Experimental Investigating of Unsupported Excavation Considering Its Effect on a Nearby Axially Loaded Pile

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ABSTRACT

An experimental model is used to simulate the loss of soil lateral confinement due to excavation nearby an individual axially loaded pile. The effects of various parameters, such as the horizontal distance of excavation, depth of excavation and pile slenderness ratios are investigated. The experimental analysis results showed the effect of excavation is more remarkable as the horizontal distance of excavation becomes closer to the pile than half pile length. The effect of excavation diminishes gradually as the horizontal distance increases beyond that distance for all the investigated pile slenderness ratios and depths of excavation. The pile head deflection, settlement and bending moments along pile increase with decreasing horizontal distance between excavation face and adjacent axially loaded pile of various depths of excavation and pile slenderness ratios. The location of maximum bending moment is positioned between 1/4 and 1/2 of pile length for all horizontal distance of excavation, depth of excavation and slenderness ratios. The bending moment profiles indicate a (single curvature) for medium flexible piles and (double curvature) for very flexible piles for different horizontal distance between excavation face and adjacent axially loaded pile and various depths of excavation. In addition the theoretical approach of wood, 2004 showed good agreement especially for very flexible pile (slenderness ratio >45).

Key words: excavation, axially loaded pile, deflection, settlement, bending moment

التحليل المختبري للحفريات غير المسندة مع مراعاة تاثيرها على ركيزة عمودية محملة رأسيا مجاورة

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الخلاصة

في هذه الدراسة تم استخدام الموديل العملي المصغرلنمذجة نقصان الضغط الجانبي للتربة الناشيء عن الحفريات غيرالمسندة المجاورة لنموذج ركيزة مفردة محملة رأسيا. تم التحري عن تاثيرعدة معاملات مثل المسافة الافقية للحفر ، عمق الحفر ونسبة الطول الى القطر المكافيء (نسبة النحافة للركيزة). لقد أثبت التحليل للنتائج العملية ان للحفريات تاثير جديربالملاحظة عندما تصبح مسافة الحفر قريبة من الركيزة وتساوي أقل من نصف طول الركيزة ، يتلاشى تاثير الحفريات تدريجيا عندما تزداد المسافة الافقية اكبر من نصف طول الركيزة لكل نسب النحافة للركيزة ولكل اعماق الحفر. ان الانحراف والهبوط لرأس الركيزة وعزوم الانحناء على طول الركيزة تزداد مع نقصان المسافة الافقية للحفر والركيزة العمودية المحملة رأسيا لكل اعماق الحفر ولكل نسب النحافة للركيزة. ان موقع اكبر عزوم انحناء يقع بين ربع ونصف طول الركيزة لكل المسافات الافقية للحفر ، اعماق الحفر ولكل نسب النحافة للركيزة. ان شكل منحي العزوم الانحناء يكون احادي التحدب للركائز المتوسطة المرونة بينما مزدوج التحدب للركائز المرنة جدا لمختلف المسافات الافقية بين الركيزة ووجه الحفر وكذلك لمختلف الاعماق . اضافة الى ذلك اظهرت النتائج النظرية توافق مع النتائج العملية وخاصة للركائز المرنة جدا (نسبة الطول /القطر المكافيء اكبر من 45).

الكلمات الرئيسية : ركيزة عمودية محملة رأسيا ، الضغط الجانبي ، الهبوط ، عزوم الانحناء

1. INTRODUCTION

In dense civilian area where landscapes of structures are nearly distance, deep excavation for underground constructions is necessary. Axially loaded piles in present structures are essentially exposed to horizontal soil movement causes by excavation , **Finno, et al.,1991and 2005 and Leung et al., 2000 and 2003**, pile supporting bridge or pile nearby embankment **Springman,1989; Ellis and Springman, 2001 and Goh et al., 2005**. That soil movement induces lateral loading on nearby pile foundations, causes additional bending moment and deflection on the piles. Horizontal soil movement generally has an adverse effect on the behavior of axially loaded piles.

The centrifuge model for passive piles nearby unsupported excavation was carried out by **Leung, et al., 2000, Leung, et al., 2003, and Ong, et al., 2004, 2006 and 2009.** Centrifuge modeling technique is considered a good alternative way to study the problem as the tests can be adopted under an organized condition such that the soil strength profile, soil deformation and elapsed time can be measured with accuracy and converted to prototype scale. The results showed that the bending moment increased with increasing depth of excavation initially. Then the bending moment decreased with increasing depth and time. The difference between soil movement and head deflection is relatively low at depth of excavation less than 0.60m. Then the difference increased significantly with increasing depth of excavation and highly soil movement were detected closely ground surface.

Chiang, and **Lee, 2007,** studied the response of individual piles under different design loads adjacent to tunneling by centrifuge model experiments. The tunnel permanence in saturated sand was observed. Two instrumented piles of depths 27 m were situated of each side with various cover-to-diameter ratios and different distances from tunnels. The bending moments and axial forces were measured at various depths during tunneling. The results showed that the unit skin frictions rapidly decreased with increasing the tunneling operation for the shallow tunneling near a long pile and substantial decay of the end bearing capacity that causes large settlement of the pile if the pile base is close to the tunnel. The depth ratio was observed to be an important effect on the bending moment variation along the piles, but both the working loads and depth ratio identify axial load response and the settlement of pile.

Guo, 2010 and **Ghee, 2009** established a new experimental apparatus comprises from a box, and a loading system that allows various horizontal soil movements shapes (rectangular, triangular and arc) and with application of vertical load simultaneously on piles/pile groups. The sand used with relative density of 89%. The tests results for single pile noticed that the bending moment increased with decreasing distance from boundary as the reduction of soil pressure. In addition, the maximum bending moment (Mmax) increased with increasing the pile diameter while the maximum pile deflection (at the sand surface) reduced as the pile diameter increased. Results of pile groups showed that an increase in bending moment, shear force and soil reaction in front pile than rear pile, but a decrease in the deflection due to axial load increases as the axial load increases from 0 to 588 N on the pile cap of pile groups. The deflection profile for test with no load indicates that piles mainly translate with slight rotation; while in test with axial load, the piles translate and rotate. In comparison the results of pile group with single free-head piles, maximum bending moment and shear force decrease of 30-60% and 40-60% respectively for the piles in groups.

