DISTRIBUTION OF BENDING MOMENTS IN LATERALLY LOADED PASSIVE PILE GROUPS A MODEL STUDY

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ABSTRACT

DISTRIBUTION OF BENDING MOMENTS
IN LATERALLY LOADED PASSIVE PILE GROUPS
A MODEL STUDY

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In this study, bending moment distributions developed in laterally loaded passive pile and passive pile groups in cohesionless soil were investigated in laboratory conditions through model pile experiments. Different from the active pile loading, the lateral load was given directly to the piles using a movable large direct shear box. In these experiments strain gauges fastened to the piles and a computer based data reading system were used. The strain values were measured at five levels on the piles. The behavior of a single pile and a pile group having five piles were investigated through strain measurements in order to observe bending moment distribution on the piles.

After evaluating the test results, the behavior of passive single pile was found to be similar to the results obtained in early studies. Negative bending moments were observed at the specified depths above the shear plane and positive bending moments were measured at the level of the shear plane and below the shear plane. Maximum bending moments were obtained at 0.7L (L: Length of Pile) for single piles and piles in the group. Above the shear plane, maximum bending moments within the pile group were found to be developed on the piles nearest to the loading. On the shear plane maximum bending moments were developed on the piles farthest from the loading just like active piles. Below the shear plane, maximum bending moments were developed mainly on the piles nearest to the loading.

Keywords: Soil Movement, Passive Piles, Bending Moment, Strain Gauge, Lateral Loading

ÖZ

YATAY YÜKLÜ PASİF KAZIK GRUPLARINDA
EĞİLME MOMENTLERİNİN DAĞILIMI
BİR MODEL ÇALIŞMASI

Öztürk, Şevki
Yüksek Lisans, İnşaat Mühendisliği Bölümü
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Bu çalışmada kohezyonsuz zeminlerde, yatay yüklü pasif kazık ve kazık gruplarında oluşan eğilme momentleri dağılımı laboratuar koşullarında yapılan model deneylerle araştırılmıştır. Aktif kazık yüklemelerinden farklı olarak, yatay yük hareket edebilen kesme kutusu kullanarak direk olarak kazıklara verilmiştir. Bu deneylerde, kazıklar üzerine yapıştırılmış gerinim pulları ve bilgisayar tabanlı okuma sistemi kullanılmıştır. Gerinim değerleri kazıklar üzerinde beş seviyede ölçülmüştür. Kazıklar üzerindeki eğilme momentleri dağılımını saptamak için, gerinim ölçümleri vasıtasıyla tek kazık ve beş kazık içeren kazık grubunun davranışı araştırılmıştır.

Deney sonuçları incelendiğinde, tekli pasif kazık davranışının daha önceki çalışmalarda elde edilen davranışlara benzediği görülmüştür. Kesme yüzeyinin üzerindeki belli derinliklerde negatif momentlerin, kesme yüzeyinde ve altındaki derinliklerde ise pozitif momentlerin oluştuğu saptanmıştır. Maksimum momentler tekli kazık ve kazık gruplarında 0.7L derinlikte elde edilmiştir. Kesme yüzeyinin üzerinde maksimum momentlerin grup içerisinde birinci sıra (yüke en yakın sıra) kazıklarda oluştuğu bulunmuştur. Kesme yüzeyinde aktif kazık yüklenmesinde

olduğu gibi maksimum momentlerin yüke en uzak kazıklarda oluştuğu gözlenmiştir. Kesme yüzeyinin altındaki derinliklerde maksimum momentler genellikle yüke en yakın sıra kazıklarda gözlenmiştir.

Anahtar Kelimeler: Zemin Hareketi, Pasif Kazıklar, Eğilme Momenti, Gerinim Pulu, Yanal Yükleme

To My Family

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D, d : Diameter of Pile
DR : Relative Density
DMT : Dilatometer Test
E : Elastic Modulus of Pile
E_s : Subgrade Reaction Modulus
GF : Gauge Factor
I : Moment of Inertia
Kp : Stiffness Matrix for Pile
Ks : Stiffness Matrix for Soil
L : Length (of Pile)
ΔL : Change in Length
M : Moment
n_h : Constant of Horizontal Subgrade Reaction
Q : Axial Load
P : Lateral Resistance of Soil per Unit Length
p_m : p-multiplier
p_{mga} : Adjustment Factor for Pre-Construction DMT Data
p_{mgb} : Adjustment Factor for Post-Construction DMT DAta
PMT : Pressuremeter Test
R : Strain Gauge Resistance
ΔR : Change in Strain Gauge Resistance
SPT : Standart Penetration Test
x : Depth along Pile
y : Lateral Deflection
y_o : Lateral Deflection of Soil due to Slope Instability in Passive Loading
y_p : Lateral Pile Deflection
V_o : Voltage Reading from Strain Gauge

V_i : Voltage Given to Strain Gauge

ε : Strain

ε_{max} : Maximum Strain

ϕ : Friction Angle of the Soil

$\phi(x)$: Curvature Profile

CHAPTER 1

INTRODUCTION

In geotechnical engineering, piles have a wide application area and are used in various projects. In most cases, the design loads are too large for a single pile to withstand. For these cases, several piles are used together and the piles are connected to each other with a pile cap forming pile groups in general.

One of the main functions of the piles is to resist lateral forces resulting from earthquakes, traffic loads, winds, waves, landslides etc. Movement of soil in the form of a landslide is a phenomenon that transfers lateral loads to the slope resisting structures. The piles that resist the lateral loads developed from a moving soil mass are commonly called passive piles (Nalçakan, 1999). Slope stabilization using passive piles is a widely utilized method in geotechnical engineering. Accurate estimation of the lateral resistance of piles in a group and the bending moments to be developed from the lateral loads are very critical for an economic and safe design.

Under lateral loads, the behavior of piles and the bending moments developed along piles are different in a pile group from that of an individual pile due to group effects. The interaction of the piles within a group results in the capacity reduction of piles in laterally loaded pile groups. The location of a pile in a group, spacing between piles and pile head conditions are some of the factors affecting that reduction. Depending on the locations of the piles in the group, resistances of the piles may differ significantly.

Bending moments developed as a result of lateral loading have a great importance for the design of the piles. The engineer should be able to estimate the moments that will develop in the pile, for proper design and for the serviceability of the pile after construction. As a result of group action, the bending moments developed along the piles in a pile group are different from each other and from the single piles.

Within the content of this study, bending moments developed along passive piles were investigated through model experiments in laboratory conditions. Single pile and a pile group containing five piles were laterally loaded with a moving soil mass in a shear box. Strain gauges were fastened on piles in order to measure the bending strains developed along the piles. Bending strains obtained were used to investigate the bending moment behavior of a single pile and piles in different positions of a pile group. The variation of bending moments from one position to another position within a pile group were investigated and bending moments developed along a pile group were compared with single pile.

Chapter 2 reviews the early studies about laterally loaded piles. The experimental study is summarized in Chapter 3. The results of the model tests and the discussion of test results are given in Chapter 4. Chapter 5 summarizes the results of the model experiments and Chapter 6 includes the conclusion.

CHAPTER 2

LITERATURE REVIEW

Pile groups subjected to lateral loads are widely used phenomenon in current practice. Past research that has been reported in the literature for laterally loaded pile groups can be divided into two categories as theoretical and experimental research.

Piles can be loaded laterally by active and passive loadings. Active piles are subjected to external lateral loads, especially from the pile cap. There are lots of experimental studies (model tests and full-scale field tests) and numerical studies about laterally loaded active piles in the literature. Since these types of problems have been widely studied, there are generally accepted methods for estimating the lateral behavior of active pile groups in the current practice.

Passive piles are subjected to lateral loads as a result of a moving soil. Existing studies on passive piles are mostly numerical and mainly involve single pile behavior. Although widely used, the lateral response of passive pile groups has not been studied in detail in the literature.

In this chapter, early studies about laterally loaded piles are summarized for both active and passive cases.

2.1. Lateral Behavior of Active Piles

When an active pile is laterally loaded, shear forces along the frontal area of the pile and compression forces behind the pile resisting the lateral forces are developed (Figure 2.1). Therefore, lateral capacity of a pile is composed of; shear forces developed between soil and pile, and stresses normal to the pile cross-section. The ultimate capacity of the pile is the summation of these load demands.

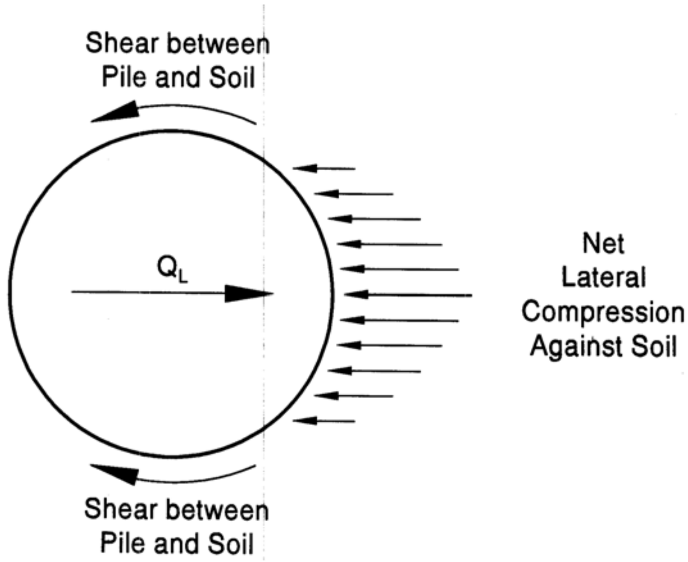

Figure 2.1 Laterally Loaded Pile Resistance, FHWA (1997)

The lateral capacity of an active pile mainly depends on soil properties, pile properties, soil-pile interaction mechanism and loading type. For a proper design, soil characteristics, especially stress-strain behavior of soil, pile characteristics such as bending of the pile, and the soil-pile interaction should be studied in details.

Different methods exist to estimate the capacity of laterally loaded active piles.

2.1.1 Theoretical Studies for Single Active Piles

2.1.1.1 Subgrade Reaction Methods

Modern researches for laterally loaded single piles started after beam-on-elastic foundation theory was published by Hetényi in 1946.

Hetényi (1946) assumed that the pile behaves as an elastic beam and represented soil with springs. Both the pile and the soil were assumed to stay in elastic limits. The equation for an elastic beam on an elastic foundation was given as;

$$\frac{d^2M}{dx^2} + Q\frac{d^2y}{dx^2} - p = 0 \qquad (2.1)$$

where M is the bending moment, x is the depth along the pile, y is the lateral deflection of pile at point x, Q is the axial load on the pile, p is the lateral resistance of soil per unit length of pile.

By assuming pile showing linear bending behavior, the related equation can be simplified as;

$$EI\frac{d^4y}{dx^4} + Q\frac{d^2y}{dx^2} - p = 0 \qquad (2.2)$$

where E is the elastic modulus of the pile and I is the moment of inertia of pile.

Subgrade reaction methods use Equation 2.2 to determine the pile behavior under lateral loads. Generally axial load on pile (Q) is ignored while solving the equation 2.2. In this method, it is assumed that "Euler-Bernoulli beam" is placed in an elastic soil that is represented with "a series of Winkler springs" (Salgado and Basu, 2001). The springs representing soil are assumed to show linearly elastic behavior with a stiffness of E_s, which was also named as subgrade reaction modulus.

For active piles, the lateral resistance of soil per unit length of the pile, p, is directly proportional with lateral deflection of the pile, y as given in Equation 2.3.

$$p = -E_s y \qquad (2.3)$$

The minus sign in Equation 2.3 indicates that soil resistance (p) is developed opposite to the deflection (y) direction.

Subgrade modulus is generally related to elastic soil properties. Poulos and Davis (1980), Valsangkar et al. (1973) are some examples of the studies relating subgrade modulus to the soil properties.

For active loadings of piles, solutions to subgrade reaction methods can be developed using different assumptions for subgrade reaction modulus. In the early models, E_s was assumed to be constant with depth such as in the case of Hétenyi (1946). After Terzaghi's work in 1955, linearly changing subgrade reaction modulus replaced the constant E_s for sands. Additionally, studies proposing higher degree functions in place of linearly changing E_s are available within the literature (i.e. Gill and Demars, 1970).

Matlock and Reese (1960) analytically described the pile response for different pile-head conditions based on the assumption of linear variation of E_s.

Poulos and Davis (1980) proposed tables and charts with constant E_s assumption and some coefficients with linearly changing E_s assumption for calculation of lateral response of piles.

Although subgrade reaction methods are widely used for laterally loaded piles, it has some shortcomings. It is a semi-empirical method, it ignores axial loads, uses discontinuous soil model and does not relate E_s with pile characteristics and deflection (Mokwa, 2002). Also in subgrade reaction method, soil is assumed to show linearly elastic behavior which does not reflect the reality.

Subgrade reaction models were then improved by including the nonlinear behavior of soil which also known as "p-y curve models".

2.1.1.2 p-y Curve Method

P-y curve method is the most widely used method for estimating the laterally loaded pile response in active loading conditions. This method was reported to be "moderately complex" and to give "reasonable results" by WSDOT, 1998.

In this method, the soil is represented by nonlinear springs and for each layer of the soil, p-y curves are developed where p is the lateral force per unit pile length and y is the pile deflection. The deflections, bending moments and lateral loads on the piles are then obtained by solving the beam equation.

There are different methods for developing p-y curves in the literature. Most accepted way for the determination of these curves is to use the instrumentation results of field tests or model tests.

The most common instrumentation is strain gauge instrumentation along the pile. The deflected shape, y, along the pile is obtained by integrating the curvature profile ($\phi(x)$) obtained from strain gauge records twice (Equation 2.4). Unit soil resistance, p, is given by the product of pile stiffness (EI) and the second derivative of the curvature obtained (Equation 2.5). For a given load, the measured response of the pile can be used to develop values of both p and y.

$$y(x) = \int\int \phi(x).dx.dx \qquad (2.4)$$

$$p(x) = EI\frac{d^2}{dx^2}\phi(x) \qquad (2.5)$$

Matlock (1970), Reese et al. (1975) and Reese and Welch (1975) are some of the well known studies that recommend p-y curves for clays, based on the results of field measurements.

For sand, Reese et al. (1974) developed p-y curves using the results of two field lateral load tests (Figure 2.2).

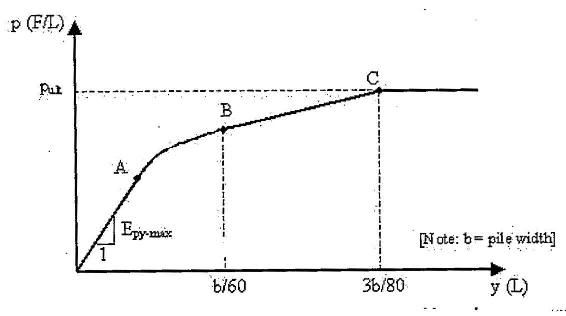

Figure 2.2 P-y Curve recommended by Reese et al. (1974)

The coordinates of point B can be obtained by using coefficients presented by the authors. The initial slope of the curve is related to relative density of the soil and is given in tabular forms. Reese et al. (1974) also recommended linearly increasing values with depth for initial slope of the curve.

Parker and Reese (1979) used hyperbolic tangent functions in order to develop p-y curves for sands. (WSDOT, 1998)

Scott (1980) performed centrifuge tests on model piles in sand to develop p-y curves. These curves were then reported to be valid for static loading cases by WSDOT (1998).

P-y curves can also be obtained from some field tests like pressuremeter test (PMT) and dilatometer test (DMT). Biraud (1986) proposed some methods to develop p-y curves from pressuremeter data. Robertson et al. (1984) also used pressuremeter data in order to develop p-y curves. Dilatometer test (DMT) methods for obtaining p-y curves were described by Robertson et al. (1989) and Gabr and Borden (1988).

Recently some computer programs using p-y curve method have been developed. The most widely used computer programs for laterally loaded single piles are COMP624 (Wang and Reese, 1993) and LPILE (Reese et al., 1997).

P-y curves are reported to have some limitations. The interaction between soil layers is not modeled with the method since the method uses independent p-y curves (Ashour and Norris, 2000). Also p-y curves assumed to be unique to a soil type are actually a function of soil properties and pile properties like pile bending stiffness, pile cross-sectional shape, pile-head fixity and pile head embedment (Ashour and Norris, 2000).

2.1.1.3 Elastic Continuum Methods

In elastic continuum methods, the soil is assumed to be isotropic, elastic, homogenous, and semi-infinite and the pile is assumed to behave like a thin strip having a finite length.

Poulos (1971) analyzed the laterally loaded active pile by using the theory of elasticity. In this method, soil displacement is evaluated from integration of Mindlin (1951) equation giving horizontal displacement caused by horizontal load over a rectangular area within semi-infinite mass. Pile displacement is found from bending equation of a thin strip.

2.1.1.4. Finite Element Methods

Finite element methods are numerical methods based on elastic continuum theory. In finite element methods, the structural system is modeled by a set of finite elements interconnected at points called nodes. The soil is considered as three-dimensional and quasi-elastic continuum (Mokwa, 2002). Complicated loading conditions can be analyzed and nonlinear behavior of soil and pile can be modeled by using this method (Mokwa, 2002). The method requires time and expertise and generally used for research purposes.

2.1.2 Theoretical Studies for Active Pile Groups

2.1.2.1 Elastic Continuum Methods

Elastic continuum methods can be used for group capacity calculations of laterally loaded active piles.

Banarjee and Davies (1977) used boundary element method in order to calculate the lateral capacity of active pile groups. In place of Mindlin (1951) equation, numerical techniques provided by boundary element methods were used.

Poulos and Davis (1980) used elastic continuum methods for single piles together with some interaction factors.

2.1.2.2 Hybrid Methods

Hybrid methods are combination of p-y curve method and elastic continuum method. For pile-soil interaction and in order to model the soil deflection around piles, p-y curves are used. For pile-soil-pile interaction elasticity methods are used.

Focht and Koch (1973) summed up the contribution of the other piles within a group to determine y-multipliers (WSDOT, 1998). Together with y-multipliers, some elasticity based factors were also used in the analysis.

O'Neill et al. (1979) studied three-dimensional pile group response to lateral, vertical, overturning and torsional loadings (WSDOT, 1998). Pile-soil-pile interaction is modeled by using Mindlin (1951) solution and expressed in terms of additional elastic pile displacements due to surrounding piles (WSDOT, 1998). This method was then reported to best represent average group response at low levels of deflection by O'Neill and Dunnavant (1985). (WSDOT, 1998)

2.1.2.3 Modified p-y Curve Methods

In this method, single pile p-y curves are modified to obtain average group curves in order to estimate the lateral response of the pile group.

Bogard and Matlock (1983) used a group efficiency factor to simulate the lateral capacity softening in pile groups (Mokwa, 2002). The pile group was represented with an imaginary pile and p-y curves obtained for a single pile were modified to represent the pile group.

2.1.2.4 Finite Element Methods

For active pile groups, finite element methods have started to be used widely with the developments of computer technology.

GPILE-3D (Kimura et al., 1995) is one of finite element computer programs used for pile groups. In this program, piles are represented by beam and column elements (Mokwa, 2002).

FLPIER (Hoit et al., 1996) is another computer program used for lateral capacity estimation of pile groups. Piles are modeled with 3-D nonlinear discrete elements. For pile cap nine-node shell elements are used. The nonlinear behavior of soil is represented with p-y curves and the soil-pile interface is modeled by interface elements.

2.1.3 Experimental Studies for Active Pile Groups

As discussed in the section 2.1.1, the most widely used method in order to estimate the lateral response of single active piles is the p-y curve method. For the pile groups, general method for lateral capacity estimation is using p-y curves of single piles with some modifications in order to represent group action effect. This concept is called “p-multiplier concept”.

The illustration of the p-multiplier concept is given in Figure 2.3. The concept is based on obtaining p-y curves for piles in a row of a pile group by inserting p-multipliers to p-y curves of single piles.

P-multipliers are generally obtained from experimental studies like full-scale field tests and centrifuge tests. Some of the most important experiments and their results are summarized in the following parts of this section.

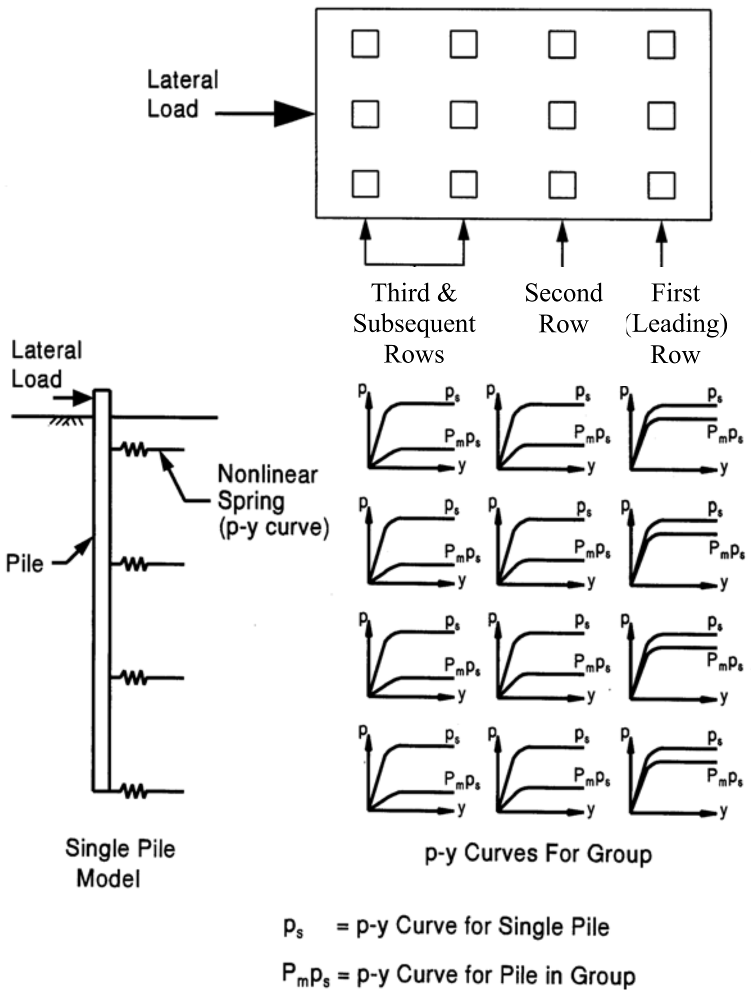

Figure 2.3 P-multiplier Concept for Active Pile Groups, FHWA (1997)

Brown et al (1987) studied pile-soil-pile interaction of pile groups in clay. The p-multipliers were reported to be as 0.7, 0.5 and 0.4 for the lead, second and third row of laterally loaded pile group in stiff clay.

Brown et al. (1988) proposed a p-multiplier, P_m, for using together with p-y curve of an individual pile in order to obtain p-y curves for piles at different locations within the pile group. A 3x3 pile group with 3D (3-pile diameter) spacing was monitored in clean medium sand.

The results of Brown et al. (1988) indicated that the leading row piles carry large loads compared to middle and trailing rows. Leading row was defined as the row not having pile rows in front of it. In other words, it is the row being ahead of the other piles and being far away from the loading. Trailing row was defined as the row nearest to the loading.

The p-multipliers were reported to be 0.8 for leading row piles by the authors. For both the middle row piles and trailing row piles the multipliers were found to be 0.4.

The group efficiency was reported to be 0.75 for the pile group by the author.

Brown and Bollman (1993) proposed a procedure for the design of laterally loaded pile groups with p-multiplier approach. In this method p-y curves for a single pile was developed by using the instrumented lateral load test at the site, the published p-y curves with correlations or in-situ test data such as pressuremeter tests. The authors recommended using multipliers of 0.8, 0.4 and 0.4 in the COM624P program for the case of pile groups consisted of 3 rows with 3D spacing. Lateral load capacities of the piles and the moments on the piles were suggested to be found from COM624P program.

Mc Vay et al. (1995) reported the results of centrifuge test on 3x3 pile groups in medium loose and medium dense sand at 3D and 5D pile spacing. Lateral group efficiencies and efficiency factors for three-row groups were studied for different spacing and soil densities.

15m-long, 0.33m diameter piles were modeled by 0.33m long and 13.5 mm diameter piles that meant to use 1/45 scale. The model tests were performed in loose and dense sands having 33% and 55% relative densities respectively.

Single pile centrifuge tests were performed and measurements were compared with the predictions of COM624P program. The comparison showed a good agreement.

Pile group tests at 3D spacing in medium dense sand indicated that leading row carried maximum of total load. 41%, 32% and 21% of total load was carried by leading row, middle row and trailing row, respectively. For p-y multipliers, COM624P program was run and they were found to be 0.8, 0.45 and 0.3 for leading row, middle row and trailing row. The results were reported to be in a good agreement with the results of Brown et al. (1988) for dense sand. From pile group tests at 3D spacing in medium loose dense sand, p-y multipliers were found to be 0.65 for leading row, 0.45 for middle row and 0.35 for trailing row. For 3-diameter spaced three row groups, the efficiency (group resistance at a given displacement) was reported to be constant and independent from soil density having a value of 0.75.

From pile group tests at 5D spacing in medium dense sand, row contributions were reported to be 36%, 33% and 31% which lead to p-multipliers computed from COM624P to be 1.0, 0.85 and 0.7 for leading, middle and trailing rows. Tests in loose sand were resulted in row contributions of 35%, 33% and 31%. The authors concluded that for 5-diameter spaced pile groups the multipliers were independent of soil density. Just like 3D spaced groups, the efficiency (group resistance at a given displacement) was reported to be constant and independent from soil density with a value of 0.93.

Ruesta and Townsend (1997) investigated the pile group behavior by large-scale lateral testing of 16 (4x4) free-headed prestressed concrete piles with a spacing of 3D in cohesionless soil.

Load-deflection (p-y) curves of a single pile obtained from strain gauge readings were compared with the p-y curves derived from in-situ tests like DMT, PMT, SPT and CPT. Analysis results show that the dilatometer test (DMT) methods for obtaining p-y curves (Robertson et al., 1989 and Gabr and Borden, 1988) are appropriate to use for small deformations whereas; pressuremeter test (PMT) methods for obtaining p-y curves (Robertson et al., 1984) are appropriate to use for large deformations. The tests results were also compared to the findings of Reese et al. (1974) and O'Neill (1983) and they were proved to be in a good agreement if the correct parameters were used. The SPT p-y curve related with the procedure of Reese et al. (1974) was also found to be a good approximation.

Ruesta and Townsend (1997) compared the measured load-deflection curve of a single pile with the measured curves of the piles in each row within the pile group. The load deflection curves for each row in a pile group were reported to be similar to the load deflection curve of a single pile. The authors concluded that p-y multipliers applied to single pile could be used for predicting the pile group behavior. In this study, p-y multipliers for leading, middle leading, middle trailing and trailing rows were found to be 0.8, 0.7, 0.3 and 0.3 respectively. These p-y multipliers were reported to agree with the centrifuge results of Mc Vay et al. (1995, 1996) and full-scale load testing results of Brown et al. (1988). The average pile group response was concluded to be softer than the single pile response. The group efficiency was reported to be 0.80.

The maximum bending moments were found to be higher for leading rows as compared to trailing rows, all within 15% range of each other.

Moss (1997) reported the results of a cyclically laterally loaded scale model pile group in medium clay. P-multipliers for different rows in a pile group were reported to be 0.60, 0.45 and 0.40.

Mc Vay et al. (1998) studied lateral pile groups (3x3 to 7x3) in which piles were spaced at 3D by centrifuge tests in loose and dense sand.

Test equipment consisted of geotechnical centrifuge allowing a payload of 12.5g-t with an arm radius of 1.610m, aluminum sample container having dimensions of 0.254m in length, 0.254 m in width and 0.305 m in length, hydraulic pile group installation apparatus capable of installing up to 21 piles and overcoming 45 times gravitational field.

Model piles were constructed from aluminum having a width of 9.525mm and 304.8 mm in length which were at 1/45 scale. The piles were connected to a pile cap ensuring fixed-head condition.

Miniature load cells for lateral load measurements, strain gauges for bending moment measurements, spring loaded linear variable differential transformer for lateral displacement measurements were used for instrumentation purposes.

In that study, two different sands were used being dense sand having 55% relative density and loose sand having 36 % relative density.

The test results indicated that with addition of a pile row, larger resistance was observed. These resistances were found to be significant for small pile groups. The lateral resistance of middle pile was observed to be smaller than the resistance of side piles within a pile row because of shadowing effect being greater for middle piles within a row.

The leading row was reported to develop the largest lateral resistance followed by second row. The third and fourth row piles were found to carry approximately same loads. For piles groups having larger than four rows, the third rows developed nearly same shear forces being smaller than the second row and larger than subsequent rows. After the 4th row, the load capacities of pile rows were observed to be similar to the capacities of the 4th row with the exception of the trail row. The trailing row had a slightly greater capacity than the row in front of itself.

The percentages of the load carried by a given row were found to be very close for dense and loose sands. Mc Vay et al. (1998) then concluded that p-multipliers are independent of soil density and are a function of pile group geometry such as spacing and row position.

P-multipliers for 3x3 pile group were reported to be 0.8, 0.4, and 0.3 as reported by Mc Vay et al. (1995). For pile groups having more than four rows, the p-multiplier was concluded to remain as 0.3 for trail row and 0.2 in between the fourth and trail row.

Rollins et al. (1998) performed a 9 pile group lateral tests in clayey silt. The p-multipliers were found to be 0.60, 0.40 and 0.40 for leading, middle and trailing rows respectively by the authors.

Huang et al. (2001) performed lateral load tests on a pile group having bored and driven precast concrete piles spaced at 3D in a site consisting of silty sand to silt. Single pile tests were also achieved for comparison purposes. In this study, cone penetration tests and dilatometer tests were carried out before and after the construction of piles to see the effects of installation. Lateral load tests were performed for pile groups consisted of 6 bored piles and 12 driven piles. Pile-cap was constructed for both driven and bored pile groups.

The authors devised a design procedure for p multiplier concept including installation effects as shown in Equation (2.6) where f_m is multipliers suggested by Reese and Wang (1996), p_{mga} is adjustment factor of pile groups for pre-construction DMT data and p_{ms} is adjustment factor of a single pile for pre-construction DMT data.

$$p_m = f_m \cdot p_{mga} / p_{ms} \qquad (2.6)$$

For single piles, LPILE (Reese and Wang, 1993) computer program was used for deflection and moment computations. P-y curves were developed by using DMT data according to Robertson et al. (1989) and compared with the measurements. The p-y curves developed from pre-construction DMT data did not agree with the measurements so the p-y curves were modified using adjustment factors. The adjustment factors of a single pile for pre-construction DMT data (p_{ms}) were found to be 0.50 for bored piles, 0.21 for driven piles.

For pile groups, GROUP (Reese and Wang, 1996) computer program was used. For p-y curves of a group; p-y curves of a single pile were used with multipliers described by Reese and Wang (1996) being 0.932, 0.704, 0.740 for leading row, middle row and trailing row of bored piles and 0.893, 0.614, 0.614 and 0.660 for leading row, middle leading row, middle trailing row and trailing row of driven piles. Huang (2001) concluded that additional adjustment factors were needed in order to construct p-y curves with pre-construction and post-construction DMT data. For bored pile groups, adjustment factor for pre-construction data (p_{mga}) was found to be 0.47 and adjustment factor for post-construction data (p_{mgb}) was found to be 0.56. For driven pile groups, these factors were reported as 0.37 and 0.26. The findings of the study pointed out that the soil "softens" for the bored pile case and "hardens" for the driven pile case.

Ng et al. (2001) performed lateral load tests on a single bored pile and three pile groups with concrete caps consisting of two bored piles in a row with 6D spacing (P26D), two bored piles in a row with 3D spacing (P23D) and three bored piles in a row with 3D spacing (P33D). FLPIER (Hoit et al., 1996) was used for modeling the nonlinear response of soil and bored pile.

By investigating load-deflection curves, in P26D group, leading and trailing piles were reported to behave similarly indicating no group effect for this group. For P23D pile group, leading piles were reported to deflect more than trailing piles under high loads. This behavior was reported to be caused due to cracks developed on pile cap near the location of leading pile which resulted in decrease in bending moment capacity and effective thickness of pile cap.

For ultimate lateral load capacity, hyperbolic curves of Kulhawy and Chen (1995) and ultimate lateral load capacity of a single flexible fixed-head pile derived from Broms (1964) together with group efficiency factors from Tamaki et al. (1971) and Levacher (1992) were compared with the measurements. Group efficiency factors were chosen to be 1.0, 0.75 and 0.70 for P26D, P33D and P23D respectively. Hyperbolic curves of Kulhawy and Chen (1995) were reported to be in good agreement with the measurements. For free head piles (P1 and P23D) Brom's theory was found to be fairly conservative being 35% smaller than hyperbolic curves. Brom's theory was also reported to predict ultimate lateral load capacities when pile cap was strong and stiff enough to provide full restraint to the pile head.

FLPIER (Hoit et al., 1996) program was also used for comparison purposes. Ng et al. (2001) developed p-y curves according to the procedures described by Reese et al. (1974). As described by McVay et al. (1998), p-multipliers were chosen to be 0.8 for leading row and 0.4 for trailing piles of P23D and P33D pile groups. Two types of analyses were carried out which differed in subgrade reaction modulus (n_h) and friction angle (ϕ) selection during p-y curve development. For the first analysis, n_h and ϕ were derived from SPT N values through empirical correlation. For n_h; upper bound values described by Elson (1984) and lower bound values described by Terzaghi (1955) were used. The second analysis was based on correlations obtained from back-analysis of single pile load test. n_h derived from Terzaghi (1955) was reported to have overestimated results whereas n_h derived from Elson (1984) agreed well for low loads. At high loads, two of the methods were reported to underestimate results due to pile cap effectiveness reducing at high depths.

Anderson et al. (2003) studied 7 case histories including lateral load tests on piles and drilled shafts. P-y curves derived from DMT, PMT and computer programs such as COM624P, LPILE, and FLPIER using SPT and CPT for input parameters were compared with the case histories.

P-y curves were developed by using computer programs including SPT and CPT correlations for input parameters. P-y curves were also developed from DMT data and PMT data. For DMT data, p-y curves were developed by using the procedure described by Robertson et al. (1989) together with data reduction procedures described by Schmertmann (1982) and Marchetti (1980). For PMT data, p-y curves were developed by using the procedure described by Robertson et al. (1985).

The p-y curves developed were compared with the measurements and SPT based predictions were found to be conservative where CPT predictions were reported to predict best field behavior. P-y curves developed from DMT data were concluded to predict well at low loads whereas p-y curves developed from PMT data predicted well for both sands and clays where pore pressure were not anticipated.

Rollins et al. (2005) performed lateral load tests for 3x3 pile group spaced with 3.3D in dense sand. The piles were 0.324m O.D. steel pipes.

For single pile, LPILE (Reese et al., 1997) and SWM (Ashour et al., 2002) computer programs were used for lateral soil response. Some soil parameters had to be entered into the program such as friction angle, effective unit weight for LPILE and friction angle, effective unit weight, lateral subgrade modulus and strain at %50 of failure load for SWM. Analysis results showed that using API (American Petroleum Institute) friction angles were resulted in higher LPILE and SWM displacement results than measured values. Bending moments were also found to be 20%-30% higher. Using Bolton (1986) correlations between friction angle and relative density, two computer programs were reported to give good estimates of the load-deflection curves, depth of maximum moment and the shape of bending moment versus depth curves.

Measured load-displacement curves of lateral loads applied to pile group indicated that leading row carried more load than middle and trailing row piles. Back row piles within a pile group were reported to carry more load than middle rows that was consistent with Mc Vay (1998).

The observed maximum moment depths were greater for trailing rows as a result of group effect softening the soil around these rows. For a given deflection, maximum moment was observed in the leading row. For a given load, maximum moment was developed in the trailing rows since the soil around the piles softens due to group effect.

Load-displacement curves obtained from GROUP (Reese, 1998) computer program with p-multipliers of 0.8, 0.4 and 0.4 for leading row, middle row and trailing row respectively, agreed well with the measured curves. Rollins et al. (2005) also reported the results of GROUP program to be in a good agreement with the other full-scale lateral load tests (Ruesta and Townsend, 1997; Brown et al., 1998) and centrifuge tests (Kothaus, 1992; Mc Vay et al., 1995 and Mc Vay et al., 1998).

Spacing effect on p-multipliers was also investigated using full-scale lateral load tests and centrifuge tests. AASHTO (2000) curves and GROUP program curves were compared with test results. For small deflections; GROUP curves were observed to be higher than the test results which lead to non-conservative estimates. Results also indicated that the AASHTO curves underestimate the p-multipliers for first, second and third row piles. Based on test data, the correlation between p-multipliers and spacing was obtained. According to this correlation, p multipliers would be 1.0 for 5D spacing for 1^{st} row, 6D for 2^{nd} and 3^{rd} rows and 8D for 4^{th} and 5^{th} rows.

SWM results were also reported to be in a good agreement with measurements without a need of p-multipliers.

Rollins et al. (2006) discussed the pile spacing effects and group interaction effects for laterally loaded pile groups in stiff clay by performing full-scale lateral load tests. The load tests were performed for 3x3 pile group with 3D spacing, 3x4 pile group with 4,4D spacing and 3x5 pile group with 5,65D spacing. The loads were applied to a load frame that was connected to the 324mm O.D. steel piles by a tied rod with pinned connection to have a fixed-head condition. For comparison, same load tests were performed for a single pile.

It was reported that as the spacing decreased, group interaction became more important. Compared to a single pile, the lateral load resistance of piles in a group with large spacing did not differ that much.

The first row (leading) piles in the group were found as carrying the greatest load. The second and third row (trailing) reported to carry smaller loads whereas fourth and fifth rows if present carried same load as third row piles. The load on back row was observed to be slightly higher than the load on the preceding row.

For a given load, maximum bending moments were found to be relatively close to that of a single pile at largest spacing. For closer spacing, the maximum bending moments of leading rows were close to a single pile whereas the trailing rows developed higher bending moments for a given load due to group interaction effect softening the soil resistance.

In case of large spacing, the maximum bending moments were found to be quite close to each other and to the single pile for a given deflection. For closer spacing, the maximum bending moments in the trailing rows were found to be smaller than the ones in the leading row but the difference was small due to smaller loads and higher moments developed for a given load in trailing rows compared to leading row.

The elastic theory predicting the edge piles carry more loads than the others did not come true for piles in a group. The authors concluded that lateral resistance was a function of row location within the group rather than location in a row.

Table 2.1 below summarizes the results of the experimental studies for active pile groups related to p-multiplier concept.

Table 2.1 Summary of Experimental Studies Related with P-multiplier Concept for Active Pile Groups, FHWA (1997)

Experimental Study	Soil Type	Experiment Type	Pile Group	Spacing of Piles	P-multipliers for rows 1, 2,3 +							Group Efficiency
Brown et al (1988)	Clean Medium Sand	Field Tests	3x3	3D	0.80	0.40	0.30					0.75
Mc Vay et al. (1995)	Medium Loose Sand	Centrifuge Tests	3x3	3D	0.65	0.45	0.35					0.73
Mc Vay et al. (1995)	Medium Dense Sand	Centrifuge Tests	3x3	3D	1.00	0.85	0.70					0.74
Mc Vay et al. (1995)	Medium Loose Sand	Centrifuge Tests	3x3	5D	0.80	0.45	0.30					0.92
Mc Vay et al. (1995)	Medium Dense Sand	Centrifuge Tests	3x3	5D	1.00	0.85	0.70					0.95
Ruesta and Townsend (1997)	Loose Fine Sand	Field Tests	4x4	3D	0.80	0.70	0.30	0.30				0.80
Mc. Vay et al. (1998)	Medium Dense Sand	Centrifuge Tests	3x3	3D	0.80	0.40	0.30					---
Mc. Vay et al. (1998)	Medium Dense Sand	Centrifuge Tests	4x3	3D	0.80	0.40	0.20	0.30				---
Mc. Vay et al. (1998)	Medium Dense Sand	Centrifuge Tests	5x3	3D	0.80	0.40	0.20	0.20	0.30			---
Mc. Vay et al. (1998)	Medium Dense Sand	Centrifuge Tests	6x3	3D	0.80	0.40	0.20	0.20	0.20	0.30		---
Mc. Vay et al. (1998)	Medium Dense Sand	Centrifuge Tests	7x3	3D	0.80	0.40	0.20	0.20	0.20	0.20	0.30	---
Brown et al (1987)	Stiff Clay	Field Tests	3x3	3D	0.70	0.50	0.40					---
Moss (1997)	Medium Clay	Model Tests	3x3	3D	0.60	0.45	0.40					---
Rollins et al (1998)	Clayey Silt	Field Tests	3x3	3D	0.60	0.45	0.40					---

2.2. Lateral Behavior of Passive Piles

Passive piles are loaded laterally with the movements of soil surrounding the piles. The loading conditions are not same for active and passive piles. In active loadings, the piles are laterally loaded with a point load especially from the pile cap. The piles are pushed with the lateral loads and the soil in front of the piles is squeezed whereas there becomes a relaxation for the soil behind the piles. In passive loading cases, soil in front of the piles and behind the piles is laterally packed with different mechanisms.

In the literature there are some studies for passive piles. The studies mentioned are commonly theoretical and group piles are not studied in detail. In the proceeding parts, a brief summary for laterally loaded passive pile studies are given.

2.2.1 Theoretical Studies for Passive Piles

2.2.1.1 Subgrade Reaction Methods

For passive piles, the method described in section 2.1.1.1 can be used with some modifications since the loading conditions are different from the active loading. Related equilibrium equation is;

$$EI\frac{d^4 y_p}{dx^4} = E_s(y_p - y_0) \tag{2.7}$$

where y_p is the lateral pile displacement at point x, y_0 is the lateral displacement of soil due to slope instability.

The solution of Equation 2.7 is difficult due to difficulties in determining y_0 values.

Fukuoka (1977) used subgrade reaction method for lateral response of passive piles. The deformations of the pile were measured and subgrade soil modulus was deduced from these measurements.

Viggiani (1981) summarized the failure modes of a passive pile using subgrade reaction theory. His method is applicable to the piles at failure since he used the ultimate capacity in his analysis.

Koirala and Tang (1988), Wang et al. (1986), Magueri and Motta (1992) are the examples for the theoretical studies based on subgrade reaction concept for passive piles.

2.2.1.2 Elastic Continuum Methods

For passive piles Poulos (1973) summarized calculations based on elastic continuum approach. Soil displacement was evaluated from integration of Mindlin (1951) equation giving horizontal displacement caused by horizontal load over a rectangular area within semi-infinite mass and pile displacement was found from bending equation of a thin strip.

2.2.1.3 Finite Element Methods

Rowe and Poulos (1973) used two-dimensional finite element model to discuss the method for passive piles.

Chen and Poulos (1993) analyzed the soil-pile interaction under lateral loading using finite and infinite element methods.

Kahyaoğlu et al. (2007) performed finite element analysis for a single passive pile in order to investigate the applicability of finite element models. They modeled the experimental setup of Poulos et al (1995) who investigated the lateral response of a passive pile in laboratory conditions. The authors concluded that the results of finite element method they used matched with the results of Poulos et al (1995).

2.2.2 Experimental Studies for Passive Piles

In the literature some experimental studies are reported for laterally loaded passive piles. The experiments are generally for a single pile.

De Beer and Wallays (1972) conducted full scale filed test in Belgium in order to investigate the embankment construction effects on piled foundations. Instrumentation was carried out for a steel pile and a concrete pile. Steel pile was 28 m in length and 0.9 m in diameter with 1.5 cm wall thickness. Reinforced concrete pile was 23.2 meter in length and 0.6 m in diameter. Soil movement, bending moments developed along the piles and pile deflections were presented for two cases.

Esu and D'Elia (1974) reported results of field tests carried out for concrete pile installed into sliding soil. Soil mainly consisted of clay and sliding part of it had a thickness of 7.5 m. The pile was 30 m in length and 0.79 m in diameter. Pressure cells were along the pile at depths of 5, 10 and 15 m below ground surface. An inclinometer was inserted into pile in order to measure pile deflections. The measurements were carried out for 8 months until a plastic hinge was observed at a depth of 11m.

Fukumoto (1975) used a rectangular iron box that can move laterally. Model rectangular piles were used in the experiments. He concluded that the shape of pile deflection changed with flexural rigidity of pile.

Fukuoka (1977) conducted simple lateral load test to a single passive pile. Lateral displacements were measured during the experiments.

Bosscher (1986) studied the soil arching in sandy soils with model experiments.

Carruba et al. (1989) gave results of a full scale test of a concrete pile used to stabilize a sliding slope in Sicily. The pile was 22 m long and 1.2 m in diameter. The sliding soil consisted of clay layer of 9.5 m thickness. Load cells and inclinometers were used for instrumentation purposes. The measurements were continued for 5 months until a capacity reduction was obtained due to plastic hinge formation at a depth of 12.5 m below the ground surface.

Kalteziotis et al. (1993) reported a case where two rows of piles were used to stabilize a slope on which a bridge had been built. The site was consisted of neogene lacustrine deposits. The sliding surface was reported to be 4 m from the ground surface. Concrete piles of 12 m length, 1 m diameter were placed with 2D spacing in order to stabilize the soil. Two of the piles were replaced with steel piles of having 1 m diameter, 18 mm wall thickness. Steel piles were instrumented with strain gauges and inclinometers. Bending moments and shear forces developed along piles and pile deflections were given based on these measurements.

Chen (1994) conducted model tests in calcareous soil and obtained some group factors for pile groups subjected to linear soil movements. These factors can be used for ultimate capacity calculation of pile groups using the single pile ultimate capacity values.

Poulos et al (1995) investigated the lateral response of a passive pile in laboratory conditions. They used a soil box having dimensions of 450 mm x 565 mm in cross section. The depth of the soil box was 700 mm. Calcareous sand having linearly increasing soil modulus with depth was placed into the soil box. A single steel pile having 25 mm outer diameter and 675 mm length was placed into the soil box. The upper part of the soil box could move in such a way that resulted linearly increasing soil movement profile. Strain gauges were used for instrumentation.

