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EFFECT OF A DRIVEN PILE ON AN EXISTING TUNNEL

Dr. Nahla Mohammed Salim[1], *Sherine Jafaar Lafta[2]

1) Assistant Prof., Civil Engineering Department, University of Technology, Baghdad, Iraq.
2) Postgraduate Student, Civil Engineering Department, University of Technology, Baghdad, Iraq.

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Abstract: It is essential to measure the response of existing tunnel-lining due to newly constructed pile to assess the safety against the additional forces/moment caused by pile driving and loading and to evaluate the critical distance for the proposed construction of any structures from the tunnel location. This study presents an experimental work to investigate the effects of driven pile during insertion and loading on existing tunnel embedded in the sandy soil. It is found that the effects of driving and loading of pile on stresses transfer to tunnel depend on the horizontal separation distance between pile's tip and tunnel, and the stresses generated due to the loading of a pile is higher than the stresses during construction period furthermore the ultimate bearing capacity of pile increased due to the presence of tunnel.

Keywords: *pile, tunnel, stress, sand*

تأثير ركائز الدق على الانفاق الموجودة

الخلاصة: من الضروري حساب الانفعالات التي تتولد في بطانة الانفاق نتيجة للاحمال المسلطة من تنفيذ ركيزة لتقييم السلامة ضد القوى \ العزوم الناتجة من تنفيذ الركيزة ولحساب المسافة الحرجة لموقع بناي اي منشأ بالنسبة لموقع النفق.هذه الدراسة تقدم نتائج لفحوصات مختبرية للتحري عن تاثير غرس الركيزة في تربة رملية خلال مرحله الانشاء والتحميل .تم التوصل الى ان تاثير الاجهادات المنتقله الى النفق تعتمد على المسافة الافقية بين حافة الركيزة وموقع النفق وكذلك فان الاجهادات المتولدة في مرحله التحميل تكون اكبر من مرحله الانشاء كما ان الحمل الاقصى للركيزة يزداد بوجود النفق.

1. Introduction

A new construction project close to existing underground structure cannot be avoided due to the limited space in big cities which usually consist of underground infrastructure system, such as subway in order to satisfy the updating demand and the possibility of causing damage to this system is of major concern. In the past, the tunnel owners used restrictive guidelines for the new construction adjacent to their tunnels. These restrictive guidelines may comprise of one or more of the following protection zone or minimum clearance between structures, maximum allowable tunnel deformation and stress changes in tunnel lining. However, these guidelines are based on experience rather than on theoretical understanding of the interaction problem.

*Corresponding Author: sherinejafaar@yahoo.com

Many researchers have summarized the pile-tunnel interaction problems, which can be categorized into two groups: effects of tunneling on piles and effects of piling on tunnels, where the second group received less attention. There are some case studies which investigated the effect of piling on existing tunnels [2] studied the behavior of two existing tunnels (British Telecom shallow tunnel and deep tunnel) during the construction and loading of large diameter underreamed bored piles. [5], [7] and [8] also conducted a set of FE analyses to investigate the interaction between pile foundations and existing tunnels [3] investigated the effect of pile row under loading adjacent to an existing subway tunnel. [9] described a series of centrifuge tests designed to investigate the effect of bored pile excavation on existing tunnels. [4] examined the influence of bored piles on adjacent tunnels; the analysis was accomplished by using a FLAC three dimensional computational model. [1] Investigated the effects of pile loading on existing tunnels embedded in cohesive soil using ABAQUS program.

[6] used three dimensional finite element program ABAQUS to analyses the impacts of single pile and pile row under loading on the subway tunnel of the Mass Rapid Transit Authority of Thailand in Bangkok. The effect of pile foundations on existing tunnels can be categorized into two parts: pile installation and the post piling period. In this study, the main objective is focused on both of them.

2. Experimental Work

2.1. Soil Used

The sandy soil used in this study was obtained from one of the construction sites in Karbala city 100 km south west of Baghdad. Standard tests were performed to determine the physical and mechanical properties of the sand according to the ASTM specifications. The details of these properties are listed in Table (1)

Table 1: Physical and mechanical properties of the sand used in the tests

	Index properties	Value	Specification
	Specific gravity, Gs	2.68	ASTM D-854
Grain size analysis	Effective size (mm), D_{10}	0.16	ASTM D-2487, D-422
	D_{30} (mm)	0.23	
	D_{60} (mm)	0.38	
	Coefficient of uniformity, Cu	2.38	
	Coefficient of curvature, Cc	0.87	
	Soil classification (USCS)*	SP	
Dry unit weights	Maximum dry unit weight γ_{dmax} (kN/m^3)	18.8	ASTM D 4253-2000
	Minimum dry unit weight $\gamma_{d\,min}$ (kN/m^3)	15.3	ASTM D 4254-2000
	Dry unit weight γ_d (kN/m^3) at Dr=50%	16.87	ASTM D 4253-00
	Dry unit weight γ_d (kN/m^3) at Dr=70%	17.59	
	Angle of internal friction Ø (at D_r = 50%)	35.5˚	ASTM D 3080
	Angle of internal friction Ø (at D_r = 70%)	38.5˚	
Void ratio	Maximum void ratio, e_{max}	0.71	------------
	Minimum void ratio, e_{min}	0.39	

* USCS refers to Unified Soil Classification System

2.2. Soil Container

The soil tank has dimensions of (80 cm) length, (80 cm) width and (80 cm) height with thickness of steel plate (0.6 cm) as indicated in Plate (1). Dimensions of the tank were chosen to enable putting the tank within the frame and there will be no interference between the walls and the zone around the pile-tunnel system. The container is adequately rigid and shows no lateral deformation during preparation of the soil bed and during the test.