Lee, et al., 2013 carried out large scale model to study the effect of combined load on pile behavior. The model consisted mainly from cylindrical steel tank and instrumented model pile with outer diameter 30 mm and length 1200 mm instrument with 18 uniaxial strain gages with resistance of 350 Ω distributed along length. Models piles are prepared in fine clean poorly graded sand at loose, medium and dense relative densities. The results examined that the combined load test effects exhibit that the presence of an axial load on a driven pile is negative to its lateral capacity and significantly increased in lateral deflection with increasing axial load. The bending moment at the head of pile increased with increasing soil relative density of the model pile head in the existence of axial loads. Consequently, the effect of axial loads should be measured in the design of laterally loaded piles in sand (particularly in the dense sand).

Muthukkumaran, and Begum, 2015. adopted the experimental model to examine the influence of slope on laterally loaded pile capacity, the study is performed on horizontal surface and two slopes (1V:2H) and (1V:1.5H), loose to medium density and various length to diameter ratio of piles that behave as flexible pile for all L/deq ratios. The results observed that the lateral resistance increased with increasing soil-pile stiffness but the capacity of lateral load reduced when the slop surface varies from horizontal surface to slope surface and the effect was reduced with increasing relative density and L/d ratio. In addition, the capacity of lateral load was increased with increasing relative density, soil depth and pile embedment length but the steeper slope was less affected. Also when the lateral load increased, the bending moment and fixity depth increased, while the increasing of relative density results in reducing fixity depth.

Most of above previous research focused on the work on pile foundations subjected to soil movement due to braced excavation, but the pile response under vertical load nearby unsupported excavation can be significantly different. Therefore, in this study an attempt is made to investigate and measured the effect of unsupported excavation on adjacent axially loaded pile throughout experimental model. In addition one of theoretical approach (wood, 2004) is adopted to verify behavior of single axially loaded under the same condition of experimental model.

2. MODEL BOX AND LOADING SYSTEM

Fig.1 shows the image of box model that made of steel plate with thickness (4 mm) with internal box dimensions measures 0.80 m as length (W_M), 0.40m as width (B_M) and 0.80 m as depth (H_M). That are composed of eight steel - U shaped parts with width 0.10 m for each one that are connected through a number of screws. The front face of mold consists of the of 8 steel moving laminar parts.

3. MEASURING SYSTEM

3.1 Data Logger

Data Logger is a sophisticated data acquisition unit that provide link between computer and the transducers connected to test equipment that is strain gauges, load cell and LVDT.

3.2 Linear Variable Differential Transformer (LVDT)

Linear Variable Differential Transformer LVDT is an energy converter that alters a linear movement or location from a mechanical reference (or zero) into a relative electrical signal comprising phase (for direction) and amplitude information (for distance).

3.3 Strain Gauge

Metal foil Rosette strain gauge with resistance **120 OHMS**, gauge factor **G.F. 2.15**, size **3 mm** and **3 m** Lead are used. The Rosette strain gauge consists of two located perpendicular strain gauge with respect to each other jointly in same carriers as shown in **Fig.2.**

4. THE INSTREMENTED MODEL PILE

Aluminum bars with rectangular cross section with constant thickness (3 mm) are used as model piles. Different length to equivalent diameter was design to simulate the problem. The model pile was instrumented with four pairs of Rosette strain gauges were each pair glued at opposite largest faces in same location at intervals of L/4, L/2, 7L/8 with bending connection. In addition At interval approximately 7L/8 other pair was existed to measure axial compression or tension connection with full bridge circuit for all pairs. **See Fig.3**.

5. SOIL PROPERTIES AND MODEL BOX PREPARATION

The selected sample classified as silty sand with trace of clay according to USCS classification. The friction angle of the soil is determined to be 36° and the constrained modulus is measured to be 5.0-7.0 Mpa. **Table1** summarizes the main physical properties of the selected soil.

The preparation process is carried out of soil for testing with different length of model box (W_M). The length of mode box is depended on the horizontal distance of excavation from face of excavation to axially loaded pile at specified length.

The model pile is tested under applied axial working load that obtained after examining different criteria such as; **Ahmed, 1997, Brinch, 1963, Butler, and Hoy, 1977, Chin, 1970 Davisson, 1970 and 1972, De Beer, 1967, Decourt,1999, Fuller,** and **Hoy, 1970**. By numerical analysis using different methods of pile load test are tabulated in **Table 2**.

6. PILE RELATIVE FLEXIBILITY

At the beginning, the pile response is defined as short rigid or infinitely long elastic pile throughout calculating the stiffness factors **R** and **T.** Those factors that combine the effect of soil and pile properties are not constant for any soil and depend on pile diameter and depth. The soil modules **k** is related to **Terzaghi's concept** of modules of horizontal subgrade reaction. In case of cohesion less soil the soil modules is function of relative density and increase linearly with depth, the stiffness factor for cohesion less soil calculated from following equations:

$$\boldsymbol{Stiffness\ Factor\ \ T = \sqrt[5]{\frac{EI}{n_h}} \qquad in\ unit\ of\ L} \tag{1}$$

Where:

E: Modules of elasticity of model pile which calculated and results are displayed in chapter three in unit of $\mathbf{F/L^2}$**.**

I: Moment of inertia about the weak axis towards the excavation **(Imin = bh^3/12)** for rectangular cross section of model pile in unit of $\mathbf{L^4}$

$\mathbf{n_h}$**:** parameter to define the variation of **Ks** with depth in unit of **F/L**^{3} **.**

Fig. 4 presents $\mathbf{n_h}$ variation as function of relative density that are suggested by **Terzaghi and Reese et al**., The $\mathbf{n_h}$ value suggested by **Reese et al** is significantly higher than Terzaghi therefore the average value of $\mathbf{n_h}$ between two approach is considered in this study $\mathbf{n_h}$ is equal **7.5 MN/m^3** for relative density about **50%** at medium dense state for soil sample prepared in model tests. The criteria for pile behavior as short rigid or long flexible are tabulated in **Table 3, Tomlinson, 1994**. **Table 4** displays the calculated **stiffness factor T** and thus determines the criteria for pile behavior. It is obviously seen all model piles behave as flexible element. Furthermore, other flexibility criteria to describe pile behavior basing on rigidity factor **(K_R = Ep.Ip/E$_s$L^4) ,Poulos, and Davis, 1980**, where:

K_R < 10e-1 (Rigid pile.

