement relationship of piled raft with 7 piles

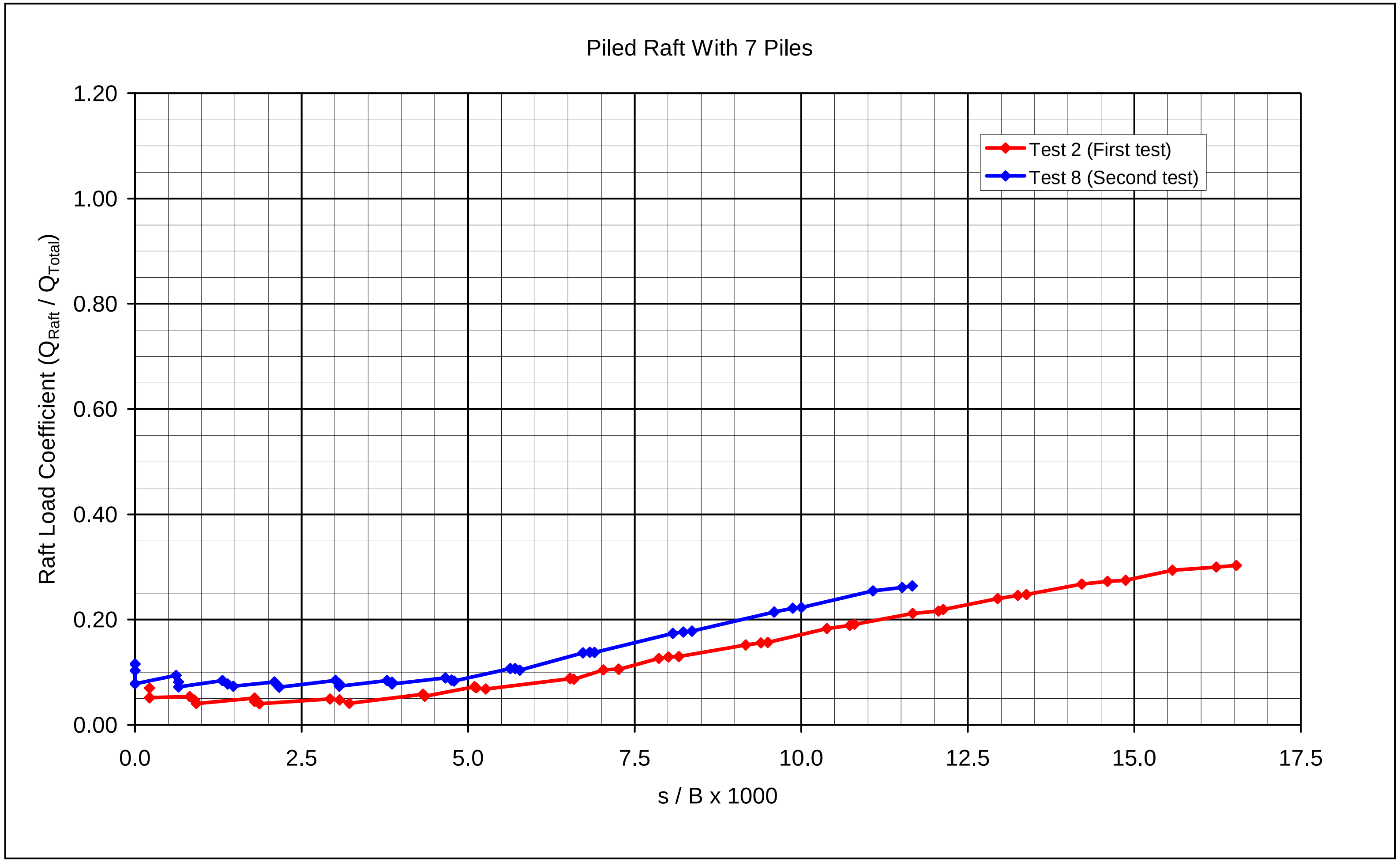

Figure 6.9 Raft load coefficient–settlement relationship of piled raft with 7 piles