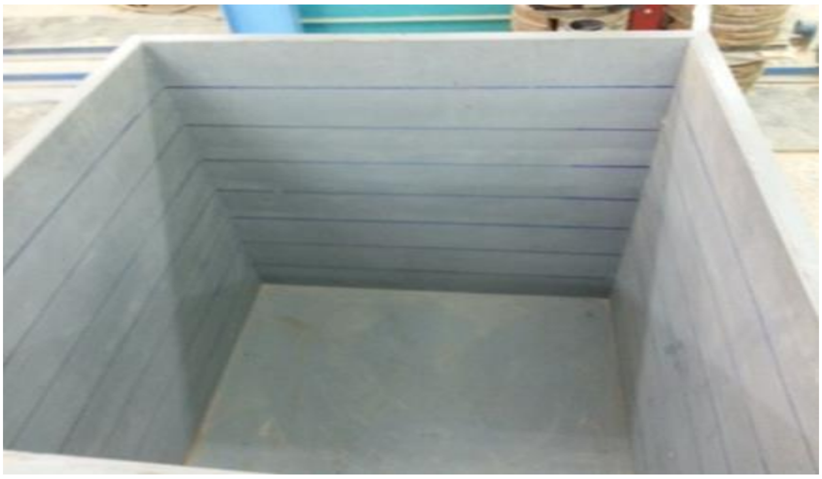


Plate 1: Soil Container

2.3. Loading System

The steel loading frame was manufactured to support the piston of hydraulic jack of (10 ton) capacity and applied load by running the piston downward as clarified in Plate(2).

(a): Steel frame and hydraulic jack

(b): Model prior to test

Plate 2: Loading System

2.4. Measurement System

During all the experimental tests the applied load is measured using a "Sewha" load cell 2 ton capacity. A digital weighing indicator "Sewha" is used to read and display the load value as shown in Plate (3).

(a): Load cell

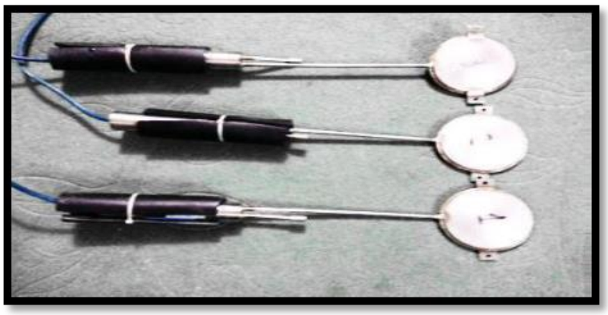
(b): Digital weighing indicator.

Plate 3: Load Cell and Digital Weighing Indicator

Plate (4a) shows earth-pressure cells which were used in this study to measure the stresses generated on tunnel lining due to driving and loading of single pile. This device was manufactured by Geokon Company in the United States of America. Plate (4b) the handheld GK-404 Vibrating-Wire Readout was used for displaying the stress measurements in digits and then converts the reading to soil pressure by the following formula:

$$P = G\,(R1 - R0) \qquad (1)$$

Where: *G*= the convert factor (-0.05438 kPa/digit),
R1= the current reading,
R0= the initial reading



(a): Total earth pressure cell

(b): vibrating wire readout

Plate 4: Earth Pressure Cell and Vibrating Wire Readout

2.5. Models of Piles and Circular Tunnel

The concrete mixture was used to cast tunnel and piles models, the gravel used is passing from sieve No.4 (4.75 mm). Water-cement ratio is (0.35).

An additive of structure 520 (Superplasticisers) was utilized in concrete mixture with a ratio of 5 liter/mP3P, to produce a high performance concrete with high workability. The concrete piles, piles cap and the tunnel were cured for 28 days. Three cubes were taken during casting to check the compressive strength after 28 days. The average strength result was (45 MPa). Table (2) demonstrates details of concrete mixture percent which used in casting the tunnel and piles.

Table 2: Concrete mixture used

Cement kg/m^3	Aggregate		Water kg/m^3	Additive L/m^3	Slump 150 ± 5mm	W/C
	Sand kg/m^3	Gravel kg/m^3				
500	725	875	175	5	155	0.35

The tunnel was reinforced by chicken wire. The reinforcement of each pile consists of three bars of (3 mm) diameter and length equivalent to the length of the pile completely. The yield strength of the reinforcement (fy) is 290 MPa.

The concrete piles and tunnel used to simulate the same friction and behavior of concrete piles and tunnel in the field. A 20mm diameter and 400mm length was selected as the model pile and the dimension of piles cap was (100×100) mm casted from the same concrete mixture used for piles and tunnel. Plate (5) shows pile and pile cap. The dimension of model tunnel used was 84mm, 780mm, 10 mm for diameter, length and thickness respectively. Plate (6) shows model tunnel and the mold used for casting. The tunnel was sealed by two glass plate with the diameter of (100mm) in order to minimize friction if any that may develop between the tunnel surfaces and the soil.