The authors moved the box and obtained bending moment distributions for various values of pile head deflections. It was concluded that bending moments increase continuously with increasing pile head deflections, and speed of increase start to decrease for the displacements greater than 50 mm. Bending moment distribution along the pile obtained in this study is given in Figure 2.4.

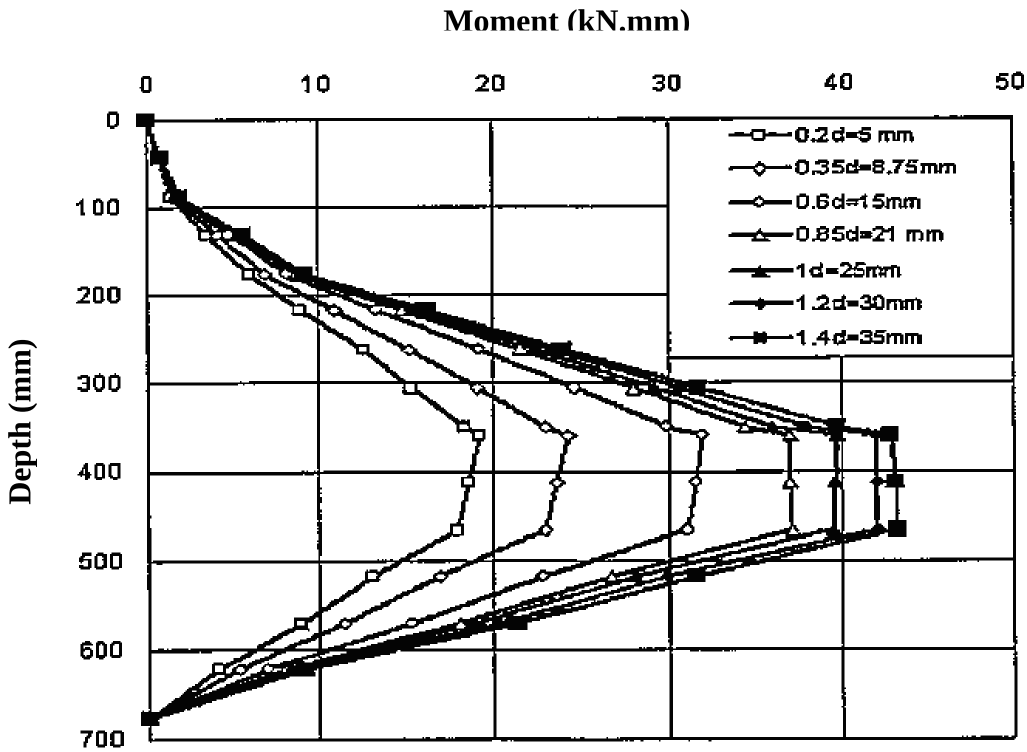

Figure 2.4 Bending Moments for Different Pile Head Displacements
Poulos et al. (1995)

2.2.3 Previous Research at M.E.T.U.

Dağistani (1992) studied lateral earth pressure distribution over a passive pile by conducting experiments in a large shear box. The shear box had dimensions of 30 cm x 30 cm in cross section and had 60 cm length. The upper part being 15 cm was movable that applied uniform lateral force to the pile inserted into the shear box. The shear box was filled with clay. Miniature stress cells were used in the soil to obtain the lateral earth pressure distribution on passive piles.

Kın (1993) studied effect of depth of penetration and soil properties on passive pile behavior using the same shear box that Dağistani (1992) used.

Nalçakan (1999) conducted experiments on model piles. Shear box same as Dagistani (1992) and Kın (1993) was used in the experiments. 10 mm model piles were inserted into clay. The results were given for two types of shear strength of soil. The group reduction for passive piles was investigated.

2.2.4 Other Studies for Passive Piles

Chow (1996) summarized a numerical method where the piles were modeled using beam finite elements and soil was modeled using a hybrid method of analysis based on subgrade reaction modulus for soil response and theory of elasticity for pile-soil-pile interaction. For a pile group system, the stiffness relationship was given as;

$$([K_p]+[K_s])\{y_p\}=[K_s]\{y_0\} \tag{2.8}$$

where K_p is stiffness matrix for pile, K_s is stiffness matrix for soil, y_p is the pile deformation y_0 is the lateral soil movement due to slope instability.

Right side of the equation 2.8 above represents the loads acting on the piles whereas left side of the equation represents the pile-soil rigidity resisting the forces.

Chow (1996) also compared the early measurements of two case histories with the results of numerical method developed. The author concluded that the method was capable of predicting the behavior of piles. The author also stated that bending moments, shear forces, pile deflections and pile rotations could be estimated by this method.

Chen and Poulos (1997) developed a chart solution for estimating maximum bending moment developed along passive piles and the pile deflections. Boundary element program, PALLAS, was used with elastic behavior of pile and soil assumption. Elastic charts were developed for uniform and linear soil stiffness profiles. (Figure 2.5 and 2.6)

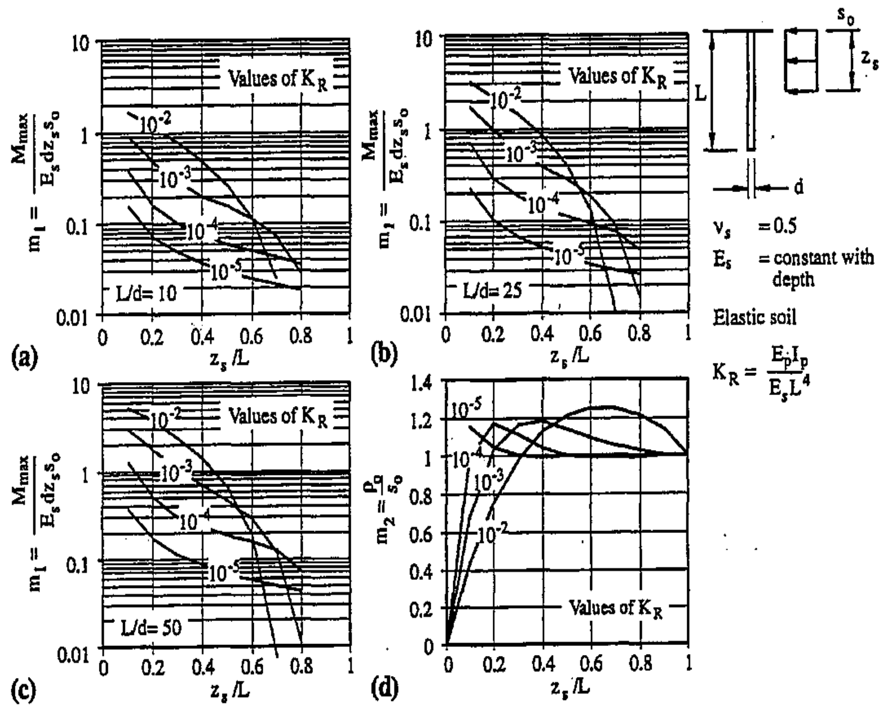

Figure 2.5 Elastic Charts for Constant Subgrade Modulus, Chen and Poulos (1997)

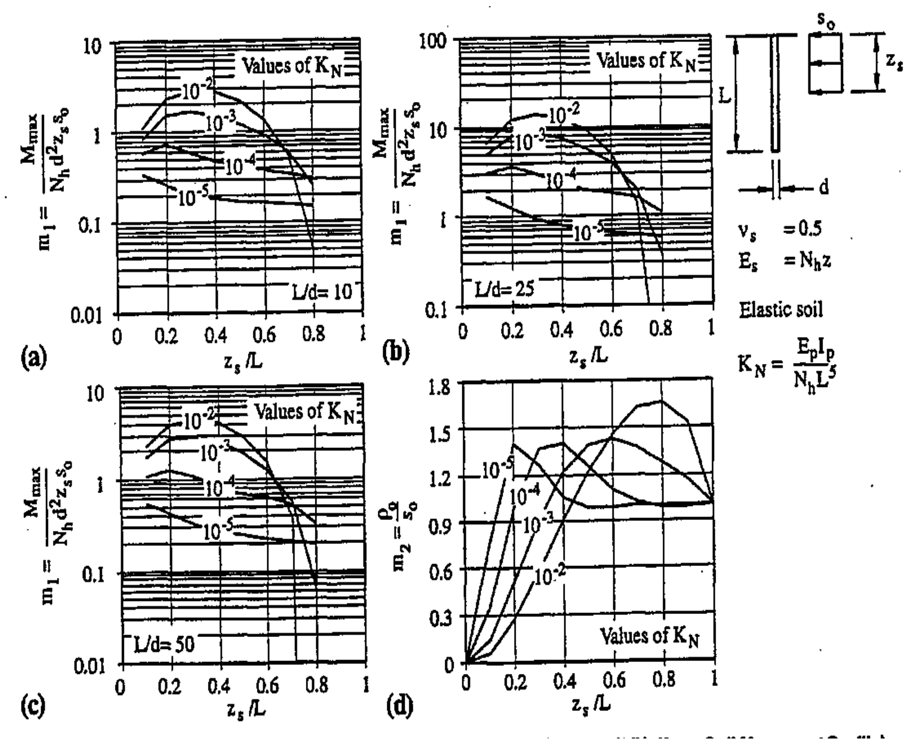

Figure 2.6 Elastic Charts for Linearly Changing Subgrade Modulus, Chen and Poulos (1997)

The chart method was then compared with some early experimental studies and the method was reported to overestimate maximum bending moments and pile deflections for large soil movements. The study concluded that reasonable pile behavior could be obtained by using the method for small soil movements, such as soil movements smaller than 0.1d.

Martin and Chen (2004) applied a displacement method using FLAC-3D computer program. The analysis included kinematic loading acting on piles caused by lateral soil movements. Single pile model undergoing lateral soil used in their study is given in Figure 2.7.

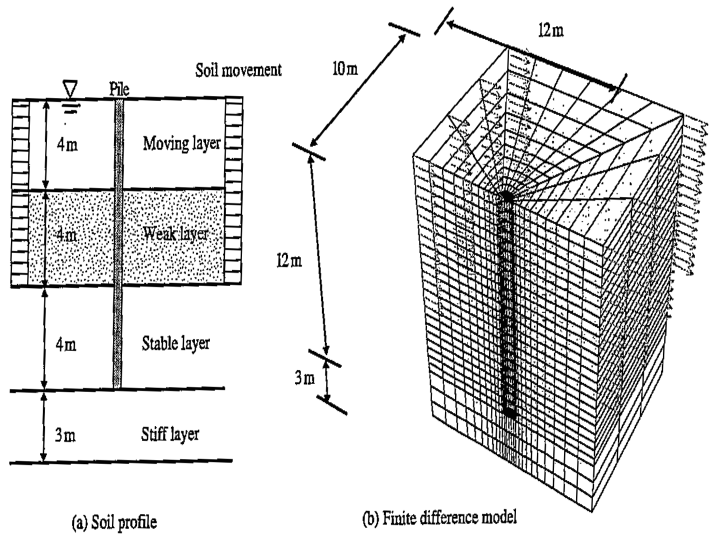

Figure 2.7 Single Pile Model, Martin and Chen (2004)

Bending moment, shear force and reaction force distributions for a single pile was given in the study. (Figure 2.8)

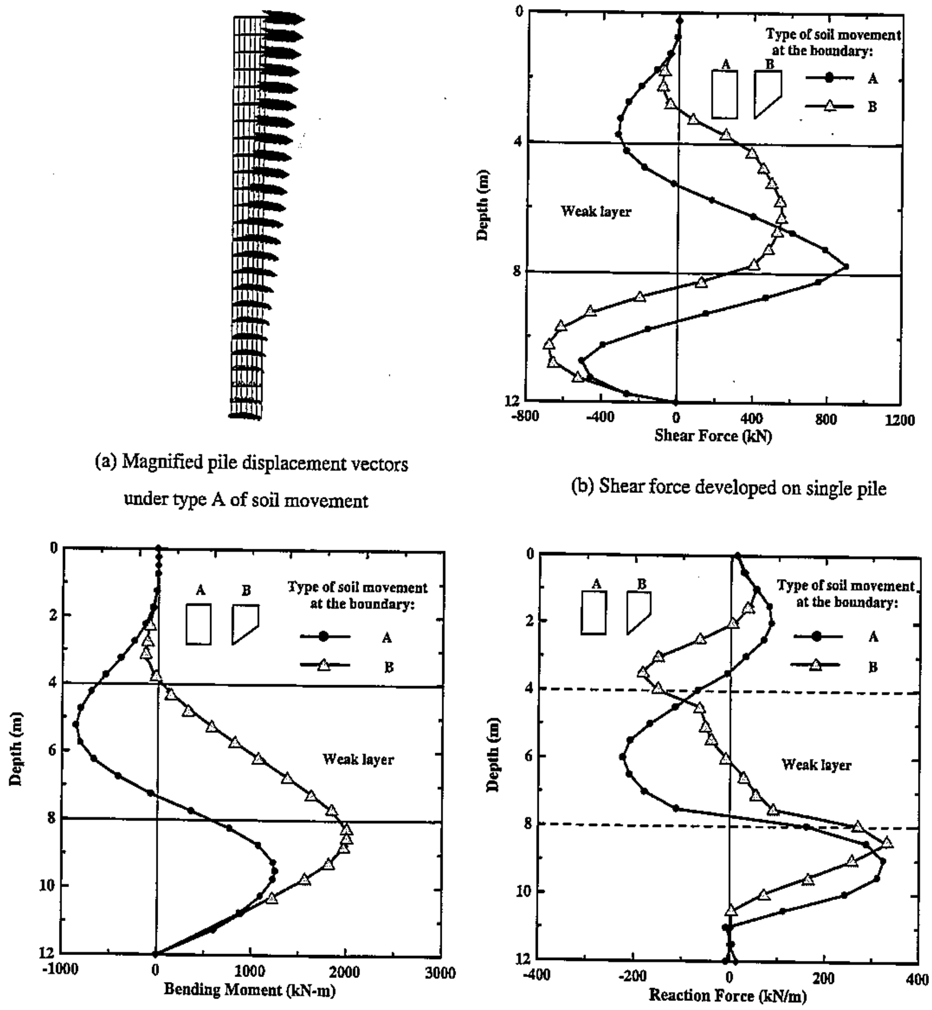

Figure 2.8 Single Pile Results, Martin and Chen (2004)

The authors also applied the method to earlier cases of field measurements, to obtain the lateral behavior of a 2x2 pile group. The obtained responses of pile groups based on finite difference analysis were reported to be in a good agreement with the earlier field measurements.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Equipment

Passive piles are laterally loaded in order to observe bending moment distribution of laterally loaded piles by using a large shear box containing cohesionless soil.

Main elements of the experimental system can be summarized as follows; a large shear box, model piles, pile-cap, strain gauges, a 24-channelled data logger, quarter-bridge cables, a computer having CODA computer program, proving ring to measure the lateral loads applied to the system, dial gauge to measure the shear box displacement, air jack and pressure gauge to measure vertical loads applied to the soil and cohesionless soil.

Model piles were placed into a large shear box that was filled with cohesionless soil. Strain Gauges were fastened on the piles at five levels and connected to a 24-channelled data acquisition system in order to measure the strain values developed on the strain gauges.

Shear box displacements were measured with a dial gauge attached to the shear box and the lateral load given to the system was measured with a load cell.

3.1.1 Testing Mechanism

In the experimental study, a large shear box (Figures 3.1 and 3.2) which was constructed by Dağistani (1992) and modified for lateral loading by Nalçakan (1999) was used.

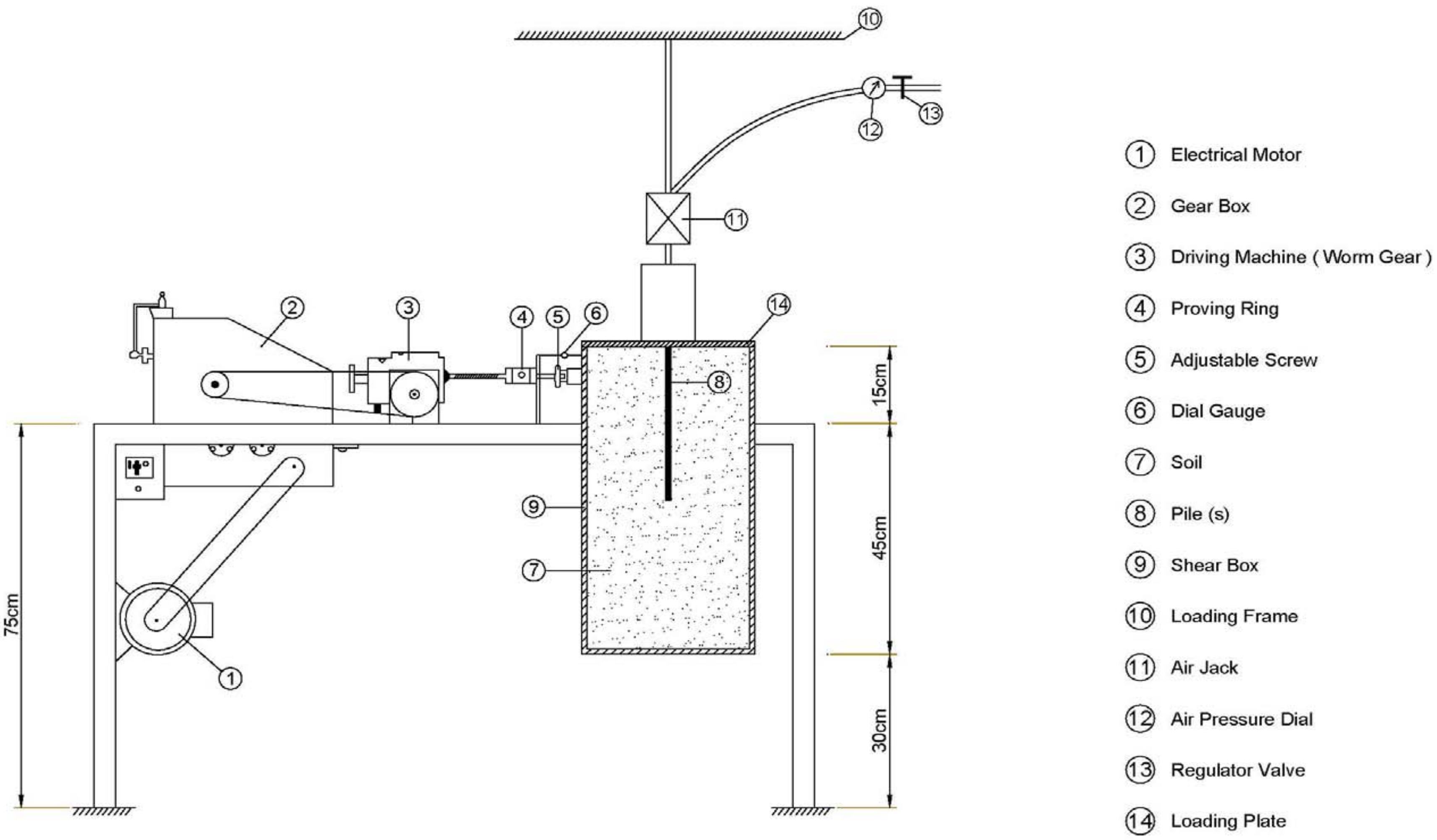

Figure 3.1 Side View of Large Shear Box, Nalçakan (1999)

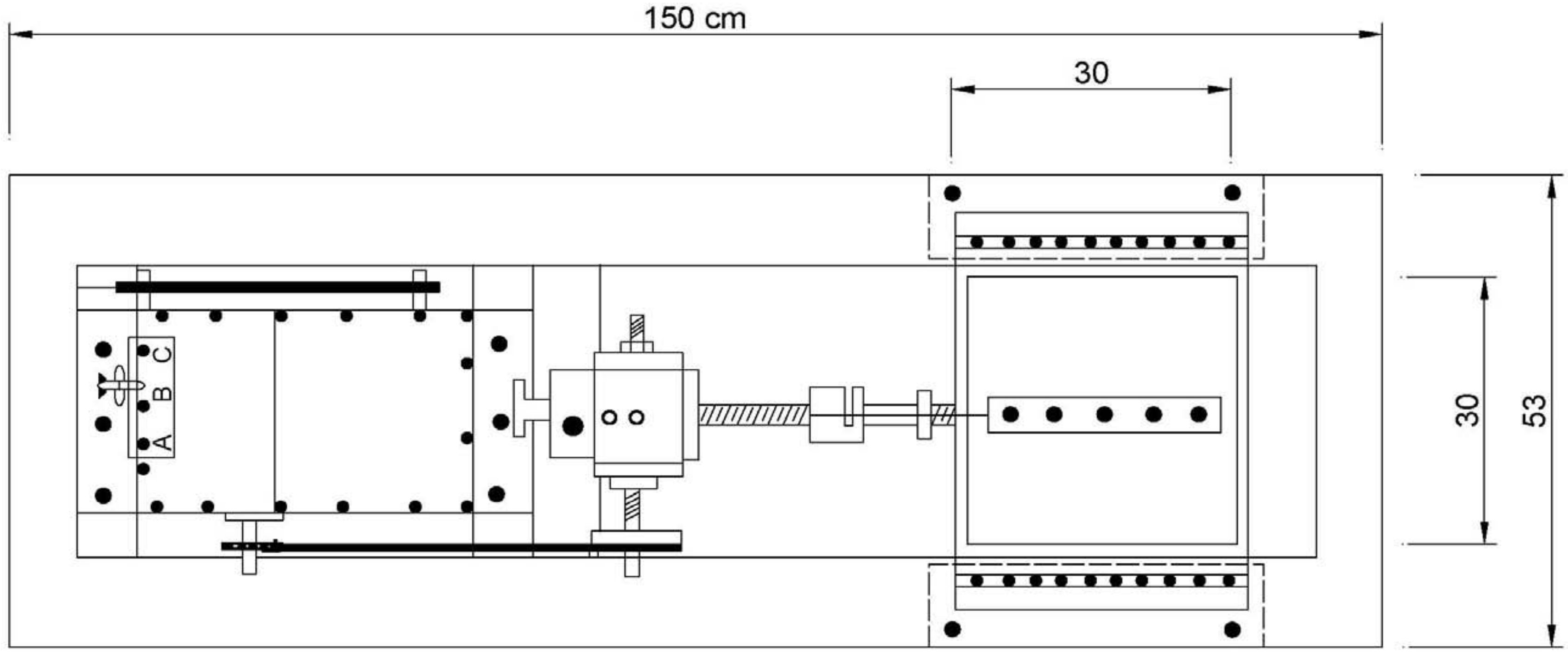

Figure 3.2 Top View of Large Shear Box, Nalçakan (1999)

The upper part moves on roller bearings in order to minimize the friction that can be developed between the upper part and the lower part. (Nalçakan, 1999)

As can be seen from the Figure 3.1 and Figure 3.2, shear box has dimensions of 30 x 30 in plan, and 60 cm deep. The lower 45 cm is stationary. The upper 15 cm is free to move along a single axis, by up to 5.5 cm. The gear mechanism that drives the shear box has three settings for shearing rates 0.006 mm/min, 0.37 mm/min and 9 mm/min. In all tests of this work 0.37 mm/min shearing rate was used.

3.1.2 Model Piles

In the experiments, aluminum model piles with a diameter of 10 mm and a length of 30 cm were used. The piles are hollow in order to accommodate strain gauges and their wiring. Inner diameter of the piles is 8 mm.

The piles were placed in the shear box so that the upper 15 cm of the piles can be sheared. In other words, the piles were sheared at the midpoints.

Mechanical properties of aluminum are given in Table 3.1 and pile properties are summarized in Table 3.2.

Table 3.1 Mechanical Properties of Aluminum

DENSITY d ($kg/m^{3)}$	**ELASTIC MODULUS E (GPa)**	**POISSON'S RATIO ν**	**YIELD STRENGTH σ_y (MPa)**	**YIELD STRAIN ($x10^{-6}$)**
2600-2800	70-79	0.33	215-505	2700-7200

Table 3.2 Pile Properties

OUTER DIAMETER d_o (mm$^)$	**INNER DIAMETER d_i (mm)**	**LENGTH L (mm)**	**AREA A (mm^2)**	**MOMENT OF INERTIA I (mm^4)**
10	8	300	28.26	289.67

3.1.3 Measurement Devices

3.1.3.1 Strain Gauges

Five strain gauges were fastened on each single pile to measure bending moments at five different locations along the length of each pile (Figure 3.3). Since five piles were used in the experiments, totally 25 strain gauges were used. “FLA-5-11” type strain gauges manufactured by TML Co., Ltd having 120 ohm resistances and single pattern configuration were used. The gauges are 0.5 mm in length and 1.2 mm in width and made of mild steel. Gauge factors of the strain gauges are 2.12. Operating temperature of the strain gauges used is -20~+80 °C. Maximum input voltage is 50V and strain limit is 3%.

Strain gauges were fastened on the piles with a “TML-CN” type adhesive (Cyanoacrylate) and coated with “TML-VM tape” (Buthyl) for moisture and water proofing and with TML-KE 348 (Silicon Rubber) for heat resistivity.

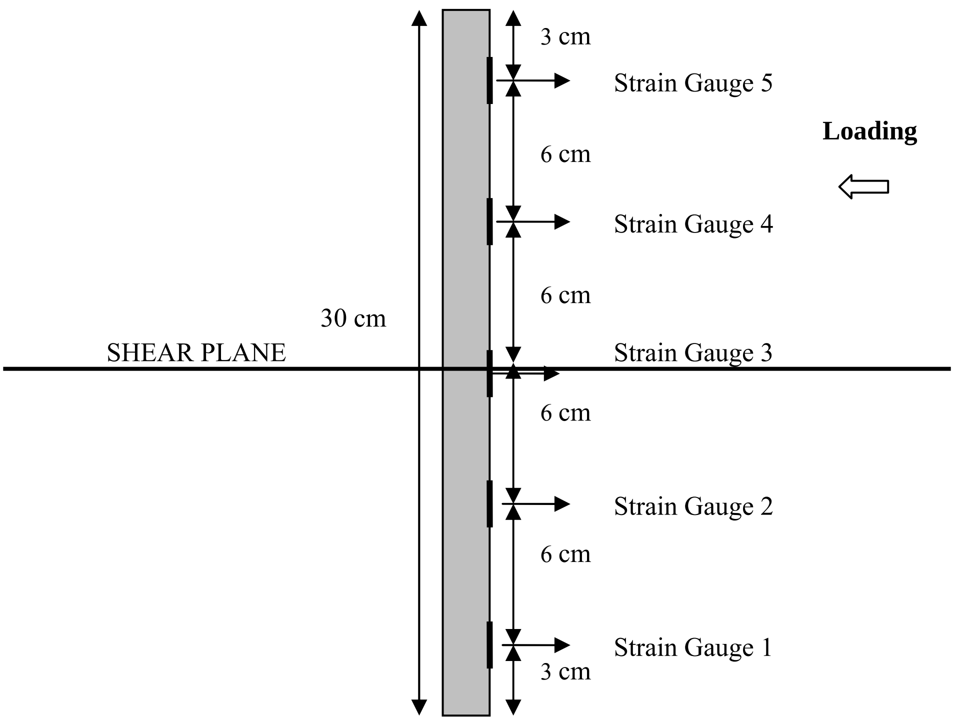

Figure 3.3 Typical Model Pile and Strain Gauge Installation

3.1.3.2 Lateral Load Measurement (Proving Ring)

For measuring lateral loads applied to shear the large shear box, a proving ring was used. Wykeham Farrance (Ring No: 3926) proving ring made from special alloy steel having 400 kg capacity was supplied with a dial gauge having 0.0001" resolution. The factor used to convert dial gauge readings to the loads (kg) is **0.3786**.

3.1.3.3 Lateral Displacement Measurement (Dial Gauge)

Lateral displacements of shear box were measured with a dial gauge. Dial gauge manufactured by ELE Soil Testing Inc. (Type: EI- 884120) having a displacement measurement range of 1" with 0.001" divisions was used. The face diameter of the dial gauge is 2-1/4".

3.1.3.4 Vertical Load Measurement (Pressure Dial and Air Jack)

For vertically loading the soil in the shear box an air jack (78.5 cm^2) was used. PEMAKS PAG 100 type air jack was pressurized with a compressor.

The air pressure was applied through a regulator valve, and was measured with a pressure dial (Brand: MAG) having a range of 220 psi and a resolution of 10 psi. Prior to experimental study, a proving ring was used together with air jack to obtain the necessary air pressure for 450 kg vertical loading. The required pressure value was marked on the pressure dial. The air pressure was maintained at that value (81.50 psi=5.73 kg/cm^2) which lead to 450 kg vertical load acting on the soil.

3.1.4 Data Acquisition System

Data acquisition system used in the experiments was mainly composed of a data logger, a computer with related data acquisition software, an adapter between computer and data logger, Q-cables (quarter bridge completion cables) connecting strain gauges to data logger.

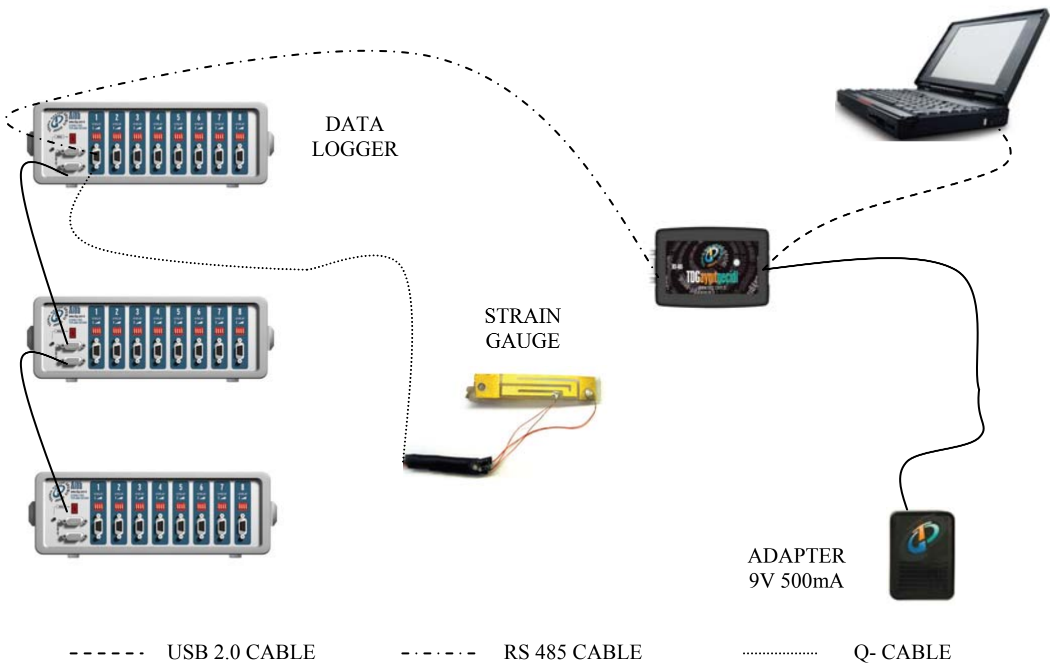

Figure 3.4 Data Acquisition System

Q-cables contain three more resistances that form the Wheatstone bridge together with the strain gauge. They were 120 ohm in resistance. With a mechanism in the cable heads, the output voltages could be adjusted to zero prior to experiments.

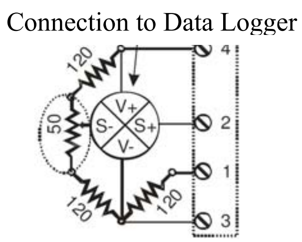

Figure 3.5 Electrical Sketch of the Q-Cable Heads

“TDG Ai8b” data logger used is a 16 bit system and it has 8 channels to which strain gauges can be connected. It converts analog signal from strain gauges to digital signals. Signal-to noise ratio of the device (SNR) is >= 72. Bit resolution of the data logger is 0.0003 Volt. For strain gauge measurements, resolution of the device is 0.137 με. Three data loggers were connected for pile group testing which lead to 24-channeled system. Since a 24-channeled system existed, only 24 strain gauges could be monitored during group testing resulting in no readings from one of the 25 strain gauges. Data acquisition system allows the strain values to be recorded at least in 0.125 s intervals. In this study, the values were recorded in 1s intervals.

A software named CODA was used. Voltage readings could directly be converted into strain values by applying some coefficients into the program. The software not only records the readings but also displays them. All readings could be viewed together in one window and results could be followed graphically during testing.

3.2 Soil Properties

3.2.1 Grain Size Distribution of the Soil Sample

Sieve analysis was performed on the soil sample that was used in the experiments. Its grain size distribution is presented in Figure 3.6 below.

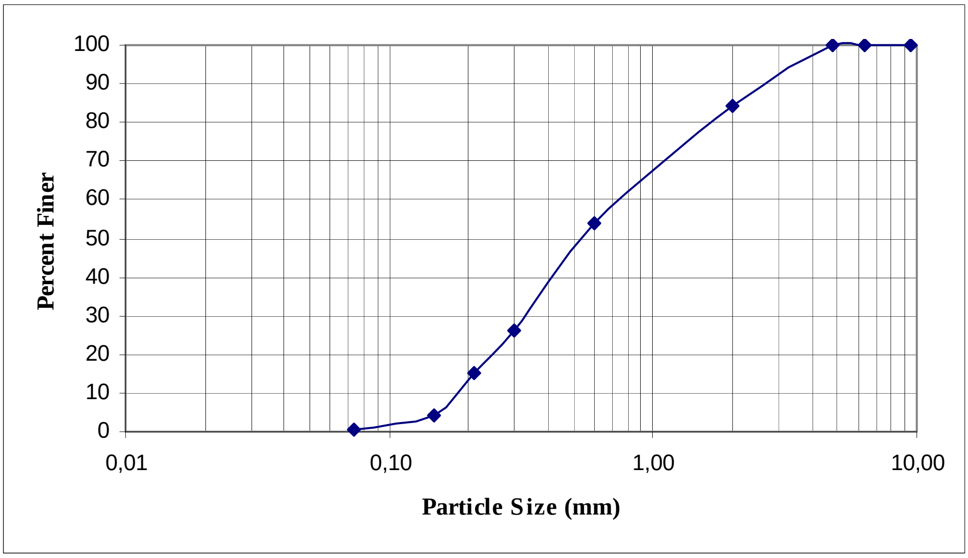

Figure 3.6 Gradation of the Soil Sample

Basic soil parameters determined from Figure 3.6 are presented in Table 3.3.

Table 3.3 Basic Soil Parameters

D_{60} (mm)	**D_{30}** (mm)	**D_{10}** (mm)	**C_u** $= \frac{D_{60}}{D_{10}}$	**C_c** $= \frac{(D_{30})^2}{(D_{60})(D_{10})}$	**Unified Soil Clasification**
0,75	0,35	0,19	3,95	0,86	SP

In the table above D_{10} is the effective size corresponding to 10% finer; D_{30} and D_{60} are the grain sizes corresponding to 30% and 60% finer. C_u is the uniformity coefficient and C_c is the coefficient of curvature. The soil sample can be classified as poorly graded sand (SP).

3.2.2 Density of the Soil Sample in the Tests

For density measurements, small density boxes were placed within the shear box at three levels in single pile tests and at one level in group pile tests. For each level, two density boxes were used. For each experiment, average soil densities obtained from these boxes are summarized in Table 3.4.

Table 3.4 Density of the Soil Sample in the Tests

TESTING TYPE	**PILE NAME**	**EXP1 g/cm^3**	**EXP2 g/cm^3**	**EXP3 g/cm^3**	**EXP4 g/cm^3**	**EXP5 g/cm^3**	**AVERAGE g/cm^3**
SINGLE	Pile A	1,71	1,70	1,70	1,71		1,71
	Pile B	1,70	1,70	1,71	1,71	1,71	1,71
	Pile C	1,70	1,70	1,71	1,71	1,71	1,71
	Pile D	1,71	1,72	1,71			1,71
	Pile E	1,71	1,70	1,71			1,71
GROUP	---	1,71	1,70	1,71	1,71	1,71	1,71

As can be seen from Table 3.4, during single pile tests and group pile tests the density of the soil in the shear box changes between 1.70 and 1.72 having an average value of **1.71 g/cm^3**.

Density of soil obtained by dividing the total weight of the soil used to the volume of the shear box was found to be **1.72 g/cm^3**.

Maximum and minimum density tests conducted according to BS 1377, 1990 indicated that maximum density of the soil to be **1.83 g/cm^3** and minimum density of the soil to be **1.59 g/cm^3**.

Relative density, DR, of the soil tested is then concluded to be within a range 54-58 % indicating that the soil used in the experiments is a medium soil.

3.2.3 Strength Parameters of the Soil Sample

For obtaining strength parameters of the soil, a direct shear test was conducted.

The soil sample having a density of 1.71 g/cm^3 (density of the soil used in lateral load experiments) was tested in direct shear box apparatus in Geotechnical Laboratory of Civil Engineering Department of M.E.T.U.

Results of the shear test conducted are summarized in Figure 3.7. Friction angle (ϕ) and cohesion of soil (c) were found to be 36.36° and 2.57 kPa, respectively.

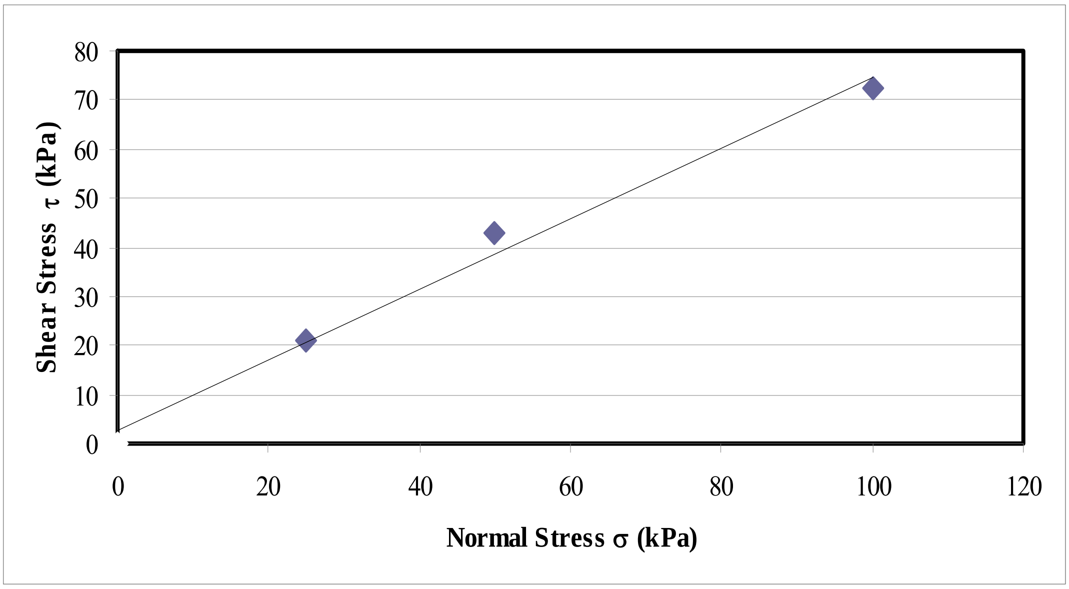

Figure 3.7 Strength Parameters of the Soil Sample

3.3 Testing Procedure

20 single pile tests were carried out for five piles. All piles used are hollow aluminum piles having 10 mm diameter, 30 cm length and 1 mm thickness but there may be manufacturing and strain gauge installation differences between these piles. Therefore the piles are named as “Pile A”, “Pile B”, “Pile C”, “Pile D” and “Pile E” Single pile tests were repeated at least three times and five group pile tests were conducted (Table 3.5). In pile group tests the pile spacing was chosen to be 3D (three pile diameter = 3 cm) and this value was remained constant in all tests.

Table 3.5 Number of Tests Executed

Test Type	Number of Tests
1. Single Pile Tests	20
1.1 Pile A	4
1.2 Pile B	5
1.3 Pile C	5
1.4 Pile D	3
1.5 Pile E	3
2. Group Pile Tests	5

The testing procedure can be summarized as follows;

1. The shear box was filled with soil up to the level where piles would be based on. (Figure 3.8)

2. Piles were placed in the shear box with a metal guide-bar in order to provide straight placement of piles. (Figure 3.9 and Figure 3.10)

3. In order to provide piles to be laterally straight and in order to maintain proper pile spacing, a wooden clamp was used. (Figure 3.10)

4. After the placement of piles, the shear box was started to be filled with soil by using glass funnel in order to have homogenous distribution of soil within the shear box. (Figure 3.11)

5. Density boxes were placed at three levels which were then used for density calculations. (Figure 3.12)

6. On top of the shear box, soil was leveled (Figure 3.13 and Figure 3.14)

7. Pile cap was placed on top of the piles. (Figure 3.15 and Figure 3.16)

8. On top of the soil, a loading plate was placed in order to transfer the vertical load to the soil. (Figure 3.17)

9. Soil was then loaded vertically by an air jack. A 450 kg load was applied to the system in all tests (0.5 kg/cm^2). (Figure 3.18)

10. Dial gauge that measures shear box displacement and proving ring that measures lateral load applied to the system by the gear box were connected. (Figure 3.19)

11. Strain gauge wires were connected to the data system with Q-cables (quarter bridge cables). (Figure 3.20 and Figure 3.21)

12. The circuitry was warmed up for 30 minutes for a proper measurement.

13. Data logger was connected to a computer. (Figure 3.22 and Figure 3.23)

14. CODA Computer program was executed. The recording interval was chosen to be 1 s.

15. Experiment was initiated by giving power to the system.

16. Lateral soil displacement , time and the load measurements were noted at intervals of 0.254 mm movement of shear box.

17. After the laterals tests ended, the soil was unfilled.

18. Since the program CODA recorded strains developed for a specific time, dial gauge readings could be related with strains developed.

