Analytical Approach for Load Capacity of Large Diameter Bored Piles Using Field Data

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ABSTRACT

An analytical approach based on field data was used to determine the strength capacity of large diameter bored type piles. Also the deformations and settlements were evaluated for both vertical and lateral loadings. The analytical predictions are compared to field data obtained from a proto-type test pile used at Tharthar –Tigris canal Bridge. They were found to be with acceptable agreement of 12% deviation.

Following ASTM standards D1143M-07e1,2010, a test schedule of five loading cycles were proposed for vertical loads and series of cyclic loads to simulate horizontal loading .The load test results and analytical data of 1.95m in diameter test pile proved efficiently to carry a working load of 450 tons. The calculated lateral displacements based on a specified coefficient of subgrade reaction are compared to the measured values from dial gauges and strain gauges placed at various locations along the length of the pile.

Keyword :bored piles, lateral displacement ,horizontal loads, vertical loads.

الاسلوب التحليلي لقوة التحمل لركائز الحفر ذات الأقطار الكبيرة باستعمال البيانات الحقلية

الخلاصة

تم تقديم تصور تحليلي مستنداً إلى نتائج فحوصات حقلية لتقييم قوة التحمل لركائز الحفر ذات الأقطار الكبيرة وكذلك تم تقييم الانحرافات والهبوطات بتأثير الأحمال العمودية والجانبية وتم مقارنة النتائج التحليلية مع نتائج الفحوصات الحقلية التي تم الحصول عليها من فحص الركيزة كاملة القياس والتي تم استخدامها في جسر كيلو 50الواقع على قناة الثرثار- دجلة . لقد وجد أن توافقاً مقبولاً في النتائج بانحراف في حدود12%.

إن برنامج الفحص وفقاً للمواصفة العالمية بخمس مراحل (ASTM standards D1143M-07e1, 2010) تمت للأحمال العمودية وسلسلة من دورات التحميل لمحاكات الأحمال الجانبية. ان النتائج التحليلية ونتائج فحص التحميل لركيزة قطرها 1,95 اثبتت كفاءتها لتحمل قوة خدمية مقدارها 450 طن وقد تم مقارنة نتائج الانحرافات الجانبية مع القياسات المأخوذة من مؤشرات الانفعال والانحراف المثبتة في نقاط مختلفة على طول الركيزة .

الكلمات الرئيسية : ركائز الحفر ,الإزاحات العرضية ,الاحمال الافقية ,الاحمال العمودية .

1. INTRODUCTION

Large diameter bored piles are non - displacement piles which are commonly used to transfer large vertical loads with or without horizontal loads and flexural bending moments to the surrounding subgrade. The preference of this type of deep foundation is economy per unit of load as compared to other types. Another advantages are early completion of the foundation construction even before land grading is experienced and elimination of pile caps ,also problems of cobbles and small boulders encountered in sub-strata have small effect in addition to smaller amounts of reinforcement .However the use of bored type piles is extremely affected by delay due to bad wet weather, building code restrictions and poor quality control or in adequate construction equipment . **Lee,1987**.

In-situ concrete piles with diameters of 0.3 m up to 3.0 m are referred to as large diameter bored piles. For their construction hollow spaces are made in the soil by means of drilling equipment. Depending on soil conditions the excavation is carried out under the protection of a casing or without casing. Subsequently the drilling holes are filled with concrete; according to static requirements a rebar cage is placed before concreting. **Poulos,1980**.

Large-diameter bored piles have a broad scope of application as foundation elements for carrying vertical building loads, foundation elements for retaining walls, temporary building pit walls components of the final structure, protection against uplift and for taking up tension loads slope security and energy piles. **Tomlinson, 1994**

2.Testing Program

2.1 Soil Investigation

Even though this type of pile requires careful and through exploration as compared to other types, limited soil investigation was done for this work .Few borings were drilled to check continuity of sub - strata and undisturbed soil samples. Two bore holes were drilled. The geological subgrade soil profile was (5-6) m of hard crested loamy clay resting on sandy layers with different gravel contents to a depth of 45m below G.L. A thick layer of sand stone was encountered at a greater depth **. Fig . 1** and **Fig.2** show standerad penetration test (SPT) results for B.H. No.1 near the test pile Cone Penetration Test(CPT) for Tharthar Tigris Canal Bridge Project KM 50, **Table 1.** Results of Atterberg Limits, Specific Gravity & Grain size. **Bowles, 1981.**

2.2 Test Pile Construction

The test pile was one of the series of piles used to support the abutments of a bridge at KM 50 Tharthar Tigris canal. All piles were drilled using Terra drill (80CA) mounted on a crawler crane (38RB).A bucket 1.5m in diameter was used with hinged reamer for 2m segmental drilling .At various levels during drilling of the pile shaft, soil samples were taken for testing in the laboratory .The hole walls were stabilized using bentonite slurry to keep them from collapsing and closing the hole particularly in the cohesionless layers .In order to avoid soil caving and keeping risk to minimum a standard pipe 14mm thick was used as a casing in each pile hole .It was driven to a depth of 15m below G.L. The reinforcement cage was then lowered into the hole . The cage extended to the entire length of the pile .A ready mix concrete was transported by a rotary drum trucks and was placed into the holes using a tremi tube. Three control cube specimens of (200×200×200) mm were taken for compressive strength tests in the laboratory,**Das,2004.** and **Head,1984.**

3.CHARACTERISTICS OF TEST PILES

The test pile was 1.95 m in diameter and total length of 25.5 m. The reinforcement cage consisted of (45—Ø32 mm) diameter bars extended to length of 14.5m below G.L. The longitudinal reinforcement was reduced to (30—Ø32 mm) diameter to the remainder length of the pile. The lateral reinforcement were 12mm diameter ties spaced at 200 mm on center spacing .The tension piles were designed to receive the loading reactions .They were 1. 5 m in diameter and 25.5 m total length. They were reinforced longitudinally with (24—Ø32 mm) diameter and laterally with 12mm diameter ties at 200 mm on center spacing. Details of the piles reinforcement are shown in **Table 2** . The concrete used in both the test pile and the tension piles had a compressive strength of 28 MPa cube strength at 28 days with the maximum slump of 100 mm.