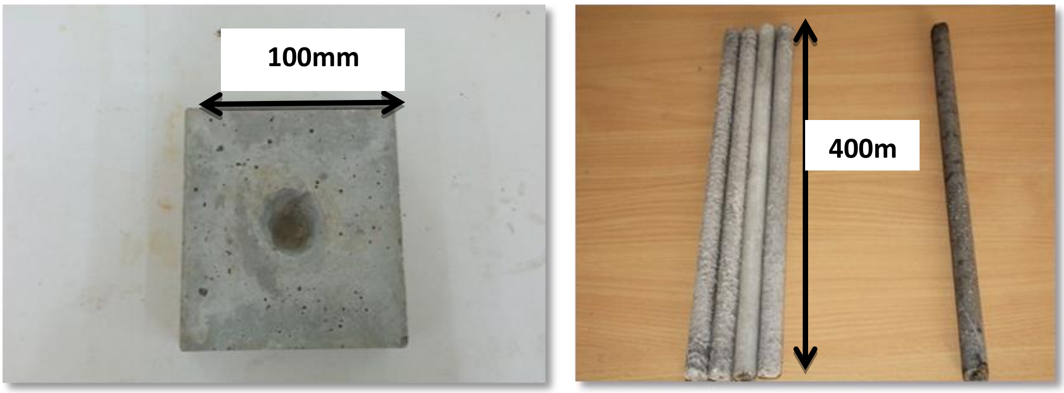


Plate 5: Model pile

Plate 6: Model tunnel

3. Physical Modeling

3.1. Sample Preparation

The sand deposit was prepared using a steel tamping hummer manufactured for this purpose. The steel container divided and singed into eight layers (each layer of 10 cm height and the same density). The volume and density for each layer were known, the weight of each layer was determined, then compacted by hammer to get the required height as demonstrated in Plate (7)

Each soil layer was compacted to a predetermined depth and the concrete tunnel with the three pressure cells that attached on certain positions were placed in the container as shown in Plate (8) and then the soil deposit was completed to final layer. After completing the final layer, the top surface was scraped and leveled by a sharp edge ruler to get as near as possible a flat surface.

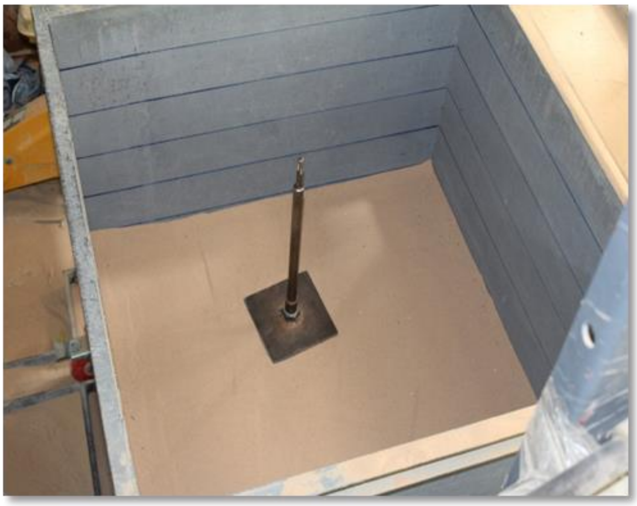


Plate 7: Preparing the models by using steel hammer

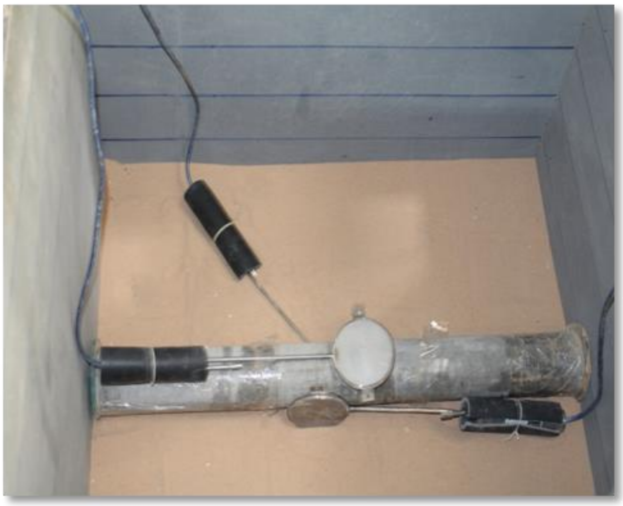


Plate 8: Position of three pressure cells

3.2. Insertion and Loading of Pile

The piles were inserted by means of a hydraulic jack. The length of each pile was divided into equal length to get a constant loading rate during insertion. A vertical load was applied through a (2 ton) load cell which was mounted between the jack pin and the pile to control the applied load; a steel holder is used to control the alignment of pile throw insertion. As the insertion process is completed then the load is applied to pile at a constant rate .The test is continued until recording a continuous displacement of the pile under constant load according to (ASTM D 1143/D 1143M – 07). The load was read from a digital weighing indicator connected to the load cell. The central displacement of the pile's cap was read by two deformation dial gages with 0.01 mm sensitivity, some of the photos during the test are shown in Plate (9). At the stage of construction with each insertion of the divided pile the stresses generated was read by the GK-404 vibrating-wire readout at (crown region, spring line region and invert region) of the tunnel, so as during loading until the pile reach the failure load.

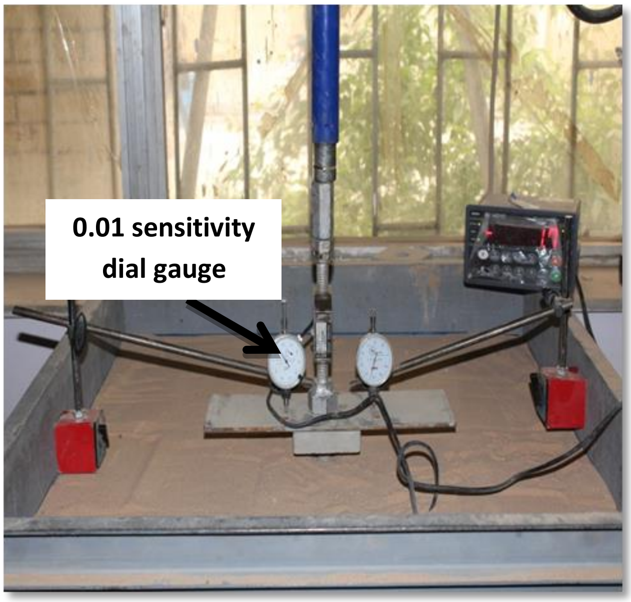


Plate 9: During insertion and loading of pile

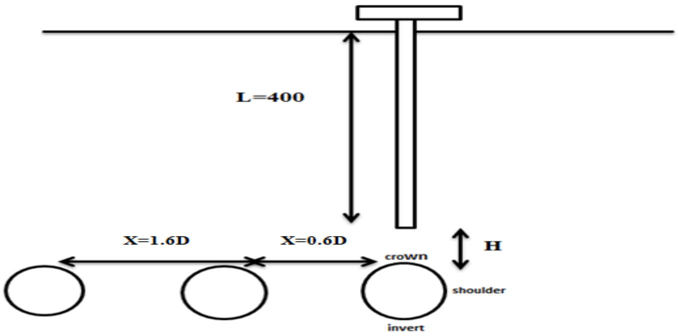


Plate 10: Positions of tunnel with respect to pile.