Figure 3.8 Shear Box with Soil before Pile Placement

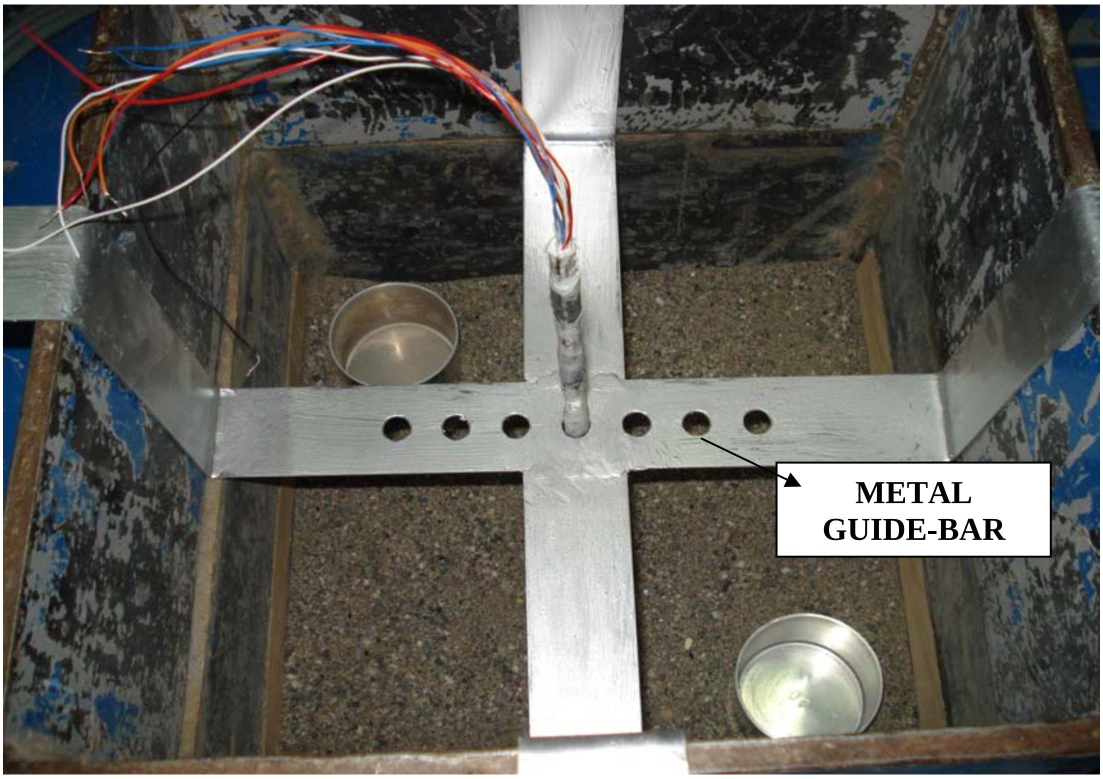

Figure 3.9 Straight Pile Placement of Single Pile

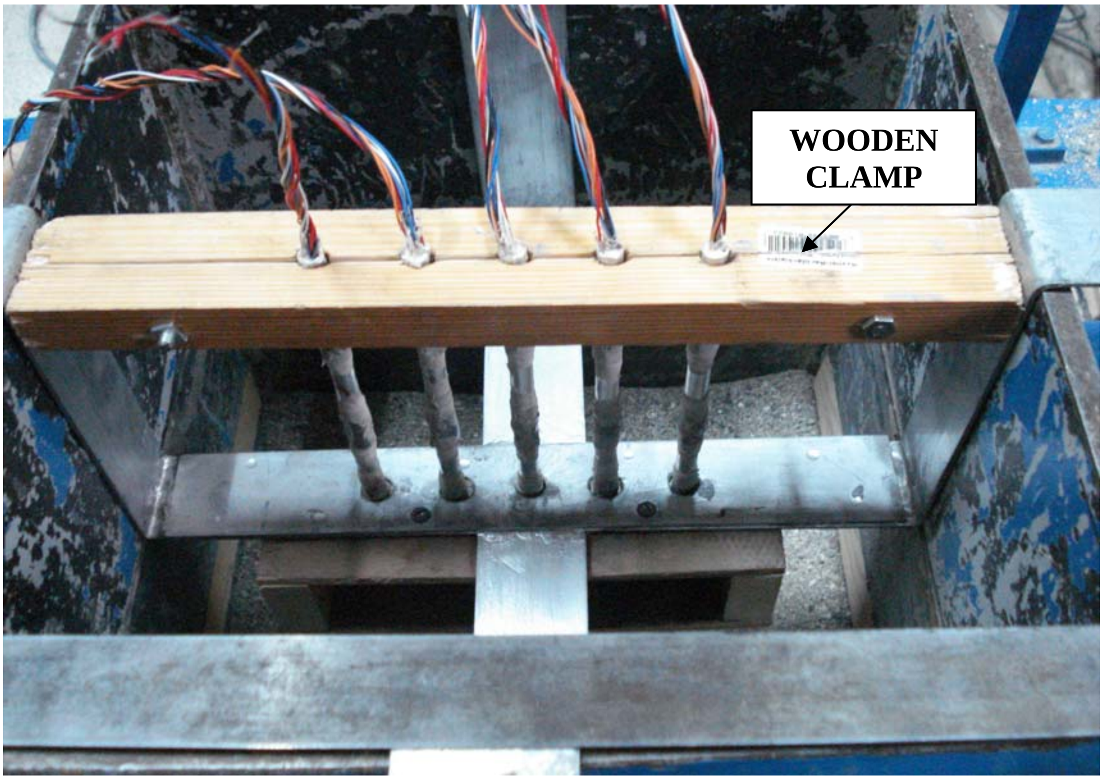

Figure 3.10 Straight Placement of Piles in Group Testing

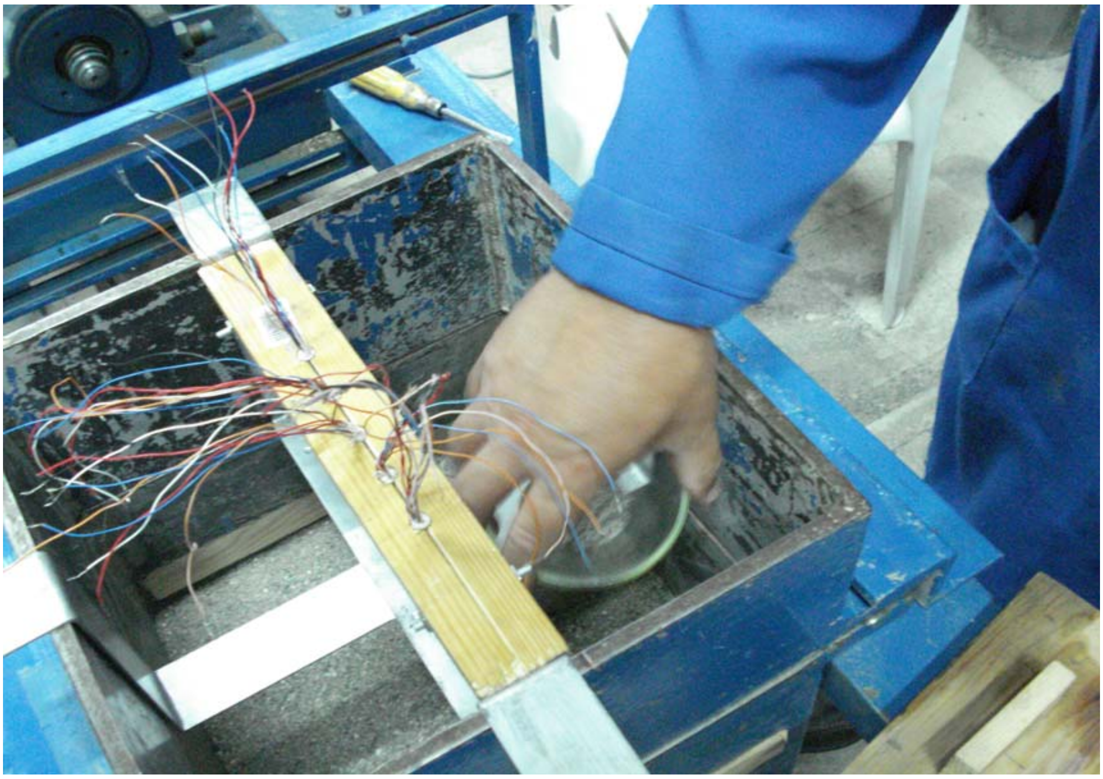

Figure 3.11 Filling Shear Box with Soil

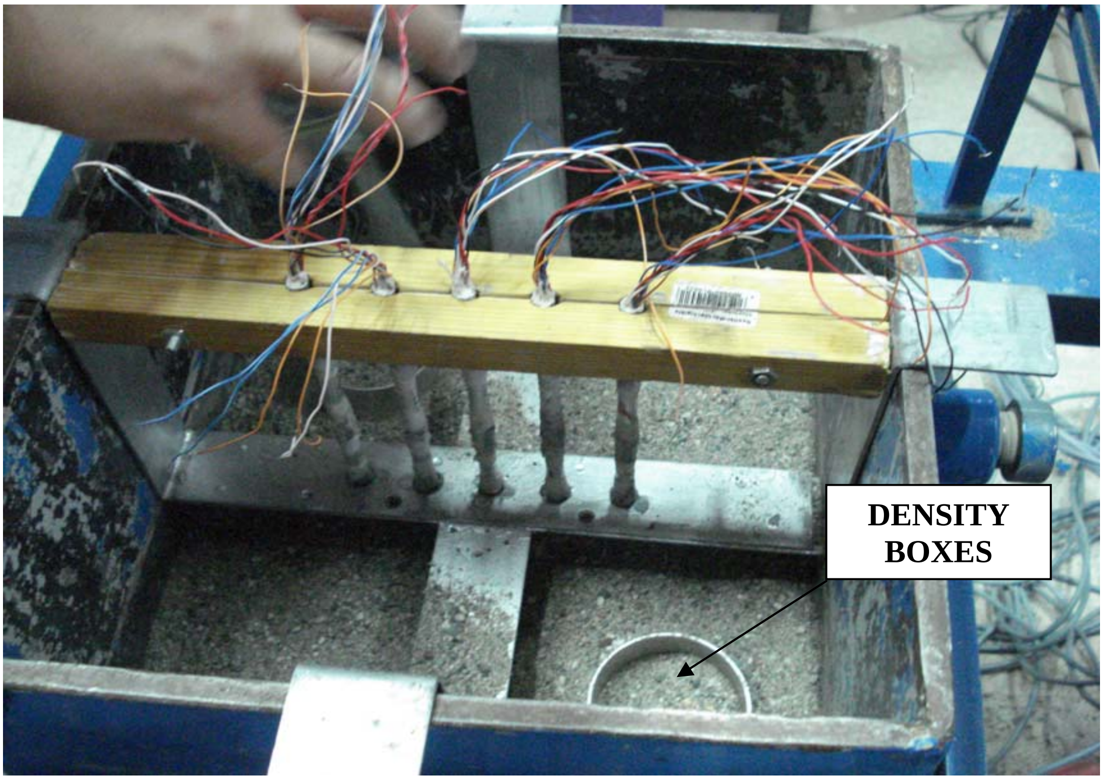

Figure 3.12 Density Boxes

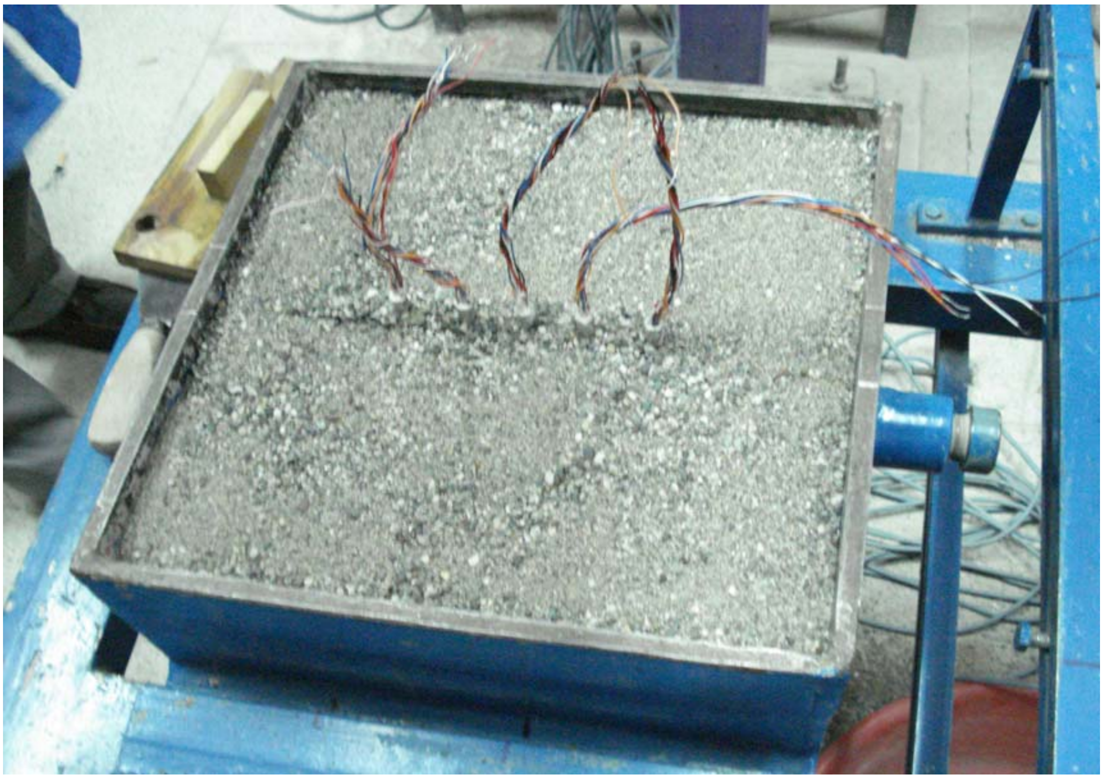

Figure 3.13 Leveling the top of the Shear Box -1-

Figure 3.14 Leveling the top of the Shear Box -2-

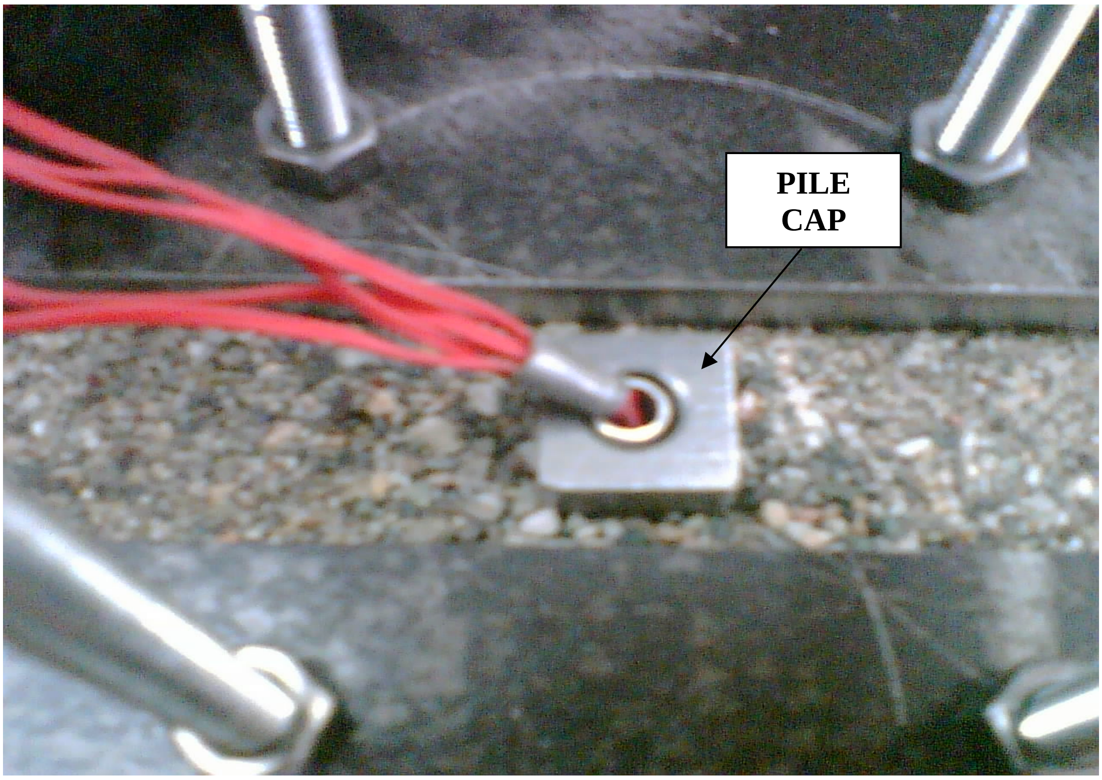

Figure 3.15 Pile Cap for Single Piles

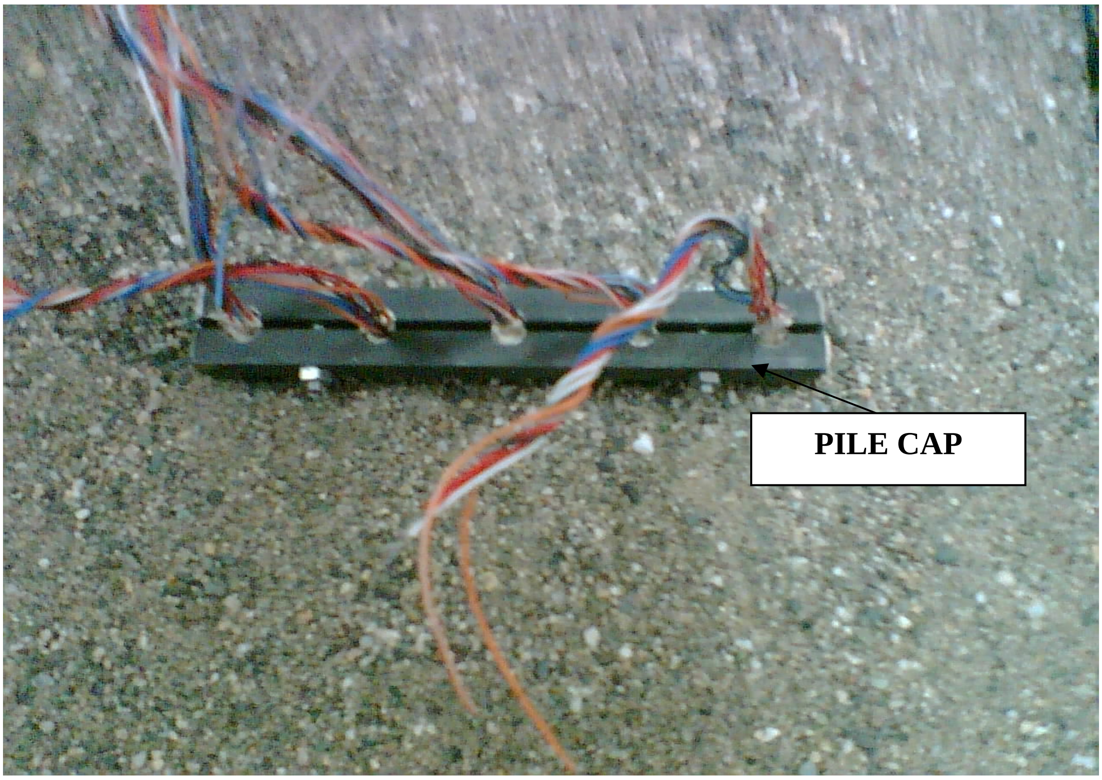

Figure 3.16 Pile Cap for Piles in Group Testing

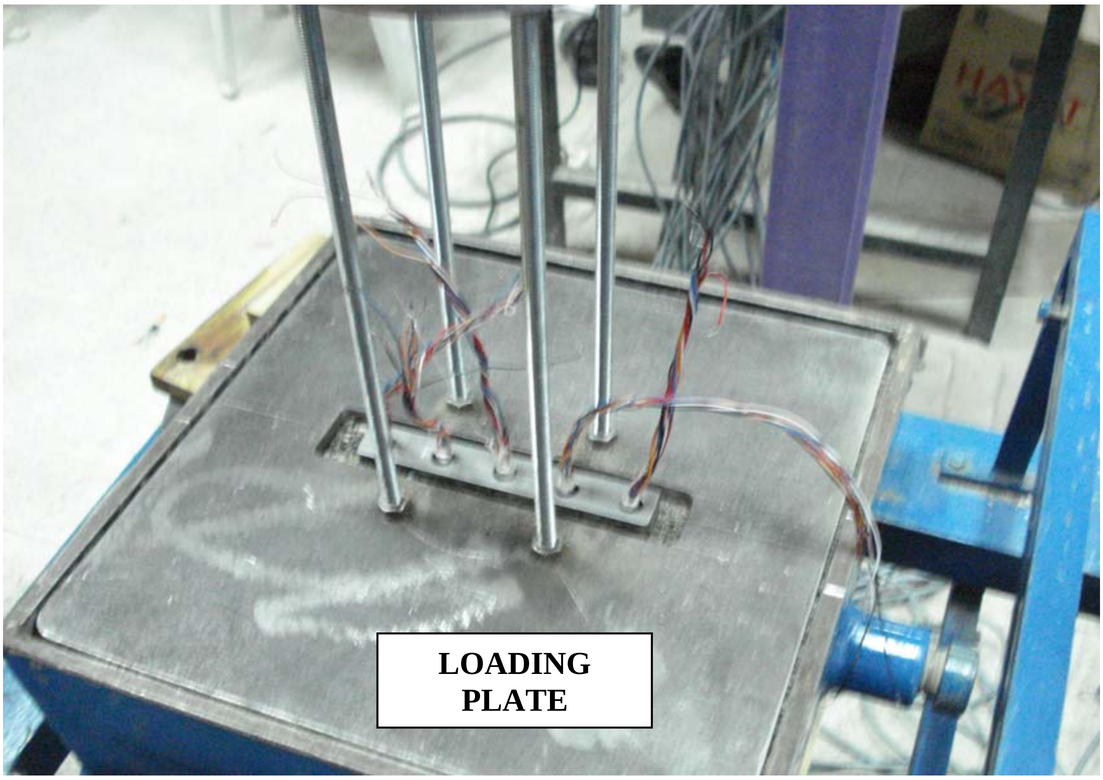

Figure 3.17 Vertical Load Transfer Mechanism

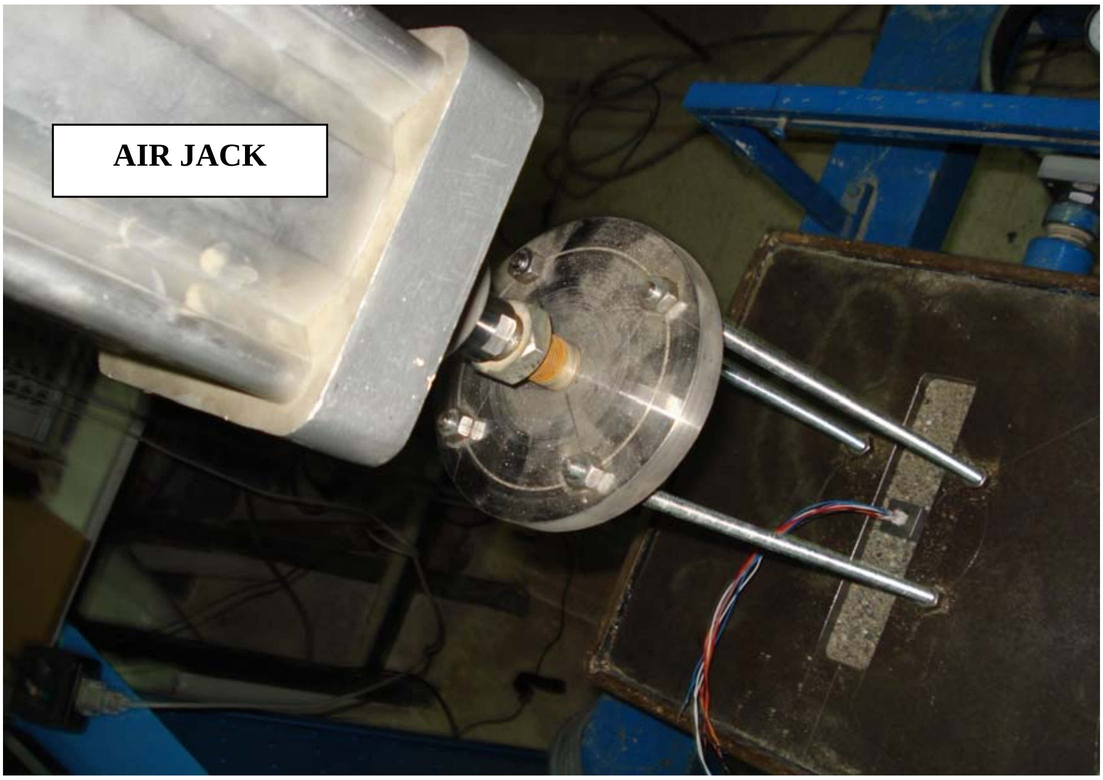

Figure 3.18 Axially Loading the System

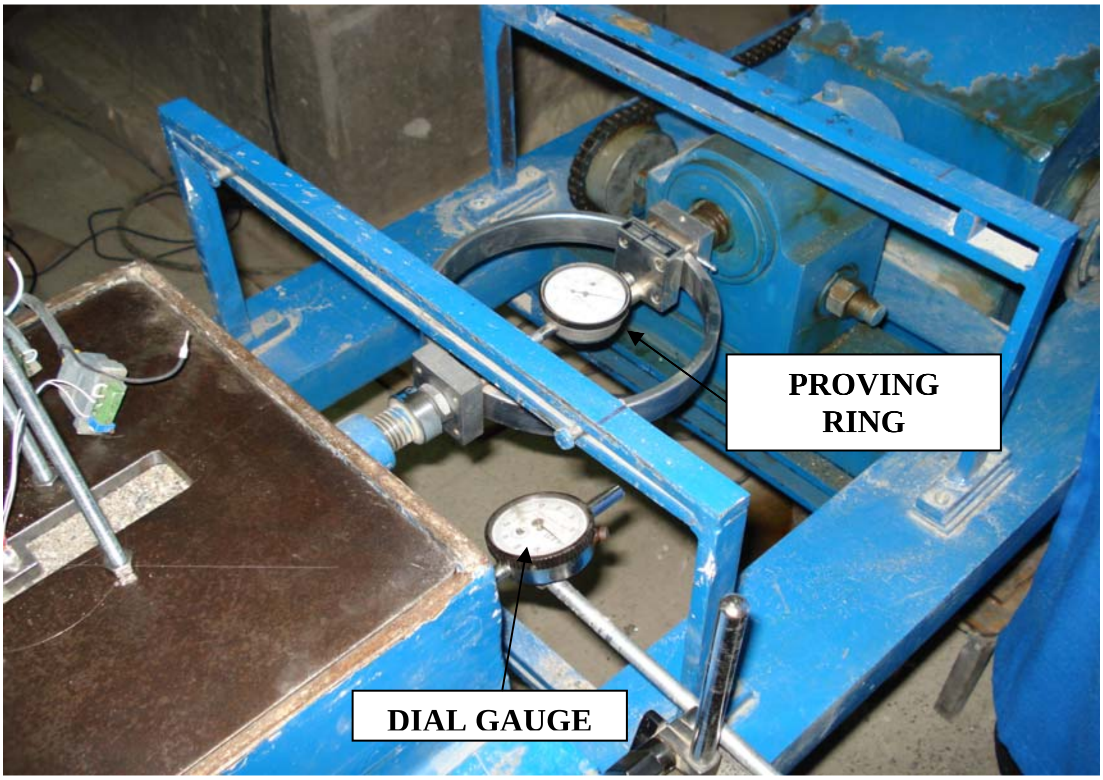

Figure 3.19 Dial Gauge and Proving Ring Setup

Figure 3.20 Cable Connection in Single Pile Tests

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Figure 3.21 Cable Connection in Group Pile Tests

Figure 3.22 Data Logger

Figure 3.23 Connecting the Data System to Computer

CHAPTER 4

RESULTS AND DISCUSSION

The results of the experiments and the evaluation of the recordings are explained briefly in this chapter. The bending moments developed along the piles were investigated in this study. Since bending moments are directly proportional to bending strains, the bending moment comparison is done by comparing the bending strains recorded.

In the results, positive bending strain means tension on the side of the lateral load from the moving soil and negative bending strain means compression.

4.1 Single Pile Tests

In order to obtain the behavior of laterally loaded passive pile and later to examine the group effect, firstly single pile tests were conducted.

As mentioned before, five different piles were used in the experiments which were named as Pile A, Pile B, Pile C, Pile D and Pile E.

Single tests were performed individually and the tests were repeated at least three times for each pile. For each pile, the average of these test results is used to obtain single pile responses. Single pile responses for Pile A, B, C, D and E are then used to determine the average single passive pile response. In the following sections of this chapter, average single passive pile response was used to compare the behavior of the piles in group with single pile.

4.1.1 Single Pile Tests for Pile A

For the pile named “Pile A”, four lateral load tests were performed. The results obtained are presented in Tables A.1 through A.5 in Appendix A.

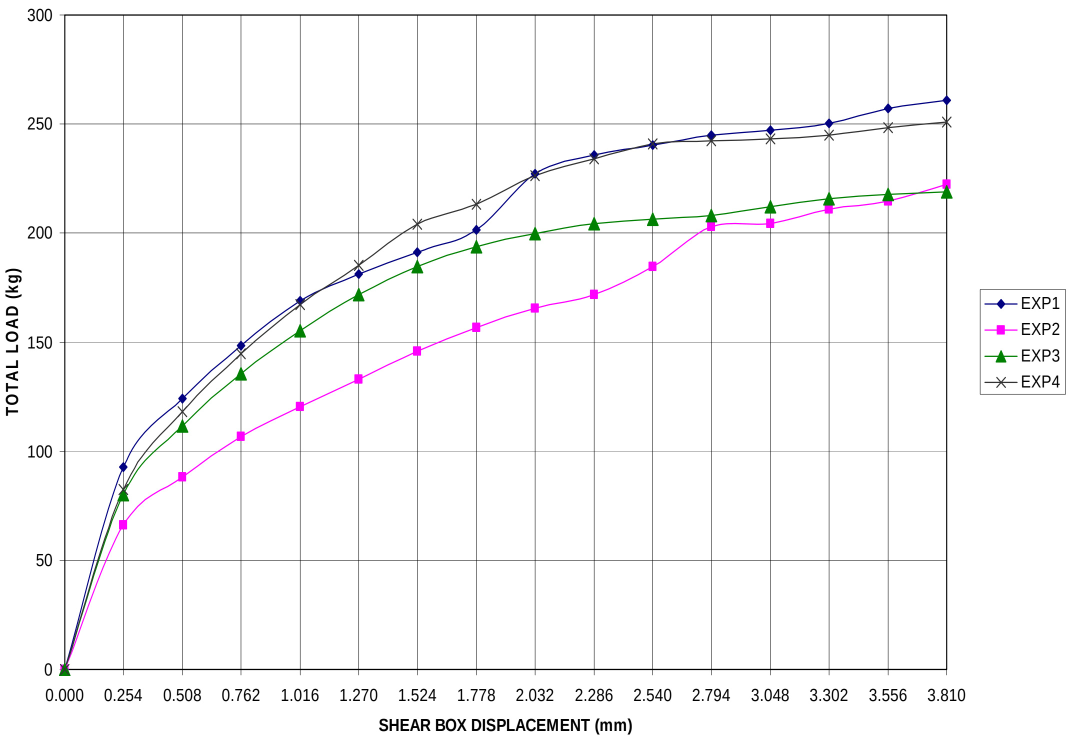


Figure 4.1 Load Measurements in Pile A Experiments

Total lateral loads measured at different shear box displacements during four lateral load experiments are summarized in Figure 4.1. As the figure implies, the total load measurements of Experiment 2 and Experiment 3 are different from the other two experiments. The reason for this may be the factors like differences in density of soil samples, placement of piles within the soil and the friction that may be developed between upper and lower parts of shear box.

It should also be noted that the measured loads are the loads applied to shear the soil sample in the large shear box and loads acting on the piles were not measured during the experiments. That’s the reason why it is not possible to absolutely conclude that there were differences in the loads acting on piles in Experiment 2 and Experiment 3 from the measured load figure. However there may be some differences in the loads acting on piles in these experiments and the bending strains developed during Experiment 2 and 3 may be different from the bending strains developed during other experiments. While evaluating the test results of Pile A, that possibility is taken into consideration.

In order to obtain pile response, the average of the results obtained from different experiments are used. The average of the test results for different strain gauges are also presented in Table A.1, A.2, A.3, A.4 and A.5. While calculating the average strain values, some test results are excluded and the remaining test results are used.

As indicated before, total loads measured in Experiment 2 are very different from that of other experiments. From tables A.1, A.2 and A.3 it can be seen that strain gauge 1, 2 and 3 results obtained in Experiment 2 are also different from the results obtained in the other experiments. For that purpose, the results of Experiment 2 are excluded in average calculation for strain gauges 1, 2 and 3.

For Strain Gauge 4, Experiment 1 results are different from the other results. There may be reading errors in that experiment and for that purpose the results of that experiment are excluded in average calculation. For Strain Gauge 5, the results of Experiment 3 are excluded for same reason. Although total loads measured in Experiment 2 and 3 are different, the strains measured at Strain Gauge 4 and 5 in these experiments are nearly same with the results of other experiments.

The Strain readings versus shear box displacement for Strain gauges 1, 2, 3, 4 and 5 are given in Figure 4.2. Average “Pile A” response is given in Figure 4.3.

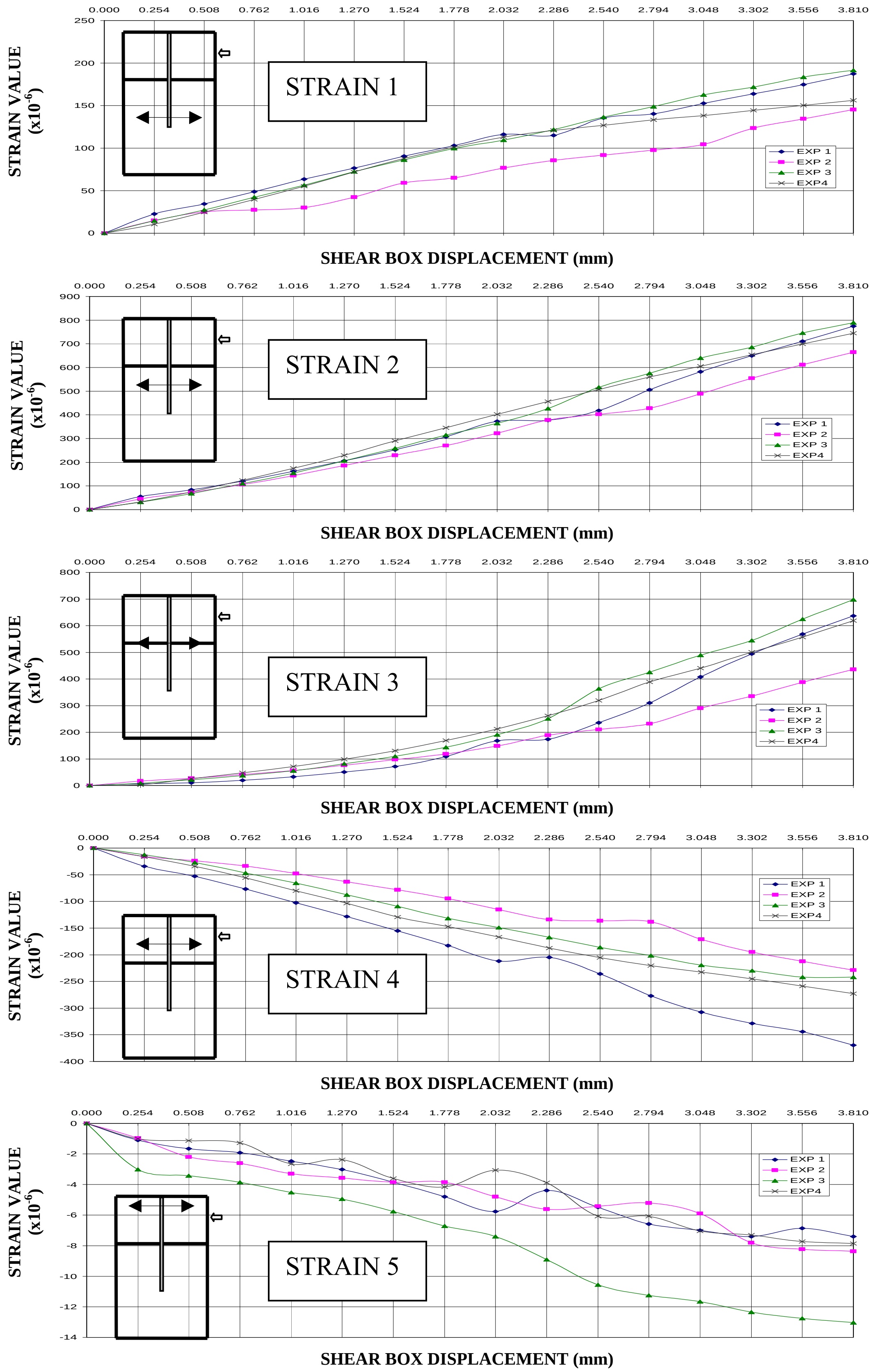


Figure 4.2 Single Test Results for Pile A

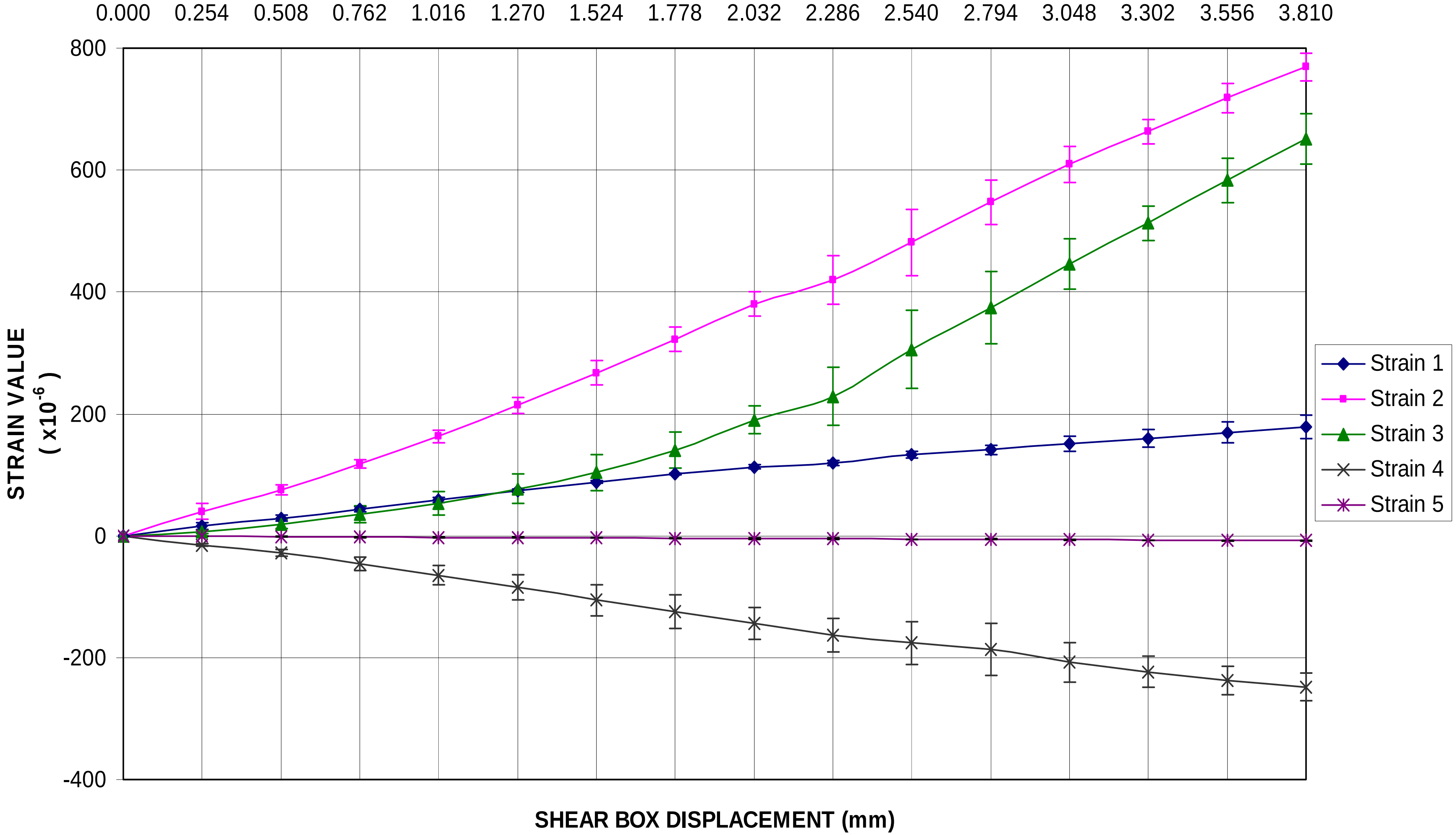


Figure 4.3 Average Pile A Response

4.1.2 Single Pile Tests for Pile B

Five lateral load experiments were performed for the pile labeled "Pile B" and the results of these experiments are summarized from Table A.6 to Table A.10 in Appendix A.

The shear box displacement versus lateral load measurement for Pile B is presented in Figure 4.4 which indicates different loading cases for all experiments. The average of the strain values is calculated for different strain gauges by excluding some of the test results. The excluded experiments are highlighted in the tables related to Pile B in Appendix A.

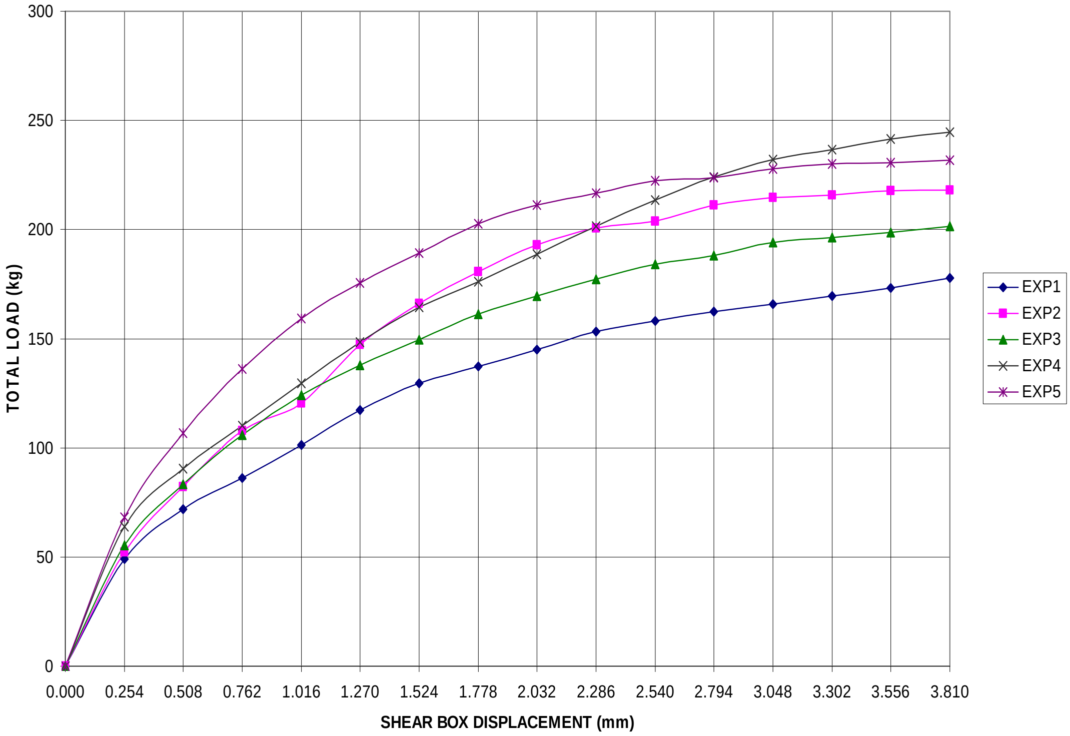


Figure 4.4 Load Measurements in Pile B Experiments

Figure 4.5 summarizes the test results. Average "Pile B" response formed by using the average strains is given in Figure 4.6.

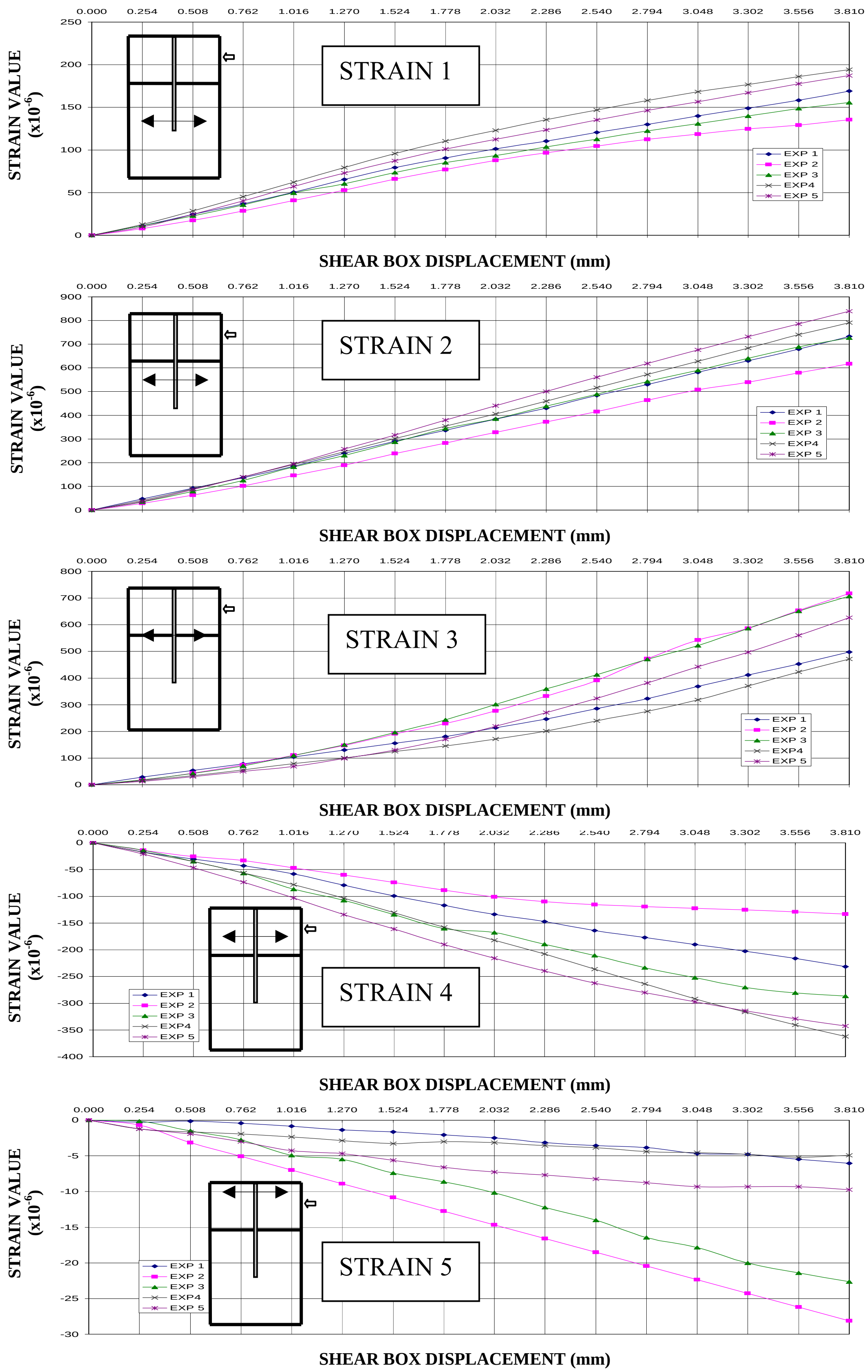
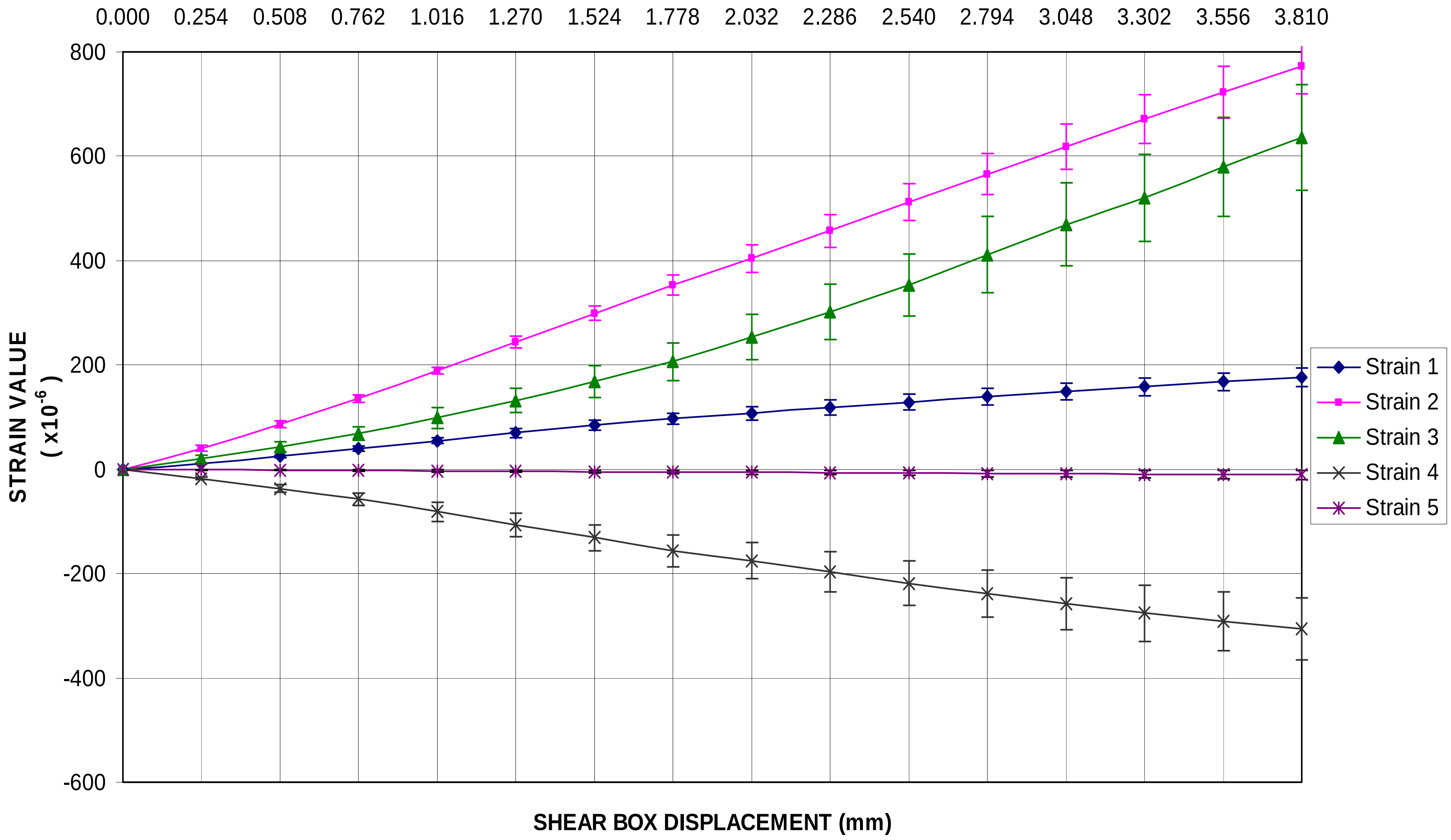


Figure 4.5 Single Test Results for Pile B



Figüre 4.6 Average Pile B Response

4.1.3 Single Pile Tests for Pile C

For the pile designated “Pile C”, five lateral load tests were performed. Table A.11, Table A.12, Table A.13, Table A.14 and Table A.15 in Appendix A summarize the tests results.