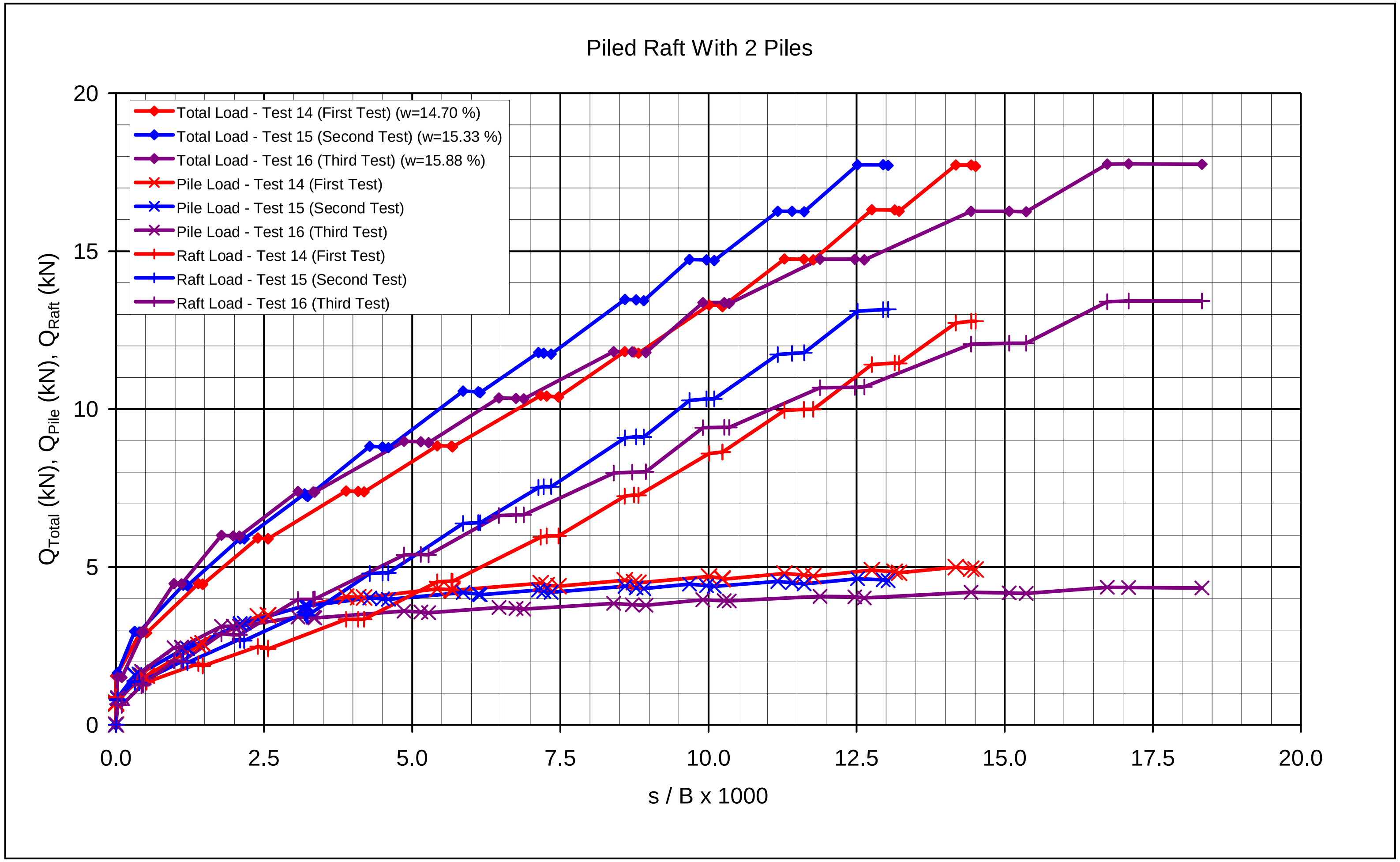

Figure 6.10 Load–settlement relationship of piled raft with 2 piles

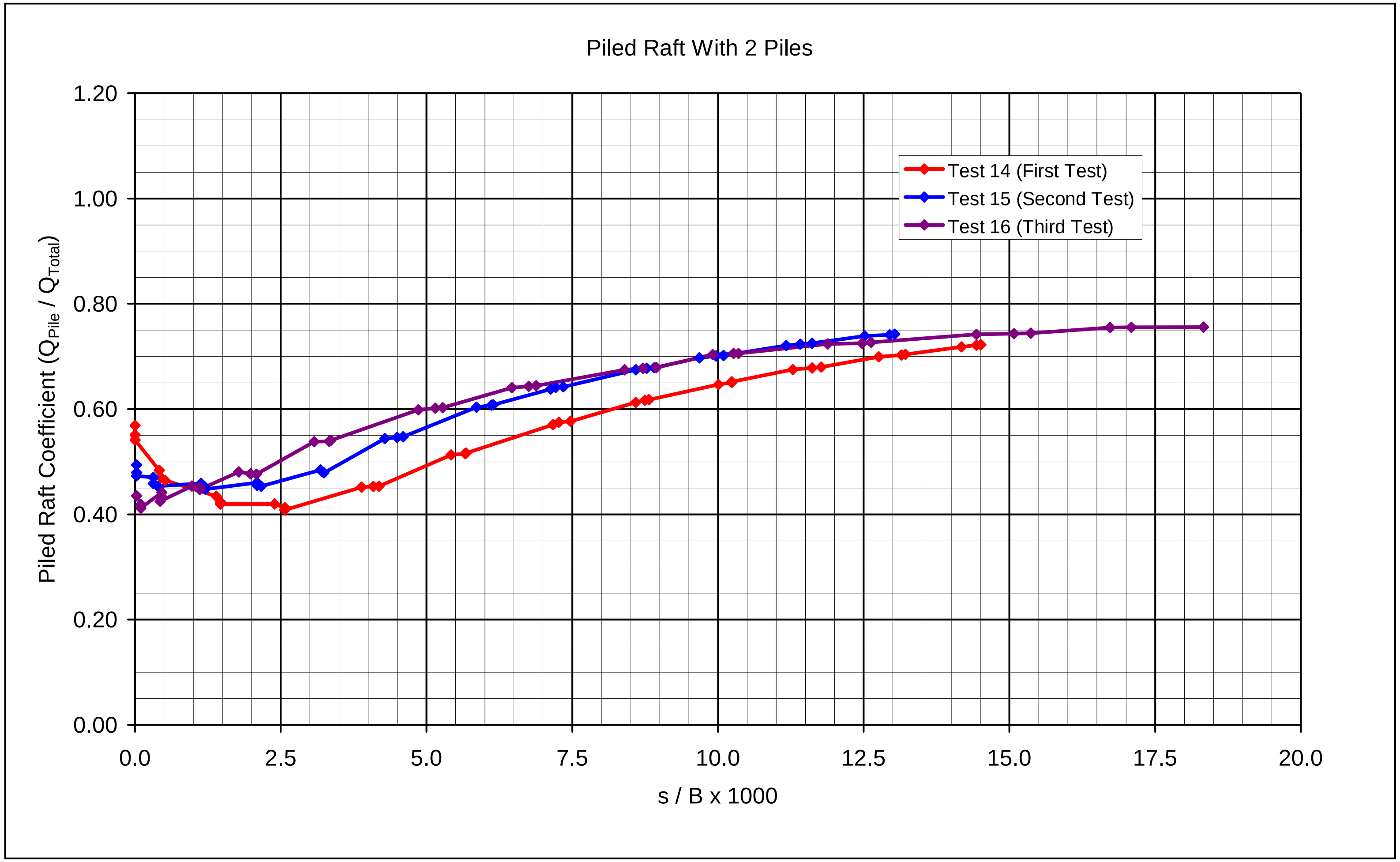

Figure 6.11 Raft load coefficient–settlement relationship of piled raft with 2 piles

6.5 Settlement Behavior of Piled Raft Foundations

Figure 6.12 shows the load-settlement behavior of different piled raft configurations and plain raft. As the number of piles increase load carrying capacity of the combined foundation improves. Increasing the number of piles reduces settlements which affect the load sharing mechanism of piled rafts. A raft with a small number of piles will settle more at the same load, but the design can be optimized controlling the settlements for serviceability and decreasing the number of piles using them with lower factors of safeties.