4. Tests Results and Discussions

Eight tests were carried out, of which two of them were conducted to determine the ultimate bearing capacity of pile without tunnel. For all the tests:-

– Two different relative densities were used: 50% for medium sand and 70% for dense sand.

– Pile was installed at three different lateral tunnel-pile clear spacing: 0D, 0.6D and 1.6D.

– Pile base was installed relative to the tunnel crown level at 6.6 cm.

– A single pile was tested.

4.1. *For Relative Density 50 %(Insertion and Loading of a Pile)*

4.1.1. Tunnel at horizontal distance (0D) from pile

1. The positive stress recorded on the crown region approximately 49.3% from the applied stress during insertion and 82.9% as the pile reached it's ultimate load.

2.The stress on the shoulder region fluctuate from negative to positive through driving and loading of pile and receive only 12% from the applied stress during insertion and decrease to 7.1 % during loading stage.
3.All stresses were positive at the invert region and the percent of stress reached during insertion and loading was 41.5% and 65% respectively

4.1.2. Tunnel at horizontal distance (0.6D) from pile

1. Positive stress on crown 40.2%during insertion and 60.3% during loading
2. Positive stress for invert 28.3% 36.3% during insertion and loading respectively.
3. Shoulder stress varies between negative and positive during insertion and loading
4.Reduction in percent of positive stresses for crown and invert during construction and loading stage by 18.5% , 27.2% and 31.8%, 43.7% for crown and invert respectively.

4.1.3 Tunnel at horizontal distance (1.6D) from pile

1. Maximum positive stress received by the crown at construction stage when load of pile reach (0.5 kN) is 3.116kPa and the percent of stress is 6.2% then reduction recorded with increasing the applied load. During loading only 2.3% of total stress received and as mention the stress would decrease with further increment of applied load
2.During construction stage the stress generated at the invert region varies from negative to positive and reach to maximum value at (40kg) to record (0.831kpa) then it would be fluctuate again to negative to receive 5.56% from applied stress. During loading stage reach (-2.75 kPa) at pile's ultimate load (4.9% from applied stress).
3. Stresses in shoulder region would change during construction from negative to positive and would receive 2.5% from applied stress. At loading stage reach at the pile's ultimate load to (3.54 kPa) (6.3% from applied stress) and further increased as the pile over its ultimate load.
4. Figures (1-6) clarified the generated stress at crown, shoulder and invert due to insertion and loading of pile for three lateral distances.

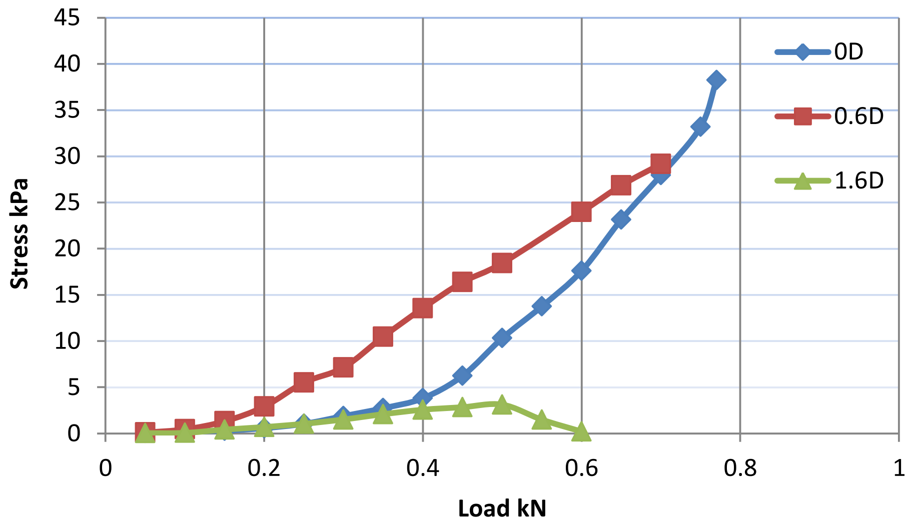


Figure 1: Crown stress generated at insertion stage of pile for different lateral distance (R.D=50%)