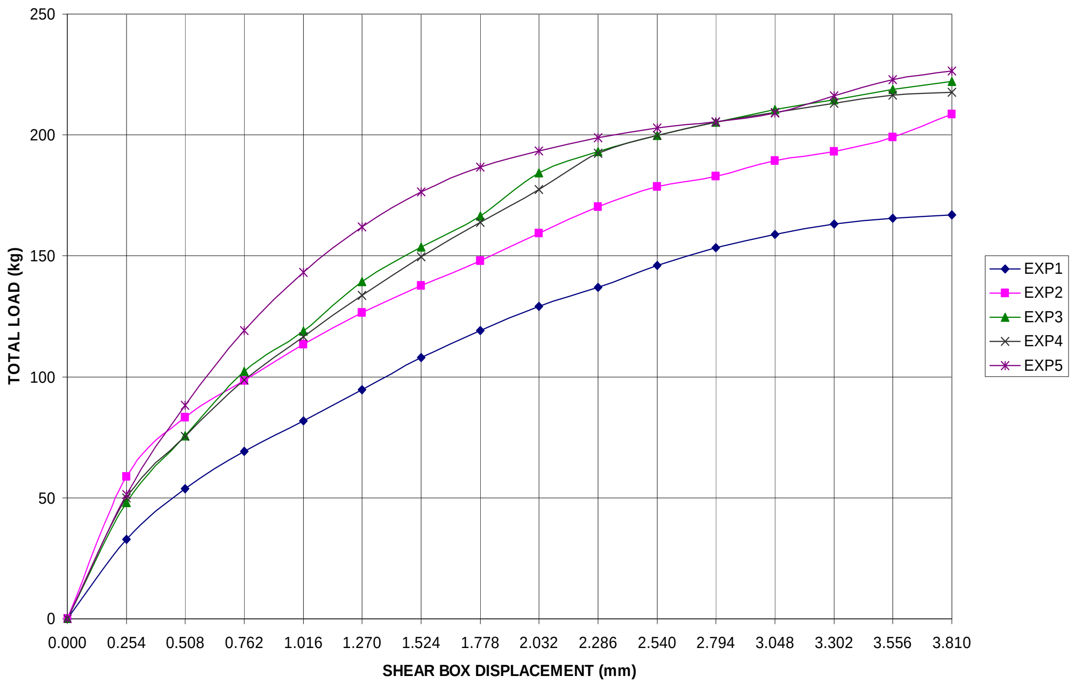


Figure 4.7 Load Measurements in Pile C Experiments

Figure 4.7 above summarizes the load measurements for all experiments conducted with Pile C. As can be seen, load measurements of Experiment 1 are differed from the others. In the average calculations, the results of Experiment 1 are excluded for all strain gauge levels except for Strain gauge 5 level. For Strain Gauge 5, results of Experiment 4 different from the others are excluded. The remaining test results are then used to calculate the pile response. The Strain readings are given in Figure 4.8 and average “Pile C” response is attached as Figure 4.9.

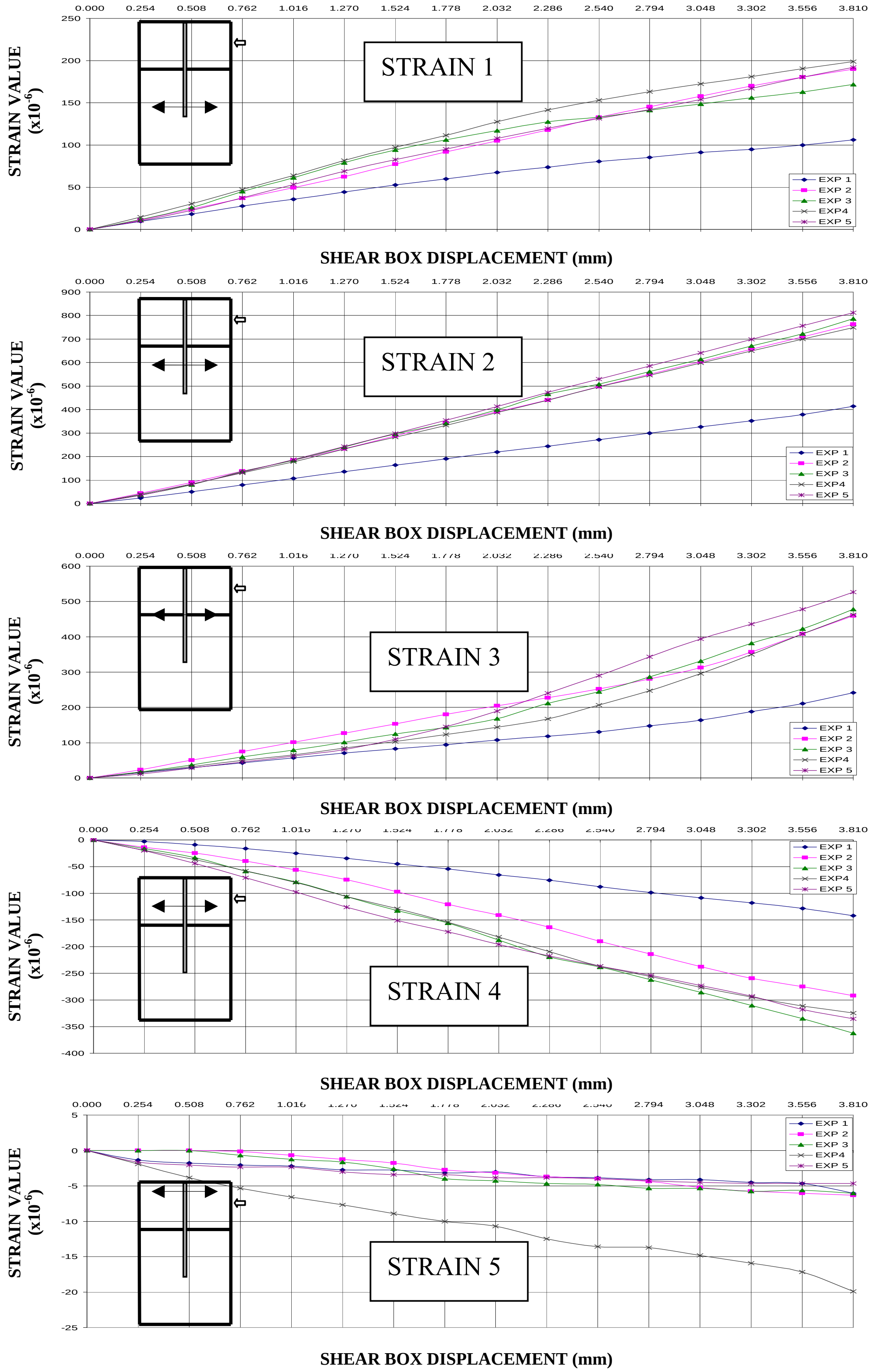


Figure 4.8 Single Test Results for Pile C

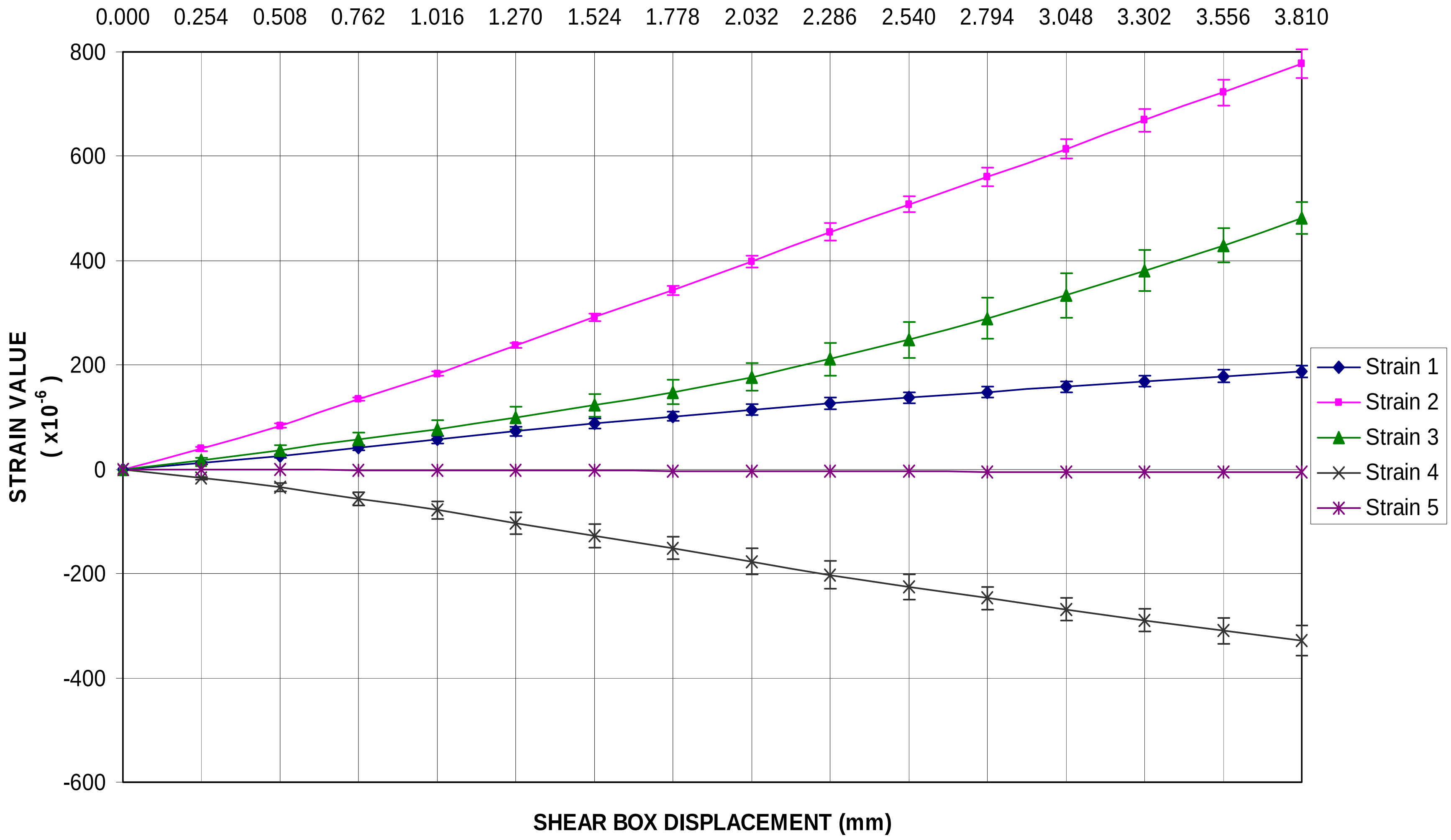


Figure 4.9 Average Pile C Response

4.1.4 Single Pile Tests for Pile D

Three lateral load tests were performed for “Pile D”. From Table A.16 to Table A.20 in Appendix A, the results are presented.

Load measurements of the Pile D experiments are summarized in Figure 4.10 below. It can be concluded that measured loads for Pile D in Experiment 1 is different from the ones in other experiments. Excluded strain values in average calculation are highlighted in the tables presented for Pile D in Appendix A.

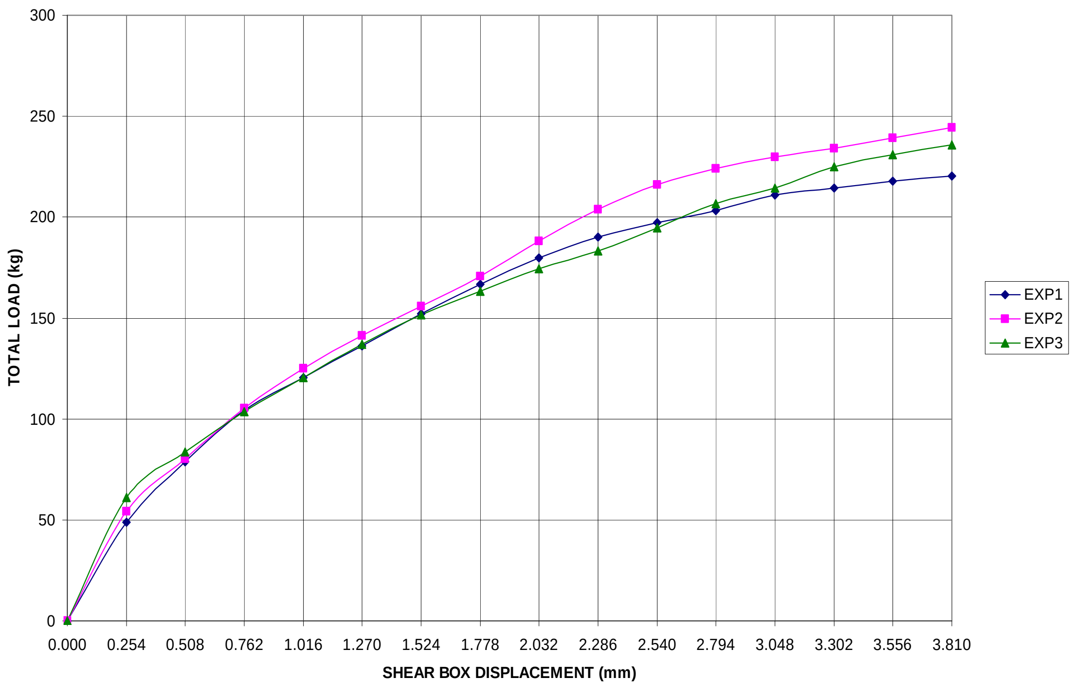


Figure 4.10 Load Measurements in Pile D Experiments

Figure 4.11 summarizes all strain readings. Average “Pile D” response which is the average strain values versus shear box displacement graph is given in Figure 4.12.

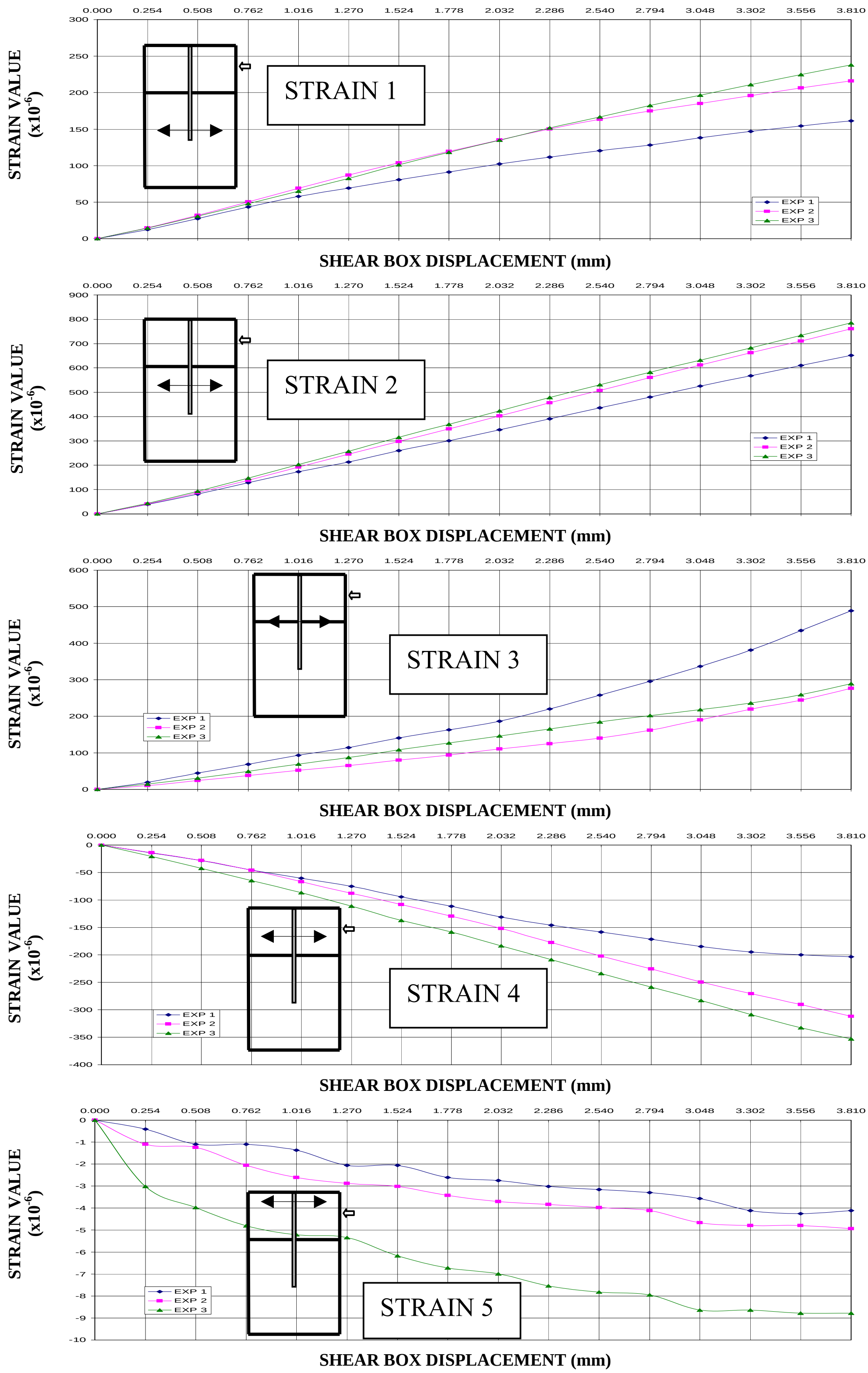


Figure 4.11 Single Test Results for Pile D

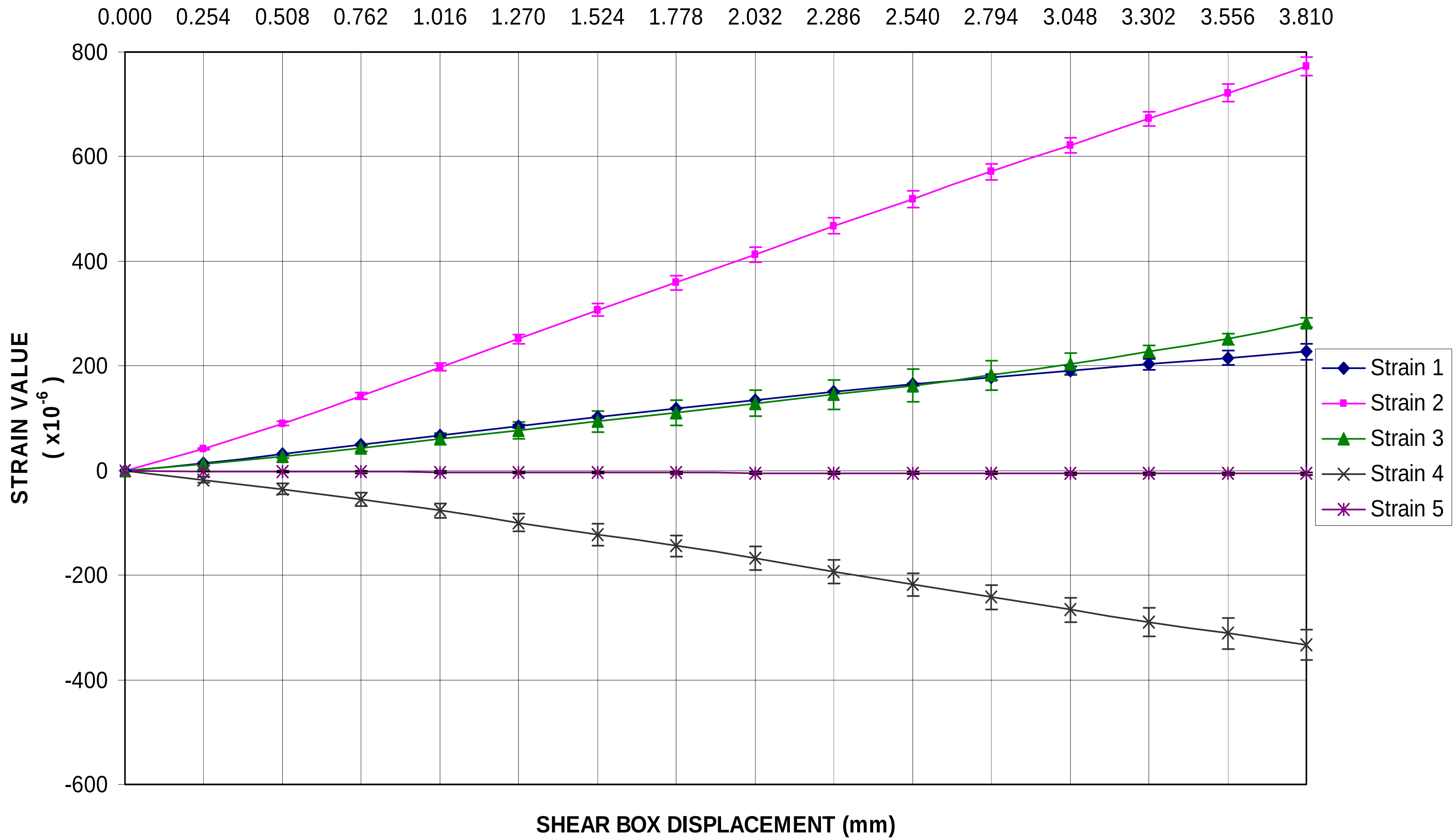


Figure 4.12 Average Pile D Response

4.1.5 Single Pile Tests for Pile E

For "Pile E", three single lateral load tests were performed. Table A.21, Table A.22, Table A.23, Table A.24 and Table A.25 in Appendix A summarize these tests results.

Load measurements for Pile E are summarized in Figure 4.13. Measured loads for Pile E in Experiment 2 are different from the ones in other experiments. The excluded values in average strain calculation are highlighted in the tables related to Pile E presented in Appendix A.

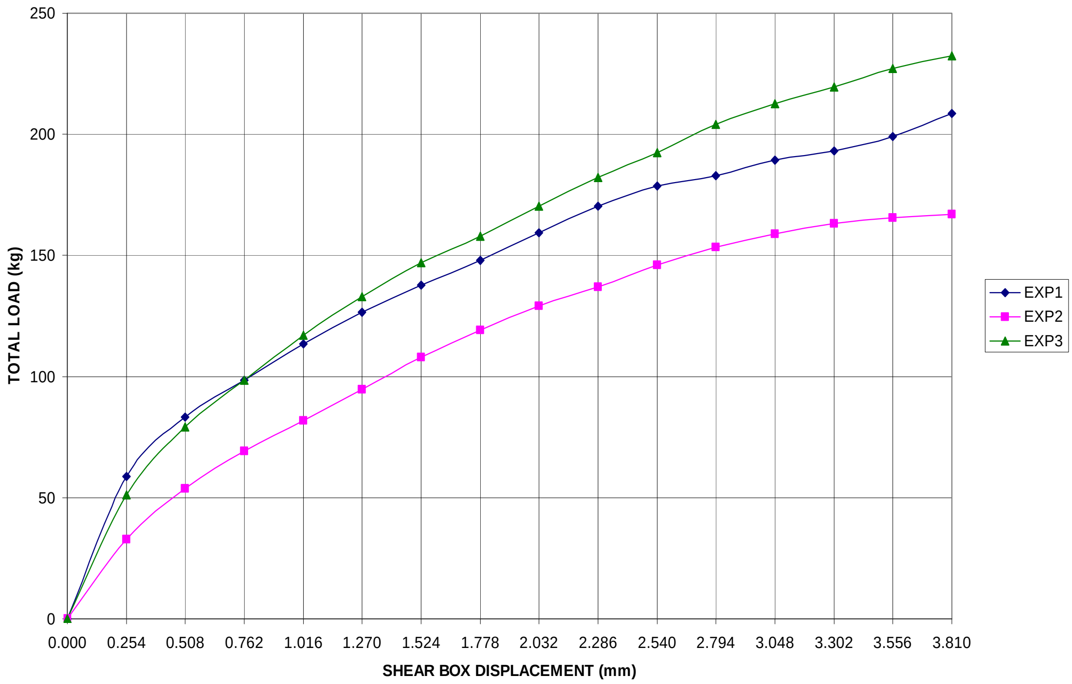


Figure 4.13 Load Measurements in Pile E Experiments

All strain readings are summarized in Figure 4.14. Average "Pile E" response is formed by using the average strain values and given in Figure 4.15.

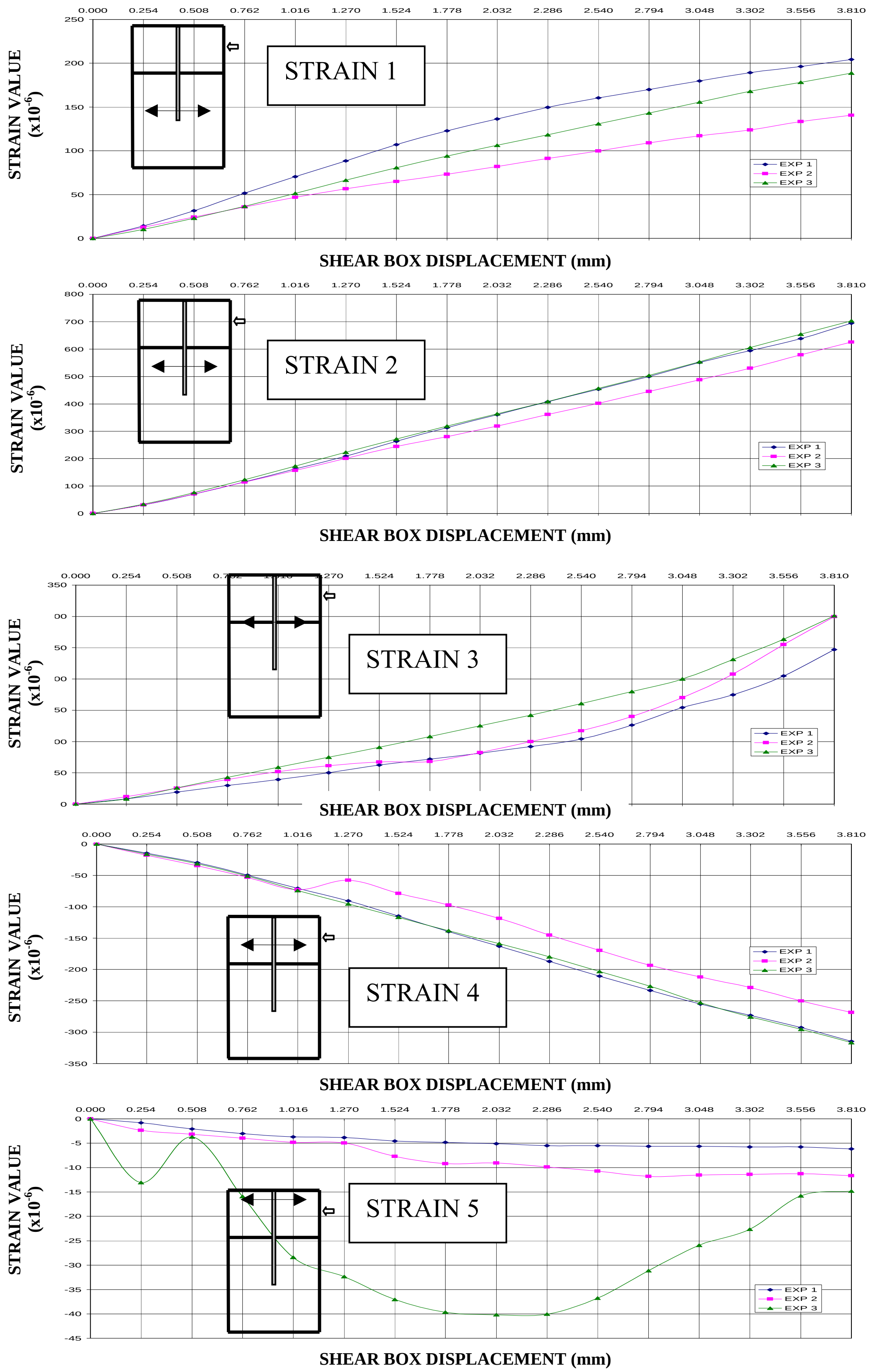


Figure 4.14 Single Test Results for Pile E

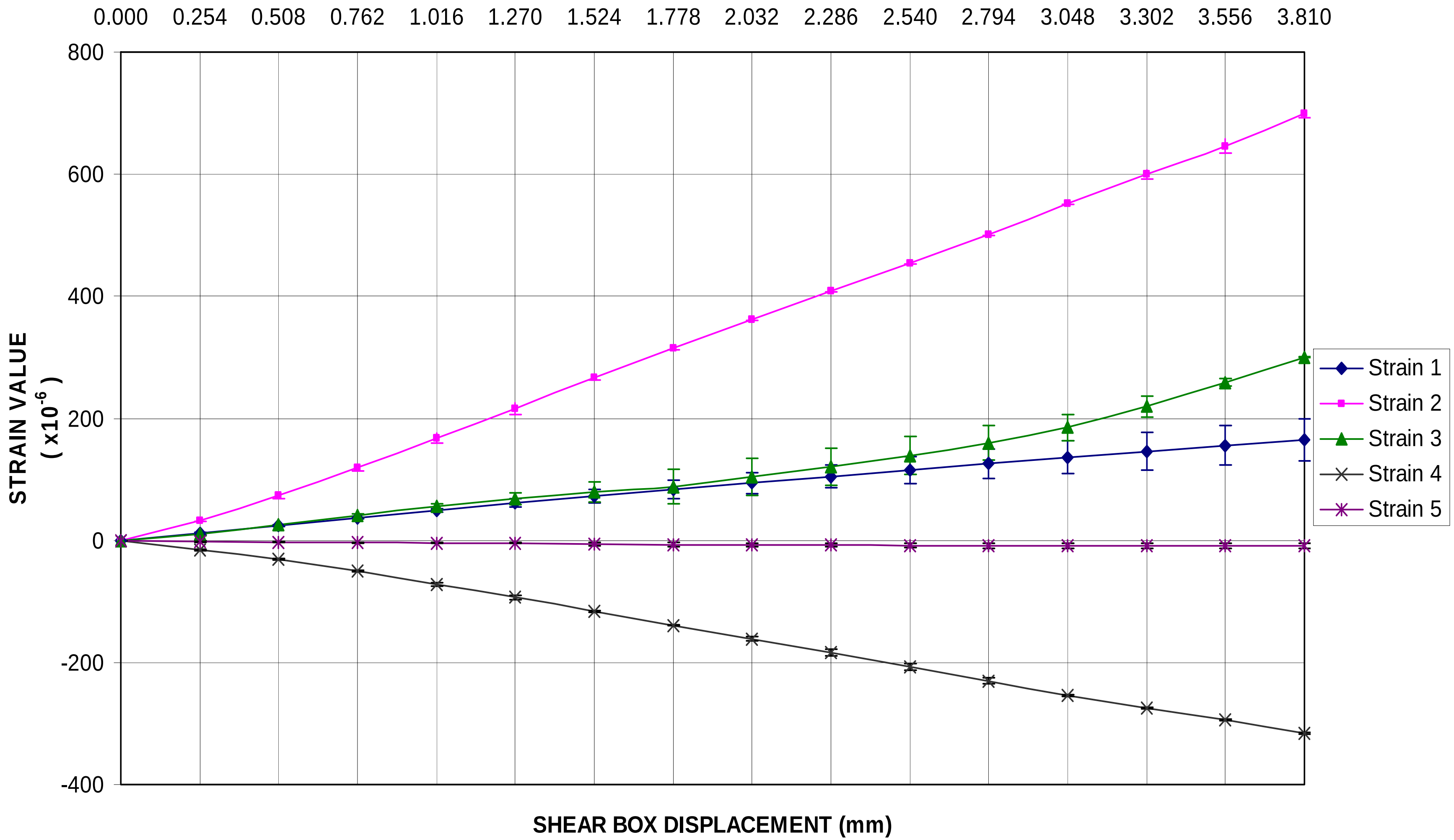


Figure 4.15 Average Pile E Response

4.1.6 Single Pile Test Results

Figure 4.16 summarizes the test results for different piles at shear box displacements of 1.016, 2.032 and 3.81 mm.

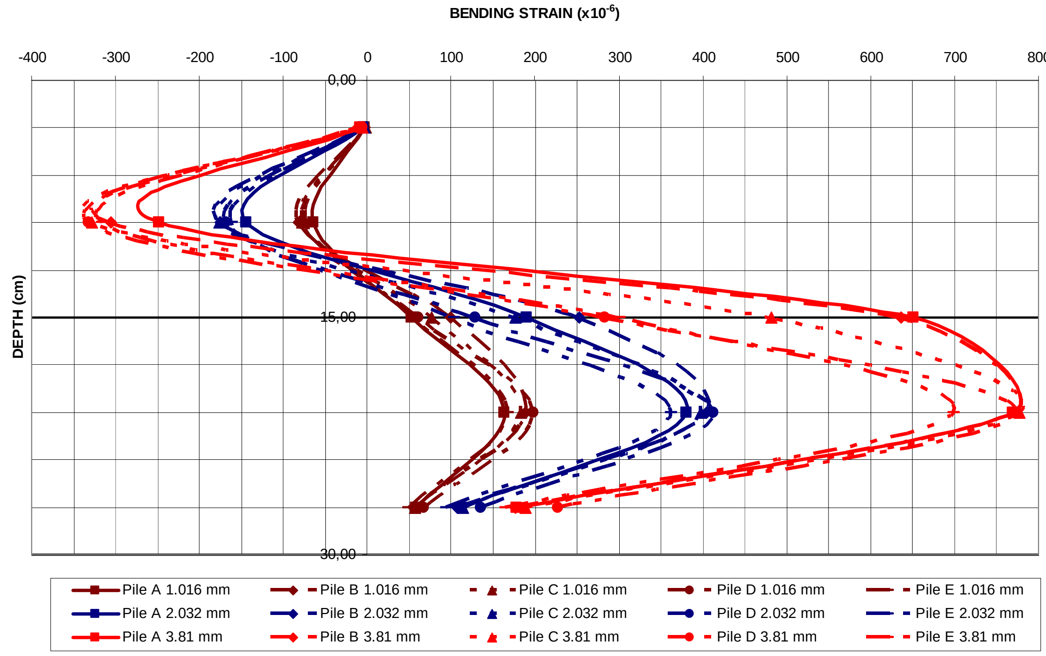


Figure 4.16 Single Pile Test Results for Different Piles at 0.1d, 0.2d and 0.38d Displacement of the Shear Box

As can be seen from Figure 4.16 the biggest strains occurred in the region where Strain Gauge 2 is fastened. Strain Gauge 3 gave the second biggest bending strains. Strain Gauge 4, Strain Gauge 1 and Strain Gauge 5 gave smaller strain magnitudes ($\varepsilon_{0.7L} > \varepsilon_{0.5L} > \varepsilon_{0.3L} > \varepsilon_{0.9L} > \varepsilon_{0.1L}$). Knowing that the upper part of shear box was moved during experiments, Strain Gauges 4 and 5 being in that region gave negative results whereas Strain Gauge 1, 2 and 3 gave positive values.

From Figure 4.16, it can also be concluded that the results are not so different except for Strain Gauge 3 level (0.5L=15cm). Strain Gauge 3 is the one fastened on the shear plane. The differences in placement of piles, testing differences may be the reason of big differences in the shearing plane. It may be possible that moment of inertia, I, of piles A,B,C,D and E are different due to different thicknesses and diameters of piles.

By using the strain values obtained from different piles, average bending strains are calculated. Average bending strains developed along single passive pile for 0.1d, 0.2d and 0.38d displacements of the shear box are in Figure 4.17 below.

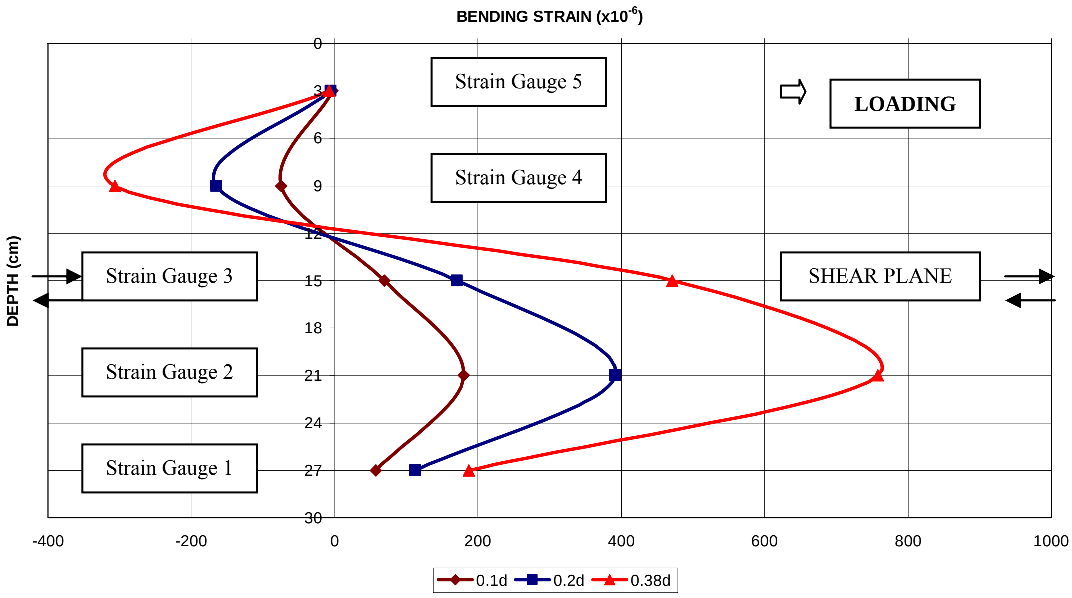


Figure 4.17 Average Single Pile Test Results at 0.1d,0.2d and 0.38d Displacement of the Shear Box

Single pile response is formed by using the pile responses obtained. Five single pile responses given in figures 4.3, 4.6, 4.9, 4.12 and 4.15 are averaged to obtain average single pile response given in Figure 4.18.

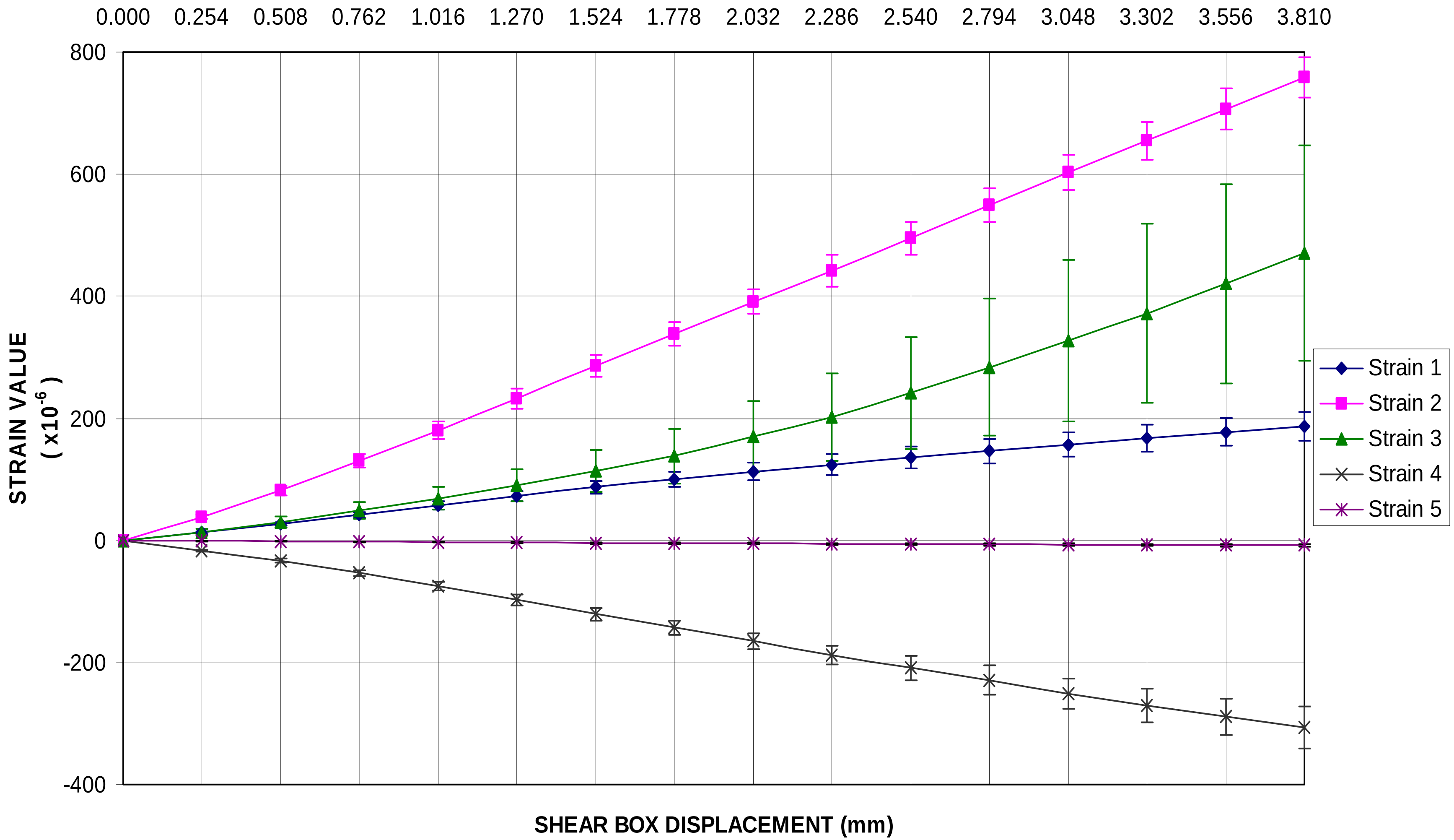


Figure 4.18 Average Single Pile Response

4.2 Pile Group Tests

Pile group tests were conducted in order to examine the pile behavior in a group and in order to understand the group action in laterally loaded passive piles. Test results of the single piles performed before were used together with the test results of pile group for that purpose.

Five different piles were used in the tests. The piles were placed with 3D (3xdiameter= 3 cm) spacing. The piles were connected with a pile cap with 15 cm width and 1 cm depth. The group testing model is given in Figure 4.19.

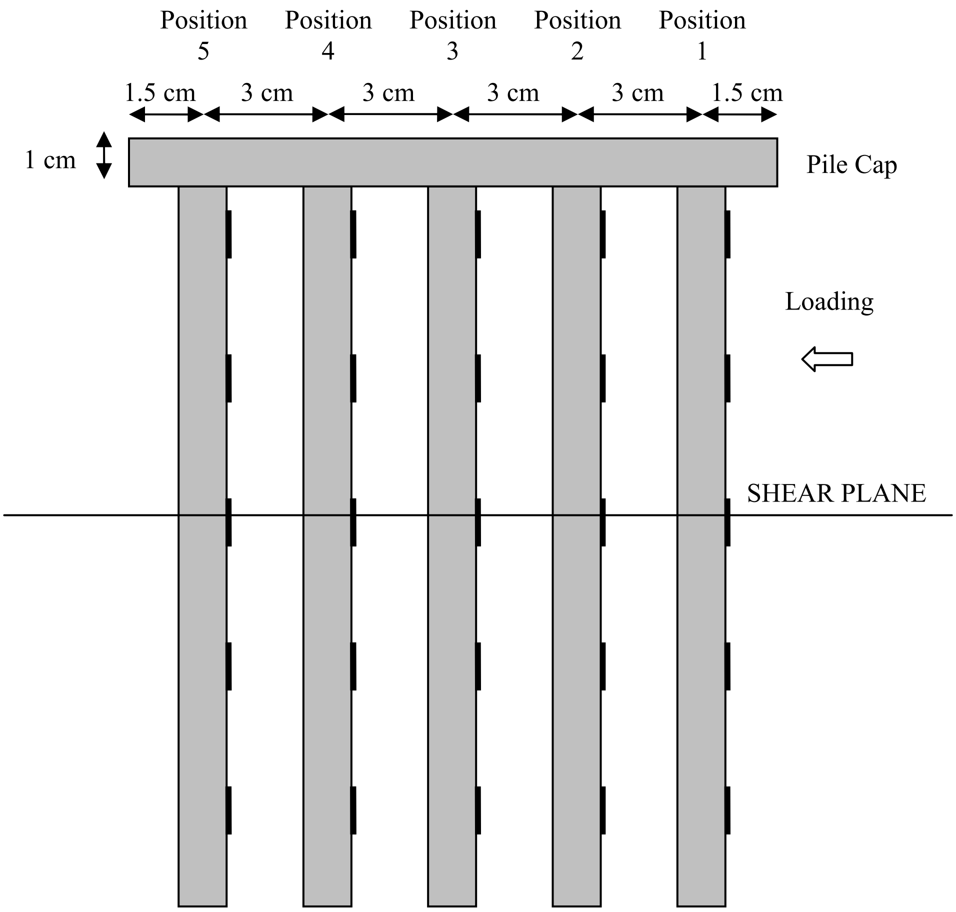


Figure 4.19 Typical Pile Group Model

Five lateral load tests were performed in order to provide all piles to be in all positions. The tests and the pile positions are summarized in Table 4.1.