K_R < 10e-3 (Med flexible pile)

K_R < 10e-5 (Very flexible pile)

Table 5 shows the determination of rigidity factor **K_R** , all model piles of different length and cross section are behavior range between medium flexible pile to very flexible pile.

7. TESTS RESULTS

The calculated bending moment is normalized with respect to coefficient of passive earth pressure K_p, total unit weight of soil γ and pile moment of inertia I. Additionally the measured pile deflection Ux and pile settlement Uy were normalized with respect to equivalent pile diameter of same recognized pile. The results of three model piles are displayed for **L/deq 20, 53 and 97**. The closest horizontal distance of excavation equals **L/4, L/8 and L/12** for **L/deq** ratios **20, 53** and **97** respectively.

Fig. 5 shows the variation of pile head deflection **Ux/deq** with excavation horizontal distance to pile length **L_{EX}/L** for model piles of **L/deq** ratios **20, 53 and 97** respectively. Each figure includes two profiles of variation the normalized pile head deflection for depth of excavation **L/2 and L**. It appears that the increases in magnitude of pile head deflection **Ux/deq** is being about **200%** as compared to previous stage especially for horizontal distance of excavation less than **L/2**.The pile head deflection is decreased by approximately **70%** as the excavation horizontal distance increases from **closest** distance to **L/2** horizontal distance and decreases by approximately **85%** as the excavation horizontal distance increased from **closest** to **L** horizontal distance.

Fig.6 shows the variation of pile head settlement profile **Uy/deq** with excavation horizontal distance to pile length **L_{EX}/L** for model piles of **L/deq** ratios **20, 53 and 97** respectively. Each figure includes two profiles of variation the normalized pile head deflection for depth of excavation **L/2 and L**. The pile head settlement is decreased by approximately **20-40%** as the excavation horizontal distance increases from **closest** horizontal distance to **L/2** horizontal distance and decreases by approximately **50%** as the excavation horizontal distance increases from **closest** horizontal distance to **L/2** horizontal distance.

Figs.7 to 9 show the variation of bending moment profile with excavation horizontal distance to pile length **L_{EX}/L** and depth of excavation for model piles of **L/deq** ratios **20, 53 and 97** respectively. In general the bending moments decrease with increasing horizontal distance of excavation for different depth of excavation and L/deq ratios. For medium flexible pile the bending moments decrease from negative value to slightly positive (reverse the excavation) with increasing horizontal distance of excavation especially as horizontal distance of excavation more than half pile length **$L_{EX} \geq L/2$** and depth of excavation less than half pile length **$H_{EX} \leq L/2$**. The maximum bending moment increases by **about 70 %** along pile length as the horizontal distance of excavation gets closer than **(L/2)** to the closest possible horizontal distance for all examined excavation depths. The largest variation of the maximum bending moment with horizontal excavation distance at L/4 and L/2 but little effect observes near pile base.

In this paper, the theoretical work of **Wood, 2004**, is adopted in addition to experimental models to verify behavior of single axially loaded pile exposed to lateral soil movement due to adjacent excavation. **Wood, 2004**, solved the differential equation of pile deformation and presented design charts to estimate bending moment and deflection along model pile. **Fig. 10** presents the normalized bending moment profiles that predicted from experimental model of different L/deq ratios. In addition the points of theoretical normalized bending moment are represented on same figures that evaluated referring to **Wood, 2004**. The measured and predicted responses of the model piles are in good agreement for very flexible pile (**L/deq > 45**) but less agreement notices for medium flexible pile (**L/deq < 45**).

8. CONCLUSIONS

1. The pile head deflection increases with decreasing horizontal distance between excavation face and adjacent axially loaded pile of various depths of excavation and lengths to cross section ratios (L/deq).

2. The pile downward settlement increases with decreasing horizontal distance between excavation face and adjacent axially loaded pile for various L/deq ratios and depth of excavation. It is attributed to decrease the confining pressure, passive resistance and density of particles distribution of soil below and surrounding model pile.

3. Insignificant effect of excavation at horizontal distance more than half pile length $L_{EX} \geq L/2$for all L/deq ratios.

4. The horizontal distance of adjacent excavation is noticeably affected on bending moments along the pile. It can be noticed that maximum bending moment increases with decreasing horizontal distance between excavation face and adjacent axially loaded pile for various depths of excavation and lengths to cross section ratio of L/deq. This finding may attributed to the soil lateral movement resulting due to the excavation.

5. The location of maximum bending moment is positioned between L/4 and L/2 of pile length for all horizontal distance of excavation, depth of excavation and L/deq ratios.

6. The bending moment profiles are showed (single curvature) for medium flexible piles and (double curvature) for very flexible piles of different horizontal distance between excavation face and adjacent axially loaded pile and various depths of excavation.

REFRENCES

- Ahmed, F.,and Pise, P.J., 1997 ,*Pile Load Test Data-Interpretation and Correlation Study*, Indian Geotechnical Conference, Vadodara, December, 17-20, 1997, pp. 443-446.
- ASTM -2007.
- Davisson, M.T., 1970, *Static Measurement of Pile Behavior, Design and Installation of pile Foundation and Cellular Structures*, Envo Publish Co., edited by H.-Y Fang, pp.159-164.
- Davisson, M.T., 1972 *High Capacity Piles*, Proceedings of Lecture Series on Innovations in Foundation Construction, American Society of Civil Engineers, ASCE, Illinois Section, Chicago, March 22, 52 pp.
- Brinch, H. 1963, J. *Discussion, Hyperbolic Stress-Strain Response, Cohesive Soils*, ASCE J. Soil Mechanics and Foundation Engineering, Vol.89, SM4, pp.241-242.
- Butler, H.D. and Hoy H.E., 1977 , *The Texas Quick-Load Method for Foundation Load Testing-User's Manual*, Report No. FHWA-IP-77-8, 59pp.