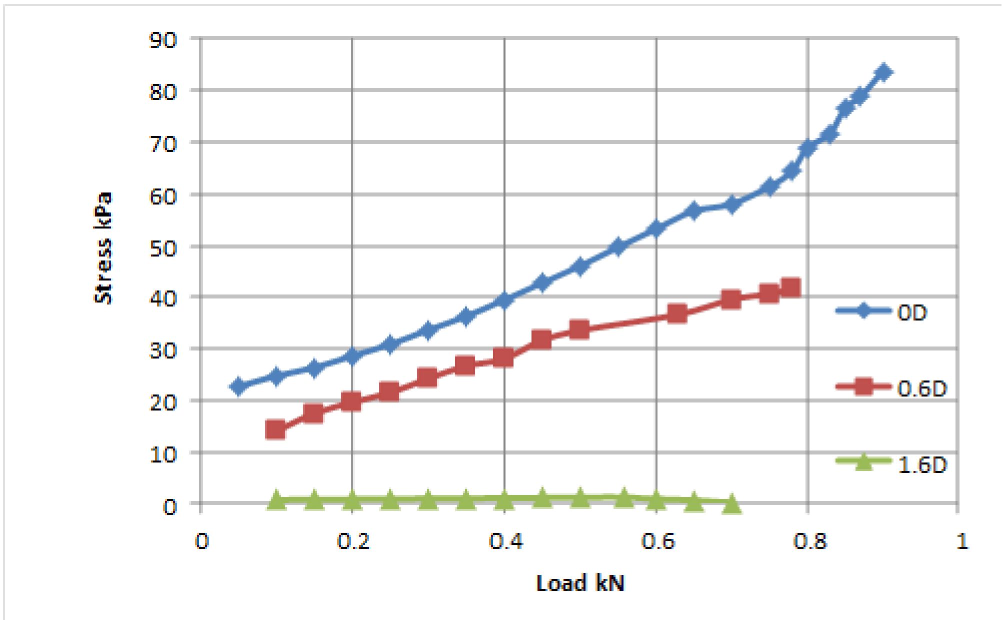


Figure 2: Crown stress generated at loading stage of pile for different lateral distance (R.D=50%)

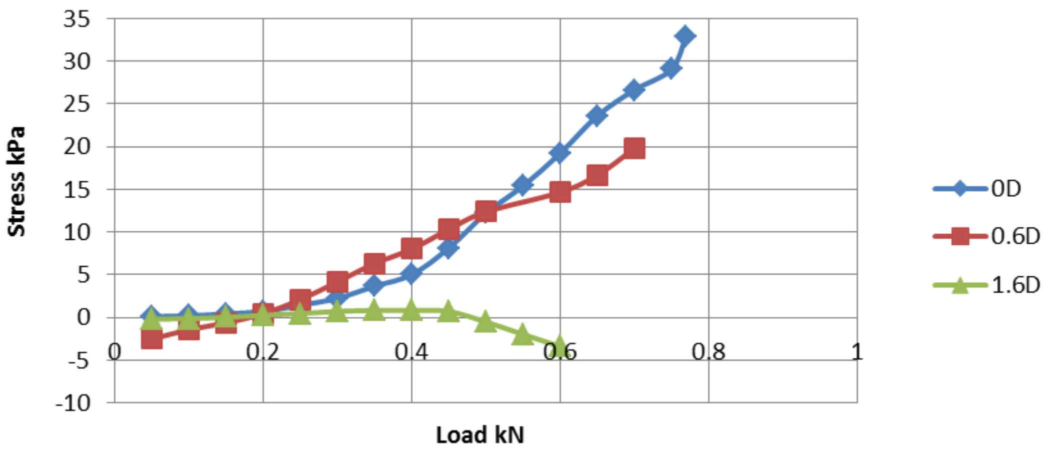


Figure 3: Invert stress generated at insertion stage of pile for different lateral distance (R.D=50%)

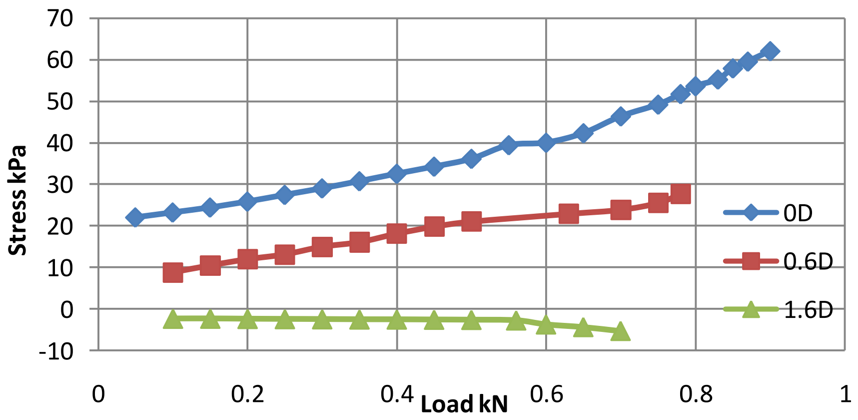


Figure 4: Invert stress generated at loading stage of pile for different lateral distance (R.D=50%)

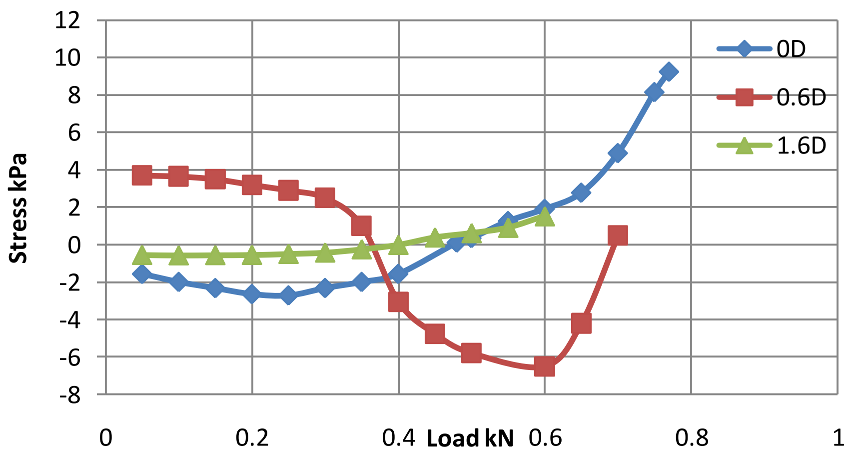


Figure 5: Shoulder stress generated at insertion stage of pile for different lateral distance (R.D=50%)