Table 4.1 Pile Placement in Pile Group Tests

	Position 1	Position 2	Position 3	Position 4	Position 5
EXP 1	A	B	C	D	E
EXP 2	E	A	B	C	D
EXP 3	D	E	A	B	C
EXP 4	C	D	E	A	B
EXP 5	B	C	D	E	A

As can be seen from Table 4.1, all piles were tested in all positions at the end of five lateral load tests. When evaluating the test results, the bending strain values for a pile are collected from different experiments. To illustrate, Pile A was tested in position 1 during Experiment 1, in position 2 during Experiment 2, in position 3 during Experiment 3, in position 4 during Experiment 4 and in position 5 during Experiment 5. The results for Pile A are collected from these different experiments. Since results from different experiments are to be used, same experiment conditions should be guaranteed.

Load given to the system was measured during experiments and the readings are summarized in Figure 4.20. As figure implies, total loads applied to the system during different experiments are similar for small displacements of shear box. As the shear box movement increased, some differences appeared in the total load measurements, especially for Experiment 2 and Experiment 3.

The loads measured are the loads applied to shear the soil sample in the large shear box. The loads on the piles could not be measured during the experiments, but it can be said that only small part of these loads is carried by the piles since these loads displace a large shear box having 30 cm x 30 cm dimension. From Figure 4.20, it is obvious that there are some differences in the measured loads of the piles tested in Experiment 2 and Experiment 3. These may be due to factors like localized differences in density of soil samples. Therefore there may be some differences in the results collected for a pile from these experiments for large movements of the shear box.

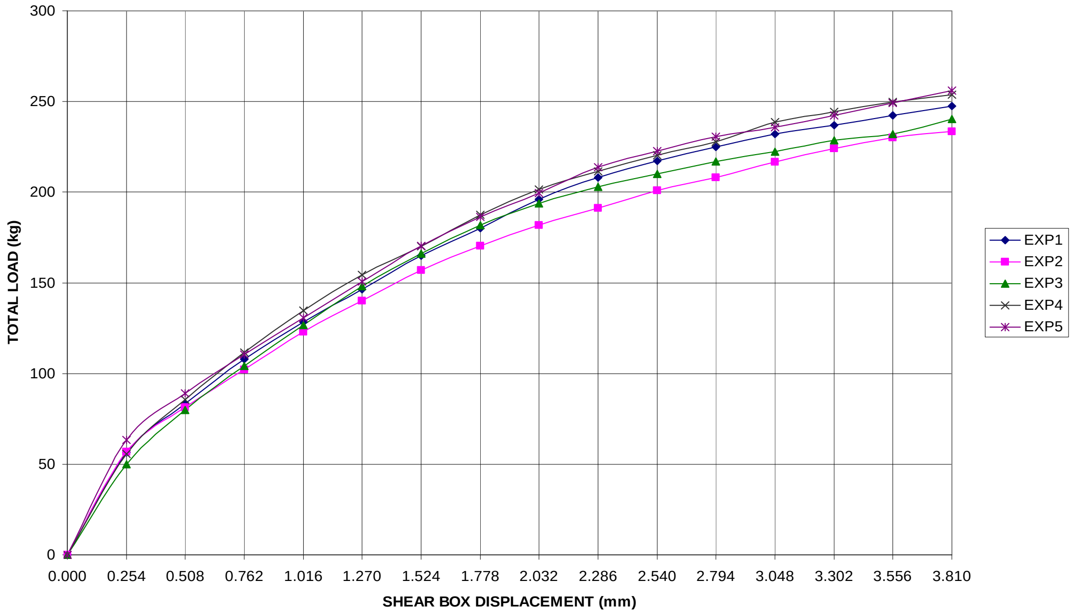


Figure 4.20 Load Measurements in Group Experiments

4.2.1 Strain Gauge Results

In this section , strain gauge results for strain gauges fastened at the same level for different piles and positions are presented. The results are given in five sub-sections. Strain Gauge 1 results for Pile A, Pile B, Pile C, Pile D and Pile E are presented in the first part of this section. The average bending strains developed at Strain Gauge 1 level are also presented in this part. Strain Gauge 2, Strain Gauge 3, Strain Gauge 4 and Strain Gauge 5 results for these piles are given in the following parts. In the last part, all results are summarized.

4.2.1.1 Strain Gauge 1 Results (Depth: 0.9L)

The Strain Gauge 1 readings of Pile A, Pile B, Pile C, Pile D and Pile E in various positions for increasing shear box movements obtained from group tests are summarized in Table B.1, B.2, B.3, B.4 and B.5 in Appendix B respectively.

Figure 4.21 summarizes Strain Gauge 1 readings for different piles. Five different graphs for five piles are presented together in order to examine the results easily. The change of bending strains on piles at 0.9L depth in different positions can be seen from Figure 4.21.

As can be seen from Figure 4.21 on the next page, up to a certain displacement of the shear box, all piles showed the same response under lateral loading. The results are numerically different but the behavior is similar. Results show that, for the depth where strain gauge 1 is fastened (0.9L), small displacement of shear box resulted in strain values numerically decreasing from position 1 to position 5 for all piles. In other words, the piles in the first position (the nearest position to the loading) had the highest strain values whereas the piles in the fifth position (the farthest position to the loading) had the lowest strain values for small displacement of the shear box.

As the shear box displacement increased, (which lead to increasing soil movement) some differences were observed in the pile responses. At large movements of the shear box, nearly constant strains were occurred for increasing soil movement at piles in various positions. For different piles, the position of this behavior changed which resulted in somewhat different results for large deformations.

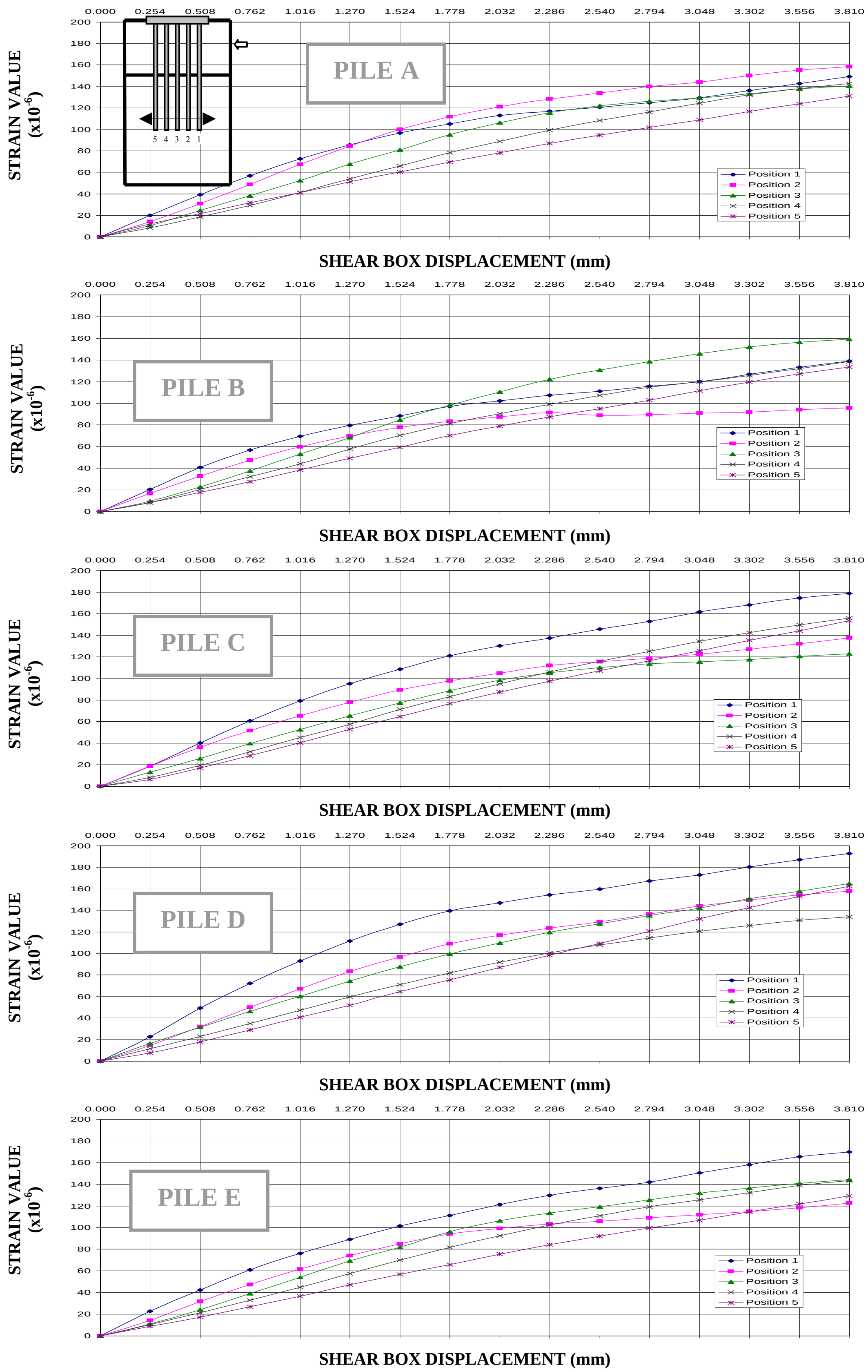


Figure 4.21 Strain Gauge 1 Readings in Group Tests

In order to compare the bending strains developed in different positions within a pile group in detail, average bending strains were calculated for the piles in different positions. For all positions, average strains developed for different shear box movements are given in Table 4.2 and in Figure 4.22.

Table 4.2 Average Bending Strains at 0.9L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1 ($x10^{-6}$)	POSITION 2 ($x10^{-6}$)	POSITION 3 ($x10^{-6}$)	POSITION 4 ($x10^{-6}$)	POSITION 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	20.99	15.69	12.15	9.40	8.60
0.508	42.33	32.72	25.78	20.53	18.24
0.762	61.56	49.04	40.15	32.26	28.73
1.016	**78.10**	**64.31**	**54.54**	**44.54**	**39.47**
1.270	92.23	77.95	69.05	57.32	50.49
1.524	104.49	89.79	82.57	69.71	61.20
1.778	114.78	99.23	95.51	81.25	71.58
2.032	**122.73**	**105.95**	**106.21**	**91.75**	**81.36**
2.286	129.15	111.71	115.28	101.47	90.87
2.540	134.72	114.67	121.97	110.08	99.60
2.794	140.54	118.78	127.84	117.99	108.31
3.048	146.90	122.68	132.91	124.94	117.01
3.302	153.90	126.71	138.07	131.76	125.75
3.556	160.62	130.85	142.73	137.91	134.02
3.810	**165.94**	**134.50**	**146.32**	**142.88**	**141.98**

The fact that the piles in position 1 carried the highest strain values and the piles in position 5 carried the lowest strain values for small displacements of the shear box described above can also be seen from Table 4.2 above and Figure 4.22.

For large movements of the shear box, Figure 4.22 indicates that the slope of the graphs for some pile positions, especially for 1, 2 and 3, starts to decrease showing that increasing movements resulted in small increases of bending strains. This behavior can also be seen from the figures for different piles presented in Figure 4.21.

From Figure 4.22, it can also be seen that for all displacements of the shear box, the biggest bending strains are developed in position 1 and the lowest bending strains are developed mostly in position 5.

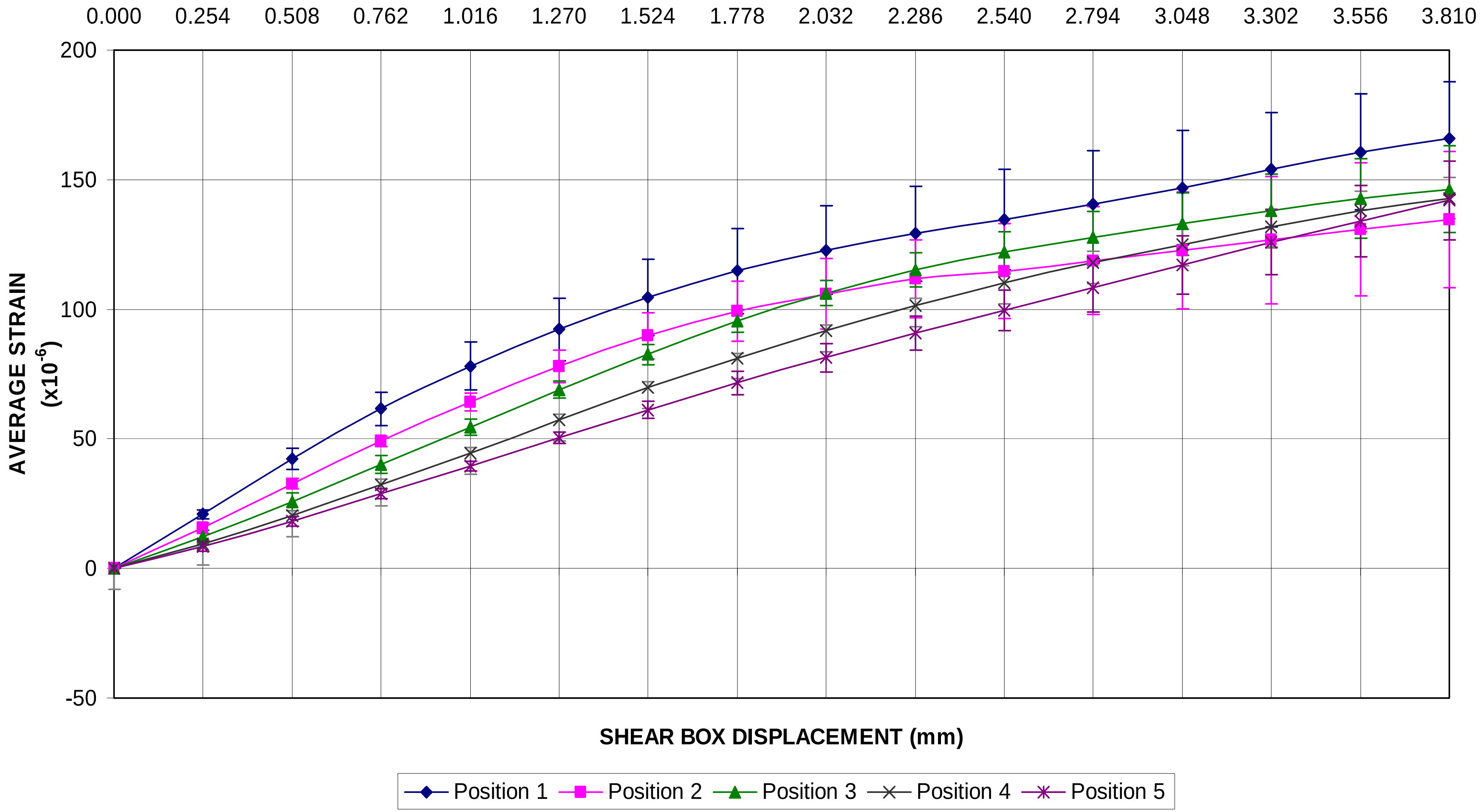


Figure 4.22 Average Strain Values for Strain Gauge 1 Level (0.9L) in Group Tests

The change of the bending strains within a pile group from one position to another position is presented in Figure 4.23 for 0.1d, 0.2d and 0.38d displacements of shear box.

Passive piles which are designed properly do not let large soil movements and they are subjected to small soil movements. For that purpose, the results of small displacements like 0.1d movement of shear box are more critical for passive piles.

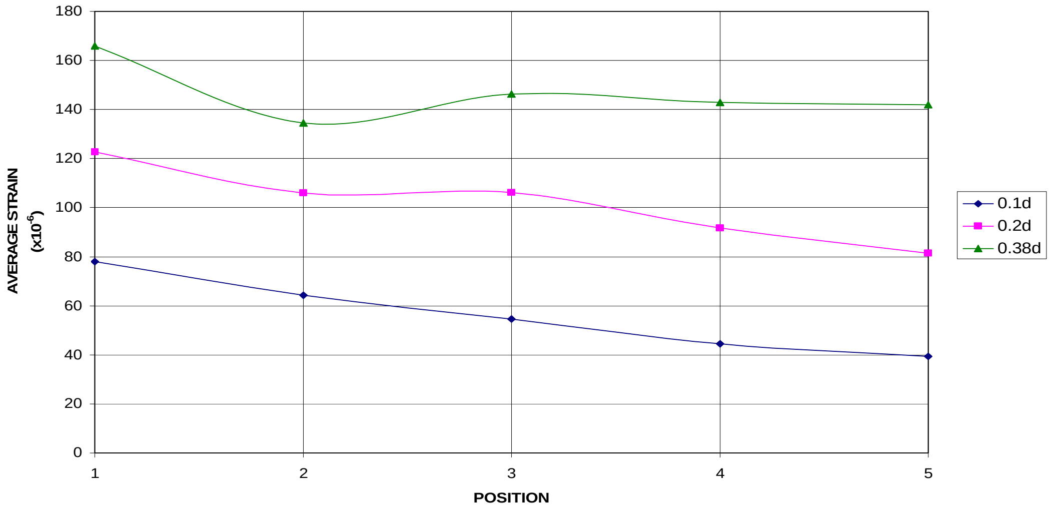


Figure 4.23 Average Strain Values at 0.9L Depth for Different Positions
(0.1d, 0.2d and 0.38d Displacement of the Shear Box)

From Figure 4.23, it is clear that for 0.1d displacement of shear box average bending strains developed at 0.9L are decreasing from position 1 to position 5 as mentioned before.

For 0.2d displacement of shear box, bending strains decrease from Position 1 to Position 2, remain constant in position 3 and start to decrease from position 3 to position 5.

For 0.38d displacement of shear box, it is obvious that strain values for position 3, position 4 and position 5 are nearly same with values larger than the values for position 2 and smaller than the values for position 1.

4.2.1.2 Strain Gauge 2 Results (Depth: 0.7L)

The Strain Gauge 2 readings of different piles for different positions in group testing are presented in Table B.6, B.7, B.8, B.9 and B.10 in Appendix B respectively.

In Figure 4.24 on the next page, the results for Strain Gauge 2 are summarized. Strain Gauge 2 is the gauge that gave the biggest strain values which means that the biggest bending strains were measured from Strain Gauge 2 fastened at 0.7L.

As can be seen from the figure 4.24, small displacements of the shear box for 0.7L depth lead to development of maximum bending strains on the piles in the first position. The order of bending strains is similar to each other for different piles for small soil movements. Bending strains, being the maximum for position 1, decrease up to 3rd or 4th position and then start to show small increase for the last positions.

As the soil movements increase, higher bending strains developed for the last positions. The pile in position 5 had the highest bending strain. For large soil movements, the behavior of bending strains are reversed which means that bending strains, being the maximum for position 5, decrease up to position 2 and then start to show small increase for position 1.

By using the results obtained from five different piles, average strains are calculated for different positions. Figure 4.25 graphically summarizes the average bending strains developed for different positions at 0.7L depth. The calculated average bending strains are given in Table 4.3.

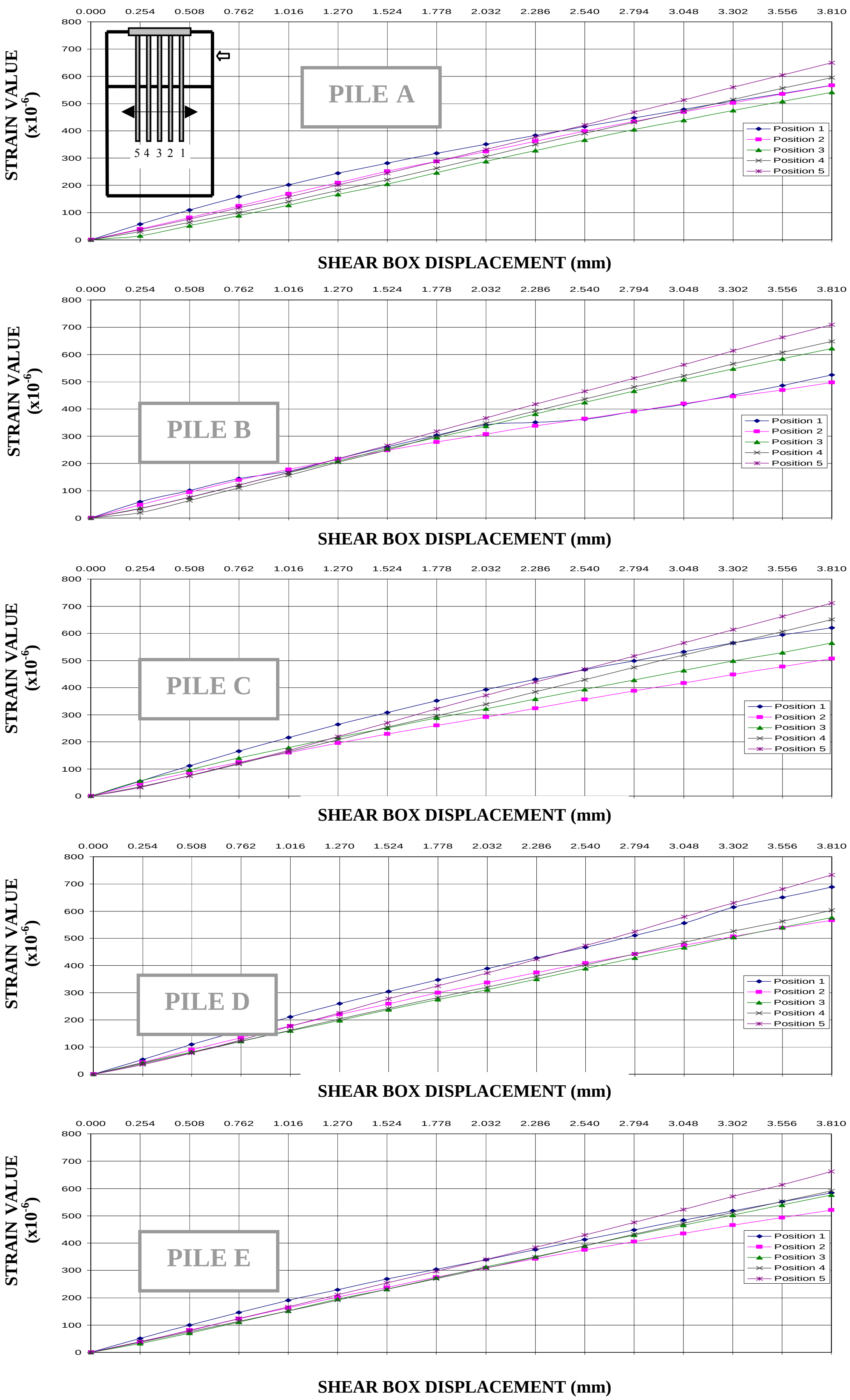


Figure 4.24 Strain Gauge 2 Readings in Group Tests

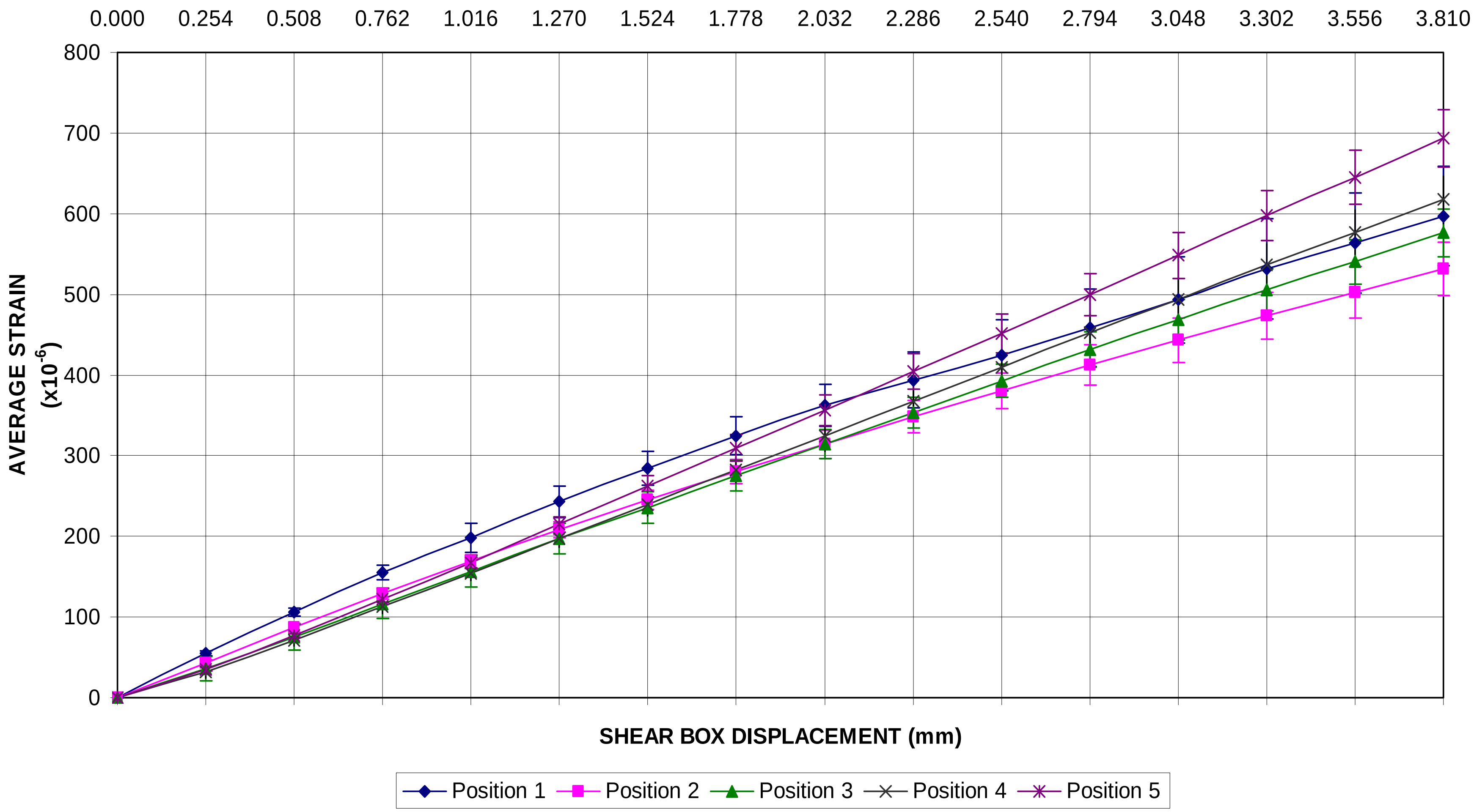


Figure 4.25 Average Strain Values for Strain Gauge 2 Level (0.7L) in Group Tests

Table 4.3 Average Bending Strains at 0.7L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1 ($x10^{-6}$)	POSITION 2 ($x10^{-6}$)	POSITION 3 ($x10^{-6}$)	POSITION 4 ($x10^{-6}$)	POSITION 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	55.13	43.00	36.04	31.78	35.41
0.508	106.16	86.66	75.02	71.19	76.96
0.762	155.18	128.87	116.36	112.68	121.86
1.016	**197.98**	**169.10**	**156.63**	**154.61**	**167.42**
1.270	242.97	208.37	196.98	197.49	214.91
1.524	284.66	245.05	235.71	239.67	262.31
1.778	324.79	280.29	275.46	282.09	309.65
2.032	**362.69**	**313.92**	**314.30**	**323.99**	**356.45**
2.286	393.84	348.30	353.58	367.02	404.34
2.540	424.60	380.38	392.61	409.57	451.44
2.794	458.99	412.37	431.21	452.22	499.47
3.048	493.38	443.12	468.43	494.12	548.22
3.302	531.64	473.71	505.57	536.70	597.76
3.556	564.02	502.66	540.49	577.12	644.94
3.810	**597.09**	**531.68**	**576.33**	**617.71**	**693.38**

As can be seen from Table 4.3 above and Figure 4.25, maximum bending strains are developed on the piles in position 1 for small displacements of the shear box as indicated before. For small displacements, bending strains being the maximum for position 1 decrease up to position 4 and then show a small increase for the last position.

For large displacement values of shear box, in the last positions higher bending strains start to be developed. Firstly the bending strain developed in position 5 becomes greater than the bending strain developed in position 1. As soil movements continue to increase, bending strains developed in position 4 also become greater than the ones developed in position 1. Bending strains for large movements of shear box decrease from position 1 to position 2 and start to increase from that position to the last position.

The change of the bending strains developed at 0.7L depth within a pile group from one position to another position is presented in Figure 4.26 for 0.1d, 0.2d and 0.38d displacements of shear box.

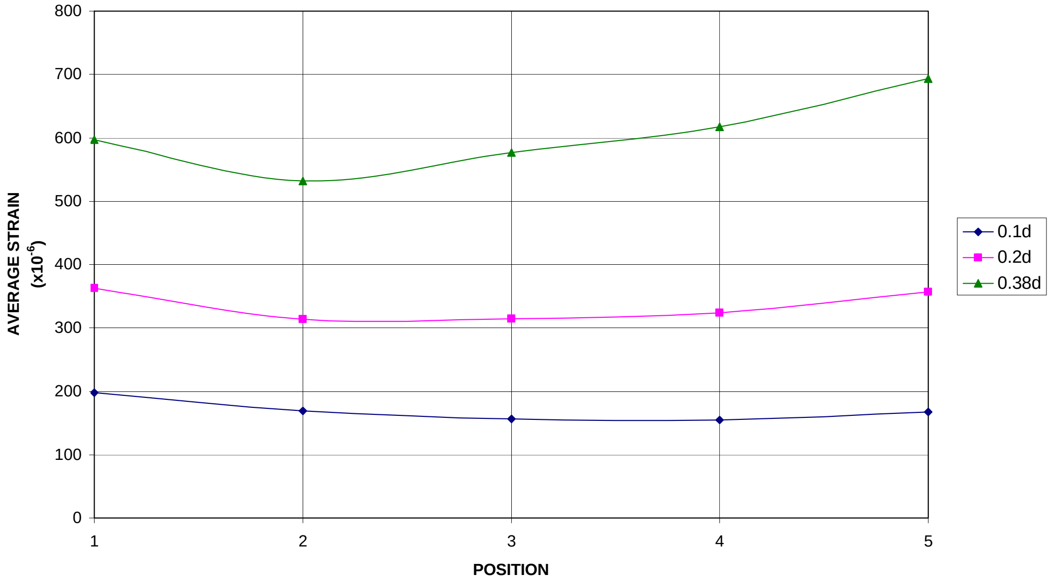


Figure 4.26 Average Strain Values at 0.7L Depth for Different Positions
(0.1d, 0.2d and 0.38d Displacement of the Shear Box)

From Figure 4.26, it is clear that for 0.1d displacement of shear box average bending strains developed at 0.7L are decreasing from position 1 to position 5 as mentioned before. The maximum bending strains are developed in position 1.

For 0.2d displacement of shear box, bending strains decrease from Position 1 to Position 3, and start to increase from position 3 to position 5. The maximum bending strains are developed in position 1. But the value in position 5 is close to the one in position 1.

For 0.38d displacement of shear box, bending strains decrease from Position 1 to Position 3, and start to increase from position 3 to position 5. The maximum bending strains are developed in position 5.

4.2.1.3 Strain Gauge 3 Results (Depth: 0.5L)

Table B.11, B.12, B.13, B.14 and B.15 in Appendix B present the Strain Gauge 3 readings at different positions for Pile A, Pile B, Pile C, Pile D and Pile E in group testing respectively. Figure 4.27 summarizes Strain Gauge 3 readings for different piles.

No readings were taken from Pile C in position 5 at 0.5L depth (Table B.15). Strain gauge fastened at this depth could not be connected to data acquisition system since 24-channeled data acquisition system is used with 25 strain gauges.

As can be seen from Figure 4.27, for all displacement values of the shear box, the behavior of bending strains developed at 0.5L are similar for different piles. The strain values increase from position 1 to position 5. Maximum bending strains are developed on the piles in the last position whereas the smallest bending strains are developed on the piles in the first position.

Although the behavior is same, the results are numerically different from one pile to another. Since Strain Gauge 3 is the one fastened at the shearing plane, the differences between piles and experiments might resulted in numerical differences.

From Figure 4.27, it can also be concluded that for small displacements the piles in position 1 show bending strains near to zero. Moreover for some piles bending strains developed in position 1 become positive for some displacement values and start to decrease and become negative at large soil movements.

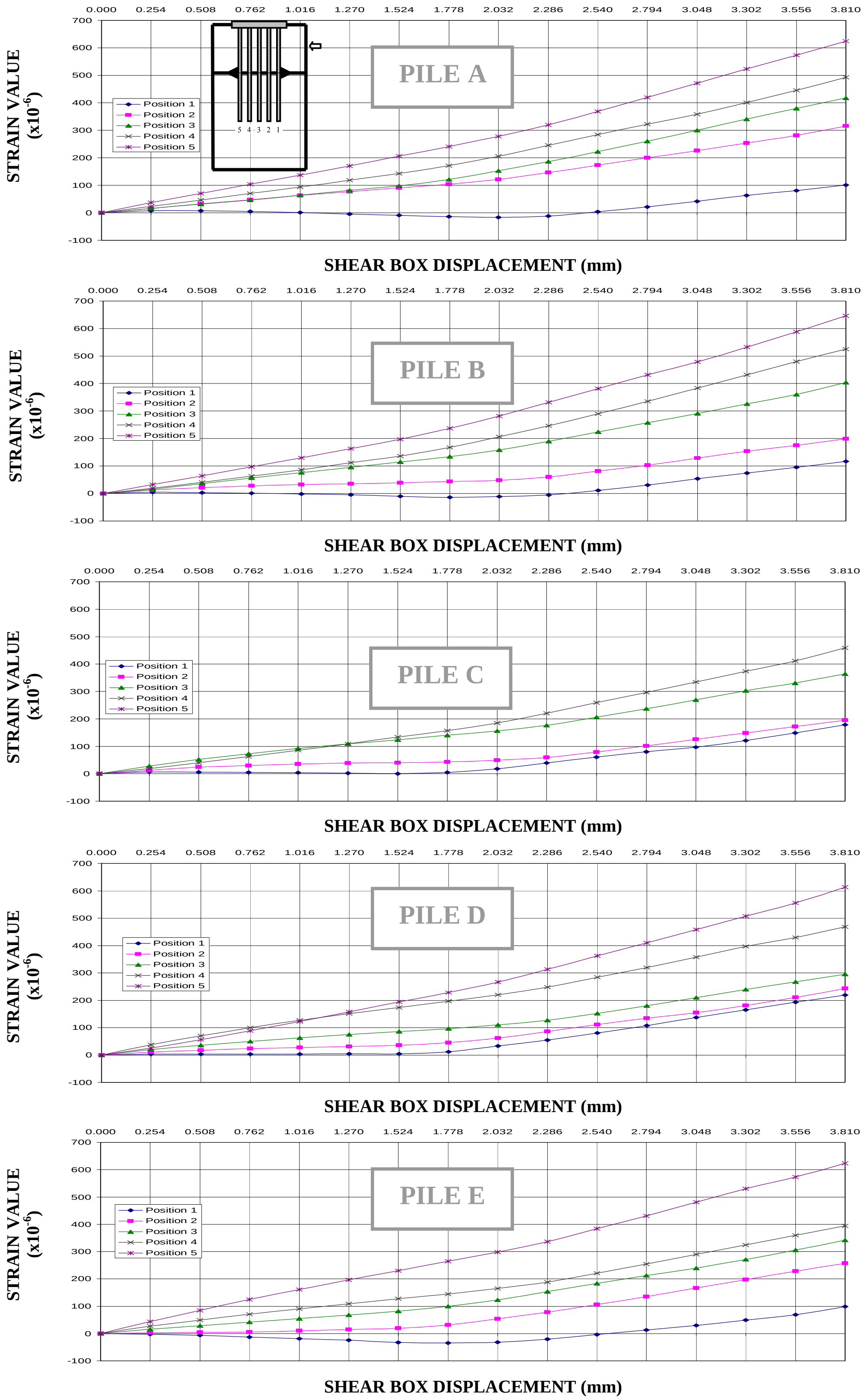


Figure 4.27 Strain Gauge 3 Readings in Group Tests

Average strains calculated at 0.5L depth for different positions are given in Table 4.4. Figure 4.28 and 4.29 graphically summarize the average bending strains developed for different positions at 0.5L depth.

Table 4.4 Average Bending Strains at 0.5L Depth

SHEAR BOX DISPLACEMENT (mm)	**POSITION 1 ($x10^{-6}$)**	**POSITION 2 ($x10^{-6}$)**	**POSITION 3 ($x10^{-6}$)**	**POSITION 4 ($x10^{-6}$)**	**POSITION 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	0.00
0.254	3.66	10.96	18.87	25.15	34.68
0.508	2.45	20.01	36.80	49.43	68.83
0.762	0.08	26.81	53.53	73.07	103.44
1.016	**-2.42**	**33.66**	**69.87**	**96.47**	**137.46**
1.270	-5.63	39.63	85.66	119.94	172.00
1.524	-9.43	45.17	100.96	142.74	206.98
1.778	-9.23	53.28	118.24	167.61	242.52
2.032	**-1.98**	**66.93**	**140.10**	**196.50**	**281.04**
2.286	11.07	86.14	166.49	229.66	325.15
2.540	30.50	110.21	197.72	267.48	374.01
2.794	50.48	134.65	229.53	305.41	422.79
3.048	71.80	160.17	262.10	344.69	472.20
3.302	94.42	187.09	295.80	385.12	523.21
3.556	117.20	213.29	328.76	425.03	572.44
3.810	**142.67**	**242.01**	**364.63**	**467.84**	**626.89**

The average bending strains calculated for different positions (Figure 4.28) and displacements of the shear box (Figure 4.29) also indicate that the bending strains increase from position 1 to position 5.

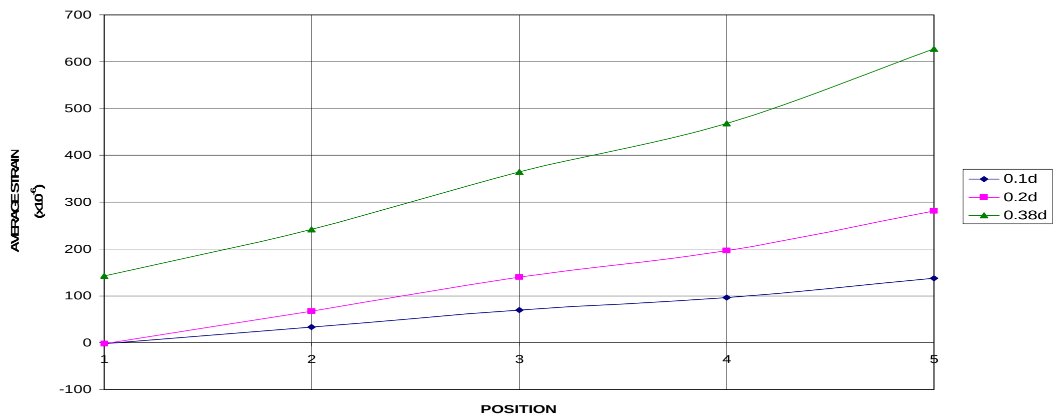


Figure 4.28 Average Strain Values at 0.5L Depth for Different Positions (0.1d, 0.2d and 0.38d Displacement of the Shear Box)

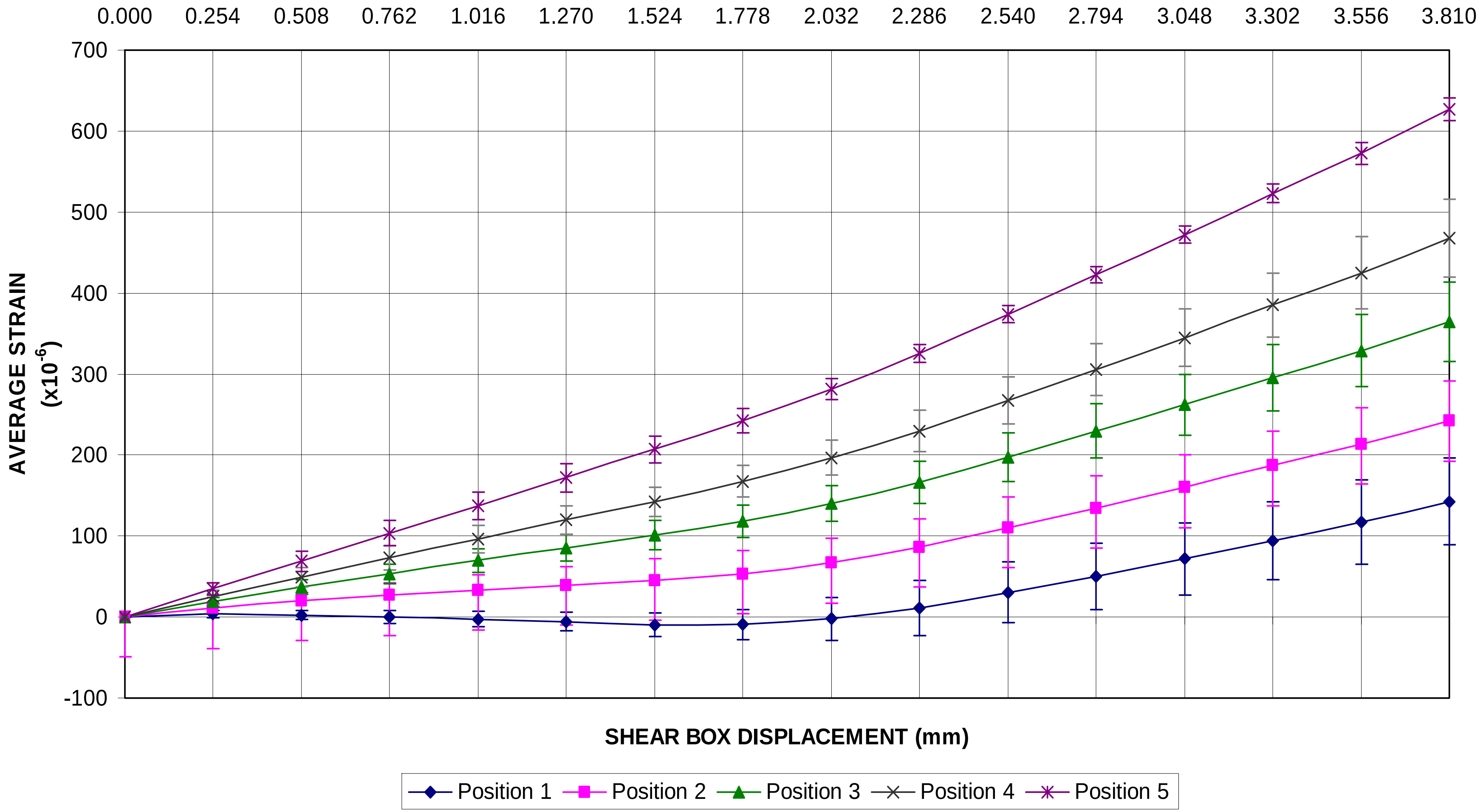


Figure 4.29 Average Strain Values for Strain Gauge 3 Level (0.5L) in Group Tests

4.2.1.4 Strain Gauge 4 Results (Depth: 0.3L)

The Strain Gauge 4 readings of Pile A, Pile B, Pile C, Pile D and Pile E for different positions in group testing are presented in Table B.16, B.17, B.18, B.19 and B.20 in Appendix B respectively.

Figure 4.30 summarizes the pile responses at the depth where Strain Gauge 4 is fastened. As can be seen from this figure on the next page, for small displacement values of the shear box, strain values decrease from position 1 to position 3. Generally from position 3 to position 4, the strain values continue to decrease and from position 4 to position 5 the strain values increase. However for some piles there exist differences in that behavior. For Pile C, strain values increase from position 3 to position 4 and decrease from position 4 to position 5. For Pile E, strain values increase from position 3 to position 4.

At large displacements of the shear box, the behavior is similar to the behavior at small displacements. Strain values decrease from position 1 to position 3. The strain values in position 4 can be smaller or larger than the values obtained in position 3. Strain values in position 5 are generally larger than the values obtained in position 3 and position 4.

Average strains at 0.3L depth calculated for different positions are given in Table 4.5.

Figure 4.31 summarizes the average bending strain values developed at 0.3L for 0.1d, 0.2d and 0.38d displacement of the shear box. Figure 4.32 graphically summarizes the average bending strains developed for different positions at 0.3L depth.