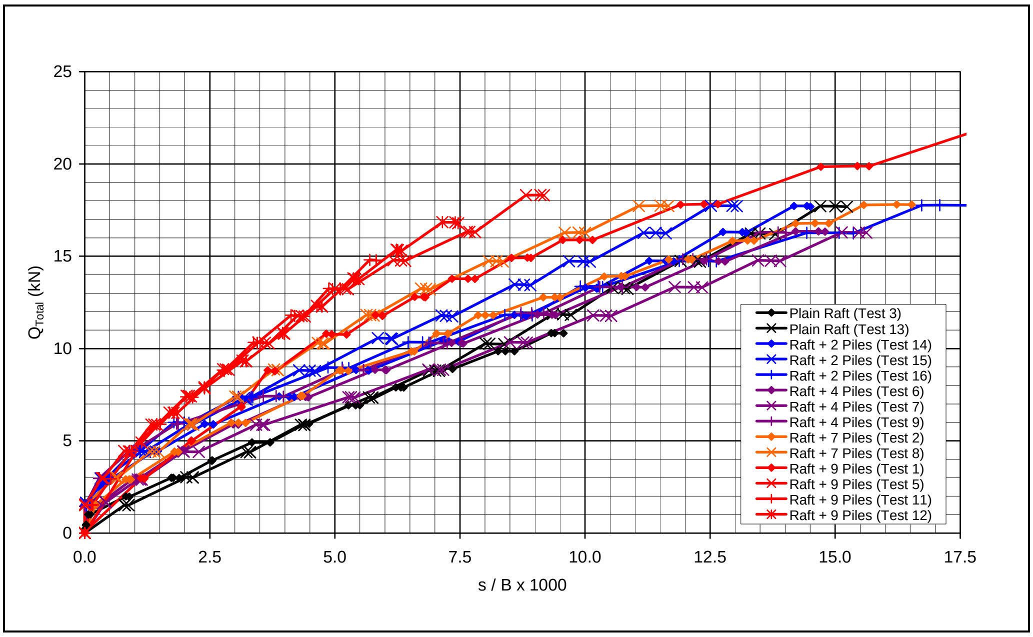

Figure 6.12 Load – settlement relationships of piled rafts and plain raft

6.6 Design and Safety Approaches of Piled Raft Foundations

In conventional design methods high safety factors are considered. This causes low settlements and accordingly low load sharing of the raft. As a result piled foundations are designed conservatively and not economically. In recent years, low factor of safety values are considered especially for foundations in which piles are used as settlement reducers. In this section test results will be used to clarify safety and design approaches of piled raft foundations.

Isolated single pile behavior under loads will be compared with the behavior of a pile as a part of the piled raft foundation, based on the measurements and observations of loading a sand-clay mixture by a model piled-raft foundation. The pile load-settlement behavior of single piled for different pile configurations is presented in Figures 6.13 – 6.17. If those figures are examined, it can be seen that load bearing capacity of a single pile is improved in the piled rafts with small number of piles. With the decreasing number of piles in the group, the piles are used up to a load level higher than ultimate load of the single isolated pile. This improvement may be due to the contact of raft to the ground. Raft transfers some of the applied loads by this contact and this contact increases the confining stress around the pile shaft. Also, pile efficiency is decreased due to interaction of piles in piled rafts with large number of piles. In Figure 6.17 effect of pile number to the load carried by piles is presented. With the increasing number of piles, the load carried by single piles decreases. In the piled rafts with 7 and 9 piles, load carried by a single pile is nearly half of the ultimate load capacity of the single isolated pile for low settlement levels. For the high settlements levels it is nearly equal to the ultimate load capacity of single isolated pile. For the small number of piles, the piles can be used up to a load level higher than the load capacity of a single isolated pile. This shows that additional improvement of pile capacity due to the contact of the raft is not observed if larger numbers of piles are used due to high safety factors (See Figure 6.13 vs. Figure 6.15).