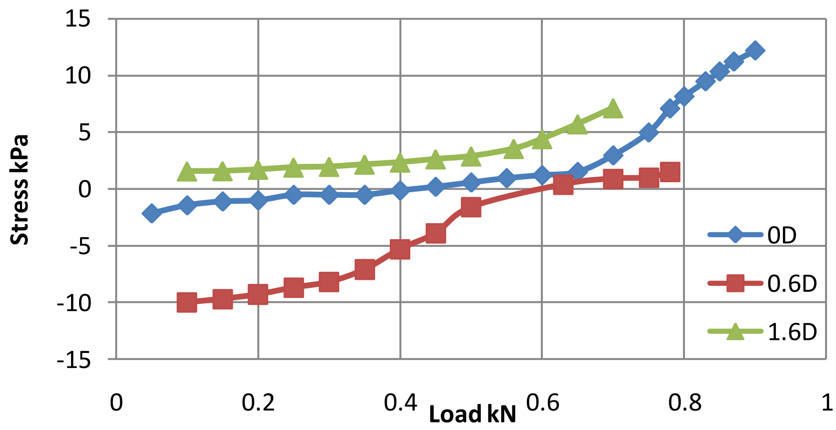


Figure 6: Shoulder stress generated at loading stage of pile for different lateral distance (R.D=50%)

4.2 For Relative Density 70 %(Insertion and Loading of a Pile)

4.2.1 Tunnel at horizontal distance (0D) from pile

1. The highest positive stress recorded at the crown region with 44.2% from the applied stress during insertion and 66.6% as the pile reached it's ultimate load.
2. Shoulder region which would be fluctuate from negative to positive through driving and loading of pile and would be approximately 9.2% from the applied stress. While during insertion would be positive and decrease to 5.6% for loading stage.
3. All stresses are positive for invert region and the percent of stress reached during insertion and loading was 34.5% and 53.3% respectively

4.2.2 Tunnel at horizontal distance (0.6D) from pile

1. Positive stress on the crown 35.6% insertion 54.3% loading
2. Positive stress for Invert 22.9% 33.1% insertion and loading respectively.
3. Shoulder stress varies between negative and positive during insertion and loading
4. Reduction in percent of positive stresses for crown and invert during construction and loading stage by 19.5% , 18.5% and 33.6%, 37.8% for crown and invert respectively.

4.2.3 Tunnel at horizontal distance (1.6D) from pile

1. Maximum positive stress received by the crown at (140kg) is 5.405 kPa and the percent of stress was 3.9 % then reduction recorded with increasing the load applied. For loading 1.4 % of total stress received only and as mention the stress would decrease with further increment of applied load
2. During construction stage the positive stress generated at invert region to reach in maximum value at (130kg) to record (5.89kpa) which represent 4.5% from the applied stress. During loading stage varies between negative and positive reach (-0.725kpa) at pile's ultimate load.

3. Stresses in shoulder region would change during construction from negative to positive to receive 6.4% from applied stress and would reach at the pile's ultimate load to 6.2%.
4. Figures (7-12) clarified the generated stress at crown, shoulder and invert due to insertion and loading of pile for three lateral distances

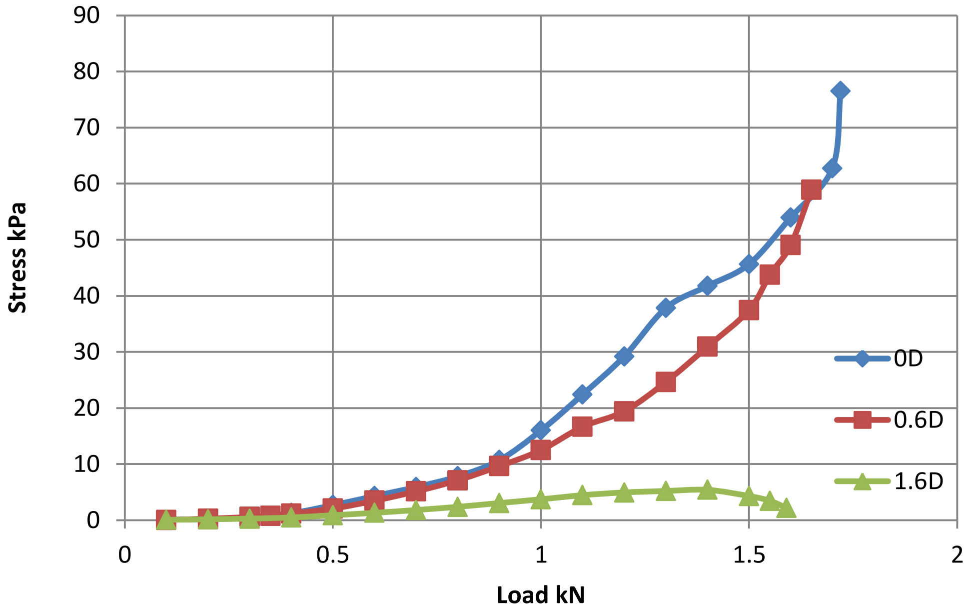


Figure 7: Crown stress generated at insertion stage of pile for different lateral distance (R.D=70%)