3.1 Expressions of the Strength Capacity and Settlement of Bored Piles:

R.D.Mindlin of Colombia presented a solution based on elasticity for a single force acting on a semi- infinit media . Mindlin took into account the transition effect of a body force in media of constant tensile strength and Young ′s modulus **,Mindlin,2007**. The equilibrium equations in Cartesian form are:

$$\frac{\partial \sigma x}{\partial x} + \frac{\partial \tau yx}{\partial y} = w_x \quad (1)$$

$$\frac{\partial \sigma y}{\partial y} + \frac{\partial \tau xy}{\partial x} = w_y \quad (2)$$

Where w_x and w_y are the body force per unit volume in x and y directions. The equation of compatibility including effect of time and volumetric strain is:

$$\frac{\partial u}{\partial t} = (k_x \frac{\partial^2 u}{\partial x^2} + k_y \frac{\partial^2 u}{\partial y^2}) * \frac{1}{\gamma} + \frac{\partial V}{\partial t} \quad (3)$$

Considering the pile as a linear elastic and the soil to follow modified cam clay model ,**Pestana ,et.al., 2002** suggested that utilizing Eq,(1) and Eq.(2) toghter with Eq. (3) that mean effective stress (σ') and deviatoric effective stress (q') are :

$\sigma' = \frac{1}{2}(\sigma_x + \sigma_y)$ (4)

$q' = \frac{1}{\sqrt{2}}\{(\sigma_x - \sigma_y)^2 + \tau^2{}_{xy}\}^{0.5}$ (5)

The pile load transfer is governed by the stresses induced initially in the soil, according to Mindlin′ s theory and the surface behaviour of the pile shaft with the surrounding soil .Therefore the pile strength capacity Q_u can be stated as the superposition of resistance at base of pile Q_B and resistance along pile shaft Q_F , **Mindlin,2007** where :

$Q_F = \pi D_p L(\propto \tau'')$ (6)

$Q_B = \frac{\pi}{4} D_p{}^2 (0.75 q_u)$ (7)

$Q_u = Q_B + Q_F$ (8)

The value of Q_B is related to the bearing area and pressure at base while Q_F is related to the traction and surface area of pile shaft. The parameters soil cohesion (τ') , effective stress (q'), shaft adhesion factor ($\propto$) and unit weight of soil (γ) are determined from lab tests .These parameters controlled the bearing capacity evaluation **,Bowles,1981.**and **Das,2004.**

3.2 Lateral Load Resistance :

The effects of lateral loading and or applied bending moments either on the supporting soil or flexural resistance in terms of over stressing the pile shaft .The problem of displacement compatibility is complex to simulate a rigorous analysis of ultimate soil resistance, particularly beyond elastic behaviour of soil.

Broms, 1995. suggested based on tests, that the ultimate lateral resistance (q_u) of cohesive soil could be related to ultimate shear resistance (τ_u) from triaxial compression test based on undrained conditions ($q_u = 9\,\tau_u$). The governing beam differential equation is :

$EI\,(d^4u/dx^4) + K_x = 0$ (9)

And for a constant soil modulus (K_s) ,it can be shown that expressions for pile moment resistance (M) and lateral displacement of pile head (u), are: **Bowles,1981.**and **Das,2004.**

$M = H_L R A_m + M_L B_m$ (10)

$u = H_L \frac{R^3}{EI} A_u + M_L \frac{R^2}{EI} B_u$ (11)

E_cI_c : flexural stiffness of pile, A_m and B_m are moment coefficients ,taken 0.7 and 0.8 respectively at point of maximum moment , A_u and B_u are lateral displacement coefficients

,taken as 2.5 and 1.5 respectively at pile head ,R = $\sqrt[4]{\frac{EI}{K}}$ is the stiffness factor and K_s is soil modules (K= $\frac{1}{2}$ k_u L) ,where $k_u = 67\tau_u$ **Bowles, 1981.**

E_c : Young $'s$ modules for concrete.
I_c : Moment of inertia of pile section .

4. SETTLEMENT ANALYSIS

Short term elastic settlement was considered in this investigation rather than long term which could be small because of slow development of base resistance. Hence effects of creep of concrete and stress transfer from skin friction to the base was ignored. The ultimate skin friction (f_u)is :

$$f_u = \propto \tau' \quad (12)$$

where $\propto$ is the shaft adhesion coefficient ,varies from (0.3 - 0.45) and $\tau' = 0.75\ F_u$

The settlement Δ_b at pile base was assumed to be related to the pressure at pile base, size of base and soil properties.

$$\Delta_b = \frac{(1-\upsilon 2)\ q\ D_b}{E} \quad (13)$$

Where q was the average pressure at pile base which could be taken as the nominal vertical stress from triaxial test. The soil Young $'s$ modulus (E) is:

$$E = \frac{\frac{1}{2}(\sigma_1 - \sigma_3)}{\epsilon_1} \quad (14)$$

The elastic shortening and pile due to applied loads was calculated from:

$$\Delta_e = \frac{(P_b + \lambda\ P_s)}{A_p\ E_c} L \quad (15)$$

5. TESTING PROCEDURE

The top of pile was prepared by bedding a steel plate (38 mm thick) in cement mortar as a capping .The reaction loads were carried from the test pile through main beams and the sub- beams and tension bars to the four reaction piles .The vertical loads had been applied using four electrically operated hydraulic jacks which work together to a total capacity of 12000kN.The measurement of the testing loads were recorded by a pressure gauge attached to the oil pump. The pressure gauge was calibrated in advance.