- Chin, F.K., 1970, *Estimation of the Ultimate Load of Piles Not Carried to Failure, Proc. 2nd Southeast Asia Conference on soil Engineering*, pp. 81-90.
- De Beer, E.E ,1967, *Proefondervindlijke bijdrage tot de studie van het grensdraag vermogen van zand onder funderingen op staal. Tijdshift der Openbar Verken van Belgie*, No. 6, 1967 and No. 4, 5, and 6, 1968.
- Decourt, L. ,1999, *Behavior of Foundations Under Working Load Conditions, Proceedings of the 11th Pan-American Conference on Soil Mechanics and Geotechnical Engineering*, Foz DoIguassu, Brazil, Vol. 4, pp. 453 – 488.
- Lee, G. T. K. and Ng, C. W. W. ,2005, *Effects of Advancing Open Face Tunneling on an Existing Loaded Pile,* Journal Of Geotechnical and Geoenvironmental Engineering, ASCE / 193-201.
- Ellis E.A. and Springman S.M, 2001, *Modeling of Soil-Structure Interaction for a Piled Bridge Abutment in Plain Strain FEM Analyses*, Computers and Geotechnics, Vol. 28, No.2, pp.79-98.
- Finno, R.J., Lawrence, S.A., Allawh, N.F. and Harahap, I. S.,1991, *Analysis of Performance of Pile Groups Adjacent to Deep Excavation*, Journal of Geotechnical Engineering, Vol. 117, No. 6, pp. 934-955.
- Finno, R.J., Voss, F.T., Rossow, E., and Blackburn, J. T. , 2005, *Evaluating Damage Potential in Building Affected by Excavation*, Journal of Geotechnical Engineering, ASCE, 131(10), 1199-1210.
- Goh, A. T. C., The, C. I., and Wong, K.S. , 2005, *Analysis of Piles Subjected to Embankment Induced Lateral Soil Movement,* Journal of Geotechnical and Geoenvironmental Eng., 123 (9), 792-801.
- Guo, W. D. and Ghee, E. H., 2011, *Behavior of Axially Loaded Pile Groups Subjected to Lateral Soil Movement,* Proceedings of the 18th Australasian Conference on the Mechanics of Structures and Materials, 2: 997-1003.
- Guo, W. D. and Ghee, E. H., 2011, *Response of Axially Loaded Pile Groups Subjected to Lateral Soil Movement – an Experimental Investigation*, Published in6th International Conference on Tall Buildings (ICTB-VI), 6-8 December, Hong Kong, pp. 333~338.
- Lee, J., Prezzi, M. and Salgado, R.,2013, *Experimental Investigation of the Combined Load Response of Model Piles Driven in Sand*, Geotechnical Testing Journal, Vol. 34, No. 6.
- Leung, C.F., Chow, Y.K. and Shen, R.F., 2000, *Behavior of Pile Subject to Excavation-Induced Soil Movement*, Journal of Geotechnical and Geoenvironmental Eng, Vol. 126, No. 11, pp. 947-2000.
- Leung, C.F., Chow, Y.K. and Shen, R.F. ,2003, *Behavior of Pile Groups Subject to Excavation-Induced Soil Movement*, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No. 1, pp. 58-65.

- Muthukkumaran,K. and Almas Begum, N., 2015,*Experimental Investigation of Single Model Pile Subjected to Lateral Load in Sloping Ground*, Department of Civil Engineering, National Institute of Technology (NIT), Tiruchirapalli 620 015, Tamilnadu,India.

- Ong, D.E.L. Leung, C.F. and Chow, Y.K., 2004, *Pile Behavior Behind A Failed Excavation, International Conference on Structural and Foundation Failures*, Singapore.

- Ong, D.E.L. Leung, C.F. and Chow, Y.K., 2006, *Pile Behavior Due to Excavation-Induced Soil Movement in Clay I: Stable Wall*, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 132(1),36-44.

- Ong, D.E.L. Leung, C.F. and Chow, Y.K., 2009, *Behavior of Pile Group Subjected to Excavation-Induced Soil Movement in Very Soft*, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 135(10), 1462-1474.

- Poulos, H.G., and Davies, E.H. , 1980, *Pile Foundation Analysis and Design*, John Wiley and Sons, New York.

- Springman S.M, 1989, *Lateral Loading of Piles Due to Simulated Embankment Construction*, Ph.D Thesis, University of Cambridge.

- Tomlinson, M.J. (1994) *Pile Design and Construction Practice* , Fourth edition, CEng, FICE, FIStructE ,1994.

NOMENCLATURE

BM: width of model box
LVDT: linear variable differential transformer
HM: depth of model box
WM: length of model box
G.F.: gauge factor
L: length of model pile.
Ux: pile head deflection
Uy: pile head settlement
deq: equivalent pile diameter
T: stiffness factor
E: modules of elasticity of model pile
I: moment of inertia
n_h: parameter to define the variation of Ks with depth.
β : parameter for soil-pile interaction.

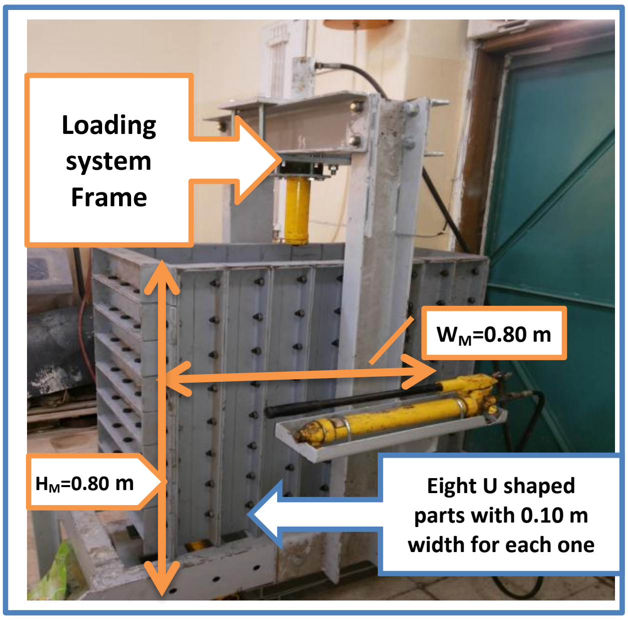

Figure 1. Image of experimental model box with detailed dimension.

Figure 2.Rosette strain gauge used in experimental work.