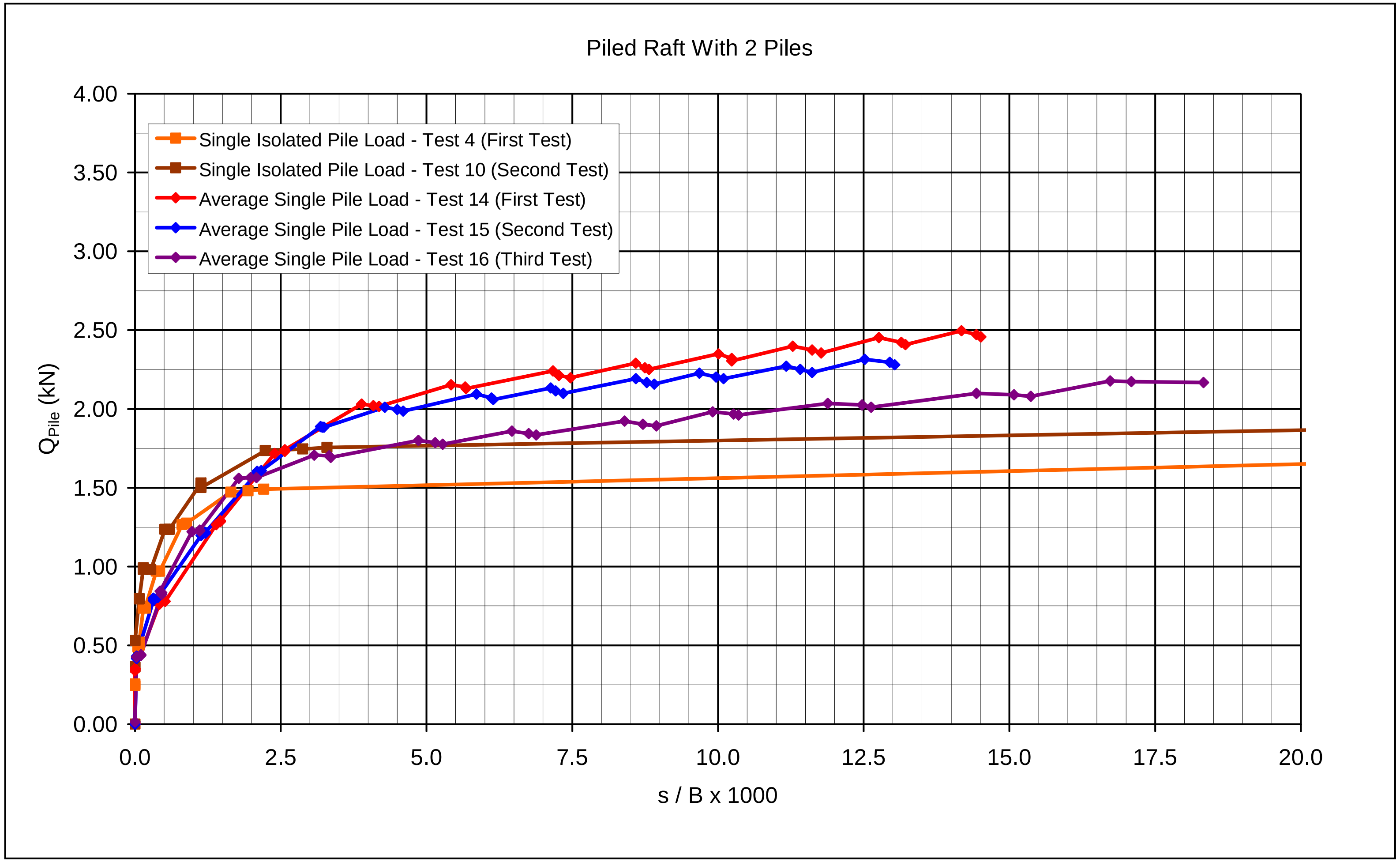

Figure 6.13 Load–settlement behavior of single pile in the piled raft with 2 piles

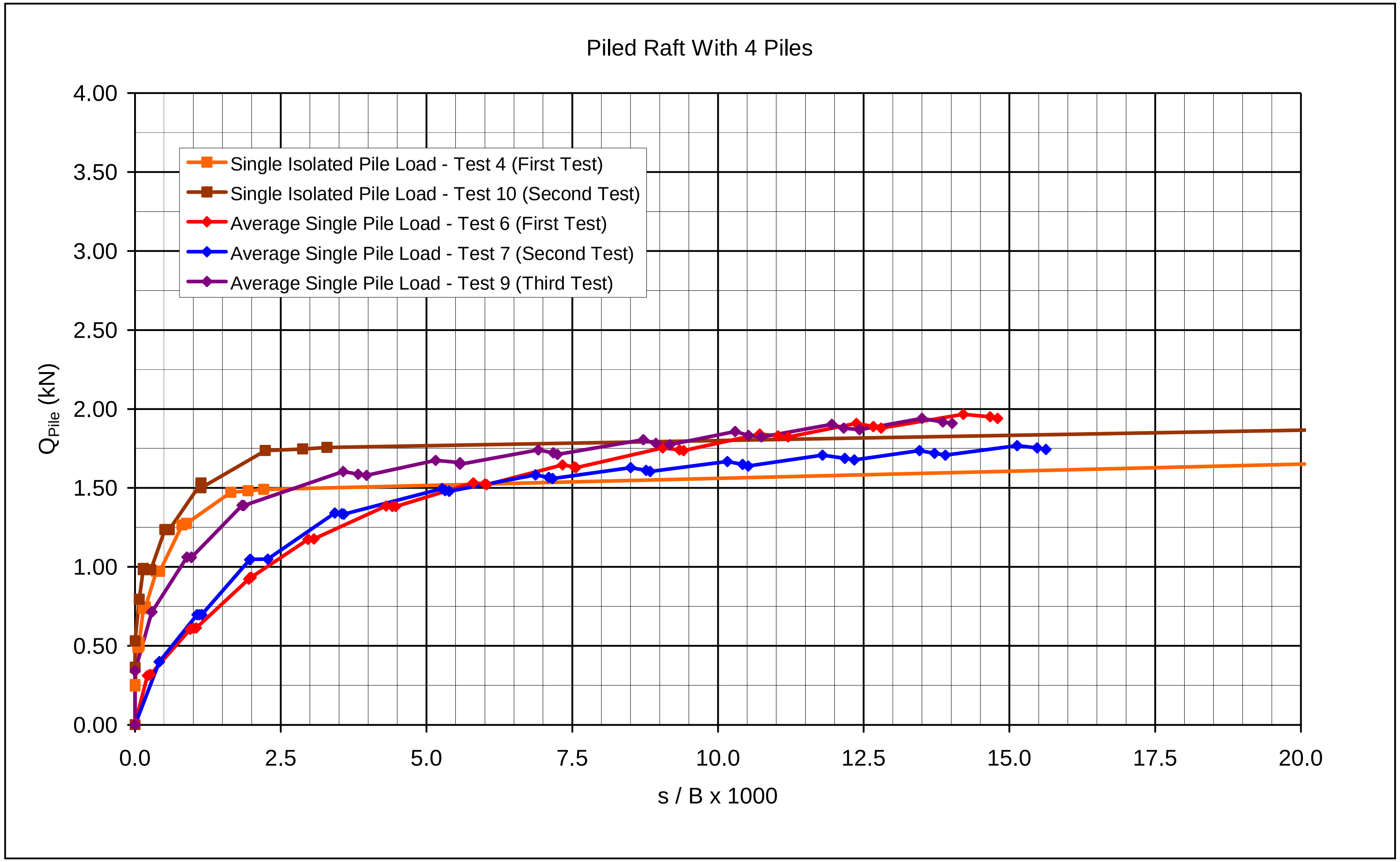

Figure 6.14 Load–settlement behavior of single pile in the piled raft with 4 piles