Following the **ASTM D1143-o7e, 2010** , a schedule of five loading cycles has been set .The test was carried out with four cycles up to twice the working load of the test pile as shown in **table 3**.The fifth cycle included an addition of 4400kN to compensate the frictional resistance of pile shaft above scour level .This was due to the fact that testing load had been applied at ground level and before excavating around the pile .

Deflection dial gauges with accuracy of 0.02 mm and a stroke of 75 mm were used to measure deformations of the test pile and reaction piles during testing .Four dial gauges were attached at the top of the test pile and one dial gauge on each of the four tension piles. All the values used in the analysis were the average of the 4 readings.

The two reference beam used in the testing rig for vertical loadings were checked for any undesirable settlements. Two targets were fixed to them, observations had been done by using a level 20 m away from the target points. It was assumed that ground level at that point had not been by the testing altered by the testing operation. There was no movement recorded during the test and hence, no adjustments were required for the settlements of test pile measured by the dial gauges.

The lateral loads were applied by a 2000 kN capacity hydraulic jack which was operated electrically. The reaction loads had been taken by a transverse beam to the two non-working reaction pile. Measurements of the applied loads were taken by 3000kN proving ring which was calibrated before testing. Details of the horizontal loading rig are shown in **Fig. 3** and **Fig. 4**.

A number of cycle loading with increments of 50 kN had been conducted for the horizontal load testing . The first 2 cycles were up to 150 kN followed by 3 cycles 300 kN then 3 cycles to 450 kN and finally the last 3cycles to 650 kN which was kept for half an hour .Unloading to zero load was then done and readings were taken after 24 hours . Five dial gauges were attached to the test pile and one dial on each of the two reaction piles as shown in **Fig. 4**.All dials were fixed to the reference beam and pieces of glass were used to provide smooth surface for indicator tips. Details of the loading rig is shown in **Fig. 5**.

5.1 Examination of Results

The effective vertical stress of soil (F_u) was calculated to be 182 kN/m^2 based on an average shear reduction factor (α = 0.55) for sandy gravel base and an ultimate shear strength (τ_u) of soil supporting the pile equal 320 kN/m^2 which was an average value obtained from the in - situ cone penetration resistance and standard penetration tests. The Meyerhof ′ s bearing capacity factor N_q was 155 based on frictional angle $\emptyset$ =32°. The previous parameters led to the ultimate bearing capacity q_u of supporting soil stratum equal 14100 kN/m^2. With the allowable value of 4700 kN/m^2.Using Eq.(7) and Eq.(8) led to strength capacity for the test pile of 14010 kN/m^2 with a working load value of 4666 kN based on factor of safety = 3 .

The design strength of the test pile having (45- $\emptyset$32mm) longitudinal bars with yield strength = 350 MPa and concrete compressive stress $f_c^{'}$ = 28MPa, cube strength was calculated to be 12662 kN and casing strength was considered 890 kN. The effect of soil negative skin traction came to 935 kN from Eq. (7) .

Theoretical considerations that most settlements of a single pile occurred immediately after load application .Based on that Young′s modules for soil was interpreted from cone point resistance as 350 $\tau^{'}$ and was found = 63700 kN/m^2. The settlements at pile base $\Delta_b$was evaluated from Eq.(13) ,considering Poisson′s ratio for soil = 0.4, bearing coefficient R_c = 12 for dense cohesionless soil. These parameters gave maximum base settlements = 41 mm. The deformation of the pile head due to elastic shorting Δe and due to shaft resistance were calculated from Eq.(15) based on shaft load influence factor $\lambda = 0.33$ and concrete modules of elasticity for deformation calculation E_c =1122800 kN/m^2 .The value came to 37 mm based on P_s = 935 kN and P_b = 4666 kN .

The value of (Δe) at twice the working load was 69 mm .Hence the total calculated settlement of pile head at working load was 78mm and at twice the working load was 110mm. The values of calculated and averaged measured value at pile head are shown in **Fig. 6** .The problem of displacement compatibility is complex to simulate a rigorous analysis Eq. (9) for lateral loading ,since soil behaviour is the problem .Hence maximum lateral displacement is at pile head and diminishes some where at two-third pile length below that point. The lateral displacement was calculated from Eq.(11),based on (k = 25×10^4 kN/m^3) and soil modulus ($K_s = 1.063 \times 10^6$ kN/m^2),hence the lateral displacement coefficient related to lateral loads is 2.0 and vanishes at a distance 8.5m below pile head . The calculated and measured lateral displacement is shown in **Fig.7**.

6. CONCLUSION

1- The design strength capacity of large diameter bored type piles could be predicted using eqs.(6,7 and 8) to within 15% accuracy. The (1.95m) diameter test pile was sufficient to carry the 4666 kN working load based on a safety factor 3.0 .

2-The pile strength to horizontal loads showed adequacy to resist a design load of 350 kN based on a safety factor 2.0 .