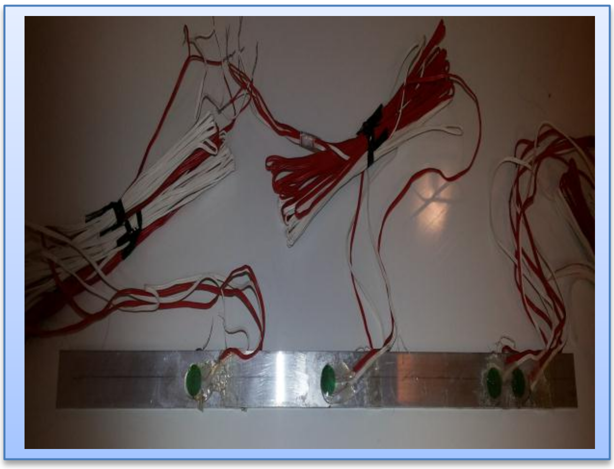

Figure 3. Instrumented model pile with four pairs of Rosette strain gauges.

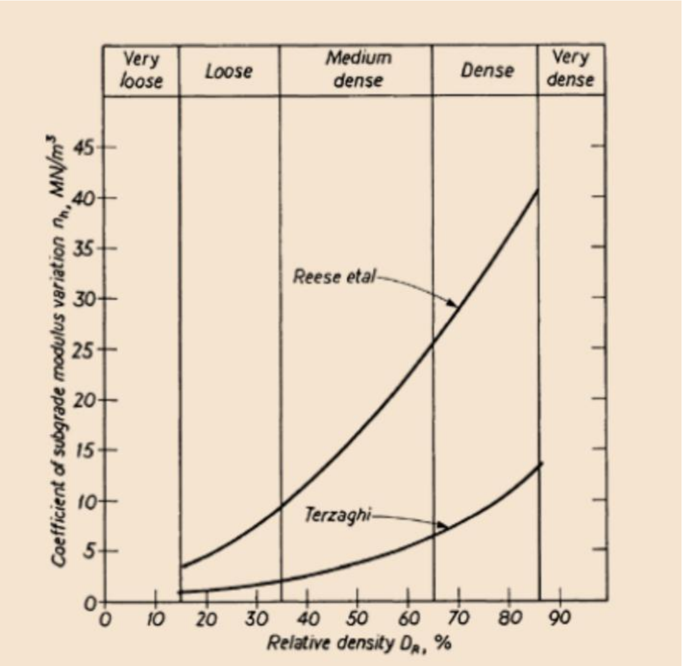

Figure 4. Relationship between coefficient of modulus variation and relative density of sands,**Tomlinson, M.J. 1994**.

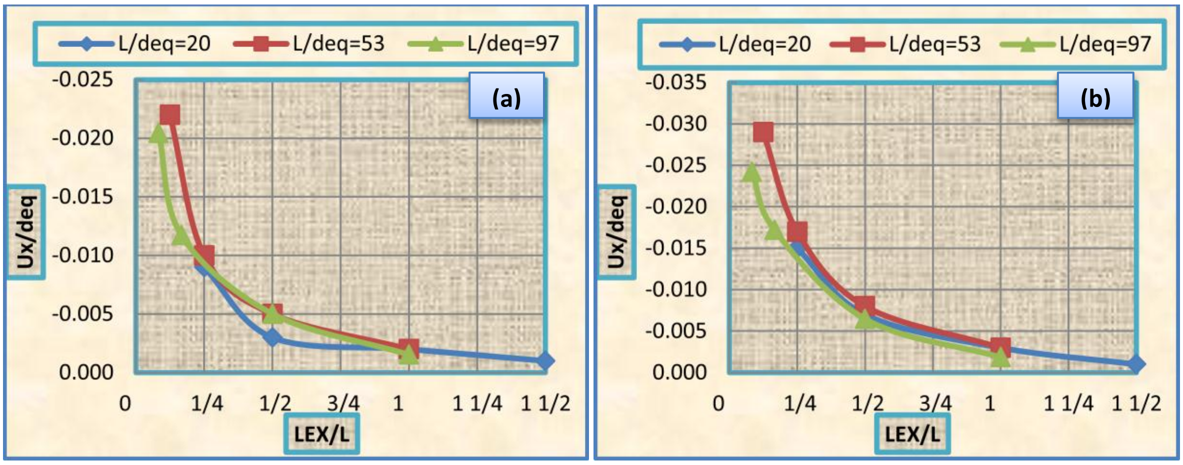

Figure 5. The Variation of pile head deflection of model piles of L/deq 20, 53 and 97 with various horizontal distance of excavation (a) Excavation depth H_{EX}=L/2, (b) Excavation depth H_{EX}=L.

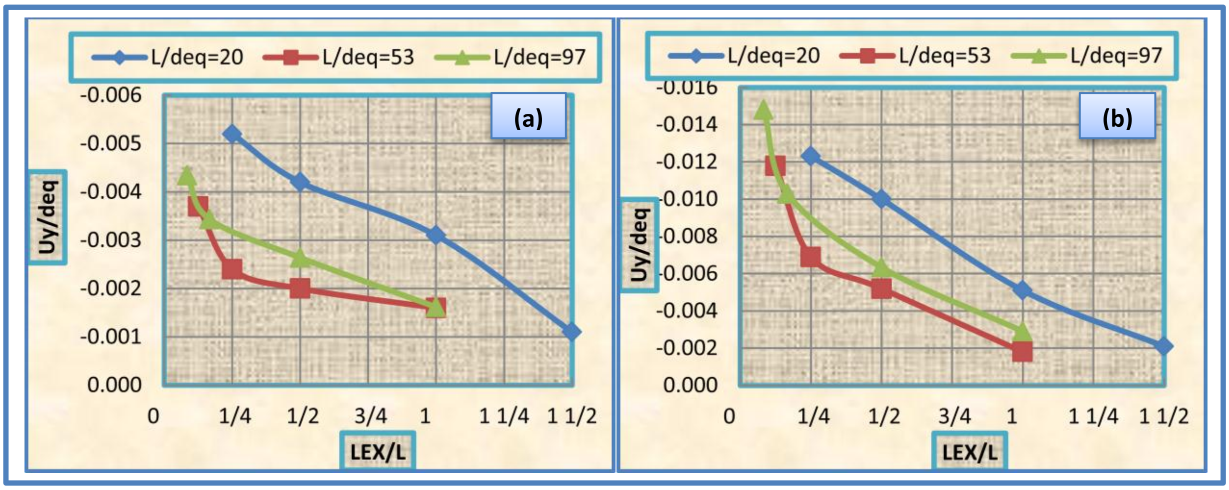

Figure 6. The Variation of pile settlement of L/deq 20,53 and 97 with various horizontal distance of excavation of (a) Excavation depth H_{EX}=L/2, (b) Excavation depth H_{EX}=L