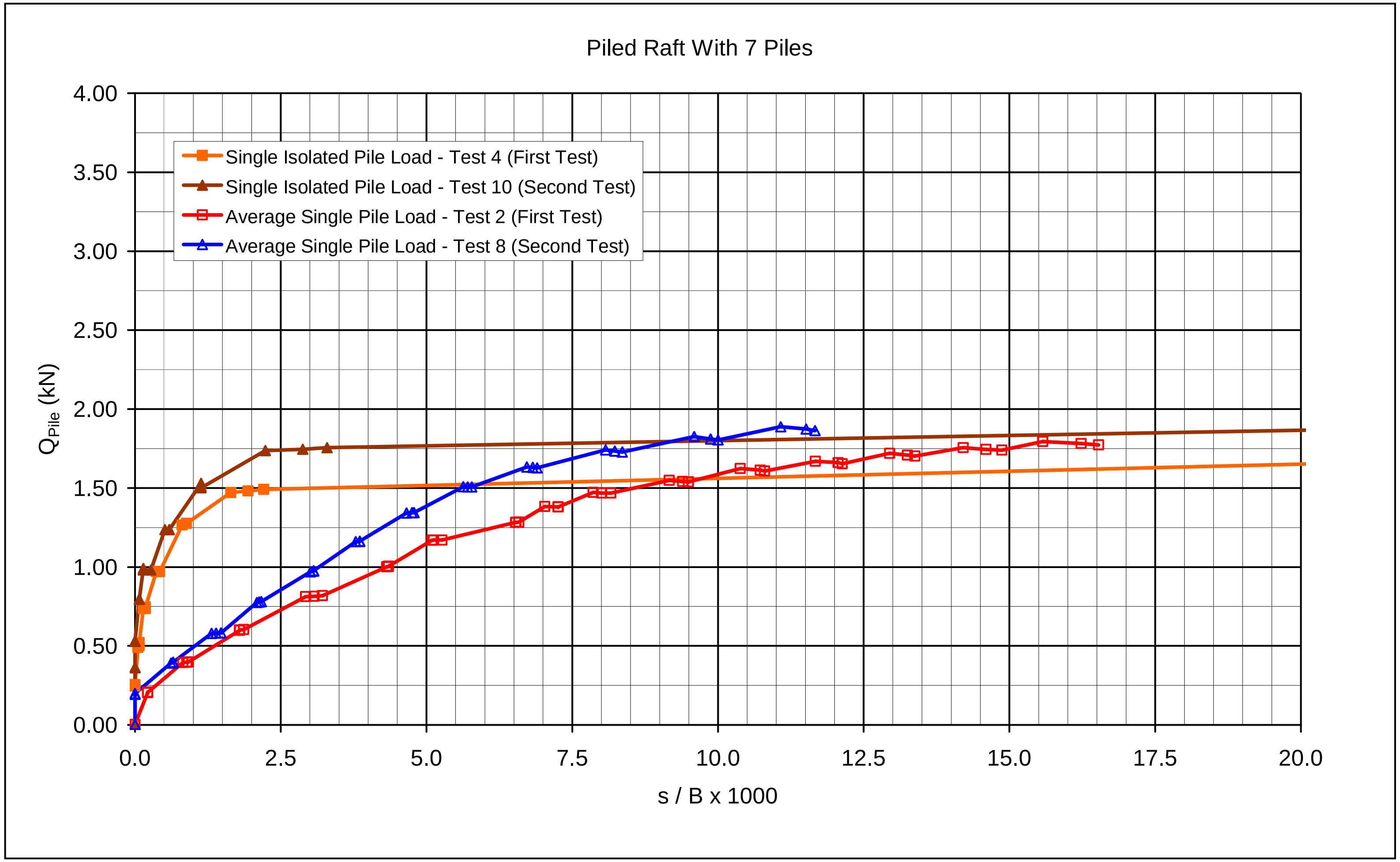

Figure 6.15 Load–settlement behavior of single pile in the piled raft with 7 piles