3-The values of soil parameters based on laboratory control tests were acceptable ,since lateral displacement and settlement were 20 % less than measured values .It was related to the proper Young's moduli Ec and E for deformation calculations .Also it could be concluded that predicted values of the cefficient of horizontal subgrade reaction Ks was within the acceptable value .

4-The load- settlement curve at the pile head was close to linear particularly at early stage of loading .At higher loads, the curve shifted from linearity ,hence it could be considered as segments of straight lines with different slopes .

5-The calculated settlements increased 3 times when the load was doubled and no effect of heave at the surface was noticed even with time delay of loading .

6- There was no cracking observed at the tension piles even during the application of maximum uplift force during testing.

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NOTATION

A_m , B_m : moment coefficients.
A_u , B_u : lateral displacement coefficients.
D_p :diameter of pile .
E_c : modulus of elasticity of concrete .
f_c' : compressive strength of concrete at 28 days.
f_y :yield strength of reinforcement .
F_u : ultimate skin friction at pile shaft .
G.L: ground level .
Gs: Specific Gravity.
H_L : horizontal load resistance .
I_c : moment of inertia of pile section with it reinforcement .
K_s : soil modulus.
K_u : ultimate coefficient of soil reaction.
K_x : soil modulus at depth x of pile.
L : length of pile.
LL: Liquid limit.
M_L : moment resistance .
PI: Plasticity index.
PL: Plastic limit.
P_b : force acting at base of pile.
P_s : force acting along shaft of pile.
q : allowable effective stress.
q′ : deviatoric effective stress.
Q_B : maximum strength of pile base.
Q_F : maximum strength of pile shaft.
Q_u : ultimate strength capacity of pile.
R : stiffness factor.
u : lateral displacement of pile head .
USCS: Unified Soil Classification System.
w_x , w_y : components of dead load in x and y directions.
$\propto$: shaft adhesion factor .
γ : unit weight of soil.

ε_{1}: axial soil strain.
Δ_b: settlement of pile base.
Δ_e : elastic shortening of pile .
σ_x , σ_y : components of normal stress in x and y directions.
τ': allowable shear traction along pile.
τ_{xy} , τ_{yx} :shearing stress components.
λ: influence factor for safety .
υ : Poisson′s ratio for soil.

Table 1. Results of Atterberg Limits, Specific Gravity & Grain size.

Depth (m)	Layer thick (m)	Gs	Atterberg Limits			Sieve & Hydrometer				USCS
			LL	PL	PI	Gravel %	Sand %	Silt %	Clay %	
0-3	3	2.66	22	NP	NP	9	55	36	0	SM
3-5	2	2.64	20	NP	NP	11	59	26	4	SM
5-6	1	2.74	42	23	19	2	3	30	65	CL
6-12	6	2.64	20	NP	NP	12	58	25	5	SM
12-17	5	2.74	40	22	12	13	55	7	25	SC
17-22	5	2.65	24	NP	NP	9	60	31	9	SM
22-29	7	2.66	NP	NP	NP	12	53	27	8	SM

Table 2. Details of the test pile and the tension piles.

Type of test	Diameter (m)	Length (m)	Reinf.	Lateral reinf.
Test piles	1.5	25.5	45 ϕ 32mm 30 ϕ32mm	ϕ 12mm@20cm .c/c with 14mm thick,15m long casing
Tension pile	1.95	22.5	24 ϕ 32mm	ϕ 12mm@20cm .c/c No casing

Table 3. Details of the four previously propose cycles.

1st cycle (1/2 Working load)		2nd cycle (2/2 Working load)		3rd cycle (3/2 Working load)		4th cycle (4/2 Working load)	
Load (kN)	Time (hrs)	Load (kN)	Time (hrs)	Load (kN)	Time (hrs)	Load (kN)	Time (hrs)
0	0	0	0	0	0	0	0
1100	1:00	2200	0:20	2200	1:00	2200	1:00
2200	1:00	3300	2:00	4400	1:00	4400	1:00
1100	0:20	4400	2:00	5500	2:00	5500	1:00
0	0.20	3300	0:20	6600	2:00	6600	2:00
		2200	0:20	5500	1:00	7700	2:00
		1100	0:20	4400	1:00	8800	1:00
		0	0:20	3300	1:00	6600	1:00
				2200	1:00	5500	1:00
				1100	1:00	4400	0:20
				0	1:00	2200	0:20
						1100	0:20
						0	0:20