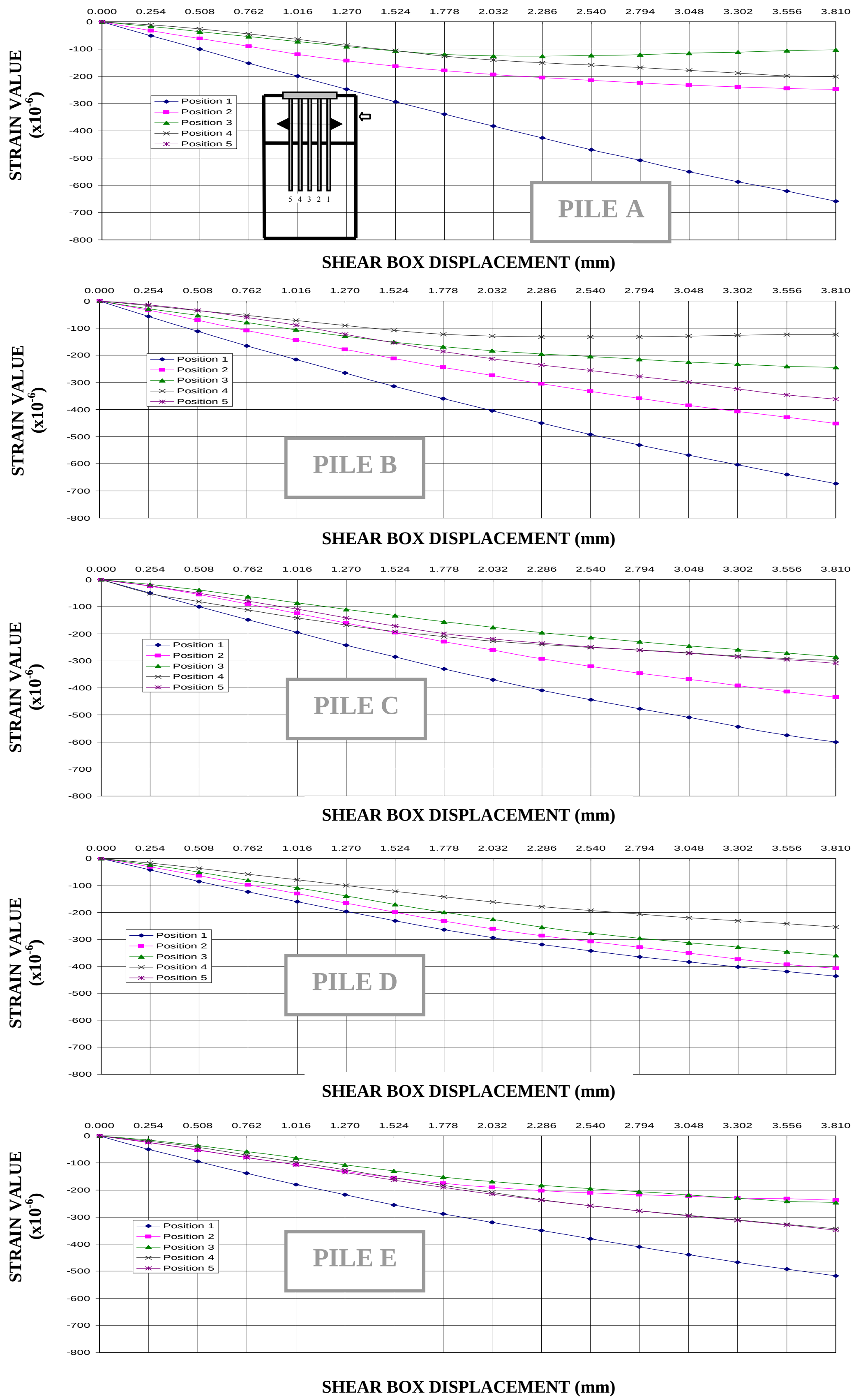


Figure 4.30 Strain Gauge 4 Readings in Group Tests

Table 4.5 Average Bending Strains at 0.3L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1 ($x10^{-6}$)	POSITION 2 ($x10^{-6}$)	POSITION 3 ($x10^{-6}$)	POSITION 4 ($x10^{-6}$)	POSITION 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-49.87	-28.77	-20.35	-23.06	-20.43
0.508	-98.31	-60.66	-42.64	-44.17	-45.44
0.762	-145.54	-93.19	-66.64	-67.61	-73.18
1.016	**-190.05**	**-124.73**	**-90.61**	**-90.47**	**-101.52**
1.270	-233.80	-155.78	-114.94	-113.86	-133.06
1.524	-276.03	-184.85	-137.98	-136.42	-162.68
1.778	-316.26	-212.13	-158.93	-156.93	-192.07
2.032	**-354.21**	**-235.93**	**-175.88**	**-173.32**	**-216.10**
2.286	-390.92	-257.97	-190.73	-187.61	-236.44
2.540	-425.77	-277.43	-202.54	-198.35	-254.31
2.794	-458.42	-295.06	-213.33	-208.58	-272.22
3.048	-490.05	-311.88	-223.16	-218.01	-289.22
3.302	-520.81	-327.89	-232.25	-227.74	-307.09
3.556	-549.34	-342.38	-240.90	-236.46	-323.49
3.810	**-577.27**	**-355.72**	**-247.71**	**-244.06**	**-340.08**

From Table 4.5 and Figure 4.32, it is clear that for all displacement values of the shear box, negative bending strains developed and the bending strains numerically decrease from position 1 to position 3. The average bending strain values obtained in position 4 are close the values obtained in position 3. At last position, the average bending strains increase.

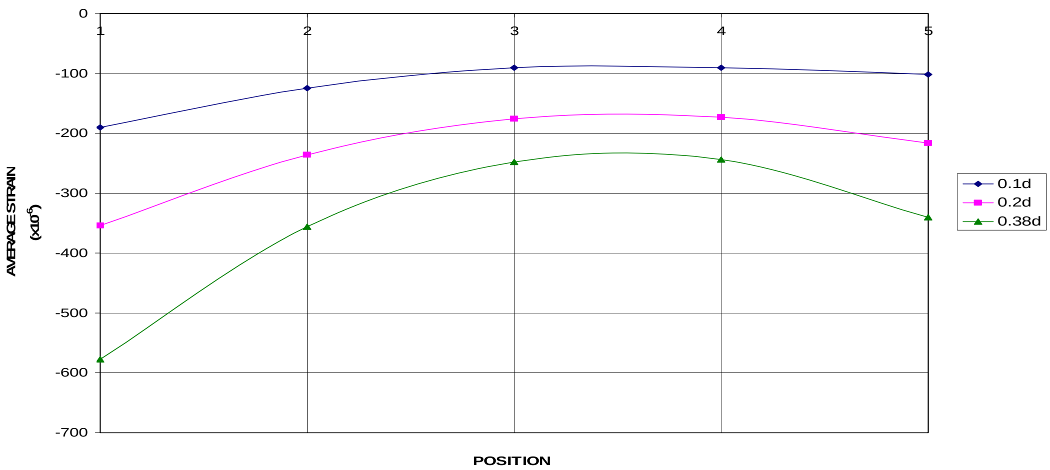


Figure 4.31 Average Strain Values at 0.3L Depth for Different Positions
(0.1d, 0.2d and 0.38d Displacement of the Shear Box)

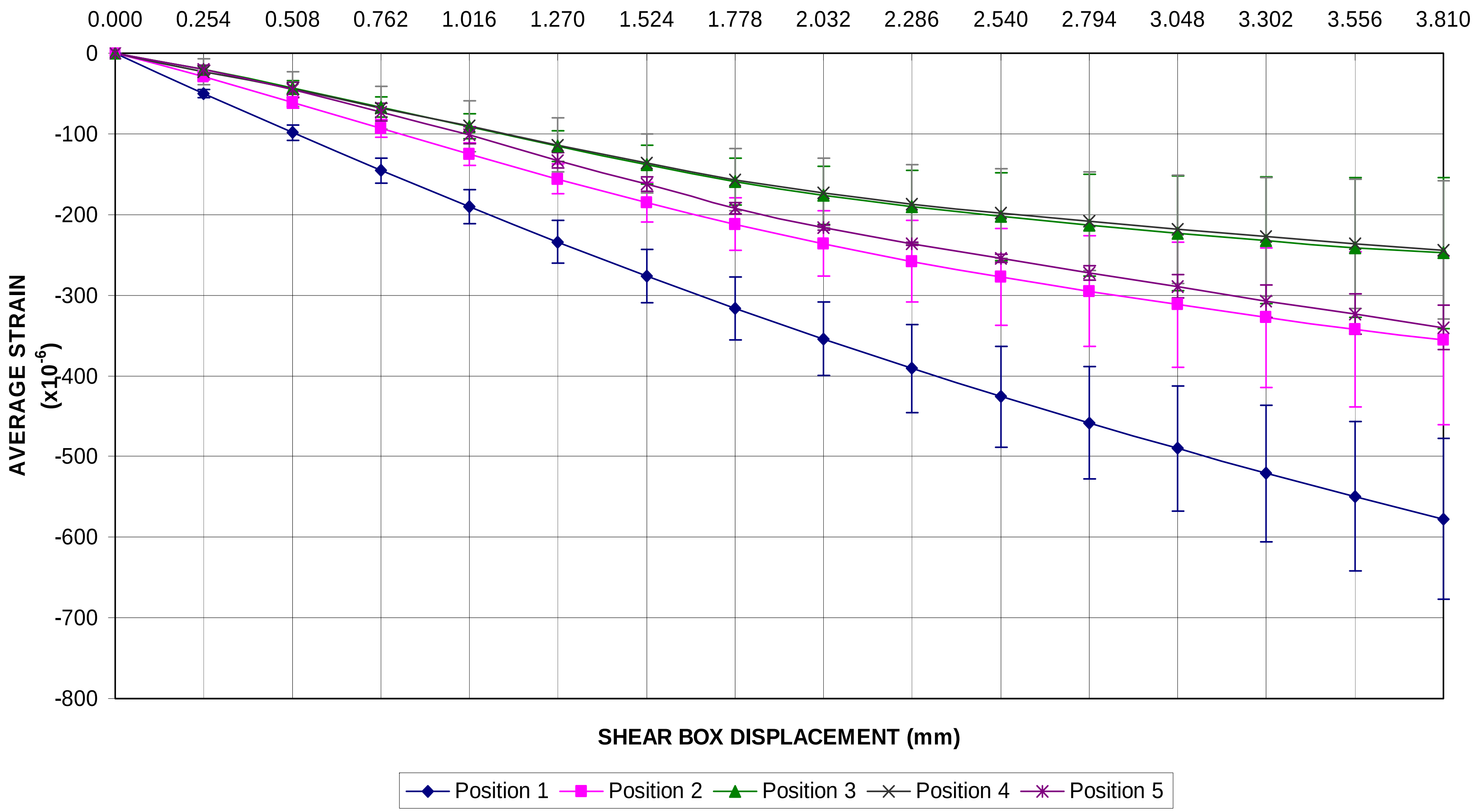


Figure 4.32 Average Strain Values for Strain Gauge 4 Level (0.3L) in Group Tests

4.2.1.5 Strain Gauge 5 Results (Depth:0.1L)

The Strain Gauge 5 readings of Pile A, Pile B, Pile C, Pile D and Pile E for different positions in group testing are summarized in Table B.21, B.22, B.23, B.24 and B.25 in Appendix B respectively. Figure 4.33 summarizes Strain Gauge 5 readings for different piles.

It is clear that the strain values for different piles in same position differ from each other. Since Strain Gauge 5 is fastened near the pile head, pile-cap connection conditions may have affected the results. Despite these differences, average bending strains developed at 0.1L are calculated and given in Table 4.6.

Table 4.6 Average Bending Strains at 0.1L Depth

SHEAR BOX DISPLACEMENT (mm)	**POSITION 1 ($x10^{-6}$)**	**POSITION 2 ($x10^{-6}$)**	**POSITION 3 ($x10^{-6}$)**	**POSITION 4 ($x10^{-6}$)**	**POSITION 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-29.41	-35.09	-31.64	-29.17	-43.66
0.508	-58.16	-67.63	-58.31	-58.10	-82.62
0.762	-85.53	-93.77	-80.72	-71.17	-111.03
1.016	**-111.18**	**-112.25**	**-99.63**	**-87.03**	**-133.55**
1.270	-135.74	-125.25	-114.80	-108.06	-153.23
1.524	-157.13	-135.99	-128.49	-131.43	-170.86
1.778	-175.98	-145.08	-140.40	-142.93	-186.94
2.032	**-192.82**	**-154.27**	**-152.72**	**-159.84**	**-201.14**
2.286	-209.14	-164.38	-165.46	-172.58	-215.94
2.540	-223.66	-175.53	-180.32	-185.68	-230.33
2.794	-236.96	-185.31	-194.18	-197.15	-243.80
3.048	-249.72	-195.05	-207.57	-208.88	-256.86
3.302	-260.74	-204.31	-220.61	-224.77	-269.24
3.556	-270.54	-213.60	-233.72	-236.71	-281.39
3.810	**-280.50**	**-223.65**	**-249.20**	**-252.94**	**-293.99**

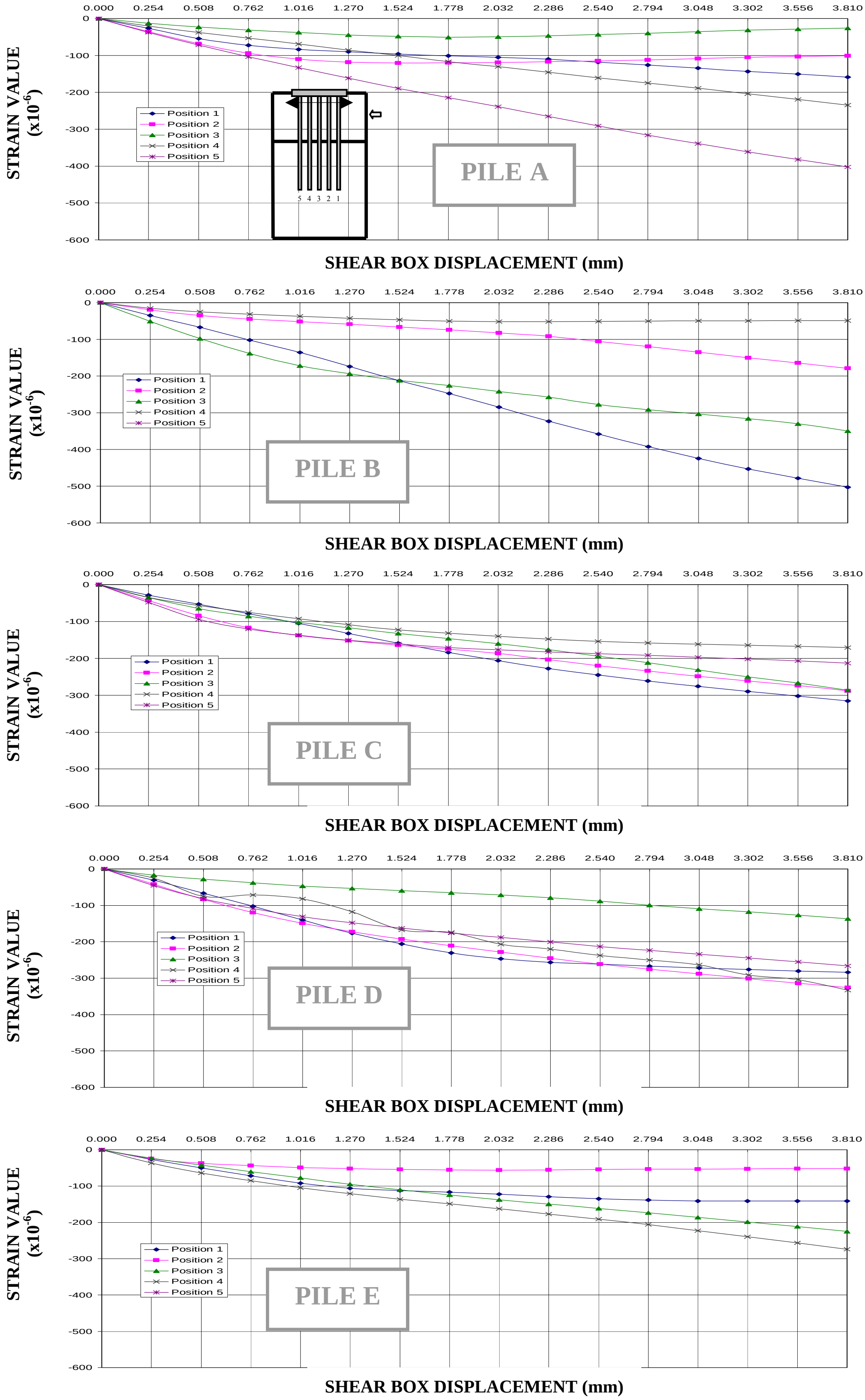


Figure 4.33 Strain Gauge 5 Readings in Group Tests

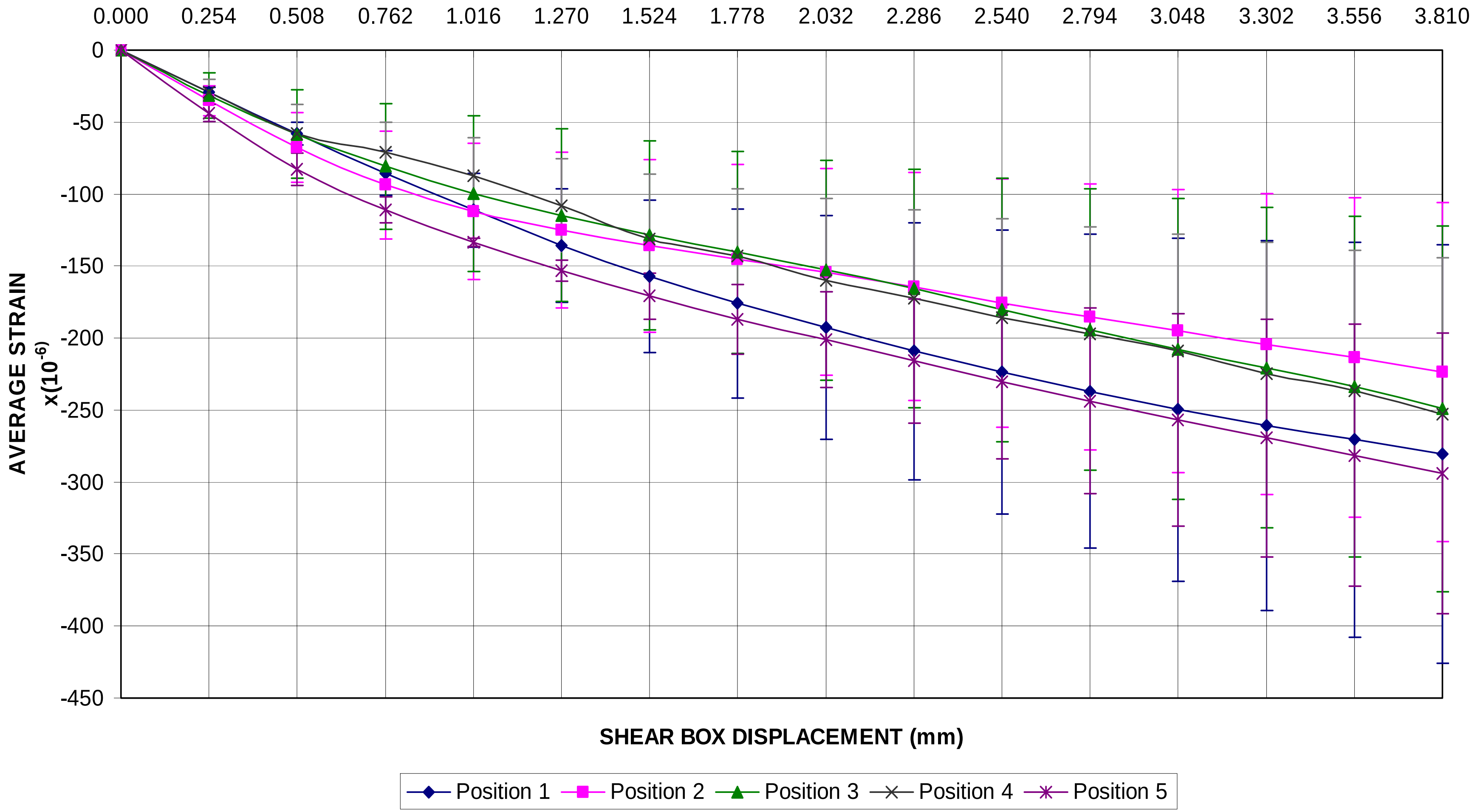


Figure 4.34 Average Strain Values for Strain Gauge 5 Level (0.1L) in Group Tests

Figure 4.34 graphically summarizes the average bending strains developed at 0.1L depth. The values highlighted in the tables B.22, B.23 and B.24 are excluded in the average bending strain calculation since it is obvious that these values have errors.

As indicated before, the results obtained from different piles in same position are different from each other. Therefore numerical values of the average strain calculated and presented in Figure 4.34 may be wrong but it can give an idea about the behavior of the piles at 0.1L depth in different positions. Figure 4.35 summarizes the average bending strain values developed at 0.1L depth for 0.1d, 0.2d and 0.38d displacement of the shear box.

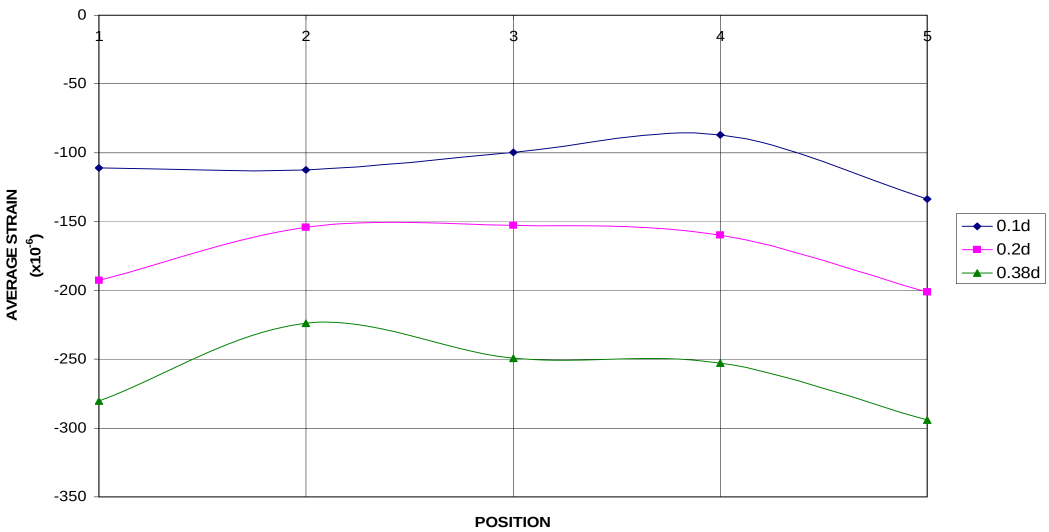


Figure 4.35 Average Strain Values at 0.1L Depth for Different Positions
(0.1d, 0.2d and 0.38d Displacement of the Shear Box)

For 0.1d shear box displacement, the average bending strains developed at 0.1L depth are nearly same for the first four positions which are smaller than the ones developed in the last position. For 0.2d and 0.38d displacement of the shear box, the average bending strains calculated for positions 1 and 5 are greater than the other positions. From Figure 4.34 and 4.35, it is clear that for all displacements of the shear box, maximum bending strains are developed in position 5 at 0.1L depth.

4.2.1.6 Summary of Strain Gauge Results for Pile Group Tests

The average strain values developed along piles in different positions for 0.1d, 0.2d and 0.38d displacements of the shear box are summarized in Figure 4.36, Figure 4.37 and Figure 4.38 respectively.

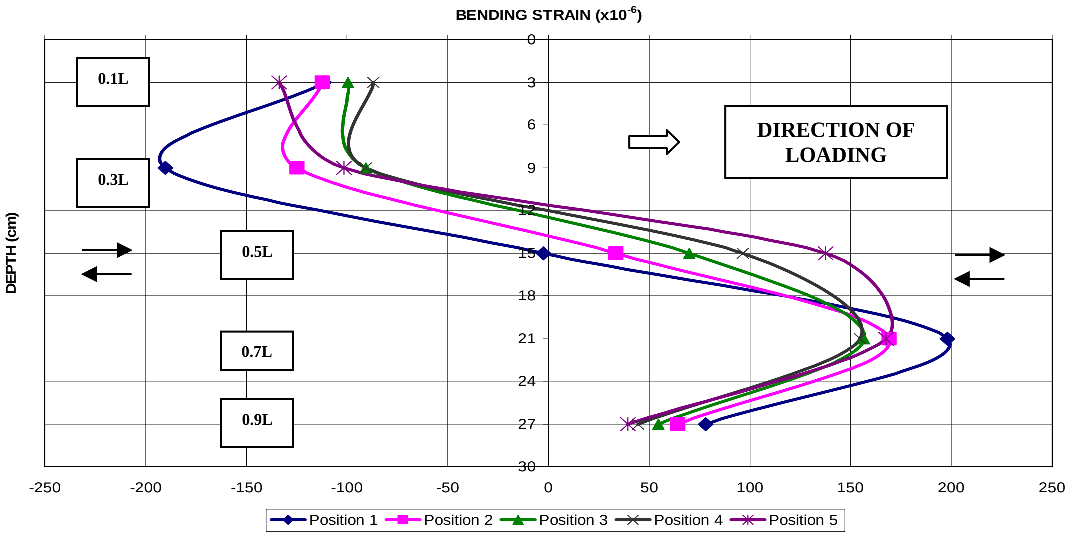


Figure 4.36 Pile Behavior for 0.10d Displacement of the Shear Box in Pile Group

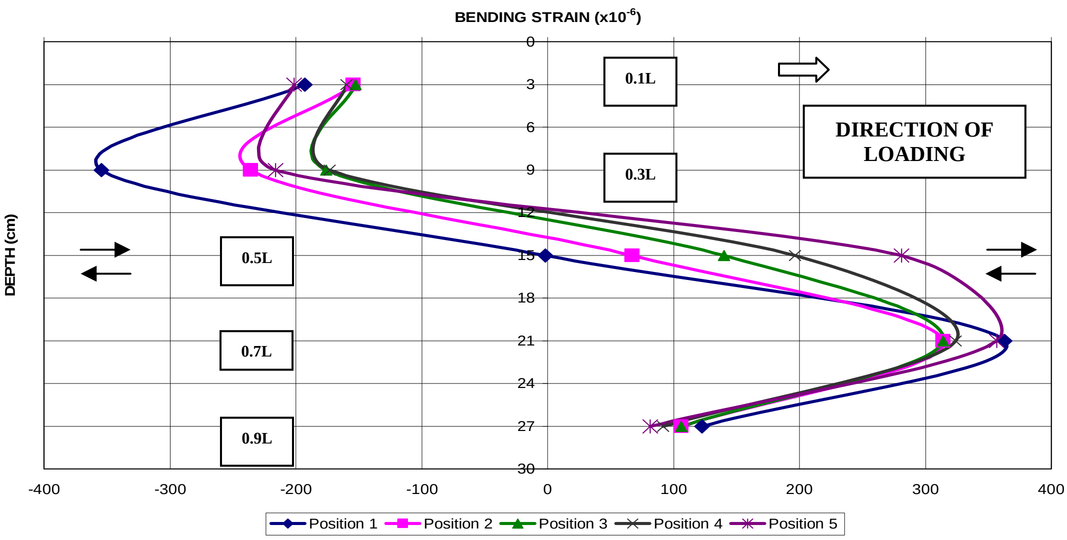


Figure 4.37 Pile Behavior for 0.20d Displacement of the Shear Box in Pile Group

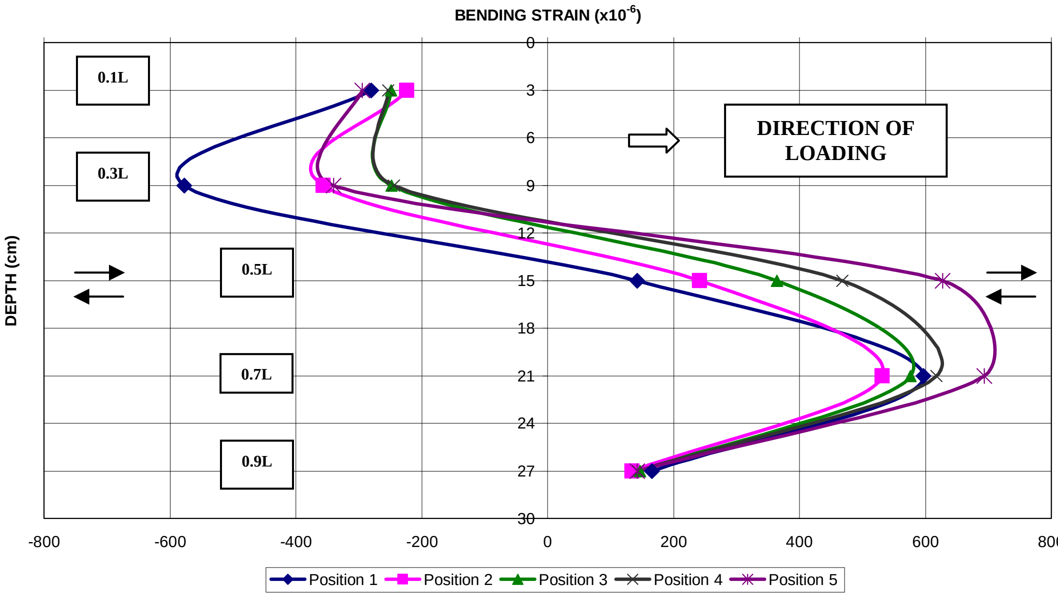


Figure 4.38 Pile Behavior for 0.38d Displacement of the Shear Box in Pile Group

From the figures above, it is clear that for 0.1d, 0.2d and 0.38d displacement values of the shear box, the maximum positive strains occurred at 0.7L (Strain Gauge 2 Level) and maximum negative strains occurred at 0.3L (Strain Gauge 4 Level). This was also the case for the single pile tests.

From the figures above, it can also be concluded that positive strain values measured at 0.5L, 0.7L and 0.9L depths and they are ordered as 0.7L, 0.5L and 0.9L from the numerically biggest to the numerically lowest. This was same in single pile experiments. Negative strain values measured at 0.3L are larger than the values measured at 0.1L. This was also the case in single pile tests.

Above the shearing plane negative strains are occurred at measured depths and maximum value was read from the piles placed in the Position 1 at 0.3L where strain gauge 4 is fastened as mentioned above. At 0.3L, the strain values for 0.1d, 0.2d and 0.38d shear box displacement are ordered as Position 1> Position 2> Position 5> Position 3 ≈ Position 4.

Below the shearing plane positive strains are occurred. Maximum value is the one read from the pile in Position 1 at 0.7L depth where Strain Gauge 2 is fastened for 0.1d and 0.2d displacement of the shear box. For 0.38d displacement of the shear box, maximum bending strains are developed in position 5.

On the shearing plane there is a steadily increase in strain values from Position 1 to Position 5. Similar to the strain values read from the gauges fastened below the shearing plane, positive strains were occurred during the pile group tests for Strain Gauge 3.

It can be concluded that above shear plane negative strains are developed and piles in position 1 (piles nearer to loading) have larger bending strains. On the shearing plane and above the shearing plane positive bending strains are developed. On the shearing plane position 5 is the position for maximum bending strains. Below the shear plane, position 1 is generally the location of the maximum bending strain.

4.2.2 Comparison of Pile Group Results with Single Pile Results

The single pile test and pile group test results are given in Section 4.1 and 4.2.1 respectively. The pile group test results are compared with the single pile tests in proceeding parts of this section.

4.2.2.1 Strain Gauge 1 Comparison (Depth: 0.9L)

The average bending strains obtained at 0.9L depth in group tests (Figure 4.22) are compared with the average bending strains obtained at the same depth in single pile tests (Strain 1 graph in Figure 4.18).

The multipliers are calculated by dividing the average bending strains obtained from pile group experiments to the ones obtained from single pile experiments and presented in Table 4.7.

Table 4.7 Moment Multipliers for 0.9L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1	POSITION 2	POSITION 3	POSITION 4	POSITION 5
0.254	1.61	1.20	0.93	0.72	0.66
0.508	1.57	1.22	0.96	0.76	0.68
0.762	1.47	1.17	0.96	0.77	0.68
1.016	**1.36**	**1.12**	**0.95**	**0.78**	**0.69**
1.270	1.27	1.08	0.95	0.79	0.70
1.524	1.20	1.03	0.95	0.80	0.70
1.778	1.14	0.99	0.95	0.81	0.71
2.032	**1.09**	**0.94**	**0.94**	**0.81**	**0.72**
2.286	1.04	0.90	0.93	0.82	0.73
2.540	0.99	0.84	0.90	0.81	0.73
2.794	0.96	0.81	0.87	0.81	0.74
3.048	0.94	0.78	0.85	0.80	0.74
3.302	0.92	0.76	0.83	0.79	0.75
3.556	0.91	0.74	0.80	0.78	0.76
3.810	**0.89**	**0.72**	**0.78**	**0.76**	**0.76**

According to Table 4.7 pile group results are greater than the single pile results for position 1 and position 2 for small displacement values of shear box. For the other positions the multipliers are smaller than 1.0.

As the shear box movement increased, the multipliers decreased for all positions except for position 5. In position 5, increasing shear box displacement resulted in increasing values of multipliers.

For larger movements of shear box, multipliers being smaller than 1.0 indicates that pile group results are smaller than single pile results for all positions.

The average multipliers are found to be **1.36, 1.12, 0.95, 0.78 and 0.69** for 0.1ddisplacement of shear box. For 0.2d displacement of the shear box, multipliers are found to be **1.09, 0.94, 0.94, 0.81 and 0.72.** For 0.38d displacement of the shear box, multipliers are found to be **0.89, 0.72, 0.78, 0.76 and 0.76.**

Moment multipliers for different positions at 0.9L depth are summarized in Figure 4.39.

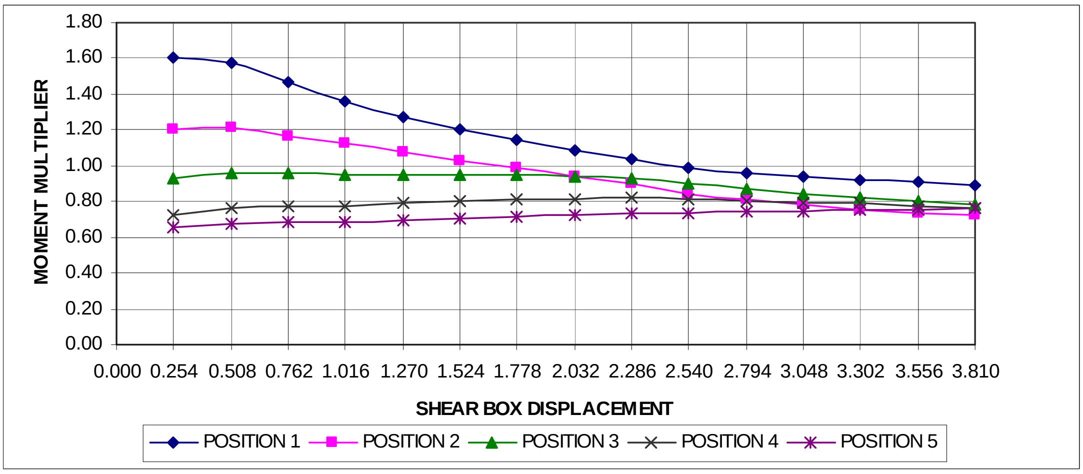


Figure 4.39 Moment Multipliers at 0.9L Depth

4.2.2.2 Strain Gauge 2 Comparison (Depth: 0.7L)

The average bending strains obtained at 0.7L depth in group tests (Figure 4.25) are compared with the average bending strains obtained at the same depth in single pile tests (Strain 2 graph in Figure 4.18).

The multipliers obtained from comparison of Strain Gauge 2 readings taken during single pile and pile group tests are presented in Table 4.8.

Table 4.8 Moment Multipliers for 0.7L Depth

cxcxxcxcxcxcccxc**SHEAR BOX DISPLACEMENT (mm)**	**POSITION 1**	**POSITION 2**	**POSITION 3**	**POSITION 4**	**POSITION 5**
0.254	1.43	1.11	0.93	0.82	0.92
0.508	1.30	1.06	0.92	0.87	0.94
0.762	1.19	0.99	0.89	0.87	0.94
1.016	**1.10**	**0.94**	**0.87**	**0.86**	**0.93**
1.270	1.05	0.90	0.85	0.85	0.92
1.524	0.99	0.86	0.82	0.84	0.92
1.778	0.96	0.83	0.81	0.83	0.91
2.032	**0.93**	**0.80**	**0.80**	**0.83**	**0.91**
2.286	0.89	0.79	0.80	0.83	0.92
2.540	0.86	0.77	0.79	0.83	0.91
2.794	0.84	0.75	0.79	0.82	0.91
3.048	0.82	0.73	0.78	0.82	0.91
3.302	0.81	0.72	0.77	0.82	0.91
3.556	0.80	0.71	0.77	0.82	0.91
3.810	**0.79**	**0.70**	**0.76**	**0.81**	**0.91**

From Table 4.8 it is clear that for 0.1d displacement of shear box, multipliers for position 1 are greater than 1.0. After that position the multipliers decrease up to position 4 and then increase in position 5, all being smaller than 1.0.

For 0.2d displacement, all multipliers are smaller than 1.0 and decrease from position 1 to position 3. After position 3 multipliers start to increase.

For 0.38d movement of the shear box, all multipliers are smaller than 1.0 and multipliers decrease from position 1 to position 2 and then start to increase with being the greatest in position 5.

The moment multipliers are found to be **1.10, 0.94, 0.87, 0.86 and 0.93** for 0.1d displacement of shear box. For 0.2d displacement, the average multipliers are found to be **0.93, 0.80, 0.80, 0.83 and 0.91.** The average multipliers are found to be **0.79, 0.70, 0.76, 0.81 and 0.91** for 0.38d displacement of shear box.

Moment multipliers for different positions at 0.7L depth are summarized in Figure 4.40.

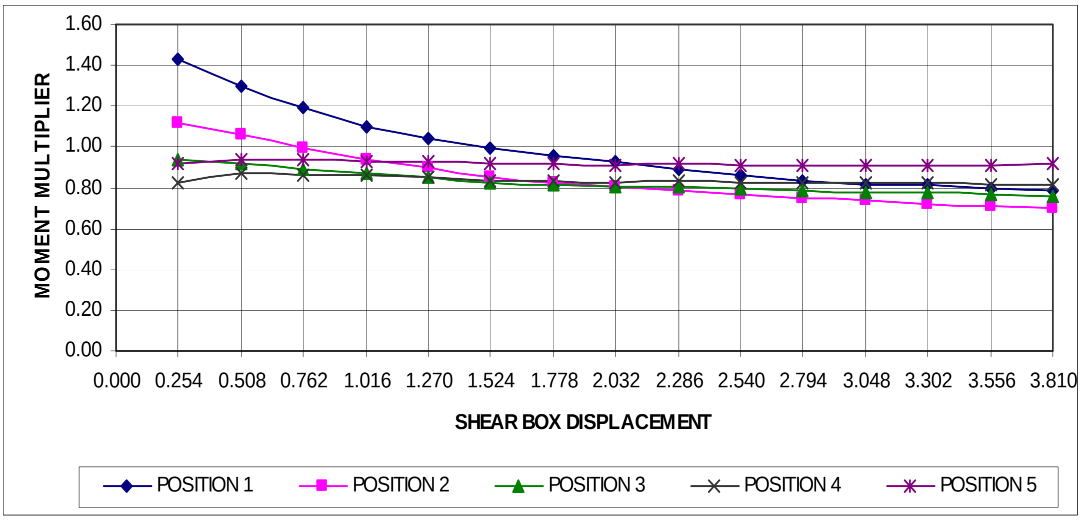


Figure 4.40 Moment Multipliers at 0.7L Depth

4.2.2.3 Strain Gauge 3 Comparison (Depth: 0.5L)

Table 4.9 summarizes the multipliers obtained from the comparison of the single pile tests and pile group tests for Strain Gauge 3.

From the Table 4.9 below, it can be concluded that multipliers are increasing for all three displacement values from position 1 to position 5.

For 0.1d displacement, the multipliers obtained for position 3, 4 and 5 are greater than 1.0.

For 0.2d displacement, the multipliers obtained for position 4 and 5 are greater than 1.0. For 0.38d movement, this is the case for position 5.

For small displacements, the multiplier in position 1 are negative indicating opposite readings in pile group tests from the readings in the single pile test.

Table 4.9 Moment Multipliers for 0.5L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1	POSITION 2	POSITION 3	POSITION 4	POSITION 5
0.254	0.28	0.84	1.45	1.94	2.67
0.508	0.08	0.66	1.21	1.62	2.26
0.762	0.00	0.54	1.09	1.48	2.10
1.016	**-0.04**	**0.49**	**1.01**	**1.40**	**1.99**
1.270	-0.06	0.44	0.95	1.33	1.90
1.524	-0.08	0.40	0.89	1.26	1.82
1.778	-0.07	0.38	0.85	1.21	1.75
2.032	**-0.01**	**0.39**	**0.82**	**1.15**	**1.65**
2.286	0.05	0.43	0.83	1.14	1.61
2.540	0.13	0.46	0.82	1.11	1.55
2.794	0.18	0.47	0.81	1.08	1.49
3.048	0.22	0.49	0.80	1.05	1.44
3.302	0.25	0.50	0.79	1.03	1.41
3.556	0.28	0.51	0.78	1.01	1.36
3.810	**0.30**	**0.51**	**0.77**	**0.99**	**1.33**

The moment multipliers for position 1 for 0.1d and 0.2d shear box movements are very small near to zero. Moment multipliers are found to be **0.49, 1.01, 1.40 and 1.99** for 0.1d displacement of the shear box and **0.39, 0.82, 1.15 and 1.65** for 0.2 d displacement of the shear box for positions 2,3,4 and 5 respectively. The average multipliers are found to be **0.30, 0.51, 0.77, 0.99 and 1.33** for 0.38d displacement of shear box.

Moment multipliers for different positions found at 0.5L depth are summarized in Figure 4.41.

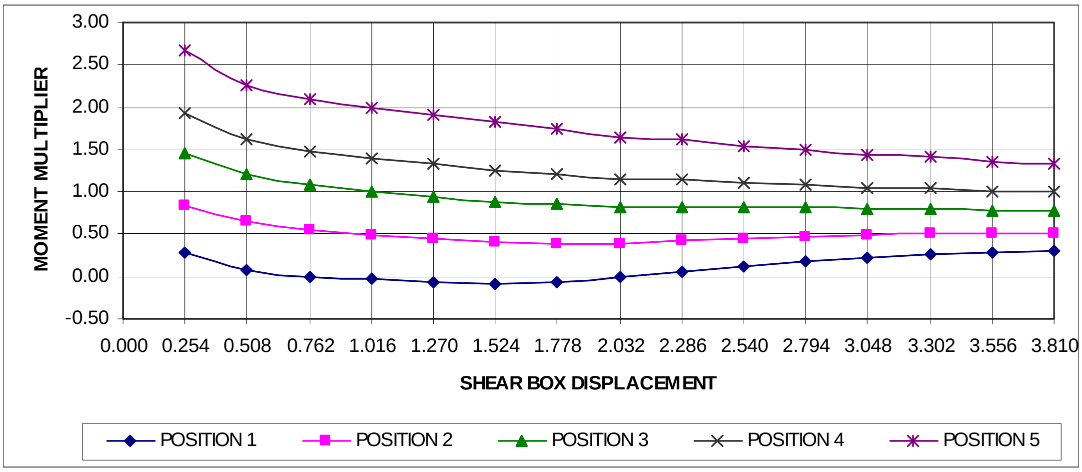


Figure 4.41 Moment Multipliers at 0.5L Depth

4.2.2.4 Strain Gauge 4 Comparison (Depth: 0.3L)

Moment multipliers are presented in Table 4.10 for the depth where Strain Gauge 4 is fastened, 0.3L.

For 0.1d and 0.2d shear box movement, all multipliers are greater than 1.0 and decrease from position 1 to position 3 and increase from position 4 to position 5.

For 0.38d, the behavior is same but the multipliers for position 3, 4 become smaller than 1.0. For all displacements of the shear box, moment multipliers calculated for position 4 are nearly same with the ones calculated for position 3.

Table 4.10 Moment Multipliers for 0.3L Depth

SHEAR BOX DISPLACEMENT (mm)	POSITION 1	POSITION 2	POSITION 3	POSITION 4	POSITION 5
0.254	3.02	1.74	1.23	1.40	1.24
0.508	2.97	1.83	1.29	1.34	1.37
0.762	2.74	1.76	1.26	1.27	1.38
1.016	**2.55**	**1.67**	**1.21**	**1.21**	**1.36**
1.270	2.40	1.60	1.18	1.17	1.37
1.524	2.29	1.53	1.14	1.13	1.35
1.778	2.21	1.48	1.11	1.10	1.34
2.032	**2.15**	**1.43**	**1.07**	**1.05**	**1.31**
2.286	2.08	1.37	1.02	1.00	1.26
2.540	2.04	1.33	0.97	0.95	1.22
2.794	2.00	1.29	0.93	0.91	1.19
3.048	1.95	1.24	0.89	0.87	1.15
3.302	1.92	1.21	0.86	0.84	1.13
3.556	1.90	1.18	0.83	0.82	1.12
3.810	**1.89**	**1.16**	**0.81**	**0.80**	**1.11**

The moment multipliers are found to be **2.55, 1.67, 1.21, 1.21 and 1.36** for 0.1d displacement of shear box. For 0.2d displacement, the average multipliers are found to be **2.15, 1.43, 1.07, 1.05 and 1.31.** The average multipliers are found to be **1.89, 1.16, 0.81, 0.80 and 1.11** for 0.38d displacement of shear box.

Moment multipliers at 0.3L depth are summarized in Figure 4.42.