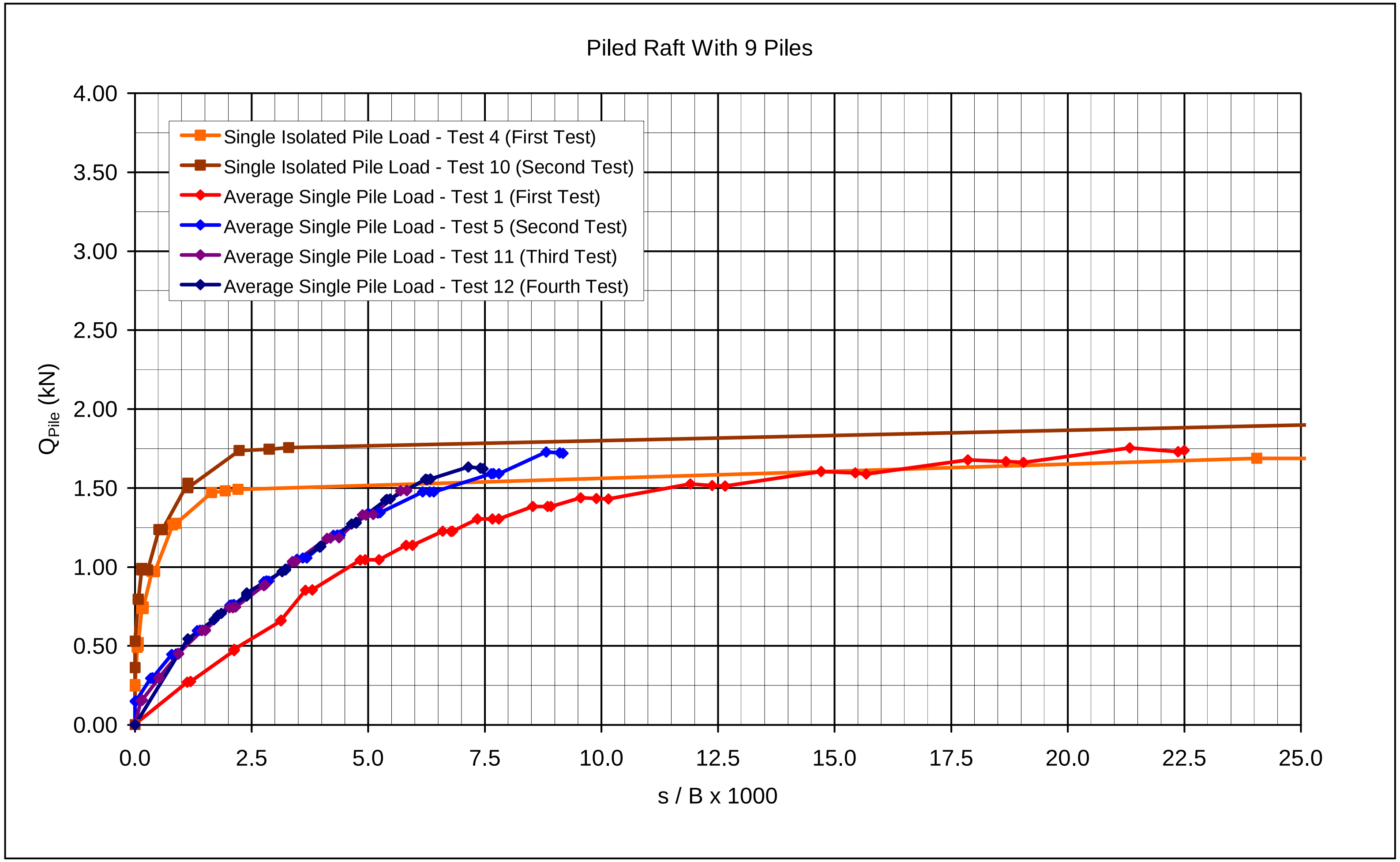

Figure 6.16 Load–settlement behavior of single pile in the piled raft with 9 piles

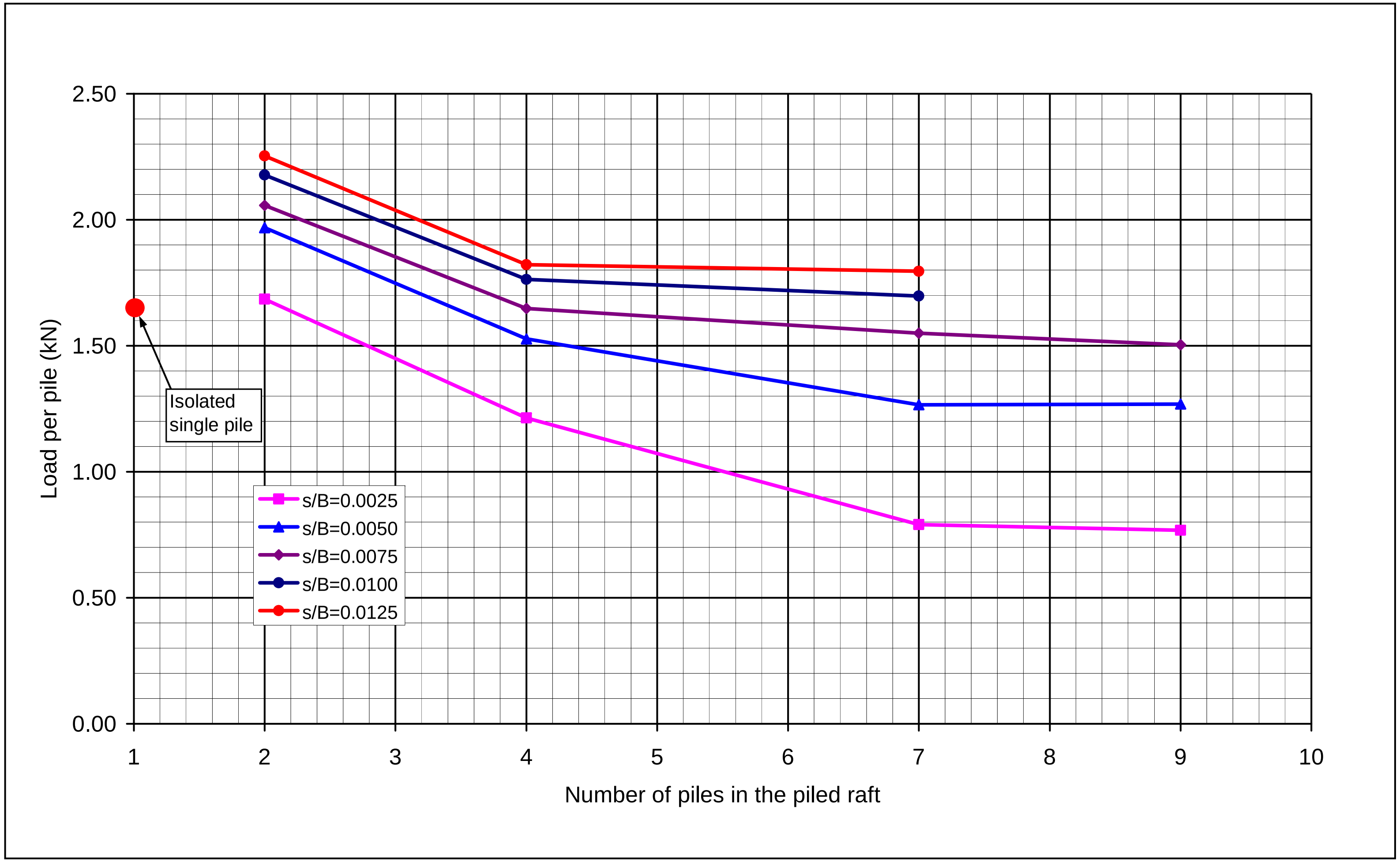

Figure 6.17 Effect of number of piles to the load carried by piles in piled rafts