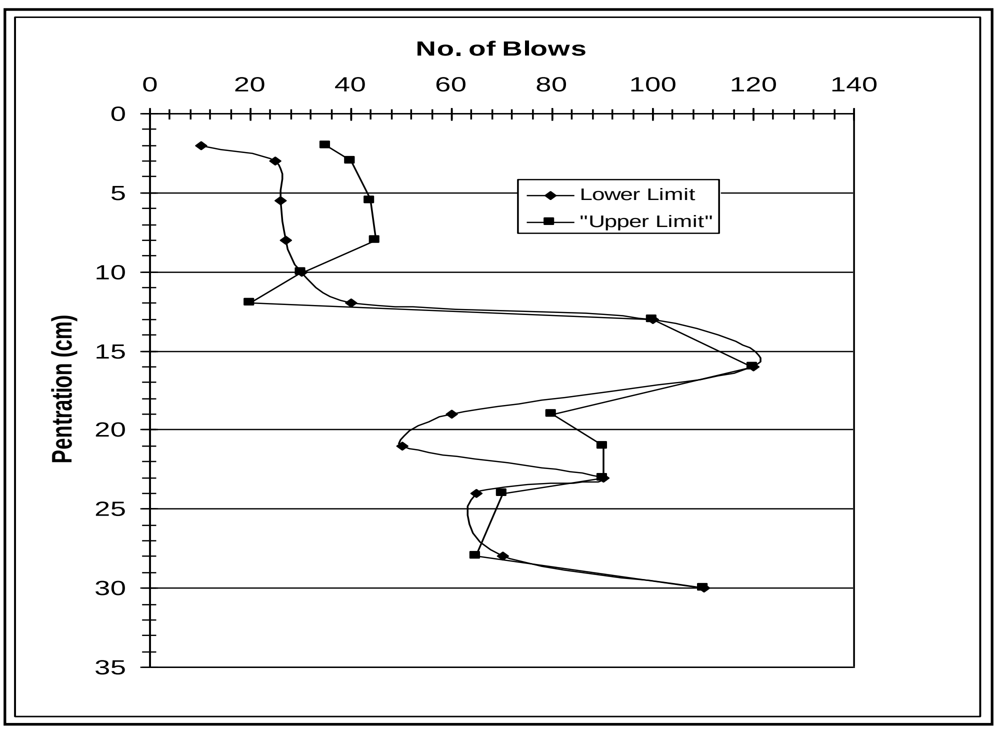

Figure 1. SPT results for B.H. no.1 near the test pile.

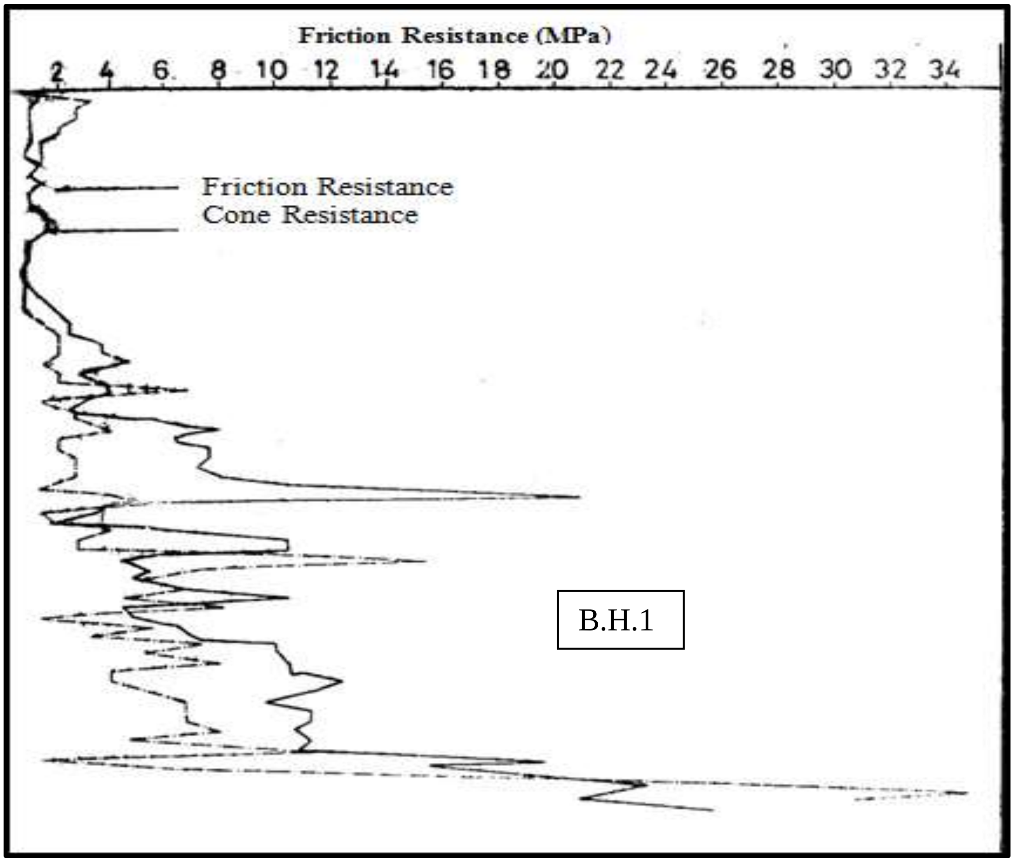

Figure 2. Cone Penetration Test(CPT) for Therthar Tigris canal bridge project KM 50.