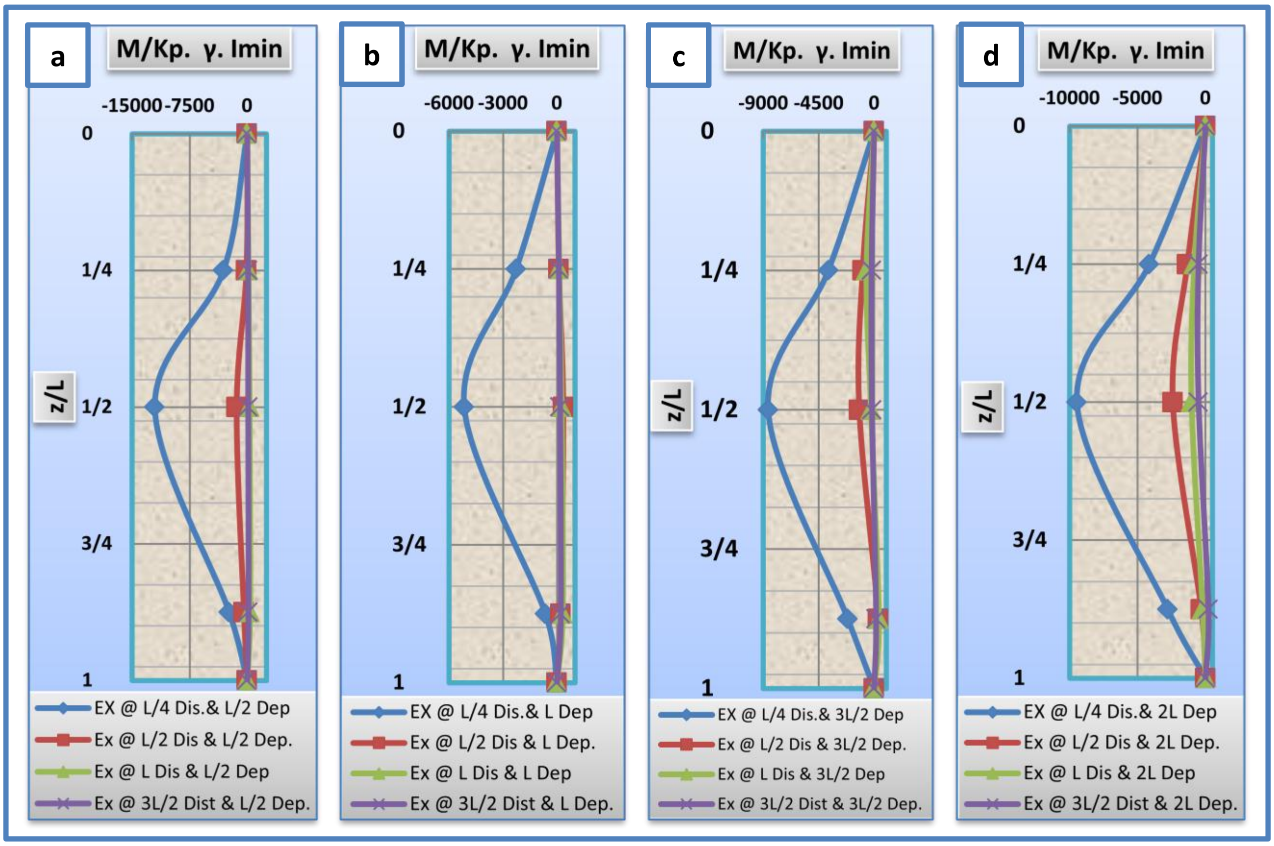

Figure 7. The effect of horizontal excavation distance for each excavation depth of **L/deq=20 (a) H_{EX}= L/2 : (b) H_{EX}= L : (c) H_{EX}=3L/2 : (d) H_{EX}= L/2.**