The load transferred by raft with different pile configurations at different load levels is presented in Figure 6.18. With the increasing pile number, the contribution of the raft to the total load bearing capacity is decreased. This shows that the contribution of raft to the load bearing capacity can be increased by reducing the number of piles to a predetermined serviceability (settlement) limit. This behavior is also presented in Figure 6.19. With the increasing number of piles, raft load coefficient decreases which means that load carried by the raft decreases.

In order to optimize the design of a piled raft foundation, the most important parameter is the factor of safety limits of the piles. Because, factor of safety concept determines the number of piles and the number of piles play an important role in using the piles and the raft effectively. In order to optimize the design of a piled raft foundation, low factors of safeties should be used resulting in acceptable settlements.

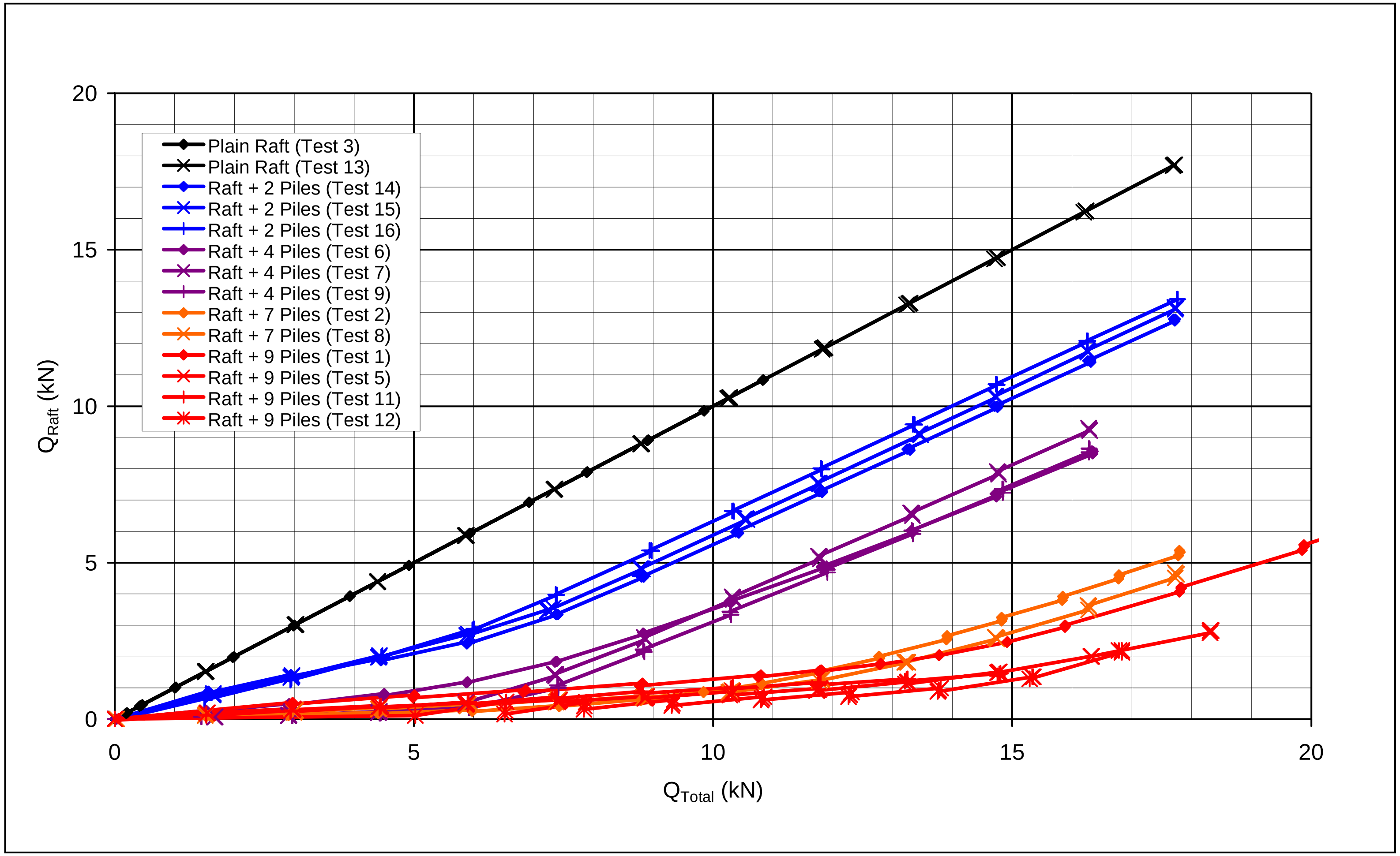

Figure 6.18 Load transferred by raft in different piled raft configurations

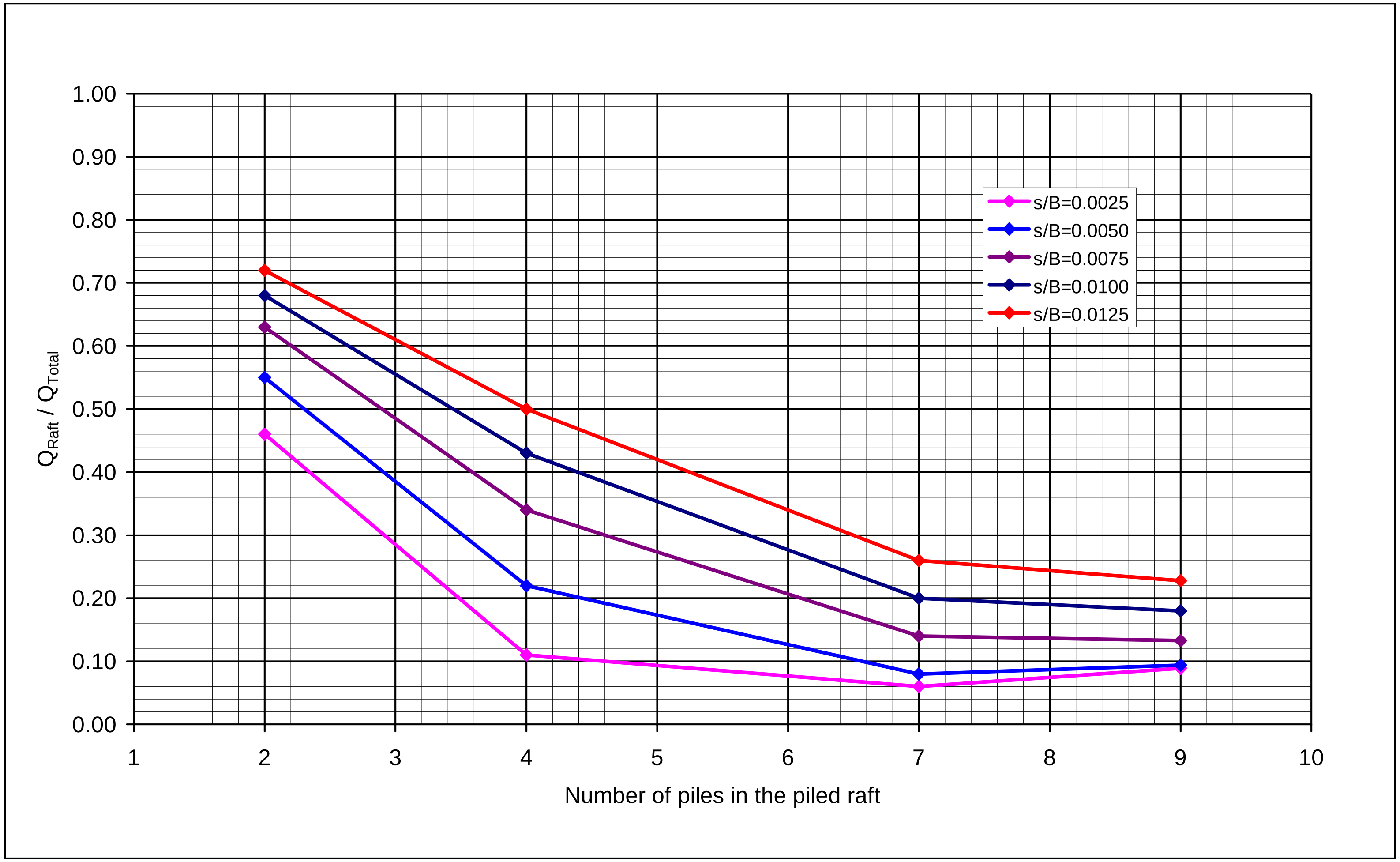

Figure 6.19 Effect of number of piles to the load carried by raft in piled rafts

CHAPTER 7

CONCLUSIONS

In this study, laboratory and field tests were performed and the load bearing behavior of piled raft foundations was investigated. Also, the piled raft foundation of a high-rise building was monitored. The conclusions drawn from this study are as follows:

1. When a piled raft is loaded gradually, piles take more load initially and after they reach their full capacity, additional loads are taken by raft.

2. Initial load sharing proportion depends on the number and capacity of piles.

3. For the piled raft foundation of the monitored building, raft load coefficient from 0.44 to 0.56 under the core and from 0.21 to 0.24 near the edge was found.

4. Observations of the field test as well as the building performance clearly show that raft may have a considerable contribution to the load bearing capacity of a piled raft in stiff clay and weathered graywacke formations respectively.

5. Raft load coefficient (Q_{Raft}/Q_{Total}) decreases with increasing number of piles. The decrease is more at smaller settlements. This decrease has a limiting value and even for an increased number of piles (9), load shared by the raft is between 6 % and 23 %, depending on the settlement level. For smaller number of piles, raft load coefficient is higher.