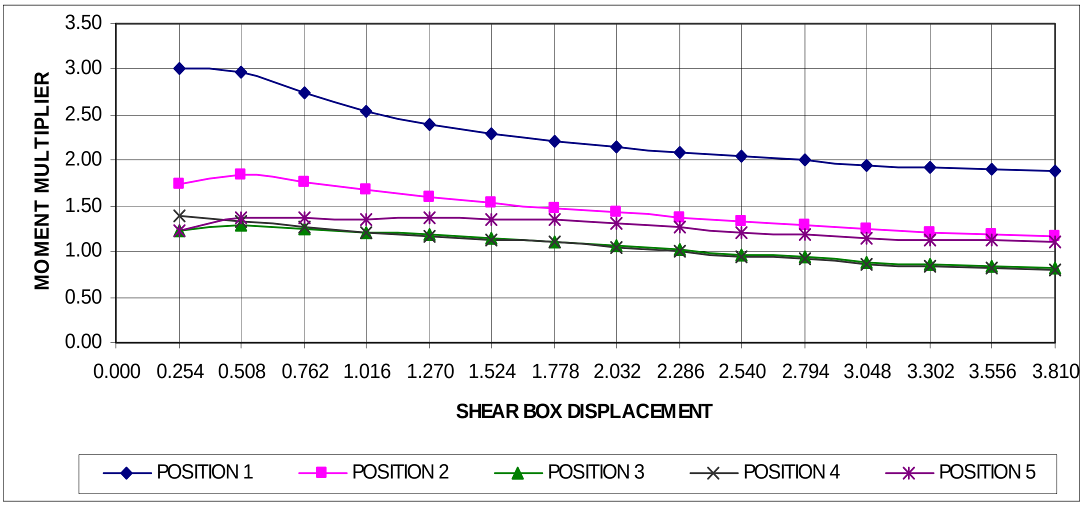


Figure 4.42 Moment Multipliers at 0.3L Depth

4.2.2.5 Strain Gauge 5 Comparison (Depth: 0.1L)

Strain Gauge 5 results in group tests are compared with the results in single pile tests and given in Table 4.11.

Since the pile-head conditions are different in single pile tests and pile group tests, the multiplier values given in Table 4.11 are too large.

Table 4.11 Moment Multipliers for 0.1L Depth

SHEAR BOX DISPLACEMENT (mm)	**POSITION 1**	**POSITION 2**	**POSITION 3**	**POSITION 4**	**POSITION 5**
0.254	26.37	31.46	28.37	26.15	39.15
0.508	33.66	39.15	33.75	33.63	47.83
0.762	37.46	41.07	35.35	31.17	48.63
1.016	**37.53**	**37.89**	**33.63**	**29.38**	**45.08**
1.270	40.97	37.80	34.65	32.61	46.25
1.524	37.86	32.77	30.96	31.67	41.17
1.778	36.79	30.33	29.35	29.88	39.08
2.032	**37.94**	**30.35**	**30.05**	**31.45**	**39.57**
2.286	37.69	29.62	29.82	31.10	38.91
2.540	36.91	28.96	29.75	30.64	38.01
2.794	36.25	28.35	29.70	30.16	37.30
3.048	35.95	28.08	29.88	30.07	36.98
3.302	35.37	27.72	29.93	30.49	36.53
3.556	35.92	28.36	31.03	31.43	37.36
3.810	**35.65**	**28.42**	**31.67**	**32.15**	**37.36**

CHAPTER 5

SUMMARY OF RESULTS

In this chapter, the findings are summarized. Bending strain distributions for a single pile and pile group are given in section 5.1 and 5.2 respectively. Bending moment profiles of single pile and pile group are presented in section 5.3. The effect of pile head conditions is discussed in section 5.4.

5.1. Bending Strain Distribution in Single Passive Pile

Typical bending strain distribution along laterally loaded passive pile is given in Figure 5.1 for 0.1d, 0.2d and 0.38d displacement of shear box.

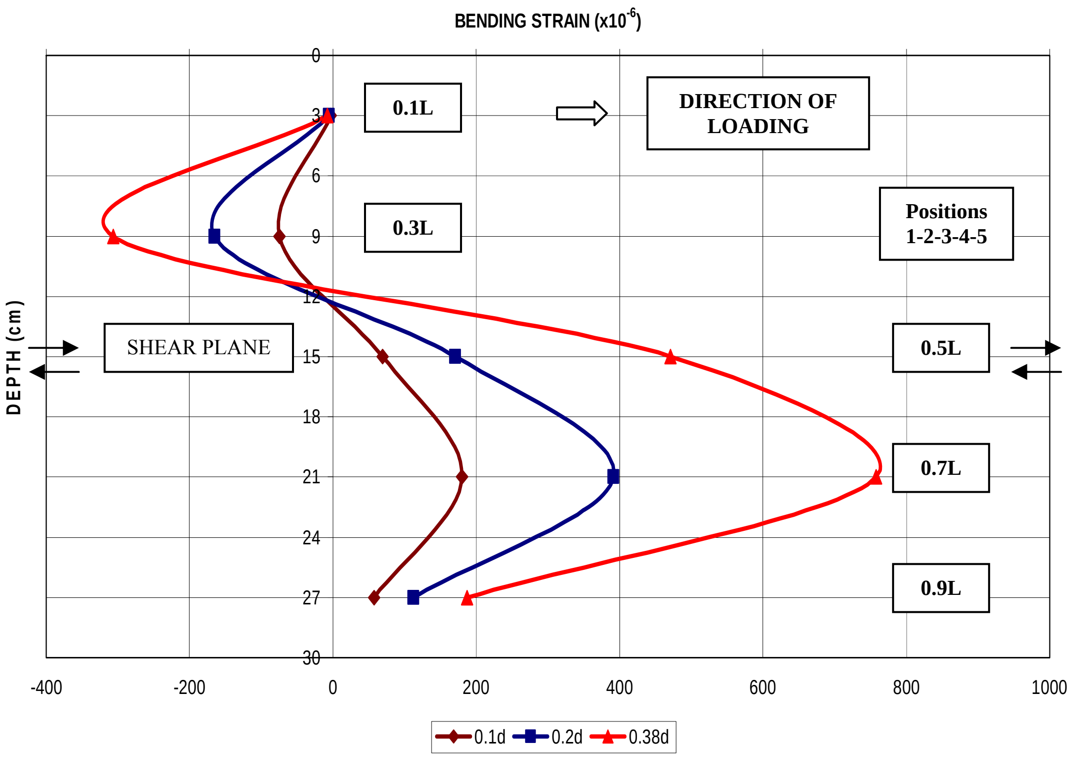


Figure 5.1 Bending Strain Profile for Passive Single Pile

The findings can be summarized as;

1. Negative bending strains are developed above the shear plane at depths 0.1L and 0.3L. The strains near to the pile head at 0.1L are close to zero.

2. Positive strains are developed on the shear plane and below the shear plane at depths 0.5L, 0.7L and 0.9L.

3. Within the instrumented depths, maximum bending strains are observed at 0.7L.

4. Numerically bending moments are ordered as $\varepsilon_{0.7L} > \varepsilon_{0.5L} > \varepsilon_{0.3L} > \varepsilon_{0.9L} > \varepsilon_{0.1L}$

5. On the shearing plane the results differ for different piles especially for large shear box movements, but the behavior remains the same. Sectional differences in the piles and experimental differences that may exist can be the reason for this behavior. Particle scale effects causing stick-slip type movements and pile alignment may have also affected the results.

5.2. Bending Strain Distribution in Passive Pile Group

Typical bending strain distribution developed on piles in different positions within a pile group is given in Figure 5.2, 5.3 and 5.4 for 0.1d, 0.2d and 0.38d displacements of the shear box respectively.

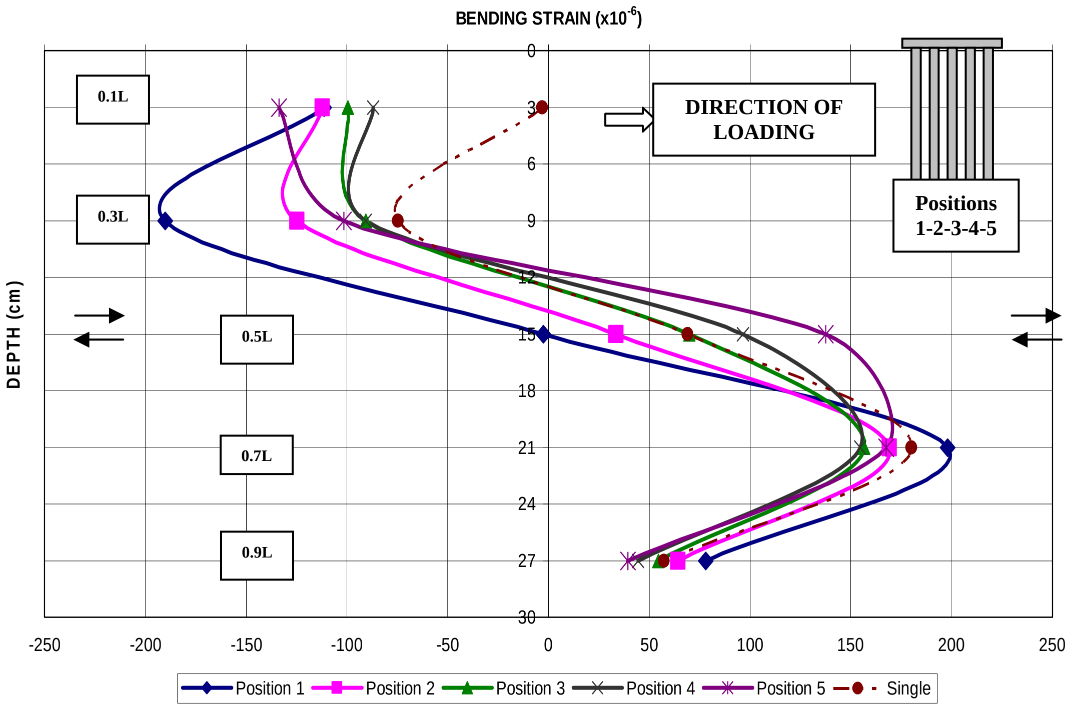


Figure 5.2 Bending Strain Profile for Passive Pile Group at 0.1d Displacement

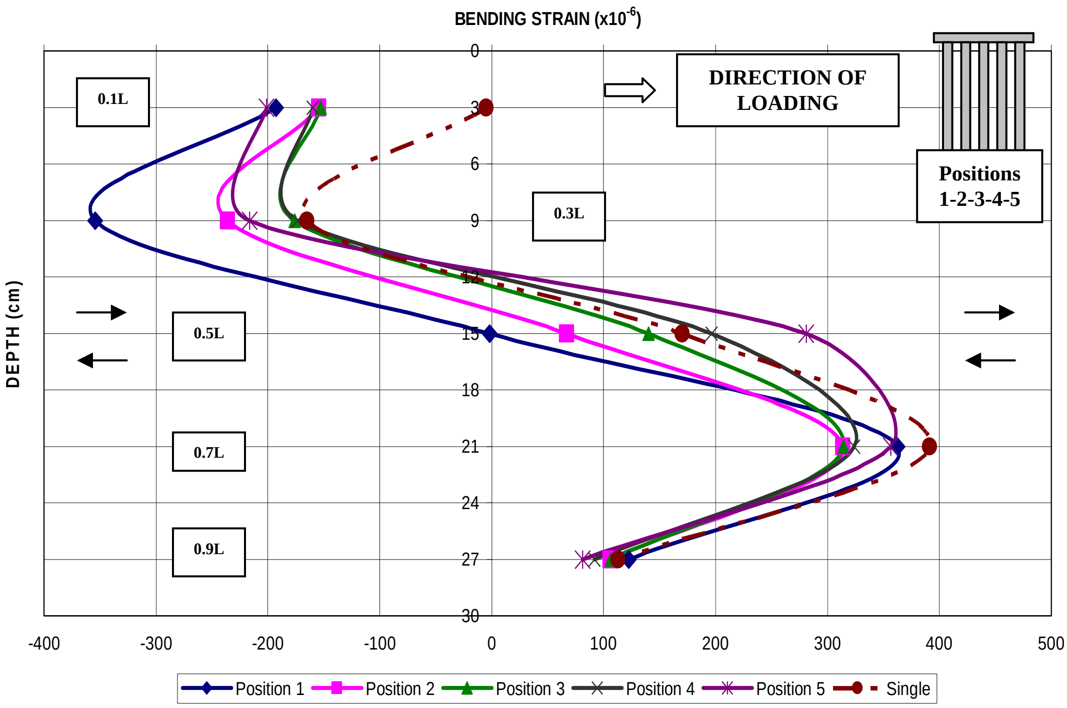


Figure 5.3 Bending Strain Profile for Passive Pile Group at 0.2d Displacement

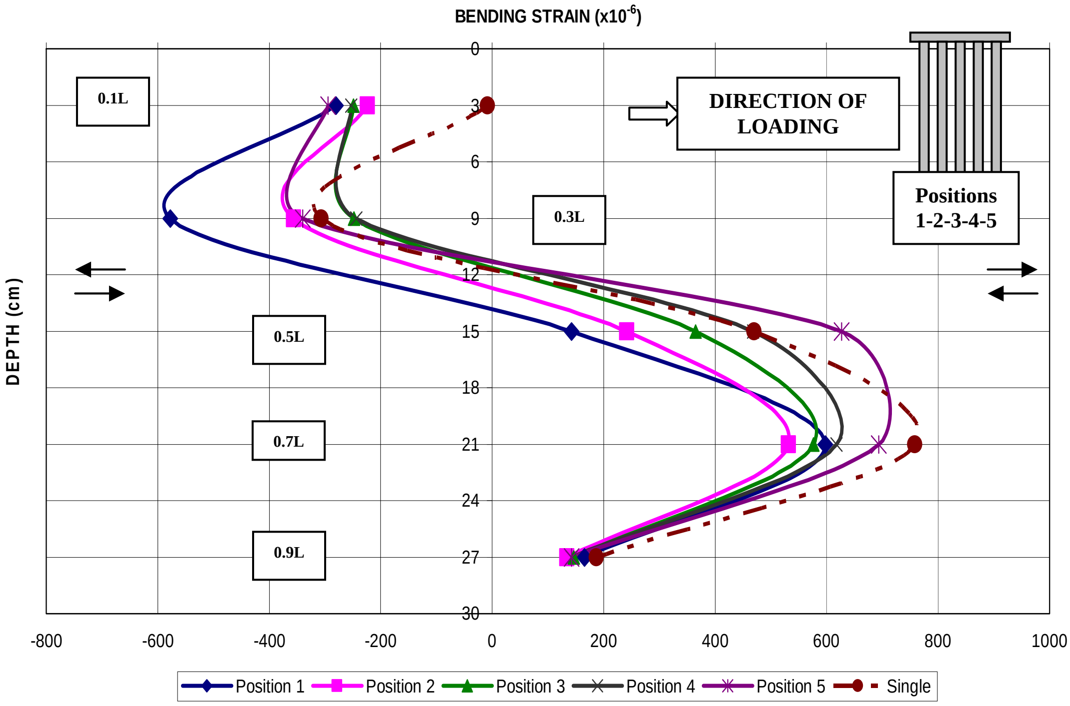


Figure 5.4 Bending Strain Profile for Passive Pile Group at 0.38d Displacement

1. The bending behavior obtained for pile group is similar to single pile behavior. Above the shearing plane negative bending strains are developed at depths of 0.1L and 0.3L. On the shearing plane and below the shearing plane positive bending strains are developed.

2. Positive bending strain values are ordered as $\varepsilon_{0.7L} > \varepsilon_{0.5L} > \varepsilon_{0.9L}$ and negative bending strain values are ordered as $\varepsilon_{0.3L} > \varepsilon_{0.1L}$ just like in single piles.

3. Maximum positive bending strains occur at 0.7L depth, maximum negative bending strains are developed at 0.3L depth which was also the case for the single pile tests.

4. Position 1 (position nearest to the loading, trailing pile position) at 0.3L depth is the position for maximum negative bending strains.

5. Maximum positive bending strains occur at position 1 at small displacements and at position 5 (position far away to the loading, leading pile position) at larger displacements.

6. Because of different pile-head conditions; strain values near the pile head are very large in pile group compared to values in single pile tests.

7. On the shear plane for all displacement values of the shear box, the strain values increase from position 1 to position 5. Maximum bending strains are developed on the piles in the leading position (5) whereas the smallest bending strains are developed on the piles in the trailing position (1).

8. Bending strains developed near each pile tip at 0.9L are the same for large shear box movements and merge to a point.

5.3 Bending Moment Profiles

Bending moment profiles for passive single pile and piles within a group are presented in Figure 5.5, 5.6, 5.7 and 5.8. ($M=\varepsilon.EI/y$ where ε: Bending Strain, E: Elastic Modulus of Pile (70GPa), I: Moment of Inertia of Pile (289.67 mm^4) and y: Distance of Strain Gauge to Neutral Axis (5 mm)).

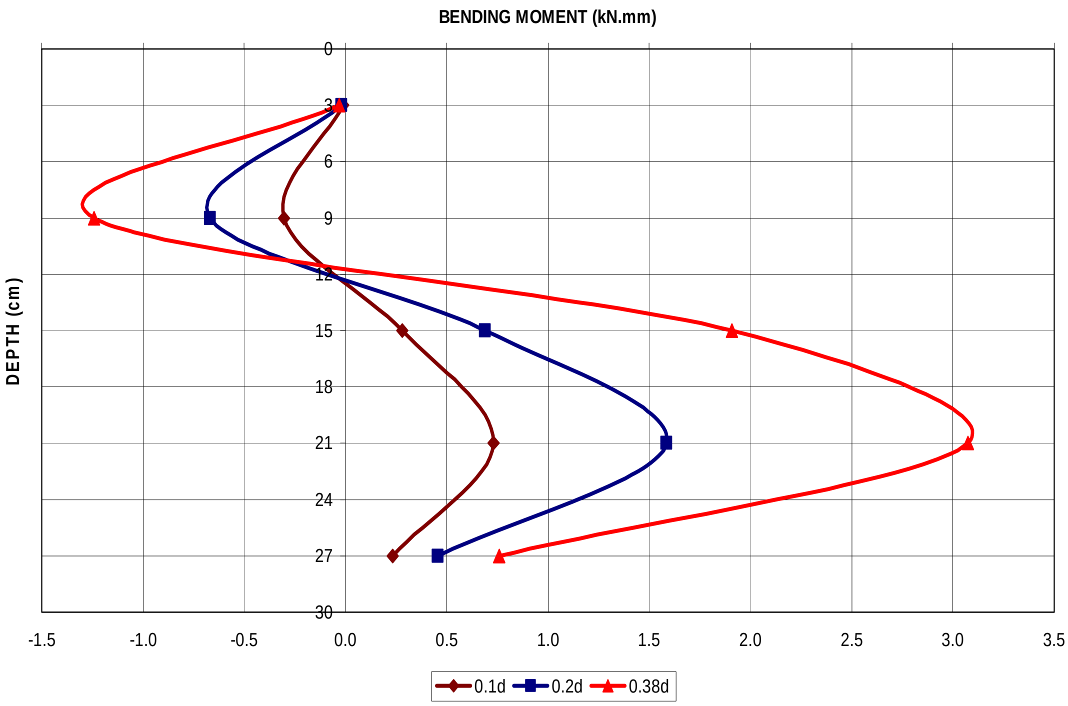


Figure 5.5 Bending Moment Profile for Passive Single Pile

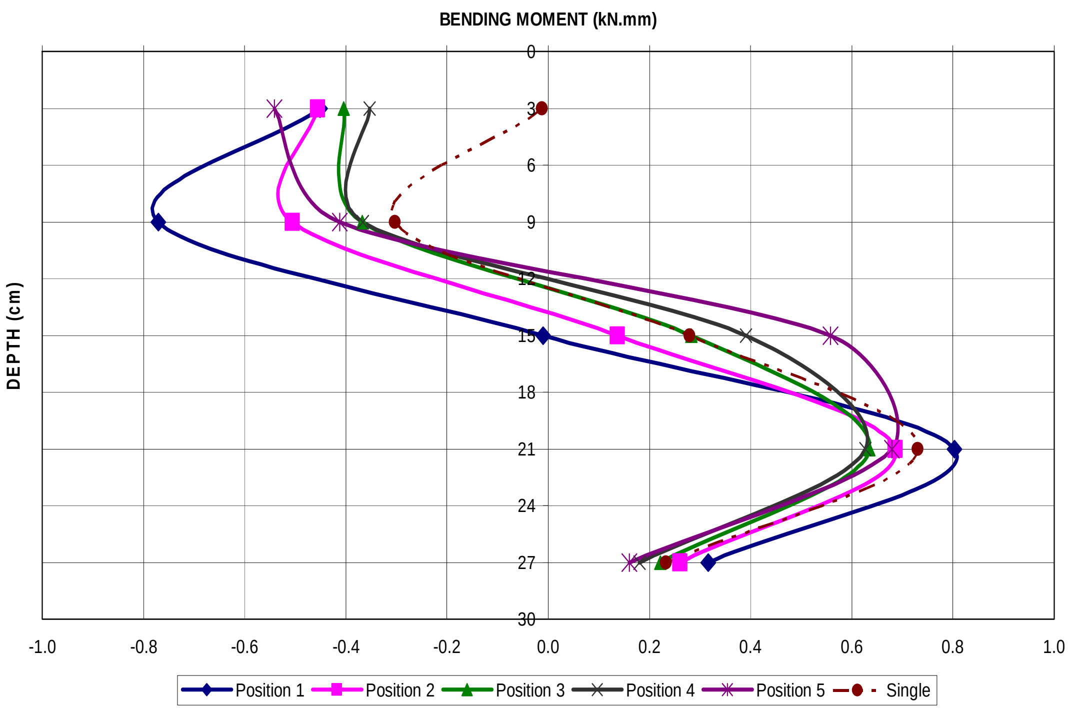


Figure 5.6 Bending Moment Profile for Passive Pile Group at 0.1d Displacement

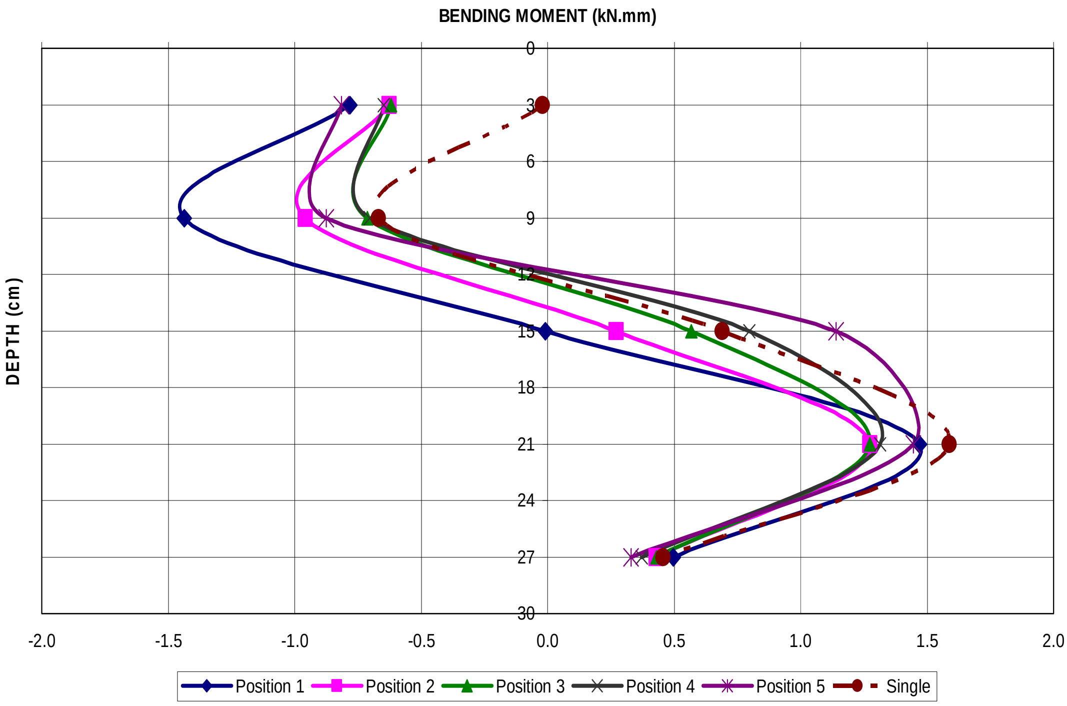


Figure 5.7 Bending Moment Profile for Passive Pile Group at 0.2d Displacement

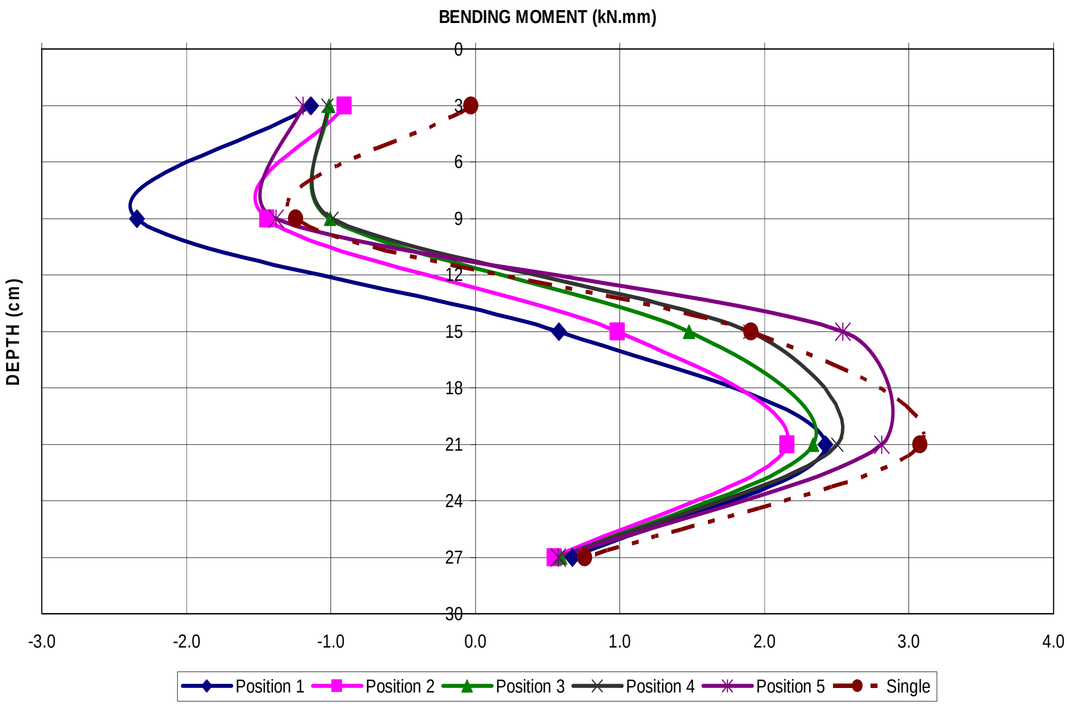


Figure 5.8 Bending Moment Profile for Passive Pile Group at 0.38d Displacement

5.4 Moment Multipliers

In order to follow the behavior of the piles in different positions within the pile group compared to the behavior of a single pile, moment multipliers have been calculated. By these multipliers, the variation of the bending strain from one position to another position can be obtained. Summary of moment multipliers for different positions at different depths are given in Table 5.1.

Table 5.1 Summary of Moment Multipliers

DEPTH	DISPLACEMENT (mm)	POSITION 1	POSITION 2	POSITION 3	POSITION 4	POSITION 5
0.1L	1,016 (0.1d)	37.53	37.89	33.63	29.38	**45.08**
	2,032(0.2d)	37.94	30.35	30.05	31.45	**39.57**
	3,81(0,38d)	35.65	28.42	31.67	32.15	**37.36**
0.3L	1,016 (0.1d)	**2.55**	1.67	1.21	1.21	1.36
	2,032(0.2d)	**2.15**	1.43	1.07	1.05	1.31
	3,81(0,38d)	**1.89**	1.16	0.81	0.80	1.11
0.5L	1,016 (0.1d)	-0.04	0.49	1.01	1.40	**1.99**
	2,032(0.2d)	-0.01	0.39	0.82	1.15	**1.65**
	3,81(0,38d)	0.30	0.51	0.77	0.99	**1.33**
0.7L	1,016 (0.1d)	**1.10**	0.94	0.87	0.86	0.93
	2,032(0.2d)	**0.93**	0.80	0.80	0.83	0.91
	3,81(0,38d)	0.79	0.70	0.76	0.81	**0.91**
0.9L	1,016 (0.1d)	**1.36**	1.12	0.95	0.78	0.69
	2,032(0.2d)	**1.09**	0.94	0.94	0.81	0.72
	3,81(0,38d)	**0.89**	0.72	0.78	0.76	0.76

The maximum values presented in Table 5.1 are highlighted as shown above.

The findings can be summarized as;

1. At 0.1L depth, moment multipliers are large due to different pile head conditions in single and group tests. In single tests, pile head was nearly free whereas in group tests pile head was fixed.

2. At 0.3L depth maximum bending strain values are developed at position 1. The bending strains developed are greater than that of the single pile.

3. At 0.5L depth (shearing plane) maximum bending strains are developed at position 5. The bending strains developed are greater than those of the single pile results. Bending strains increase from position 1 to position 5. For 0.1d and 0.2 d displacements bending strains for position 1 are very small (close to zero).

4. At 0.7L depth maximum bending strains are developed in position 1 for 0.1d and 0.2d shear box movements and in position 5 for 0.38d movement. The strain value developed in position 1 for 0.1d movement is slightly greater than the strain value of single pile. In other positions for 0.1d displacement and in all positions for 0.2d and 0.38d displacements the bending strains developed in the pile group are smaller than the ones developed in single pile.

5. At 0.9L depth for 0.1d and 0.2d displacements of the shear box, strain values at position 1 are greater than that of single pile and the strains of the other positions. For 0.38d displacement strain values of position 1 is smaller than the strain value of the single pile and greater than the strain values of the other positions.

5.5 Pile Head Condition Effects

In order to see the effects of pile head condition, a single pile was laterally loaded with fixed pile head conditions. The results of this experiment are presented in Table A.26 in Appendix A and modification factors obtained for moment multipliers (Table 5.1) are presented in Table 5.2.

As can be seen from Table 5.2, the moment multipliers obtained for 0.5L, 0.7L and 0.9L depths are not much affected by the pile-head conditions. The moment multipliers calculated for 0.3L depth are little affected whereas the moment multipliers obtained for 0.1L depth are greatly affected by changing pile head conditions. When applying moment multipliers to the results of a single pile with fixed head conditions, the moment multipliers presented in Table 5.1 should be corrected with factors presented in Table 5.2.

Table 5.2 Moment Multipliers Modification Factors
for Fixed Head Single Pile Conditions

DEPTH	DISPLACEMENT (mm)	MODIFICATION FACTOR
0.1L	1,016 (0.1d)	**0.10**
	2,032(0.2d)	**0.06**
	3,81(0,38d)	**0.03**
0.3L	1,016 (0.1d)	0.74
	2,032(0.2d)	0.69
	3,81(0,38d)	0.61
0.5L	1,016 (0.1d)	0.99
	2,032(0.2d)	1.11
	3,81(0,38d)	1.20
0.7L	1,016 (0.1d)	1.00
	2,032(0.2d)	1.04
	3,81(0,38d)	1.06
0.9L	1,016 (0.1d)	1.01
	2,032(0.2d)	1.04
	3,81(0,38d)	1.07

CHAPTER 6

CONCLUSION

6.1 Achievements and Conclusions

Bending moment distribution in laterally loaded passive pile groups in cohesionless soil were investigated in laboratory conditions through model pile experiments.

The bending moment variation in different positions within a pile group was discussed and bending moments developed along the piles of a 1x5 passive pile group were compared with the bending moments developed along a single passive pile.

Maximum bending moments were obtained at 0.7L depth (L: Length of Pile) for single piles and piles in the group. The bending moments near the pile head at 0.1L depth were observed to be small. It was also observed that pile head conditions affect the results at the depths near the pile head.

Above the shear plane, the position for maximum bending moments within the pile group was found to be the position nearest to the loading. On the shear plane maximum bending moments were developed on the piles farthest from the loading just like active piles. Below the shear plane, maximum bending moments were developed mainly on the piles nearest to the loading.

The behavior of a passive pile (single and pile group) was found to be similar to the results obtained in early studies in the literature. Negative bending strains were observed at the specified depths above the shear plane and positive bending moments were measured at the level of the shear plane and below the shear plane.

6.2 Practical Use of This Study

By comparing the bending moments developed within a pile group with the bending moments developed in a single pile, moment multipliers are obtained and presented for a 1x5 passive pile group. For obtaining bending moment distribution of single passive pile, there exists some methods in the literature. For piles in similar soil conditions, the multipliers obtained in this study can be used together with a bending moment distribution of a single passive pile in order to obtain bending moment distribution of a passive pile group containing five rows of piles.

6.3 Recommendations for Future Research

In the literature, the most common way to estimate the lateral response of laterally loaded piles is using p-y curves. This method is mainly used for active piles but it can also be used for passive piles. For that purpose, in order to obtain p-y curves a detailed study should be executed by using the results obtained from this study.

Laterally loaded passive piles are being widely used for various purposes. In this study, a 1x5 passive pile group was laterally loaded in one type of soil mass. More model studies should be executed for laterally loaded passive pile groups having various geometries in different soil conditions. The effects of pile group geometry, pile properties, pile-cap rigidities and soil conditions should be studied in detail.

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APPENDIX A

RESULTS OF SINGLE PILE EXPERIMENTS

The results of the single pile experiments are given in tabular form in this part.

Table A.1 Strain Gauge 1 Readings for Pile A

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**EXP 4 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	**0.00**
0.254	22.77	14.95	14.68	10.70	**16.05**
0.508	34.29	24.96	27.43	24.83	**28.85**
0.762	48.83	27.43	42.24	39.64	**43.57**
1.016	63.64	29.90	56.51	55.41	**58.52**
1.270	76.40	42.24	72.28	72.15	**73.61**
1.524	90.66	58.98	86.27	88.06	**88.33**
1.778	103.00	64.88	99.71	101.23	**101.31**
2.032	116.03	76.67	109.31	113.02	**112.79**
2.286	115.07	85.72	121.79	120.98	**119.28**
2.540	135.51	91.69	136.61	126.87	**133.00**
2.794	140.31	97.66	148.95	133.32	**140.86**
3.048	152.79	104.38	162.67	138.12	**151.19**
3.302	163.76	123.58	171.86	144.43	**160.02**
3.556	174.60	134.41	183.52	150.19	**169.44**
3.810	187.49	145.25	191.33	156.23	**178.35**

Table A.2 Strain Gauge 2 Readings for Pile A

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	**0.00**
0.254	54.79	44.91	31.31	32.96	**39.69**
0.508	83.77	72.92	67.43	74.98	**75.39**
0.762	120.85	105.60	110.00	123.87	**118.24**
1.016	161.63	143.64	154.08	174.41	**163.37**
1.270	205.99	186.35	206.40	229.48	**213.96**
1.524	252.68	229.33	258.72	291.01	**267.47**
1.778	307.34	270.12	314.48	345.66	**322.49**
2.032	372.84	321.75	364.87	402.52	**380.08**
2.286	377.10	378.47	426.81	455.94	**419.95**
2.540	418.71	402.98	517.03	507.44	**481.06**
2.794	506.32	427.50	575.67	559.76	**547.25**
3.048	582.26	488.88	640.21	605.22	**609.23**
3.302	649.55	554.25	685.39	653.83	**662.93**
3.556	710.94	612.06	745.40	699.15	**718.50**
3.810	774.38	664.93	788.94	744.75	**769.35**

Table A.3 Strain Gauge 3 Readings for Pile A

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	**0.00**
0.254	6.18	16.90	8.66	3.16	**6.00**
0.508	10.44	27.62	21.16	25.42	**19.01**
0.762	20.06	41.63	37.37	47.81	**35.08**
1.016	32.70	56.33	55.51	70.90	**53.03**
1.270	50.83	76.39	81.33	98.79	**76.98**
1.524	71.72	97.82	109.77	130.11	**103.87**
1.778	109.09	118.43	143.98	168.72	**140.60**
2.032	167.61	148.24	190.97	212.41	**190.33**
2.286	173.80	188.63	250.60	262.28	**228.89**
2.540	235.89	210.48	362.98	319.03	**305.97**
2.794	309.95	232.32	424.94	388.27	**374.39**
3.048	407.22	290.58	489.51	440.48	**445.74**
3.302	493.77	335.09	544.60	500.11	**512.83**
3.556	567.82	387.71	624.56	557.13	**583.17**
3.810	636.65	435.93	698.07	619.09	**651.27**

Table A.4 Strain Gauge 4 Readings for Pile A

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	**0.00**
0.254	-34.19	-15.79	-12.63	-16.61	**-15.01**
0.508	-53.13	-23.75	-27.18	-34.33	**-28.42**
0.762	-77.02	-33.64	-47.09	-55.88	**-45.54**
1.016	-102.70	-48.05	-65.49	-80.05	**-64.53**
1.270	-128.65	-63.16	-87.87	-103.80	**-84.94**
1.524	-155.01	-78.26	-109.15	-129.61	**-105.67**
1.778	-182.88	-94.60	-131.80	-147.32	**-124.57**
2.032	-211.85	-115.33	-149.10	-166.82	**-143.75**
2.286	-205.12	-134.27	-167.23	-187.55	**-163.02**
2.540	-235.87	-136.40	-186.31	-205.26	**-175.99**
2.794	-277.06	-138.53	-201.82	-220.37	**-186.91**
3.048	-307.40	-171.21	-219.26	-232.72	**-207.73**
3.302	-328.55	-194.96	-229.69	-245.36	**-223.34**
3.556	-344.06	-212.40	-242.05	-258.67	**-237.71**
3.810	-369.32	-228.73	-241.78	-272.82	**-247.78**

Table A.5 Strain Gauge 5 Readings for Pile A

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	**0.00**
0.254	-1.10	-0.96	-3.02	-1.00	**-1.02**
0.508	-1.65	-2.19	-3.43	-1.14	**-1.66**
0.762	-1.92	-2.61	-3.84	-1.28	**-1.93**
1.016	-2.47	-3.29	-4.53	-2.65	**-2.80**
1.270	-3.02	-3.57	-4.94	-2.37	**-2.99**
1.524	-3.84	-3.84	-5.76	-3.61	**-3.76**
1.778	-4.80	-3.84	-6.72	-4.16	**-4.27**
2.032	-5.76	-4.80	-7.41	-3.06	**-4.54**
2.286	-4.39	-5.62	-8.92	-3.88	**-4.63**
2.540	-5.49	-5.42	-10.56	-6.08	**-5.66**
2.794	-6.58	-5.21	-11.25	-6.08	**-5.96**
3.048	-7.00	-5.90	-11.66	-7.04	**-6.64**
3.302	-7.41	-7.82	-12.34	-7.31	**-7.51**
3.556	-6.86	-8.23	-12.76	-7.72	**-7.60**
3.810	-7.41	-8.37	-13.03	-7.86	**-7.88**

Table A.6 Strain Gauge 1 Readings for Pile B

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	11.38	7.96	11.52	12.89	10.01	**11.45**
0.508	24.41	17.56	22.77	28.67	24.42	**25.07**
0.762	36.90	28.67	35.52	45.40	40.33	**39.54**
1.016	50.61	40.87	49.65	62.27	57.20	**54.93**
1.270	65.42	52.94	60.49	79.41	72.97	**69.57**
1.524	79.55	66.11	73.52	95.74	87.37	**84.04**
1.778	90.66	77.22	85.31	110.27	100.95	**96.80**
2.032	101.22	88.05	93.54	123.03	112.47	**107.57**
2.286	110.41	96.70	103.69	135.37	123.58	**118.26**
2.540	120.70	104.65	112.61	147.03	135.24	**128.89**
2.794	130.02	112.33	122.48	158.00	146.35	**139.21**
3.048	140.04	118.64	130.71	168.15	156.64	**148.88**
3.302	149.09	124.68	139.76	176.79	166.93	**158.14**
3.556	158.42	129.20	148.68	186.12	177.49	**167.68**
3.810	169.11	135.65	155.67	194.08	187.23	**176.52**

Table A.7 Strain Gauge 2 Readings for Pile B

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	47.38	28.56	34.61	41.34	37.08	**40.10**
0.508	92.56	62.90	78.55	89.40	86.24	**86.69**
0.762	136.36	101.76	125.38	140.35	140.08	**135.54**
1.016	185.25	145.84	181.68	192.39	195.83	**188.79**
1.270	239.22	189.10	230.71	246.23	257.08	**243.31**
1.524	290.58	238.81	287.01	302.25	316.41	**299.06**
1.778	336.59	283.03	343.45	354.44	379.58	**353.51**
2.032	384.24	327.52	384.79	406.21	440.56	**403.95**
2.286	430.38	371.74	438.48	459.49	500.02	**457.09**
2.540	483.66	415.14	488.61	515.80	560.17	**512.06**
2.794	529.67	463.61	542.30	571.82	618.54	**565.58**
3.048	581.16	507.42	589.54	628.13	675.67	**618.62**
3.302	630.19	539.55	640.35	683.06	732.11	**671.43**
3.556	678.80	579.79	688.28	739.91	785.81	**723.20**
3.810	732.50	617.55	726.45	790.17	838.96	**772.02**

Table A.8 Strain Gauge 3 Readings for Pile B

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	28.71	17.72	18.69	15.94	13.47	**19.65**
0.508	54.27	43.83	43.00	34.90	31.19	**43.07**
0.762	78.59	74.88	71.03	55.92	50.56	**68.77**
1.016	104.42	110.87	110.46	79.14	69.52	**98.82**
1.270	130.66	147.83	150.17	100.71	98.79	**131.86**
1.524	155.52	190.97	195.78	124.75	130.39	**168.17**
1.778	180.94	229.71	243.73	145.63	170.51	**206.22**
2.032	213.36	277.25	301.98	171.32	219.42	**253.00**
2.286	246.34	332.20	359.68	201.96	270.39	**302.15**
2.540	285.49	391.42	412.71	240.02	323.56	**353.30**
2.794	322.59	472.20	470.83	275.46	381.68	**411.83**
3.048	368.61	542.82	522.07	318.60	442.68	**469.05**
3.302	411.48	585.82	585.82	370.67	496.26	**519.85**
3.556	452.28	653.14	650.39	422.47	560.43	**579.06**
3.810	497.34	716.75	706.31	471.51	626.65	**636.76**

Table A.9 Strain Gauge 4 Readings for Pile B

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0,00	0,00	0,00	0,00	0,00	**0,00**
0.254	-17,03	-14,00	-14,14	-17,57	-21,14	**-17,47**
0.508	-30,21	-25,81	-34,74	-35,01	-46,82	**-36,70**
0.762	-42,70	-32,95	-56,98	-56,29	-73,73	**-57,43**
1.016	-58,21	-46,96	-86,50	-78,53	-103,25	**-81,62**
1.270	-79,22	-60,27	-107,91	-103,52	-134,28	**-106,23**
1.524	-99,26	-74,00	-134,14	-130,71	-161,33	**-131,36**
1.778	-117,11	-88,56	-160,50	-158,03	-190,02	**-156,42**
2.032	-133,59	-101,19	-168,05	-182,05	-215,97	**-174,92**
2.286	-147,46	-109,84	-189,60	-208,00	-239,59	**-196,16**
2.540	-163,93	-115,47	-210,61	-236,15	-262,52	**-218,30**
2.794	-177,25	-119,17	-233,68	-263,74	-280,37	**-238,76**
3.048	-190,29	-122,47	-252,21	-291,89	-297,39	**-257,95**
3.302	-202,65	-125,49	-270,61	-316,60	-314,14	**-276,00**
3.556	-216,51	-129,19	-280,63	-340,77	-328,97	**-291,72**
3.810	-231,75	-133,31	-286,53	-362,05	-342,84	**-305,79**

Table A.10 Strain Gauge 5 Readings for Pile B

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	-0.27	-0.69	-0.14	-1.23	-1.23	**-0.72**
0.508	-0.14	-3.16	-1.51	-1.65	-1.92	**-1.31**
0.762	-0.41	-5.08	-2.74	-1.92	-3.02	**-2.02**
1.016	-0.82	-7.00	-4.94	-2.33	-4.25	**-3.09**
1.270	-1.37	-8.92	-5.49	-2.88	-4.66	**-3.60**
1.524	-1.65	-10.84	-7.41	-3.29	-5.62	**-4.49**
1.778	-2.06	-12.76	-8.64	-3.02	-6.58	**-5.08**
2.032	-2.47	-14.68	-10.15	-3.16	-7.27	**-5.76**
2.286	-3.16	-16.60	-12.21	-3.57	-7.68	**-6.66**
2.540	-3.57	-18.52	-13.99	-3.84	-8.23	**-7.41**
2.794	-3.84	-20.44	-16.46	-4.39	-8.78	**-8.37**
3.048	-4.66	-22.36	-17.83	-4.53	-9.33	**-9.09**
3.302	-4.80	-24.28	-20.03	-4.80	-9.33	**-9.74**
3.556	-5.49	-26.20	-21.40	-5.21	-9.33	**-10.36**
3.810	-6.04	-28.12	-22.63	-4.94	-9.74	**-10.84**

Table A.11 Strain Gauge 1 Readings for Pile C

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	9.46	10.97	11.52	14.54	10.01	**11.76**
0.508	18.24	24.00	25.92	30.17	22.63	**25.68**
0.762	27.71	36.76	44.99	47.32	37.58	**41.66**
1.016	35.80	49.38	61.31	63.92	53.22	**56.95**
1.270	44.44	62.54	79.00	81.88	68.99	**73.10**
1.524	52.67	77.36	94.36	97.24	82.57	**87.88**
1.778	59.66	91.89	106.16	111.37	95.19	**101.15**
2.032	67.34	104.79	117.27	127.56	107.95	**114.39**
2.286	73.79	117.82	127.42	141.41	119.88	**126.63**
2.540	80.65	132.77	133.32	153.07	131.40	**137.64**
2.794	85.45	145.39	141.13	163.08	142.10	**147.92**
3.048	91.21	157.73	148.54	172.54	153.90	**158.18**
3.302	94.91	170.07	155.95	181.18	167.06	**168.57**
3.556	99.99	180.50	162.94	190.51	180.50	**178.61**
3.810	106.02	190.10	171.86	198.74	191.89	**188.15**