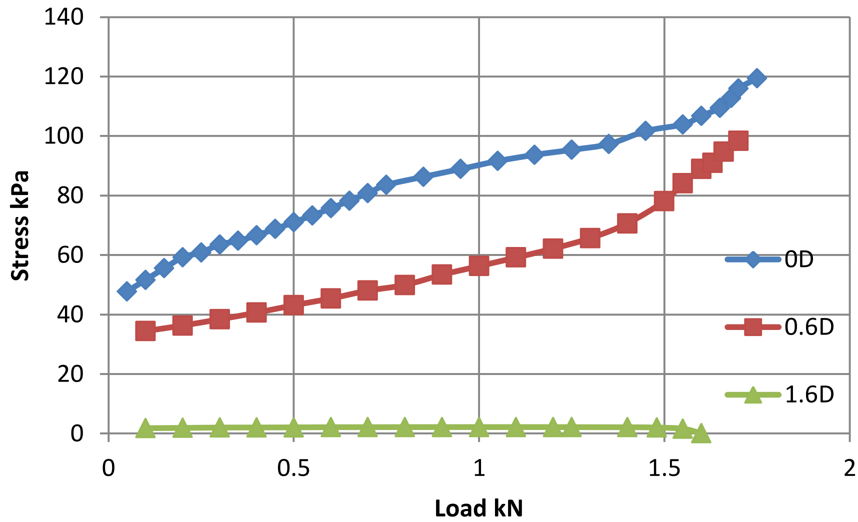


Figure 8: Crown stress generated at loading stage of pile for different lateral distance (R.D=70%)

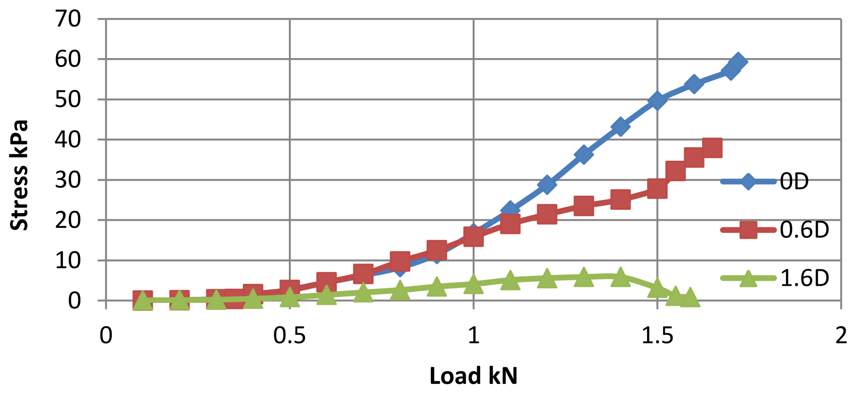


Figure 9: Invert stress generated at insertion stage of pile for different lateral distance (R.D=70%)

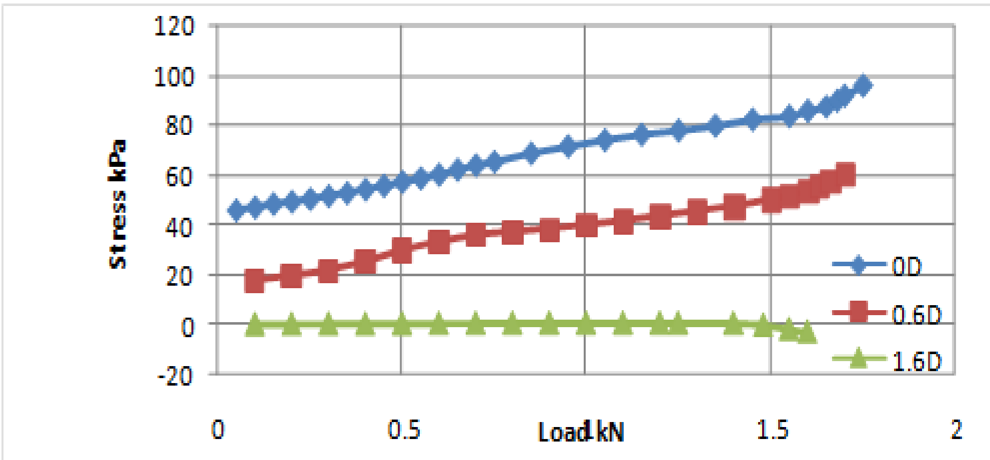


Figure 10: Invert stress generated at loading stage of pile for different lateral distance (R.D=70%)

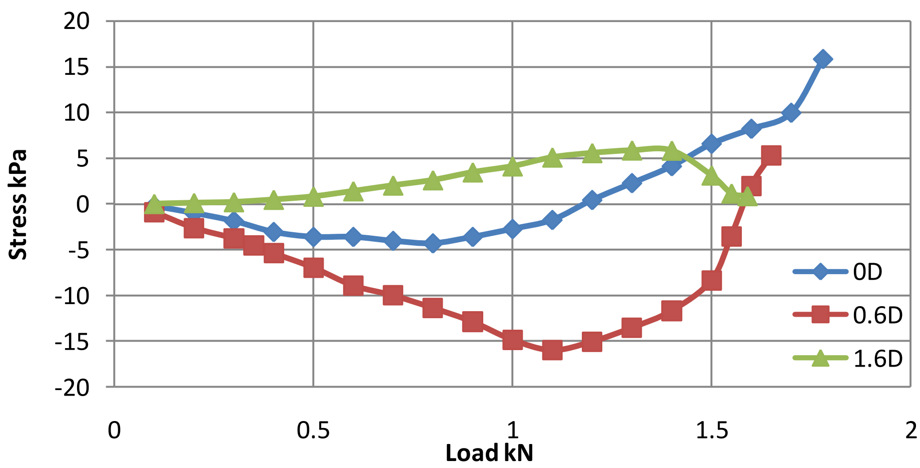


Figure 11: Shoulder stress generated at insertion stage of pile for different lateral distance (R.D=70%)