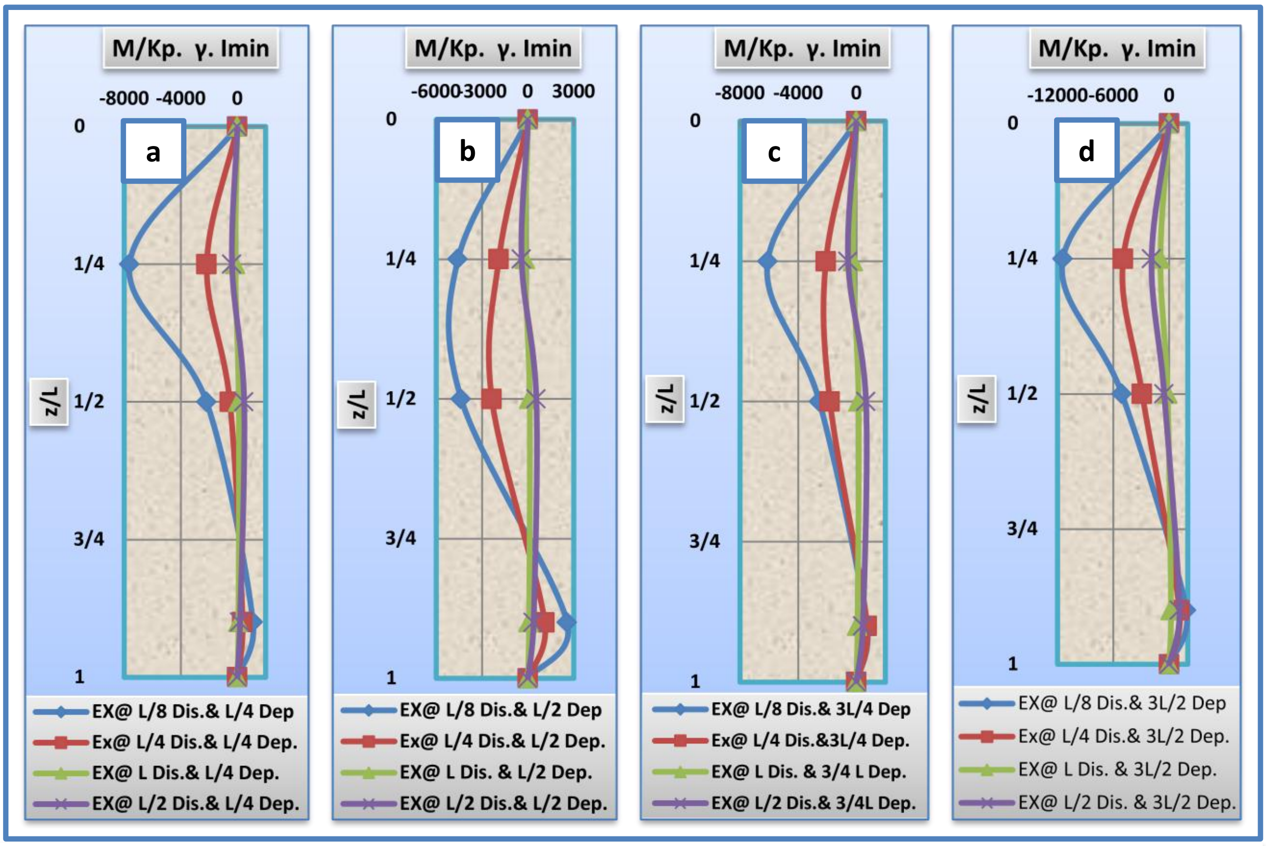

Figure 8. The effect of horizontal excavation distance for each excavation depth of **L/deq=53 (a) H_{EX}= L/4 : (b) H_{EX}= L/2 : (c) H_{EX}=3L/4 : (d) H_{EX}= 3L/2.**

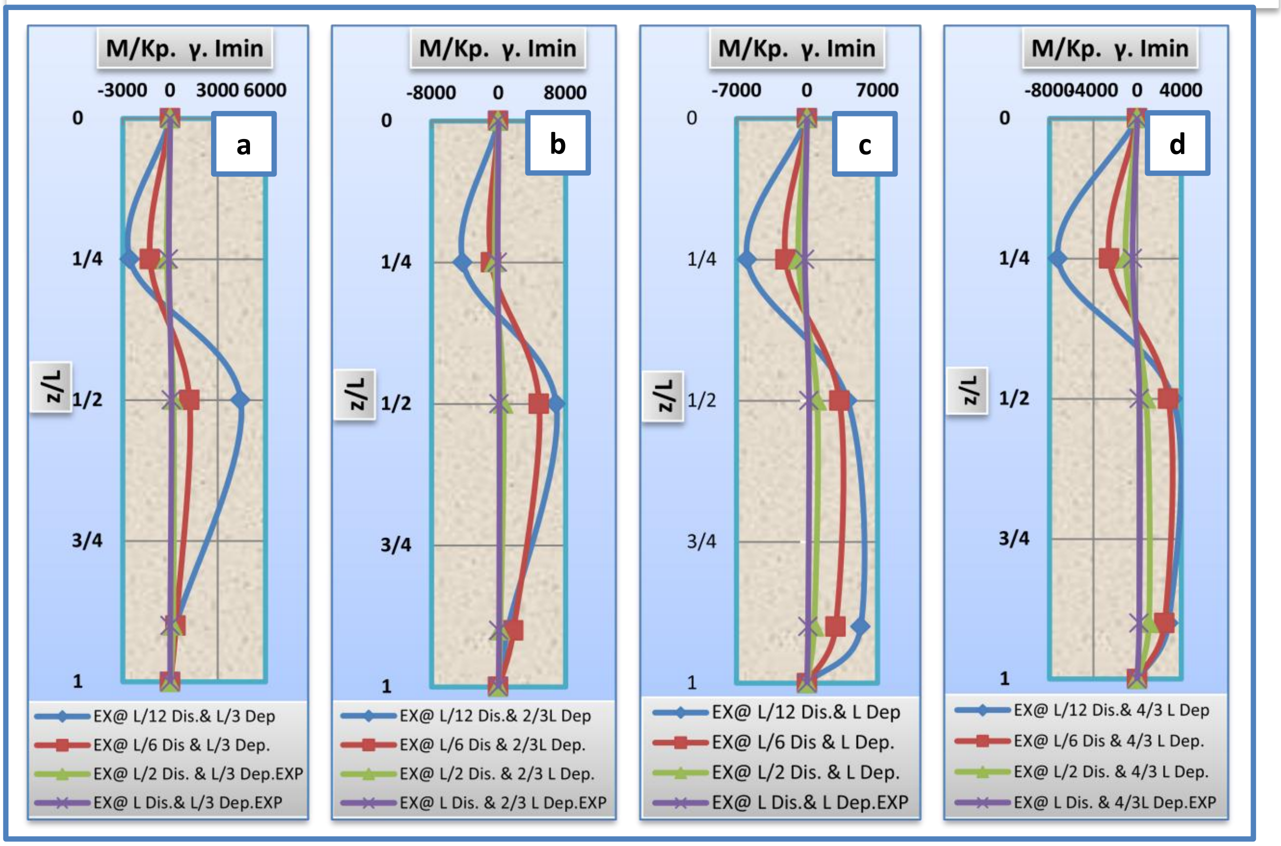

Figure 9. The effect of horizontal excavation distance for each excavation depth of **L/deq=97 (a) H_{EX}= L/3 : (b) H_{EX}= 2L/3 : (c) H_{EX}=L : (d) H_{EX}= 4L/3.**