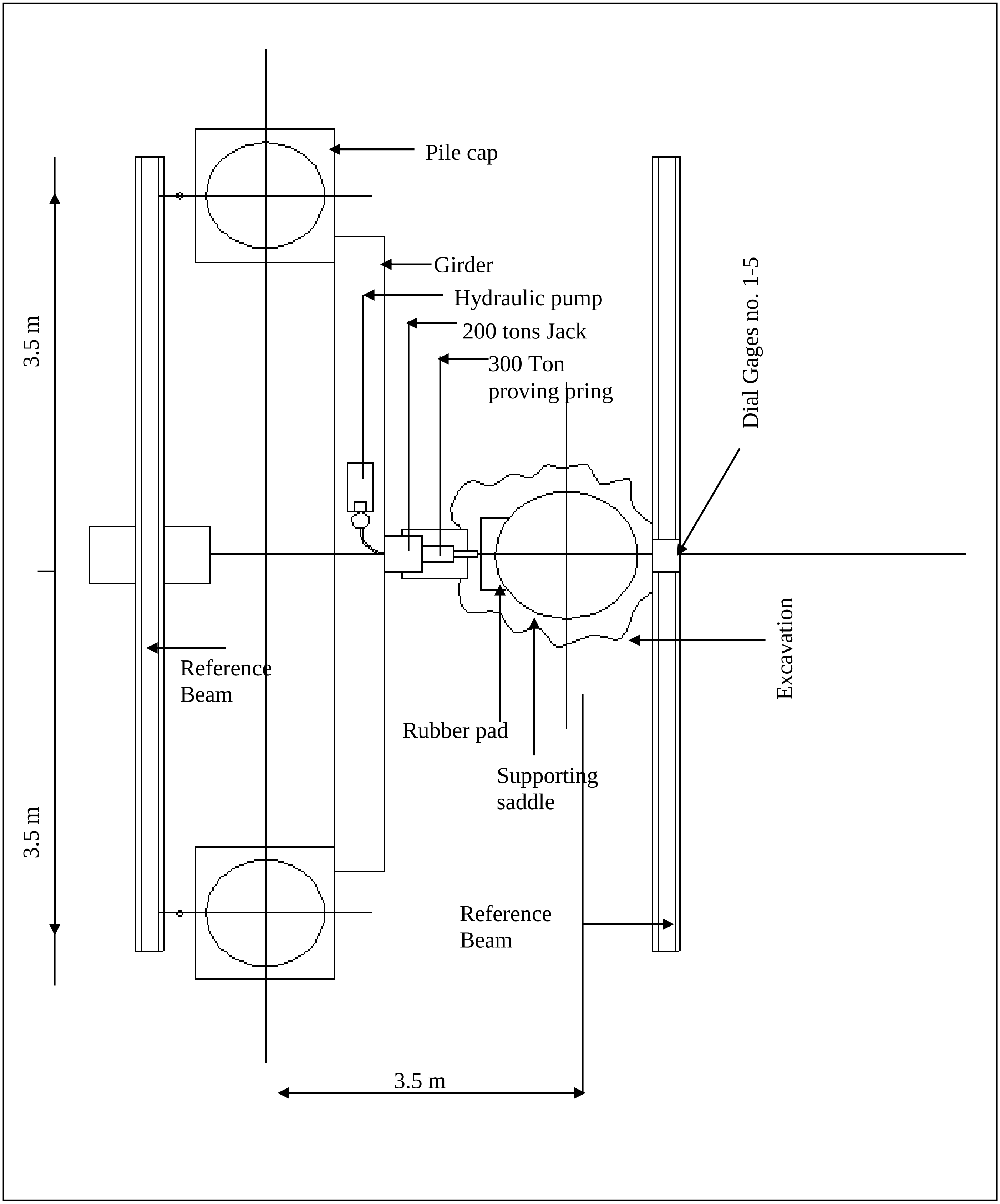

Figure3. Lateral testing insulation (Plan).