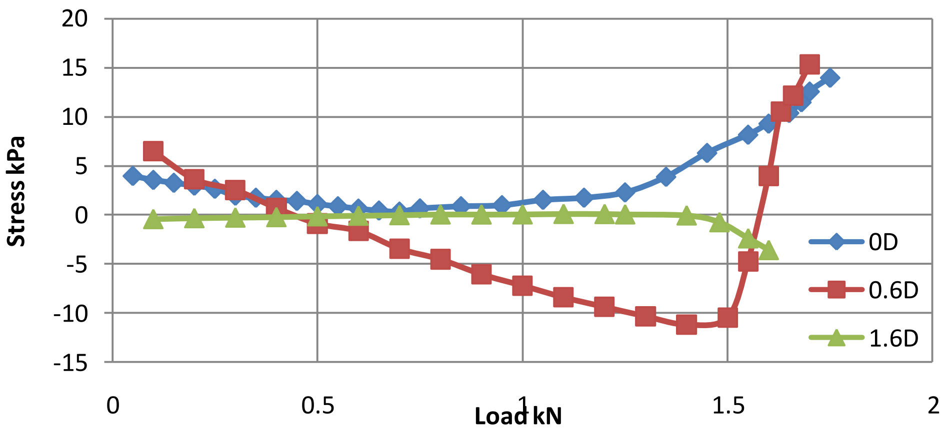


Figure 12: Shoulder stress generated at loading stage of pile for different lateral distance (R.D=70%)

4.3. Effect of tunnel on the pile ultimate bearing capacity

The bearing capacity of pile increased in the presence of tunnel and it is decreased as the tunnel moved to lateral distances. The percent of increase for R.D 50% equal to 22.8%, 18.18%, and 7.4% for lateral distances of 0D, 0.6D and 1.6D respectively. While for R.D 70% the percent was 34%, 31.81% and 28.57% for 0D, 0.6D and 1.6D respectively

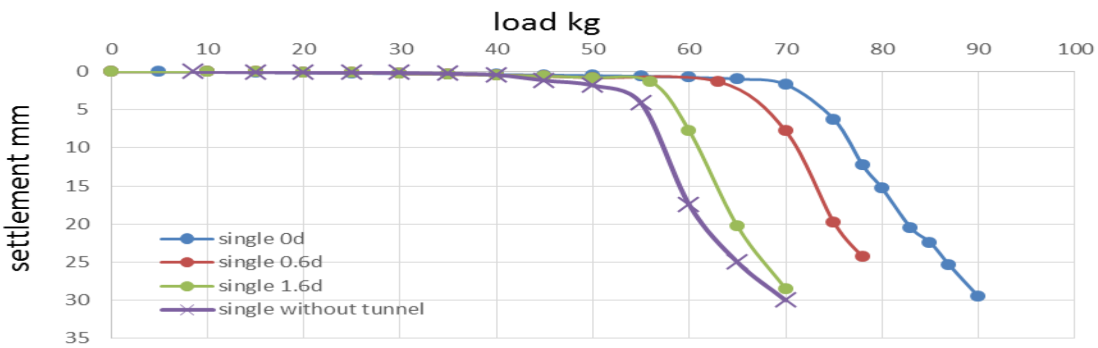


Figure 13: load-settlement curve for R.D 50%

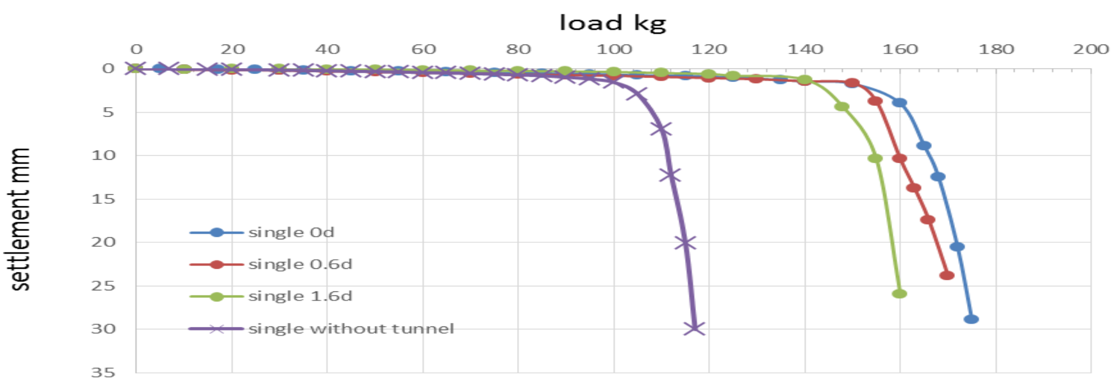


Figure 14: load-settlement curve for R.D 70%

5. Conclusions

By comparing the stresses generated in tunnel lining between the driven and loading of single pile using two relative densities (50%, 70%) the following points are noticed:

1. When the stage construction completed a significant stress relief occrued
2. The stresses generated at tunnel lining are higher at stage of loading than the construction stage.
3. Crown and invert regions experienced maximum values of stress which made them most important points as compared to the shoulder which their values vary between negative and positive.
4. Stress ratio generated within the tunnel decreased with the increases of relative density. This is because of an arching phenomenon which occurs by transformation part of vertical load laterally within adjacent sand grains.
5. The effect of piles position on the stresses generated at the tunnel was clear and direct when it applied at the center of the tunnel crown region (X=0D, X: is the horizontal distance between the tip of the pile and existing tunnel)), the stress values were high and affected all the tunnel measured points (regions), whereas the effect decreased with the increasing of X value and several points experienced an increment or decrement for their stress values depends on other soil conditions.
6. At (1.6D) there the stress could be negligible and could name it as safe distance.
7. Load carrying capacity of pile increased with the presence of the tunnel. Maximum increment occurs when pile located at the center of the tunnel (0D) and reduced as moved lateral distance as but still higher than the ultimate load without existing of the tunnel.
8. Through the driving of pile, the stresses increased with increasing of the insertion depth for cases when tunnel located at distances (0D, 0.6D) while at (1.6D) the stresses would increase to a certain depth then significant reduction would accrue. That is right also for loading stage when piles reach their ultimate load.

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