6. When the number of piles is increased, load per pile is decreased. The decrease is more pronounced at smaller settlements (s/B = 0.25 % and 0.50 %).

7. It was observed that, the behavior of a pile as a part of the piled raft is different from its behavior as a single pile. If the pile group is designed as a piled raft and the raft is in contact with the ground, a pile in that group carries a load which is higher than the ultimate load capacity of a single isolated pile. This improvement may be due to increase in the confining stresses by the contact pressure of the raft.

8. It was observed that position of the piles and the loads in the piled raft effected the raft load distribution in case of the tall building. The load was applied at the center and center piles carry more load than edge and corner piles in the model tests. Corner piles carry the least amount of load in the tests. These observations show that concentration of piles under heavily loaded areas may be good practice for an optimized design of a piled raft.

9. The bearing contribution of raft is not insignificant and negligence of it (which is the case until present) should not be practiced in piled raft foundation design.

Recommendations for future research:

- Similar efforts should be given on full scale structures through monitoring, i.e. measurement of pile loads, settlements and raft loads.

- Piled raft behavior under lateral loads should be investigated.

- Analytical and numerical studies for the calculation of piled raft settlement with differing number of piles (and in different patterns) should be made.

- It is understood that the optimized solution of a piled raft lies in the capability of matching the acceptable piled raft settlement (i.e. 50 to 100 mm) to the use of minimum number of piles under the raft. The criterion of pile safety should be reviewed compared to the conventional old practice where high safety factors are used in the design of piles which increase the number of piles. If piles are used with lower factors of safety values, rafts will share some of the total load and the design of the foundation system will be optimized. More effort should be given along these lines.

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