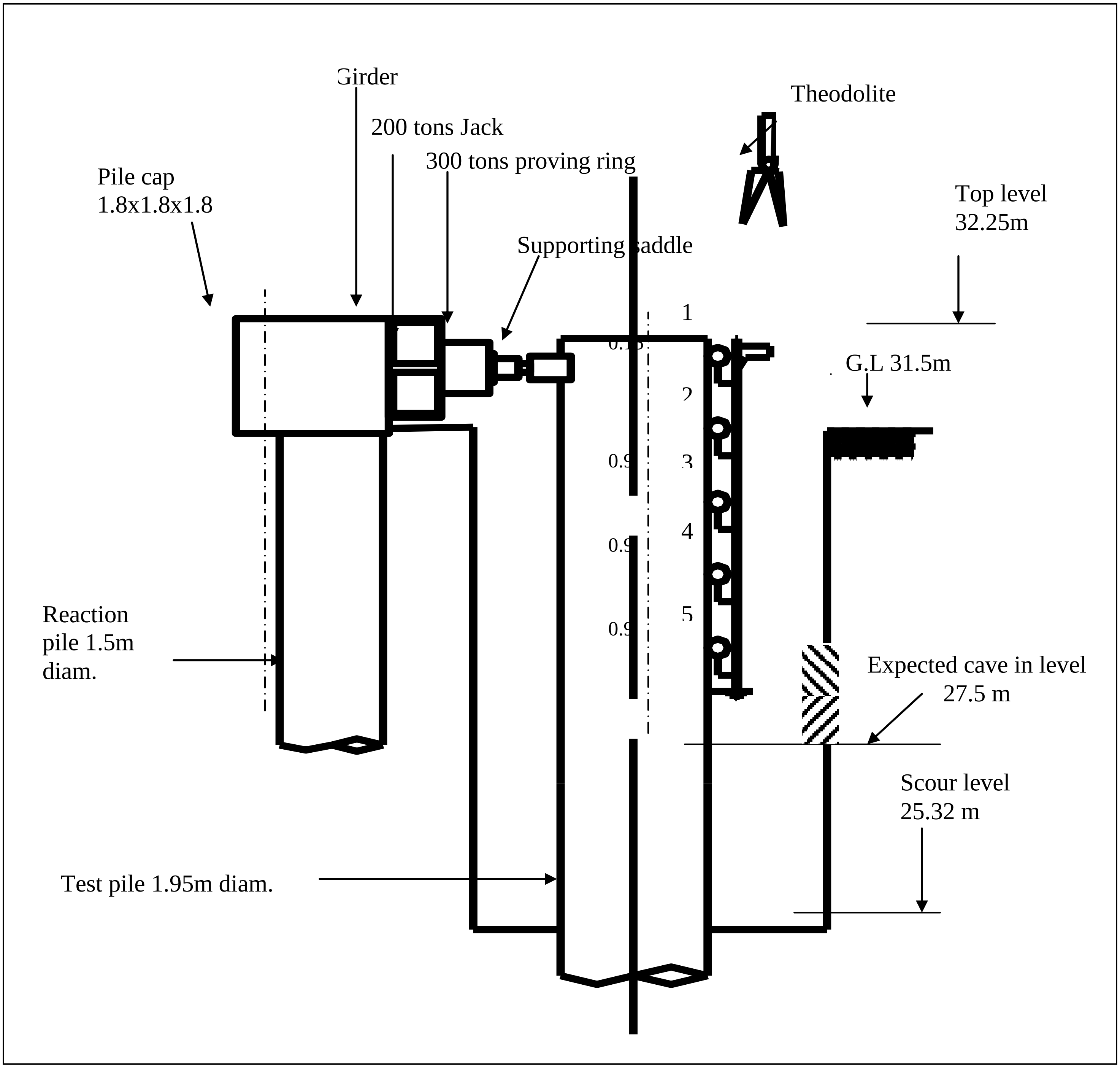

Figure 4. Lateral testing insulation (section).

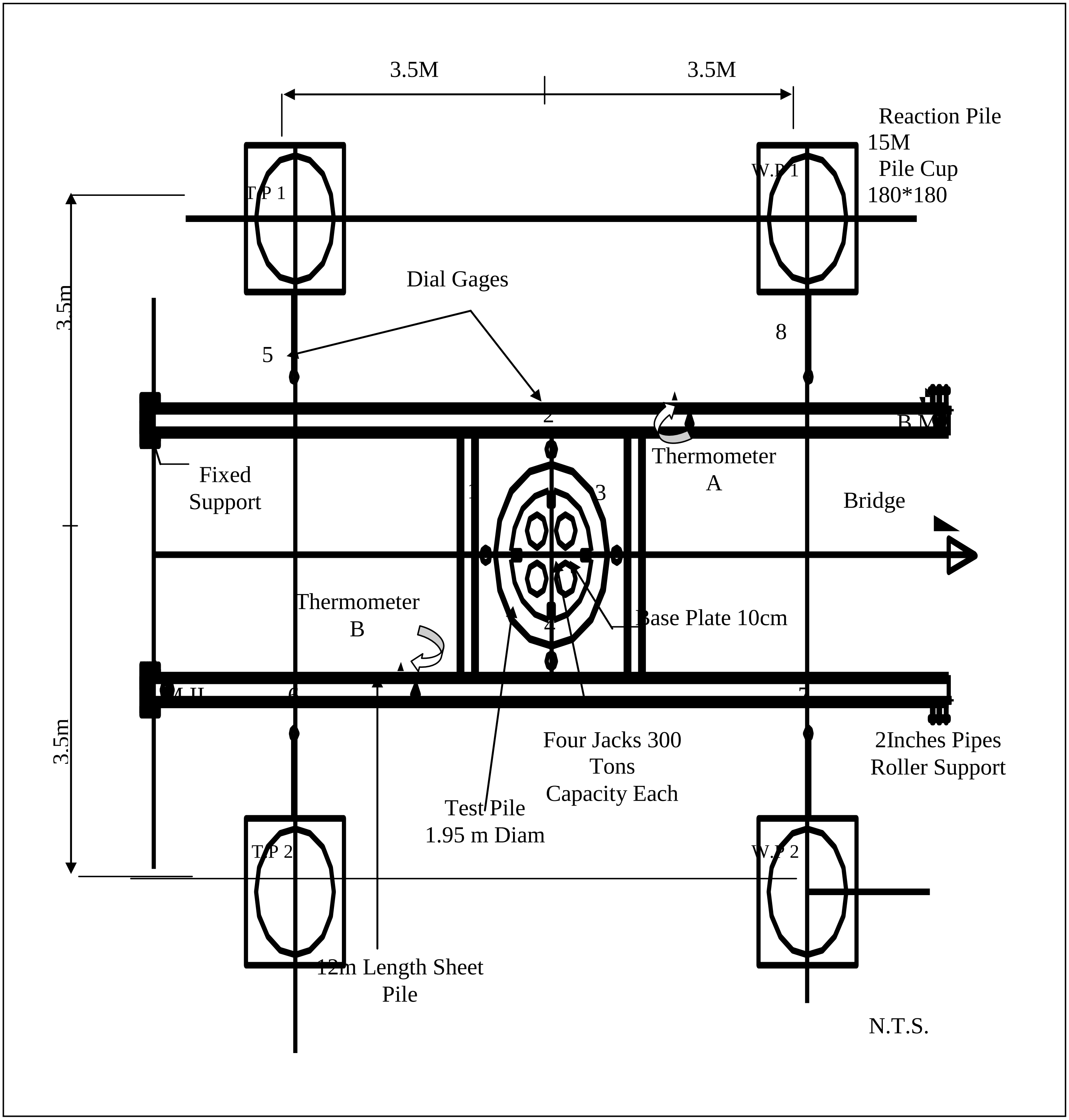

Figure 5. Vertical testing installation (plan).