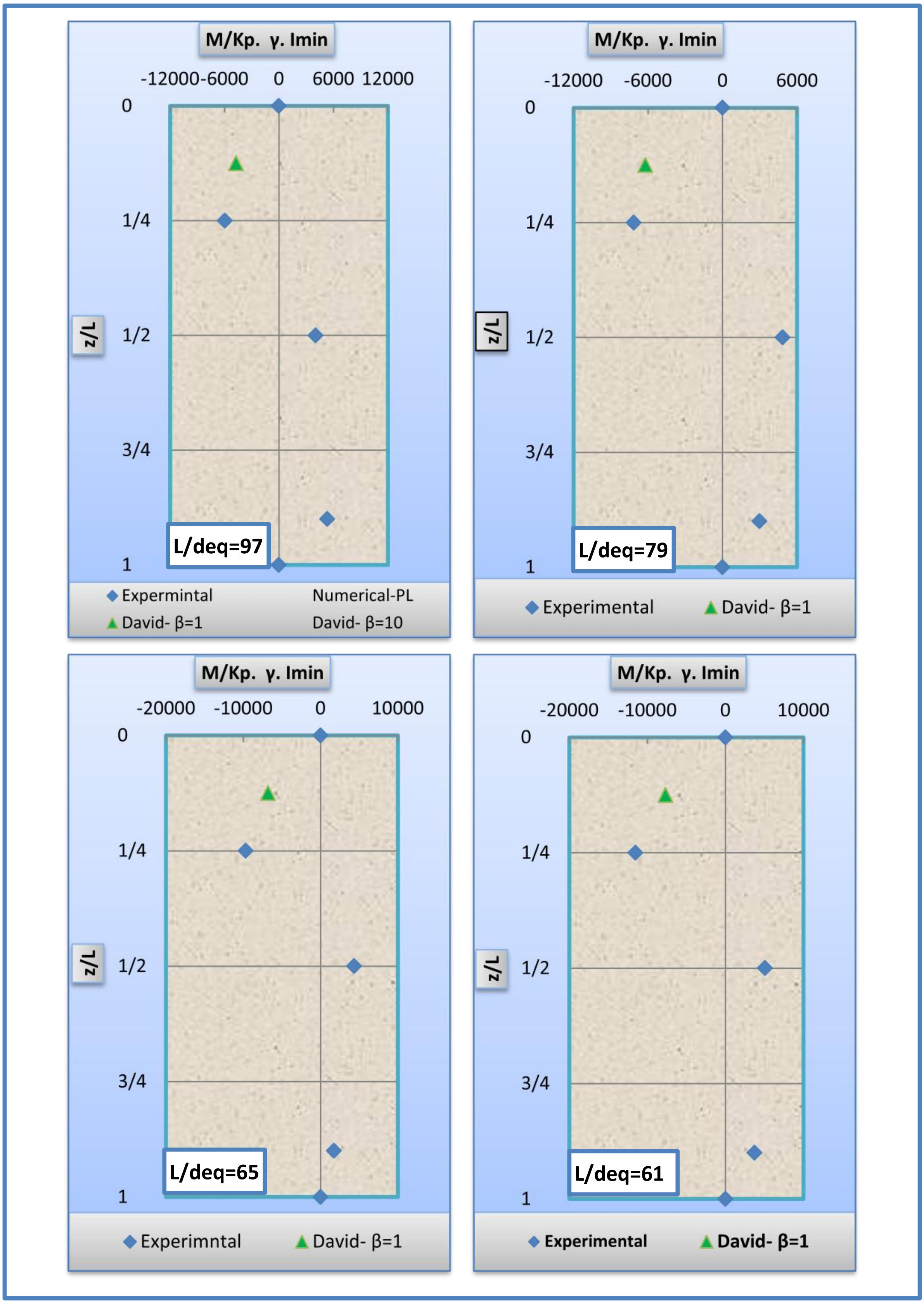

Figure 10 Comparisons of theoretical normalized bending moment from ,**Wood, 2004**, with experimental results of different L/deq of model pile

Table1. Material properties of selected soil.

Test Name	Standard	Soil Property	Value
Specific Gravity	(ASTM D-854)	Specific Gravity, G_s	2.67
Water Content	(ASTM D-2216)	Natural Water Content, ω_c %	8-10
Grain Size Analysis • Sieve Analysis • Hydrometer Analysis	(ASTM D-422)	D_{10},mm	0.07
		D_{30},mm	0.18
		D_{60},mm	0.23
		Coefficient of Uniformity, Cu	3.286
		Coefficient of Curvature ,Cc	2.012
		Clay %	3.02
		Silt %	6.10
		Coarse to Medium Sand %	14.85
		Fine Sand %	74.45
		Gravel %	1.58
		Unified Classification System (USCS)	SP-SM
Amount of Material finer about No.200 (75-µm)	(ASTM D-1140)	Amount of Material finer about No.200 (75-µm)%	14.60
Maximum Index Unit Weight	(ASTM D-4253)	Maximum Dry Unit Weight γ_{max} gm/cm^3.	1.672
Minimum Index Unit Weight	(ASTM D-4254)	Minimum Dry Unit Weight γ_{min} gm/cm^3	1.367
Relative Density Calculation	ASTM D-4254 & ASTM D-4253	Relative Density, RD %	48-55 Med. Dense
Organic Matter	BS 1377:1990 Part 3	Percent of Organic matter %	4.07

Table 2. Working load values of different pile length and equivalent diameter.

Pile Length mm	Equivalent Diameter (mm)	L/deq	Working Load KN
200	9.775	20	0.220
400	7.571	53	0.180
600	6.182	97	0.250

Table 3. The criteria of pile behavior, Tomlinson, M.J. 1994.

Pile Type	**Soil Modules**
Rigid (Free Head)	$L \leq 2T$
Elastic (Free Head)	$L \geq 4T$

Table 4. Model piles flexibility basis on stiffness factor T.

Embedment Depth(m)	**L/deq**	**Width (m)**	**I_p (min)**	**Ep.Ip (MN.m^2)**	**T**	**4T**	**2T**	**Pile Criteria**
0.185	20	25.00	5.625E-11	4.22E-06	0.056	0.225	0.112	$\geq 4T$ **Elastic**
0.385	53	15.00	3.375E-11	2.53E-06	0.051	0.203	0.102	
0.585	97	10.00	2.25E-11	1.69E-06	0.047	0.187	0.094	

Table 5. Model piles flexibility basis on rigidity factor K_R.

Pile Length mm	**Pile Cross Area mm2**	**Equivalent Diameter mm**	**L/deq**	**I min m^4**	**K_R $E_p.I_p/E_sL^4$**	**Relative Pile Flexibility**
200	75	9.775	20	5.625E-11	2.25E-03	**Med. Flexible Pile**
400	30	6.182	65	2.250E-11	4.27E-05	**Very Flexible Pile**
600	30	6.182	97	2.250E-11	7.72E-06	**Very Flexible Pile**