Table A.12 Strain Gauge 2 Readings for Pile C

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	23.07	43.53	36.80	40.10	35.29	**38.93**
0.508	50.40	89.54	80.06	83.08	82.12	**83.70**
0.762	79.10	137.60	136.78	131.01	134.04	**134.86**
1.016	107.11	184.57	184.15	178.11	187.05	**183.47**
1.270	136.36	233.59	240.73	232.36	242.66	**237.34**
1.524	164.10	288.25	296.07	282.20	298.70	**291.31**
1.778	190.20	341.94	341.94	333.02	354.73	**342.91**
2.032	219.31	391.10	399.21	387.26	413.23	**397.70**
2.286	243.62	440.68	465.12	440.13	473.52	**454.86**
2.540	272.04	497.94	508.65	496.02	529.55	**508.04**
2.794	299.37	550.40	561.80	546.14	585.17	**560.88**
3.048	326.01	603.27	614.26	598.19	641.06	**614.20**
3.302	352.10	657.52	670.70	649.14	699.15	**669.13**
3.556	379.29	709.97	722.33	700.09	757.11	**722.38**
3.810	414.45	763.12	786.05	749.39	812.31	**777.72**

Table A.13 Strain Gauge 3 Readings for Pile C

SHEAR BOX DISPLACEMENT (mm)	EXP 1 (x10^{-6})	EXP 2 (x10^{-6})	EXP 3 (x10^{-6})	EXP 4 (x10^{-6})	EXP 5 (x10^{-6})	AVERAGE (x10^{-6})
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	15.25	23.77	16.90	15.39	11.40	**16.86**
0.508	29.26	50.28	36.96	32.29	28.58	**37.03**
0.762	43.00	75.15	60.04	49.87	45.48	**57.63**
1.016	57.15	100.84	79.27	65.67	61.96	**76.94**
1.270	70.76	127.08	101.26	84.91	80.51	**98.44**
1.524	82.98	153.19	124.47	103.18	109.50	**122.59**
1.778	93.97	180.25	143.43	123.24	145.22	**148.04**
2.032	107.30	204.57	168.03	143.98	189.47	**176.51**
2.286	118.15	226.96	211.30	167.61	240.03	**211.48**
2.540	130.24	252.38	244.28	206.63	290.31	**248.40**
2.794	147.83	280.96	286.45	247.16	343.62	**289.55**
3.048	163.63	312.83	331.65	295.66	393.91	**333.51**
3.302	188.08	356.66	381.80	349.79	436.09	**381.08**
3.556	211.17	408.45	422.88	408.18	478.27	**429.44**
3.810	241.67	459.42	478.38	462.45	526.90	**481.79**

Table A.14 Strain Gauge 4 Readings for Pile C

SHEAR BOX DISPLACEMENT (mm)	EXP 1 (x10^{-6})	EXP 2 (x10^{-6})	EXP 3 (x10^{-6})	EXP 4 (x10^{-6})	EXP 5 (x10^{-6})	AVERAGE (x10^{-6})
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	-3.02	-13.73	-16.20	-19.36	-19.91	**-17.30**
0.508	-8.79	-24.30	-33.09	-36.80	-43.80	**-34.50**
0.762	-16.20	-39.40	-58.63	-57.80	-70.98	**-56.70**
1.016	-24.85	-56.02	-78.67	-79.77	-97.62	**-78.02**
1.270	-34.32	-74.41	-105.99	-105.99	-125.90	**-103.07**
1.524	-44.76	-97.34	-132.35	-128.92	-150.76	**-127.34**
1.778	-54.09	-120.68	-155.83	-154.46	-172.18	**-150.79**
2.032	-65.76	-140.86	-187.55	-181.92	-195.65	**-176.50**
2.286	-75.38	-163.66	-219.53	-209.24	-217.48	**-202.48**
2.540	-87.73	-189.88	-238.07	-236.97	-236.98	**-225.48**
2.794	-98.44	-214.32	-262.23	-255.92	-253.73	**-246.55**
3.048	-108.33	-237.66	-285.99	-276.37	-273.09	**-268.28**
3.302	-117.94	-259.35	-310.56	-294.64	-293.00	**-289.39**
3.556	-128.37	-275.14	-335.14	-311.25	-317.71	**-309.81**
3.810	-142.10	-291.75	-362.05	-324.57	-335.43	**-328.45**

Table A.15 Strain Gauge 5 Readings for Pile C

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	EXP 4 ($x10^{-6}$)	EXP 5 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00	**0.00**
0.254	-1.37	0.00	0.00	-1.92	-1.65	**-0.75**
0.508	-1.78	0.00	0.00	-3.84	-2.06	**-0.96**
0.762	-2.06	-0.14	-0.69	-5.35	-2.33	**-1.30**
1.016	-2.19	-0.69	-1.23	-6.58	-2.33	**-1.61**
1.270	-2.74	-1.23	-1.65	-7.68	-3.02	**-2.16**
1.524	-2.74	-1.78	-2.61	-8.92	-3.43	**-2.64**
1.778	-3.16	-2.74	-3.98	-10.01	-3.43	**-3.33**
2.032	-3.02	-3.16	-4.25	-10.70	-3.84	**-3.57**
2.286	-3.70	-3.70	-4.66	-12.48	-3.84	**-3.98**
2.540	-3.84	-3.98	-4.80	-13.58	-3.98	**-4.15**
2.794	-4.12	-4.39	-5.35	-13.72	-4.25	**-4.53**
3.048	-4.12	-5.21	-5.35	-14.81	-4.53	**-4.80**
3.302	-4.53	-5.76	-5.76	-15.91	-4.66	**-5.18**
3.556	-4.66	-6.04	-5.62	-17.14	-4.66	**-5.25**
3.810	-6.04	-6.31	-6.04	-19.89	-4.66	**-5.76**

Table A.16 Strain Gauge 1 Readings for Pile D

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	**0.00**
0.254	12.34	14.68	14.40	**14.54**
0.508	27.29	31.82	30.59	**31.20**
0.762	43.20	50.20	47.73	**48.97**
1.016	57.74	68.85	65.02	**66.93**
1.270	69.13	86.82	82.43	**84.63**
1.524	80.79	103.83	101.09	**102.46**
1.778	91.21	119.46	118.37	**118.92**
2.032	102.18	135.10	134.83	**134.96**
2.286	111.65	150.19	151.70	**150.94**
2.540	120.29	163.35	166.79	**165.07**
2.794	128.24	174.74	182.43	**178.58**
3.048	137.98	185.02	196.42	**190.72**
3.302	146.76	195.86	210.95	**203.41**
3.556	154.30	206.28	224.81	**215.55**
3.810	161.43	216.16	238.11	**227.14**

Table A.17 Strain Gauge 2 Readings for Pile D

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	**0.00**
0.254	39.00	40.24	43.12	**41.68**
0.508	81.02	87.20	93.25	**90.23**
0.762	128.13	138.56	147.22	**142.89**
1.016	173.03	192.53	202.84	**197.68**
1.270	213.13	245.13	257.22	**251.17**
1.524	260.10	298.13	315.45	**306.79**
1.778	301.02	349.08	368.60	**358.84**
2.032	346.06	402.36	423.26	**412.81**
2.286	391.10	456.88	478.19	**467.54**
2.540	436.01	507.69	530.37	**519.03**
2.794	480.09	560.15	582.15	**571.15**
3.048	525.13	612.06	632.27	**622.17**
3.302	568.25	662.73	682.12	**672.43**
3.556	610.00	710.25	733.49	**721.87**
3.810	652.16	760.78	785.67	**773.23**

Table A.18 Strain Gauge 3 Readings for Pile D

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	**0.00**
0.254	19.37	10.30	14.29	**12.30**
0.508	44.38	24.32	30.78	**27.55**
0.762	68.56	38.06	49.05	**43.55**
1.016	93.01	52.21	69.11	**60.66**
1.270	114.44	64.98	87.38	**76.18**
1.524	140.96	79.82	107.99	**93.91**
1.778	163.22	93.84	126.95	**110.39**
2.032	186.16	110.87	146.05	**128.46**
2.286	219.82	125.16	165.42	**145.29**
2.540	258.15	139.86	184.38	**162.12**
2.794	296.07	161.71	202.24	**181.97**
3.048	336.60	189.87	218.32	**204.09**
3.302	381.11	219.55	236.18	**227.86**
3.556	434.56	244.00	259.12	**251.56**
3.810	488.69	276.42	289.21	**282.82**

Table A.19 Strain Gauge 4 Readings for Pile D

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	**0.00**
0.254	-14.55	-13.87	-20.87	**-17.37**
0.508	-28.56	-27.87	-42.29	**-35.08**
0.762	-45.45	-45.99	-64.81	**-55.40**
1.016	-60.41	-66.73	-86.77	**-76.75**
1.270	-75.38	-88.01	-111.21	**-99.61**
1.524	-94.46	-108.46	-137.30	**-122.88**
1.778	-111.62	-129.61	-158.58	**-144.09**
2.032	-131.39	-152.12	-183.43	**-167.78**
2.286	-145.94	-177.66	-208.70	**-193.18**
2.540	-158.44	-202.37	-233.82	**-218.10**
2.794	-171.62	-225.58	-258.81	**-242.19**
3.048	-184.80	-249.60	-283.25	**-266.43**
3.302	-194.68	-270.88	-308.79	**-289.84**
3.556	-200.18	-290.24	-332.68	**-311.46**
3.810	-203.75	-312.07	-353.14	**-332.60**

Table A.20 Strain Gauge 5 Readings for Pile D

SHEAR BOX DISPLACEMENT (mm)	**EXP 1 ($x10^{-6}$)**	**EXP 2 ($x10^{-6}$)**	**EXP 3 ($x10^{-6}$)**	**AVERAGE ($x10^{-6}$)**
0.000	0.00	0.00	0.00	**0,00**
0.254	-0.41	-1.10	-3.02	**-1,51**
0.508	-1.10	-1.23	-3.98	**-2,10**
0.762	-1.10	-2.06	-4.80	**-2,65**
1.016	-1.37	-2.61	-5.21	**-3,06**
1.270	-2.06	-2.88	-5.35	**-3,43**
1.524	-2.06	-3.02	-6.17	**-3,75**
1.778	-2.61	-3.43	-6.72	**-4,25**
2.032	-2.74	-3.70	-7.00	**-4,48**
2.286	-3.02	-3.84	-7.54	**-4,80**
2.540	-3.16	-3.98	-7.82	**-4,99**
2.794	-3.29	-4.12	-7.96	**-5,12**
3.048	-3.57	-4.66	-8.64	**-5,62**
3.302	-4.12	-4.80	-8.64	**-5,85**
3.556	-4.25	-4.80	-8.78	**-5,94**
3.810	-4.12	-4.94	-8.78	**-5,95**

Table A.21 Strain Gauge 1 Readings for Pile E

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	**0.00**
0.254	14.26	12.76	10.29	**11.52**
0.508	31.55	24.41	23.04	**23.73**
0.762	51.71	35.80	36.62	**36.21**
1.016	70.50	46.91	51.44	**49.17**
1.270	88.60	56.78	66.39	**61.58**
1.524	107.12	64.88	80.79	**72.83**
1.778	122.89	73.24	94.09	**83.67**
2.032	136.33	82.02	106.44	**94.23**
2.286	149.77	91.35	118.37	**104.86**
2.540	160.47	99.71	130.85	**115.28**
2.794	169.94	109.18	143.06	**126.12**
3.048	179.81	117.13	155.82	**136.47**
3.302	189.28	123.99	168.02	**146.01**
3.556	196.41	133.45	178.31	**155.88**
3.810	204.36	140.59	188.87	**164.73**

Table A.22 Strain Gauge 2 Readings for Pile E

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	**0.00**
0.254	31.45	31.04	33.78	**32.62**
0.508	70.31	71.14	76.22	**73.27**
0.762	115.35	114.12	123.60	**119.48**
1.016	162.18	157.10	173.31	**167.75**
1.270	209.15	201.05	223.03	**216.09**
1.524	263.67	244.03	271.23	**267.45**
1.778	312.83	280.01	318.61	**315.72**
2.032	360.62	319.01	363.79	**362.20**
2.286	407.72	361.03	408.70	**408.21**
2.540	452.90	402.09	456.35	**454.63**
2.794	499.73	445.07	503.32	**501.52**
3.048	550.95	488.06	553.45	**552.20**
3.302	594.21	530.08	605.36	**599.78**
3.556	638.15	579.10	654.52	**646.34**
3.810	694.59	625.11	703.41	**699.00**

Table A.23 Strain Gauge 3 Readings for Pile E

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	**0.00**
0.254	8.52	11.82	8.38	**10.10**
0.508	19.37	25.55	25.83	**25.69**
0.762	29.81	39.43	42.73	**41.08**
1.016	39.43	51.93	58.94	**55.44**
1.270	50.01	61.41	75.02	**68.21**
1.524	62.37	67.46	90.82	**79.14**
1.778	71.99	68.01	107.85	**87.93**
2.032	81.33	82.30	125.03	**103.66**
2.286	91.78	99.88	142.06	**120.97**
2.540	104.14	117.19	160.75	**138.97**
2.794	126.12	139.86	179.85	**159.85**
3.048	154.42	170.09	199.91	**185.00**
3.302	174.76	207.46	231.23	**219.34**
3.556	204.85	255.13	263.25	**259.19**
3.810	247.02	299.64	301.03	**300.34**

Table A.24 Strain Gauge 4 Readings for Pile E

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	**0.00**
0.254	-14.69	-17.71	-16.20	**-15.45**
0.508	-29.79	-34.74	-31.58	**-30.69**
0.762	-49.56	-53.13	-51.21	**-50.39**
1.016	-70.71	-72.90	-74.14	**-72.42**
1.270	-90.48	-57.66	-95.70	**-93.09**
1.524	-114.92	-78.81	-116.84	**-115.88**
1.778	-139.49	-97.34	-138.40	**-138.95**
2.032	-163.11	-118.76	-158.99	**-161.05**
2.286	-187.27	-145.12	-180.00	**-183.64**
2.540	-210.75	-169.83	-203.20	**-206.98**
2.794	-233.40	-193.72	-226.68	**-230.04**
3.048	-255.09	-211.98	-252.91	**-254.00**
3.302	-273.22	-229.01	-275.70	**-274.46**
3.556	-292.71	-250.15	-295.33	**-294.02**
3.810	-314.54	-268.41	-316.89	**-315.72**

Table A.25 Strain Gauge 5 Readings for Pile E

SHEAR BOX DISPLACEMENT (mm)	EXP 1 ($x10^{-6}$)	EXP 2 ($x10^{-6}$)	EXP 3 ($x10^{-6}$)	AVERAGE ($x10^{-6}$)
0.000	0.00	0.00	0.00	**0.00**
0.254	-0.82	-2.33	-13.03	**-1.58**
0.508	-2.06	-3.16	-3.70	**-2.61**
0.762	-3.02	-3.98	-15.91	**-3.50**
1.016	-3.70	-4.80	-28.39	**-4.25**
1.270	-3.84	-4.94	-32.37	**-4.39**
1.524	-4.53	-7.68	-37.03	**-6.10**
1.778	-4.80	-9.19	-39.64	**-6.99**
2.032	-5.08	-9.05	-40.19	**-7.06**
2.286	-5.49	-9.88	-40.05	**-7.68**
2.540	-5.49	-10.70	-36.76	**-8.09**
2.794	-5.62	-11.80	-31.14	**-8.71**
3.048	-5.62	-11.52	-25.92	**-8.57**
3.302	-5.76	-11.38	-22.63	**-8.57**
3.556	-5.76	-11.25	-15.77	**-8.50**
3.810	-6.17	-11.66	-14.81	**-8.92**

Table A.26 Strain Readings for Fixed Head Single Pile

SHEAR BOX DISPLACEMENT (mm)	STRAIN GAUGE 1 ($x10^{-6}$)	STRAIN GAUGE 2 ($x10^{-6}$)	STRAIN GAUGE 3 ($x10^{-6}$)	STRAIN GAUGE 4 ($x10^{-6}$)	STRAIN GAUGE 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	12.48	39.14	15.80	-24.44	-6.86
0.508	25.24	82.67	31.74	-45.86	-12.07
0.762	41.70	131.15	50.56	-72.77	-20.57
1.016	56.92	180.18	69.66	-101.05	-30.04
1.270	71.74	230.30	90.13	-134.01	-41.70
1.524	85.45	278.10	109.78	-165.86	-56.10
1.778	97.39	328.91	129.84	-204.58	-70.09
2.032	108.63	376.97	153.06	-239.73	-86.82
2.286	120.15	426.96	178.20	-278.45	-107.12
2.540	129.34	478.46	212.00	-318.81	-132.77
2.794	138.12	525.70	247.86	-356.84	-157.05
3.048	147.59	573.63	280.28	-394.60	-182.29
3.302	157.32	622.80	315.18	-434.69	-207.53
3.556	166.38	668.25	351.31	-471.08	-230.84
3.810	174.88	712.61	390.75	-505.68	-250.18

APPENDIX B

RESULTS OF PILE GROUP EXPERIMENTS

The results of the pile group experiments are given in tabular form in this part.

Table B.1 Pile A Strain 1 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	20.03	14.12	10.42	8.24	11.95
0.508	39.23	30.85	24.54	18.55	21.56
0.762	56.92	48.82	38.39	29.13	31.73
1.016	72.56	67.61	52.51	41.22	41.07
1.270	85.73	84.47	67.73	53.99	51.23
1.524	96.84	100.11	80.90	65.81	60.43
1.778	105.07	111.90	95.15	78.31	69.63
2.032	113.02	121.22	106.26	88.89	78.15
2.286	117.00	128.35	115.58	99.33	86.94
2.540	120.57	133.84	122.03	108.40	94.63
2.794	124.82	140.01	126.14	116.23	101.91
3.048	129.48	144.12	129.16	124.34	108.77
3.302	136.20	150.02	133.27	132.17	116.60
3.556	142.65	155.23	137.80	137.94	123.88
3.810	149.23	158.52	140.26	142.75	131.02

Table B.2 Pile B Strain 1 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	20.57	16.73	9.60	8.38	8.24
0.508	40.74	32.77	22.76	20.47	17.72
0.762	56.79	47.31	37.43	32.15	27.61
1.016	69.40	59.79	53.20	44.24	38.46
1.270	79.55	69.80	68.42	57.70	49.31
1.524	88.33	77.75	84.73	70.34	59.47
1.778	97.11	83.24	98.17	81.20	70.18
2.032	102.19	87.49	110.37	90.54	78.97
2.286	107.40	91.33	122.30	98.92	87.35
2.540	111.24	88.72	130.80	107.16	95.04
2.794	115.76	89.55	138.62	114.86	102.87
3.048	119.88	90.92	145.89	119.80	111.66
3.302	126.87	91.88	152.06	125.71	119.62
3.556	133.18	94.21	156.44	132.17	127.18
3.810	139.08	95.85	159.18	138.49	133.50

Table B.3 Pile C Strain 1 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	18.79	18.79	13.16	8.24	6.46
0.508	40.19	36.34	25.78	19.51	17.03
0.762	60.76	51.84	39.63	32.15	28.43
1.016	79.14	65.27	52.65	45.34	40.52
1.270	95.19	77.89	65.40	57.57	52.88
1.524	108.63	89.41	77.47	71.30	64.69
1.778	121.11	97.77	88.57	83.12	76.77
2.032	130.17	104.77	98.31	94.94	87.21
2.286	137.30	111.90	105.30	106.06	97.51
2.540	145.80	115.46	110.24	115.96	107.13
2.794	152.80	118.62	113.53	125.16	116.47
3.048	161.58	122.32	115.58	134.37	125.67
3.302	168.02	127.12	117.64	142.47	135.28
3.556	174.61	132.06	120.66	149.75	144.21
3.810	178.72	137.68	122.85	155.80	153.55

Table B.4 Pile D Strain 1 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	22.77	14.54	16.45	11.68	7.55
0.508	49.24	31.95	31.54	22.81	17.72
0.762	72.28	49.92	46.21	34.90	28.98
1.016	93.13	67.19	60.19	47.12	40.65
1.270	111.51	83.38	74.31	59.76	51.92
1.524	127.15	96.68	87.75	71.03	64.55
1.778	139.49	109.02	99.54	81.88	75.40
2.032	147.04	116.97	109.69	91.91	87.07
2.286	154.31	123.69	119.70	100.57	98.34
2.540	159.79	129.45	127.51	107.85	109.19
2.794	167.34	136.58	135.19	114.44	120.59
3.048	172.96	144.12	142.18	120.49	132.12
3.302	180.23	149.61	150.96	125.98	142.70
3.556	187.09	154.41	157.95	130.79	153.00
3.810	192.71	157.84	164.94	134.09	162.61

Table B.5 Pile E Strain 1 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	22.77	14.26	11.11	10.44	8.79
0.508	42.25	31.68	24.27	21.30	17.17
0.762	61.04	47.31	39.08	32.97	26.92
1.016	76.26	61.71	54.16	44.79	36.67
1.270	89.16	74.19	69.38	57.57	47.11
1.524	101.50	85.02	81.99	70.07	56.86
1.778	111.10	94.21	96.11	81.75	65.92
2.032	121.25	99.28	106.40	92.46	75.40
2.286	129.76	103.26	113.53	102.49	84.19
2.540	136.20	105.87	119.29	111.01	92.02
2.794	141.96	109.16	125.73	119.25	99.71
3.048	150.60	111.90	131.76	125.71	106.85
3.302	158.15	114.92	136.42	132.44	114.54
3.556	165.55	118.34	140.81	138.90	121.82
3.810	169.94	122.60	144.38	143.30	129.24

Table B.6 Pile A Strain 2 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	57.27	39.54	14.96	29.34	37.33
0.508	109.04	81.14	51.74	64.17	75.89
0.762	158.07	124.26	89.21	100.23	117.47
1.016	202.01	168.19	127.09	139.44	157.82
1.270	244.18	209.66	166.76	181.26	201.32
1.524	281.53	251.81	204.64	220.47	244.82
1.778	317.37	288.06	246.50	263.25	288.33
2.032	351.16	324.17	287.54	305.62	331.42
2.286	383.57	362.47	328.16	349.63	376.43
2.540	415.70	398.72	366.73	390.76	421.58
2.794	447.01	434.42	404.33	431.48	468.10
3.048	478.33	469.29	439.33	471.93	513.39
3.302	509.22	502.66	474.74	514.98	560.05
3.556	537.10	534.92	508.64	556.67	604.92
3.810	568.00	567.05	541.45	595.47	650.35

Table B.7 Pile B Strain 2 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	59.46	48.47	35.14	19.88	33.90
0.508	100.66	94.19	74.80	64.17	75.48
0.762	144.88	138.54	120.23	110.24	120.35
1.016	170.98	177.94	165.52	156.85	167.01
1.270	217.53	214.60	208.76	204.43	217.38
1.524	260.79	247.96	254.46	250.09	265.82
1.778	303.91	278.99	295.50	299.86	317.56
2.032	341.68	307.42	337.36	347.03	366.96
2.286	350.74	337.62	381.83	392.55	417.60
2.540	361.59	363.71	424.24	436.56	464.67
2.794	390.30	391.17	465.82	480.57	512.57
3.048	416.94	419.45	508.51	521.70	561.70
3.302	451.00	445.95	547.21	565.72	613.43
3.556	485.88	469.84	584.40	607.53	663.11
3.810	524.74	496.89	622.15	648.26	709.36

Table B.8 Pile C Strain 2 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	54.66	45.86	56.14	34.00	31.84
0.508	111.51	86.64	96.49	74.45	75.20
0.762	165.76	124.67	140.41	118.33	121.04
1.016	215.89	159.68	178.97	163.71	168.80
1.270	264.50	194.97	216.44	207.58	219.99
1.524	307.76	229.02	251.17	254.20	269.53
1.778	351.71	260.05	287.95	295.75	321.81
2.032	392.63	290.94	322.26	338.66	371.49
2.286	430.95	324.17	358.22	384.04	420.21
2.540	465.97	356.43	393.63	429.02	467.97
2.794	498.92	388.15	428.35	474.13	516.68
3.048	531.88	417.12	463.21	520.19	564.58
3.302	564.84	448.15	499.04	564.07	614.39
3.556	594.78	477.12	529.37	606.85	662.15
3.810	620.19	507.05	565.05	651.00	711.28

Table B.9 Pile D Strain 2 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	53.42	43.39	41.45	38.94	35.27
0.508	109.45	89.66	81.80	78.56	78.36
0.762	160.82	134.42	121.47	121.07	126.39
1.016	210.80	177.12	159.62	161.65	176.76
1.270	259.42	220.37	198.05	203.20	225.34
1.524	304.19	259.09	237.17	242.68	277.62
1.778	347.45	299.45	274.63	281.90	324.42
2.032	389.06	337.21	311.28	320.56	372.59
2.286	427.65	374.28	349.98	360.46	423.23
2.540	467.20	408.33	388.83	402.01	473.18
2.794	510.60	442.11	427.94	442.73	524.64
3.048	555.92	474.37	465.55	484.27	578.85
3.302	614.69	506.50	504.39	525.82	630.45
3.556	650.95	538.22	540.49	562.56	680.95
3.810	688.85	566.50	576.44	603.01	733.37

Table B.10 Pile E Strain 2 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	**POS. 1 ($x10^{-6}$)**	**POS. 2 ($x10^{-6}$)**	**POS. 3 ($x10^{-6}$)**	**POS. 4 ($x10^{-6}$)**	**POS. 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	0.00
0.254	50.81	37.76	32.53	36.75	38.70
0.508	100.11	81.69	70.27	74.59	79.87
0.762	146.40	122.47	110.49	113.53	124.06
1.016	190.20	162.56	151.93	151.37	166.74
1.270	229.21	202.24	194.89	190.99	210.52
1.524	269.03	237.39	231.13	230.89	253.74
1.778	303.50	274.88	272.71	269.70	296.15
2.032	338.93	309.89	313.06	308.09	339.79
2.286	376.29	342.98	349.71	348.40	384.25
2.540	412.54	374.69	389.65	389.53	429.81
2.794	448.11	406.00	429.59	432.17	475.38
3.048	483.82	435.38	465.55	472.48	522.58
3.302	518.43	465.31	502.47	512.93	570.48
3.556	551.39	493.18	539.52	552.00	613.57
3.810	583.66	520.92	576.58	590.81	662.56

Table B.11 Pile A Strain 3 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	7.69	15.90	15.38	23.04	37.08
0.508	7.83	32.75	31.45	45.94	70.59
0.762	4.81	47.55	46.55	70.08	103.68
1.016	0.69	62.63	63.44	93.80	136.64
1.270	-4.40	76.88	81.43	118.76	170.83
1.524	-9.62	90.86	98.46	143.04	206.54
1.778	-13.88	103.88	121.26	171.56	240.32
2.032	-17.04	121.01	152.98	205.57	277.81
2.286	-12.09	146.08	185.80	245.07	319.28
2.540	4.12	173.49	222.47	284.16	368.45
2.794	20.88	199.67	260.10	322.14	419.67
3.048	41.91	225.57	300.19	358.62	471.58
3.302	63.34	254.07	340.29	400.59	523.07
3.556	80.24	281.07	379.84	445.57	572.92
3.810	101.12	316.01	417.75	492.47	624.28

Table B.12 Pile B Strain 3 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	4.40	13.02	16.07	19.61	32.27
0.508	2.34	21.24	36.25	41.01	63.86
0.762	0.69	27.41	56.44	62.54	96.95
1.016	-1.92	32.34	75.94	86.12	129.36
1.270	-4.95	35.63	95.03	111.91	163.28
1.524	-9.76	38.51	114.67	136.04	197.20
1.778	-13.60	43.17	134.72	167.59	237.02
2.032	-11.13	48.38	158.61	206.12	281.38
2.286	-5.50	60.43	189.65	246.58	331.92
2.540	10.85	81.13	224.12	290.19	381.77
2.794	30.78	103.05	257.76	335.31	431.34
3.048	53.45	128.54	290.99	383.31	478.86
3.302	74.19	153.76	326.15	431.17	532.55
3.556	95.49	174.72	360.62	479.17	588.03
3.810	116.78	198.71	403.46	524.97	646.26

Table B.13 Pile C Strain 3 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	NO TEST RESULT
0.254	6.46	12.06	27.74	18.65	
0.508	5.63	24.12	51.91	40.59	
0.762	4.53	30.29	73.06	62.67	
1.016	4.40	35.49	92.15	85.85	
1.270	1.79	39.33	108.90	108.89	
1.524	0.69	40.56	124.01	133.58	
1.778	4.67	42.76	139.94	157.44	
2.032	17.59	49.75	156.00	185.28	
2.286	39.02	59.61	176.74	219.97	
2.540	60.45	79.07	206.13	258.78	
2.794	80.10	101.27	236.75	296.22	
3.048	97.14	125.39	269.71	334.07	
3.302	120.63	148.69	302.67	373.02	
3.556	148.38	171.71	330.96	411.56	
3.810	178.06	195.28	363.91	458.87	

Table B.14 Pile D Strain 3 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	3.02	10.96	19.64	37.44	25.54
0.508	3.30	17.27	35.84	70.08	56.03
0.762	3.71	23.30	49.71	99.70	88.44
1.016	3.30	27.82	62.76	126.58	122.36
1.270	3.98	31.38	74.84	150.86	157.38
1.524	3.98	36.18	85.83	173.48	194.04
1.778	11.82	45.22	96.13	197.07	228.37
2.032	32.84	61.80	110.14	220.25	266.82
2.286	54.82	86.33	127.03	248.09	312.97
2.540	80.65	111.41	152.43	283.74	361.99
2.794	107.44	134.44	180.45	319.54	409.64
3.048	136.84	154.58	210.11	358.07	457.84
3.302	165.15	181.03	239.22	396.34	507.28
3.556	193.04	210.35	267.24	429.39	555.62
3.810	219.00	242.83	295.66	468.34	613.16

Table B.15 Pile E Strain 3 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	**POS. 1 ($x10^{-6}$)**	**POS. 2 ($x10^{-6}$)**	**POS. 3 ($x10^{-6}$)**	**POS. 4 ($x10^{-6}$)**	**POS. 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-3.30	2.88	15.52	27.02	43.81
0.508	-6.87	4.66	28.56	49.51	84.87
0.762	-13.33	5.48	41.88	70.35	124.69
1.016	-18.55	10.00	55.07	89.96	161.50
1.270	-24.59	14.94	68.11	109.30	196.51
1.524	-32.43	19.73	81.85	127.54	230.16
1.778	-35.17	31.38	99.15	144.41	264.35
2.032	-32.15	53.72	122.77	165.25	298.13
2.286	-20.88	78.25	153.26	188.57	336.45
2.540	-3.57	105.93	183.47	220.52	383.83
2.794	13.19	134.85	212.58	253.85	430.52
3.048	29.68	166.78	239.50	289.37	480.50
3.302	48.78	197.88	270.67	324.48	529.94
3.556	68.83	228.58	305.14	359.45	573.20
3.810	98.37	257.22	342.35	394.55	623.87

Table B.16 Pile A Strain 4 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	NO TEST RESULT
0.254	-50.94	-31.98	-16.48	-10.83	
0.508	-100.23	-60.80	-35.97	-25.63	
0.762	-151.72	-90.17	-53.82	-44.14	
1.016	-199.22	-118.99	-71.94	-63.47	
1.270	-247.00	-142.33	-90.48	-85.95	
1.524	-293.69	-163.33	-106.40	-105.96	
1.778	-338.86	-178.97	-119.58	-125.56	
2.032	-382.11	-193.52	-125.08	-140.10	
2.286	-426.04	-204.36	-125.76	-150.38	
2.540	-469.29	-214.52	-123.43	-158.05	
2.794	-508.70	-223.72	-120.41	-167.79	
3.048	-549.61	-232.50	-115.05	-177.38	
3.302	-586.68	-238.54	-110.93	-188.21	
3.556	-621.15	-244.44	-105.85	-197.94	
3.810	-658.08	-247.46	-102.83	-200.82	

Table B.17 Pile B Strain 4 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-57.12	-33.76	-28.42	-16.86	-14.25
0.508	-111.49	-70.41	-53.27	-35.78	-34.80
0.762	-166.00	-108.70	-79.22	-53.46	-60.84
1.016	-215.97	-144.11	-106.27	-71.69	-89.20
1.270	-264.99	-178.84	-129.61	-90.61	-122.77
1.524	-314.56	-211.91	-151.57	-107.88	-153.46
1.778	-360.41	-244.85	-168.46	-122.82	-186.34
2.032	-404.49	-274.36	-183.56	-128.99	-213.47
2.286	-449.80	-305.10	-194.96	-132.28	-236.36
2.540	-492.36	-333.38	-204.71	-132.28	-256.22
2.794	-531.63	-358.63	-215.00	-132.01	-277.87
3.048	-568.42	-384.85	-224.75	-128.99	-299.25
3.302	-604.12	-407.49	-232.85	-126.94	-323.64
3.556	-639.55	-428.49	-241.09	-123.65	-345.70
3.810	-673.73	-452.10	-244.80	-123.37	-362.00

Table B.18 Pile C Strain 4 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-49.57	-23.88	-17.71	-51.13	-22.66
0.508	-99.96	-55.17	-38.31	-81.29	-50.40
0.762	-148.42	-90.31	-62.33	-111.72	-78.96
1.016	-195.10	-124.76	-85.40	-142.15	-108.76
1.270	-242.61	-160.17	-109.56	-167.37	-141.31
1.524	-285.59	-195.58	-132.76	-191.77	-171.52
1.778	-329.93	-229.21	-155.28	-210.83	-199.67
2.032	-370.57	-260.22	-176.29	-227.28	-219.17
2.286	-409.57	-292.48	-195.78	-239.89	-234.83
2.540	-443.89	-320.89	-213.49	-250.44	-248.56
2.794	-476.98	-345.73	-229.28	-260.18	-261.47
3.048	-509.25	-368.51	-245.35	-270.32	-272.45
3.302	-543.98	-391.30	-258.66	-282.52	-284.95
3.556	-575.01	-413.80	-271.43	-291.98	-295.80
3.810	-600.69	-434.25	-285.44	-298.70	-309.40

Table B.19 Pile D Strain 4 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	NO TEST RESULT
0.254	-42.29	-30.61	-23.75	-17.27	
0.508	-85.26	-63.96	-50.39	-36.19	
0.762	-123.57	-97.17	-80.04	-58.26	
1.016	-160.23	-129.84	-108.33	-78.55	
1.270	-196.75	-165.93	-138.26	-100.34	
1.524	-231.08	-199.01	-169.97	-121.59	
1.778	-263.89	-232.22	-199.76	-142.43	
2.032	-293.96	-261.05	-225.85	-161.21	
2.286	-319.36	-286.03	-254.13	-179.16	
2.540	-342.84	-307.99	-276.65	-192.60	
2.794	-364.81	-329.81	-295.87	-205.89	
3.048	-383.48	-350.81	-312.35	-219.46	
3.302	-402.57	-373.18	-328.68	-230.70	
3.556	-418.77	-392.94	-345.02	-241.26	
3.810	-436.07	-406.94	-358.89	-254.69	

Table B.20 Pile E Strain 4 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	**POS. 1 ($x10^{-6}$)**	**POS. 2 ($x10^{-6}$)**	**POS. 3 ($x10^{-6}$)**	**POS. 4 ($x10^{-6}$)**	**POS. 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-49.43	-23.61	-15.38	-19.19	-24.39
0.508	-94.60	-52.98	-35.29	-41.95	-51.11
0.762	-137.99	-79.60	-57.80	-70.46	-79.74
1.016	-179.73	-105.96	-81.14	-96.50	-106.60
1.270	-217.62	-131.62	-106.82	-125.02	-135.10
1.524	-255.24	-154.41	-129.19	-154.90	-163.05
1.778	-288.19	-175.40	-151.57	-183.00	-190.18
2.032	-319.91	-190.50	-168.60	-209.05	-215.67
2.286	-349.84	-201.89	-183.01	-236.32	-238.14
2.540	-380.46	-210.40	-194.41	-258.39	-258.14
2.794	-409.98	-217.40	-206.08	-277.04	-277.32
3.048	-439.50	-222.75	-218.30	-293.90	-295.96
3.302	-466.68	-228.93	-230.11	-310.35	-312.67
3.556	-492.22	-232.22	-241.09	-327.48	-328.98
3.810	-517.76	-237.85	-246.58	-342.70	-348.85

Table B.21 Pile A Strain 5 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-26.34	-35.53	-12.22	-20.45	-37.27
0.508	-54.18	-67.91	-23.20	-37.34	-71.39
0.762	-72.56	-93.70	-31.03	-53.12	-103.45
1.016	-83.26	-110.30	-37.34	-68.77	-132.77
1.270	-89.84	-118.26	-44.48	-85.52	-161.41
1.524	-96.15	-120.72	-47.77	-100.20	-189.22
1.778	-101.09	-120.04	-50.66	-116.67	-214.71
2.032	-104.93	-119.35	-49.42	-130.40	-238.96
2.286	-109.87	-117.02	-46.95	-145.77	-264.86
2.540	-118.51	-114.83	-42.83	-160.60	-290.61
2.794	-126.05	-111.94	-39.40	-174.46	-315.96
3.048	-134.42	-108.93	-35.83	-188.60	-339.26
3.302	-143.47	-105.09	-31.57	-203.70	-361.18
3.556	-150.60	-102.75	-28.69	-219.21	-382.42
3.810	-158.70	-100.97	-26.08	-234.45	-402.42

Table B.22 Pile B Strain 5 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	NO TEST RESULT
0.254	-34.84	-19.76	-51.34	-15.65	
0.508	-66.94	-34.85	-97.61	-25.26	
0.762	-102.05	-44.45	-138.79	-31.71	
1.016	-135.38	-51.58	-172.29	-37.06	
1.270	-173.92	-58.58	-193.84	-42.69	
1.524	-212.33	-66.67	-211.82	-46.53	
1.778	-247.58	-74.22	-225.83	-50.24	
2.032	-284.34	-82.31	-241.61	-51.47	
2.286	-323.02	-91.78	-257.12	-52.02	
2.540	-358.13	-105.91	-277.30	-51.34	
2.794	-392.42	-119.76	-291.58	-50.38	
3.048	-424.65	-134.86	-303.66	-49.69	
3.302	-453.04	-150.08	-316.02	-49.55	
3.556	-478.15	-164.08	-329.88	-49.28	
3.810	-502.56	-179.03	-349.38	-49.00	

Table B.23 Pile C Strain 5 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-28.26	-42.94	-35.01	-34.87	-48.09
0.508	-53.22	-84.23	-65.07	-56.14	-94.13
0.762	-78.59	-117.16	-85.80	-75.08	-120.71
1.016	-105.07	-138.01	-102.27	-92.79	-136.88
1.270	-132.09	-151.87	-117.24	-108.30	-150.72
1.524	-158.70	-164.08	-132.34	-122.17	-161.00
1.778	-183.93	-175.05	-146.20	-131.77	-170.45
2.032	-205.74	-186.71	-160.21	-140.01	-176.89
2.286	-227.28	-203.17	-176.13	-147.42	-182.51
2.540	-244.83	-219.64	-194.11	-154.01	-187.58
2.794	-260.88	-234.18	-211.69	-157.85	-191.55
3.048	-275.83	-248.31	-231.04	-161.29	-196.89
3.302	-289.41	-260.79	-249.57	-164.44	-201.69
3.556	-301.89	-273.83	-266.87	-167.05	-206.62
3.810	-315.61	-288.37	-286.37	-170.76	-212.93

Table B.24 Pile D Strain 5 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	POS. 1 ($x10^{-6}$)	POS. 2 ($x10^{-6}$)	POS. 3 ($x10^{-6}$)	POS. 4 ($x10^{-6}$)	POS. 5 ($x10^{-6}$)
0.000	0.00	0.00	0.00	0.00	0.00
0.254	-31.00	-42.12	-17.02	-25.12	-45.63
0.508	-66.39	-83.55	-28.28	-74.81	-82.35
0.762	-102.46	-119.76	-37.89	-71.65	-108.93
1.016	-140.18	-149.12	-46.68	-81.95	-130.99
1.270	-176.80	-172.31	-53.13	-117.50	-147.57
1.524	-206.02	-192.47	-59.85	-167.33	-162.37
1.778	-230.43	-210.99	-65.48	-174.19	-175.66
2.032	-246.89	-228.69	-71.66	-206.72	-187.58
2.286	-256.36	-245.56	-79.07	-220.17	-200.46
2.540	-261.70	-261.75	-88.55	-237.33	-212.79
2.794	-266.78	-275.33	-99.80	-250.23	-223.89
3.048	-272.13	-288.09	-109.14	-263.27	-234.44
3.302	-276.24	-301.26	-117.92	-291.55	-244.85
3.556	-280.50	-313.75	-126.98	-303.90	-255.13
3.810	-284.06	-326.23	-136.46	-332.87	-266.64

Table B.25 Pile E Strain 5 Readings in Pile Group Tests

SHEAR BOX DISPLACEMENT (mm)	**POS. 1 ($x10^{-6}$)**	**POS. 2 ($x10^{-6}$)**	**POS. 3 ($x10^{-6}$)**	**POS. 4 ($x10^{-6}$)**	**POS. 5 ($x10^{-6}$)**
0.000	0.00	0.00	0.00	0.00	NO TEST RESULT
0.254	-26.61	-24.83	-23.20	-36.24	
0.508	-50.06	-37.18	-42.28	-64.10	
0.762	-72.01	-43.76	-60.40	-84.83	
1.016	-92.04	-48.84	-77.29	-104.60	
1.270	-106.03	-52.13	-95.00	-120.93	
1.524	-112.47	-54.05	-109.96	-136.03	
1.778	-116.86	-55.56	-124.10	-149.07	
2.032	-122.21	-56.38	-137.42	-162.25	
2.286	-129.21	-55.56	-149.50	-176.93	
2.540	-135.10	-54.33	-161.30	-190.80	
2.794	-138.67	-53.50	-173.66	-206.03	
3.048	-141.55	-53.09	-186.43	-222.37	
3.302	-141.55	-52.95	-198.92	-239.39	
3.556	-141.55	-51.99	-211.14	-256.68	
3.810	-141.55	-52.13	-224.59	-273.70	

APPENDIX C

THEORY OF STRAIN GAUGE MEASUREMENT

When a material is stretched, length of the material will increase. Conversely, if the material is compressed the length of it will decrease. Therefore there will be a change in the length of a material under loading. Strain is defined as ratio of the change in length of a member due to an applied load to its initial length. Related equation of strain is given as Equation C.1 where ΔL is the change in the length and L is the initial length of the member under loading.

$$\varepsilon = \frac{\Delta L}{L} \tag{C.1}$$

Strain gauges are composed of very fine wires parallel to each other arranged in a grid pattern. The grid pattern is bonded to a thin carrier which is fastened on a member under loading. Under loading there become changes in the length of this member which will result in changes in the length of the wires of strain gauges. The length change in these wires will result in changes of electrical resistances of these wires.

As discussed above the resistances of the strain gauges changes directly proportional with the strain. Gauge Factor (GF) is defined as the ratio of the change in the resistance of strain gauge to the strain and defined as;

$$G.F = \frac{\Delta R / R}{\Delta L / L} \tag{C.2}$$

where R is resistance, L is the length of the strain wires, ΔR is the change in resistance and ΔL is the change in the length of the strain wires.

Knowing that, strain is directly proportional with the change in resistance of the strain gauge, the changes in the strain gauge resistances should be measured in order to obtain strain values. For measuring the changes in resistances, Wheatstone bridges are formed with three dummy resistances and a strain gauge. Wheatstone bridge is given in Figure C.1.

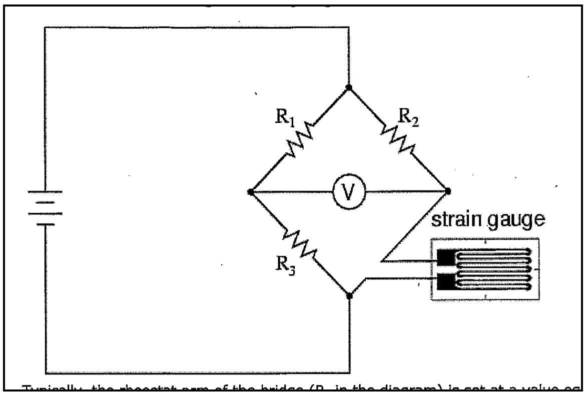

Figure C.1 Wheatstone Bridge (from Strain Gauge Tutorial of National Instruments)

When a voltage of V_i is given to the Wheatstone bridge, the voltage reading V_0 will be;

$$V_o = \left(\frac{R_3}{R_3 + R_1} - \frac{R_2}{R_2 + R_{SG}}\right)V_i \qquad \text{(C.3)}$$

As can be seen from Figure C.1 and the Equation C.3, four resistive arms exists in the bridge. For measurements with only one strain gauge, three resistive arms having resistances equal to the resistance of strain gauge should be used to form a bridge. Knowing that $R_1=R_2=R_3=R$ and change in the resistance, $\Delta R=R.GF.\varepsilon$, Equation C.3 can be rewritten as;

$$V_o = \frac{-GF.\varepsilon}{4}.\left(\frac{1}{1+GF.\frac{\varepsilon}{2}}\right).V_i \qquad \text{(C.4)}$$

It can be concluded that strain can be obtained by knowing the gauge factor, GF, given voltage V_i and reading the output voltage V_0.