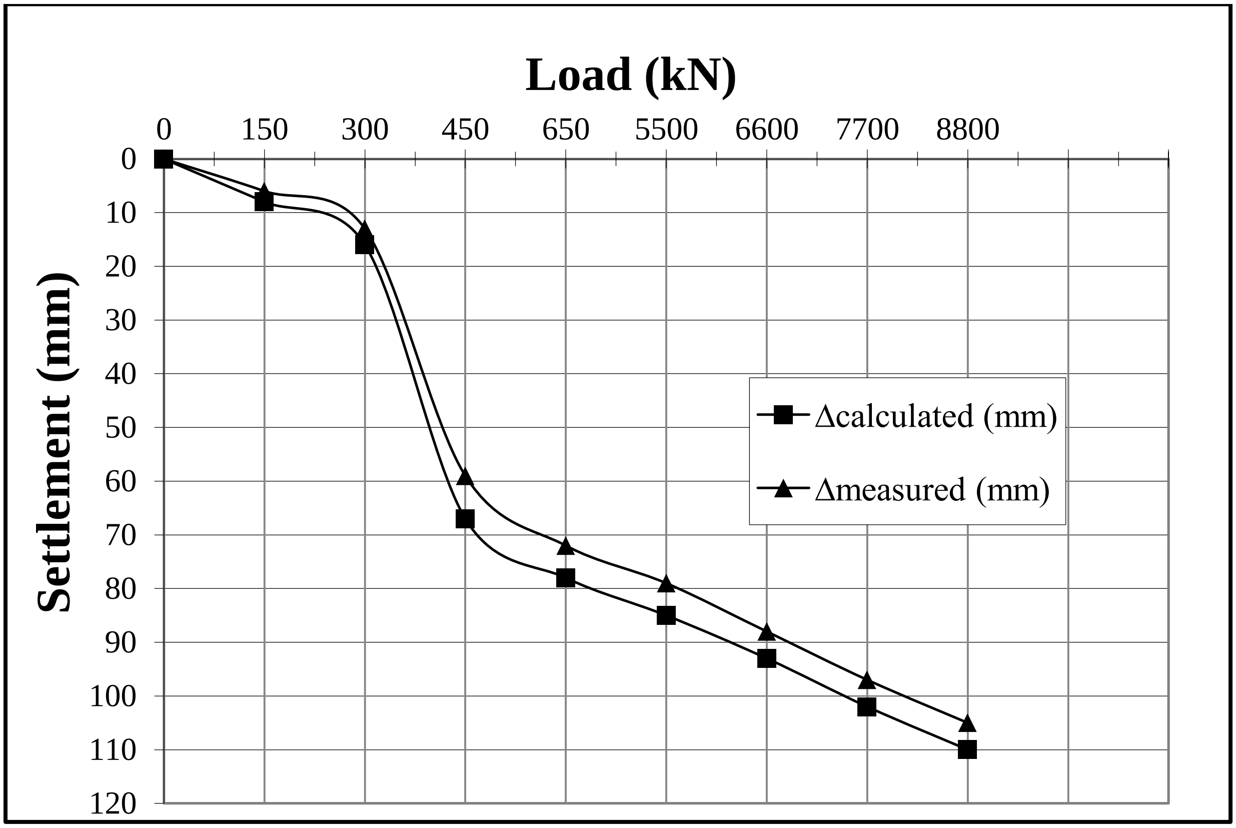

Figure 6. Load – Settlement curve for the pile head .

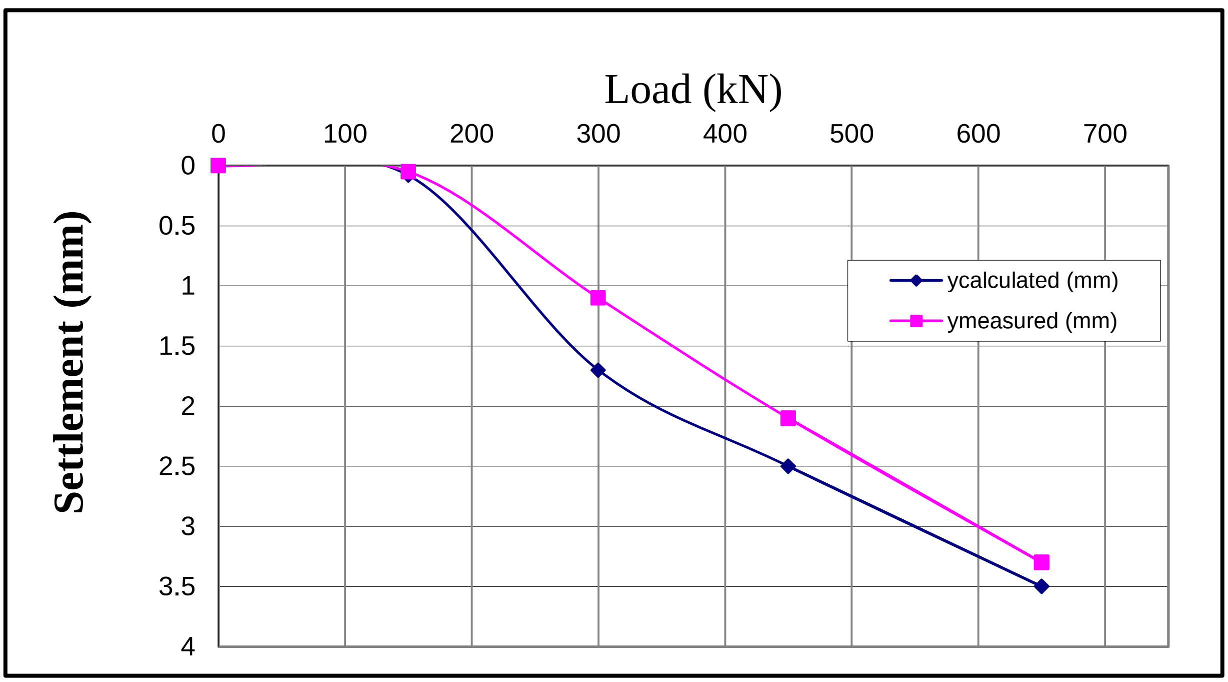

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Figure 7. The calculated and measured lateral displacement for the pile head.