Lateral Resistance of a Single Pile Embedded in Sand with Cavities

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ABSTRACT

The research presents an experimental study of the interaction between cavity and adjacent pile in sandy soil. Experimental studies were performed to investigate the effects of the different factors (such as cavity locations, batter angle of pile, pulling height and vertical dead loads) on the lateral movements, rotations, and ultimate lateral resistance of the pile for three states of soil (dry, water at rest and water flowing laterally).

The analysis of the experimental results of the dry models indicate that the model tests for very deep or shallow cavity with negative distance ratio(the horizontal distance from the centerline of the pile to the centerline of the cavity, S/B=-8) carries more load than the cavity case with positive distance ratio. Different failure modes can be observed for each model tests depending upon the geometry of the problem. The resistance of the batter pile are generally smaller than that of the vertical pile case for cavity with (depth of the cavity to length of the pile, D/L=1 and S/B=0). Also for the same cavity location, the effects of lateral load position on batter pile are very low. The pile with vertical dead load of (228.6 N) carries more lateral load than pile with no vertical load for the same cavity condition. This behavior is reversed for soil without cavity. In spite of that the constant lateral load is greater than the ultimate lateral resistance of the case (F.S=0.8) during the observations of the lateral displacement with time, failure does not occur for cavity condition with (D/L=0.5 and S/B=-8).

The results of the model tests with the presence of the water show the methodology of the water flowing in the lateral load direction is more dangerous on the pile stability than water at rest state for no cavity condition, but the water at rest becomes very dangerous state for any cavity condition.

Keywords: Lateral resistance, Single pile, Sandy soil, Cavity, Al-Najaf soil

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المقاومة الأفقية لركيزة منفردة تخترق تربة رملية ذات فجوات

الخلاصة

يشمل البحث جزئيين رئيسين، الأول دراسة مختبريه و الأخرى نظرية لإيجاد التفاعل بين الفجوة و الركيزة المجاورة في الترب الرملية. انجزت الدراسة المختبريه لتخمين تأثيرات العوامل المختلفة(موقع الفجوة، ميل الركيزة الأصلي،موقع الحمل الأفقي عن سطح الأرض و مقدار الحمل العمودي الساكن) على الإزاحات الأفقية و الدوران و قابلية التحمل القصوى للركيزة و لثلاث حالات مختلفة للتربة. الحالة الأولى عندما تكون التربة جافة و الثانية عندما يرتفع منسوب المياه الجوفية عمودياً إلى الأعلى و الثالثة عندما تكون المياه الجوفية بحالة جريان جانبي. تلك الحاوية صممت بطريقة تسمح بتمثيل حالات التربة الثلاثة.

أظهر تحليل النتائج المختبرية للموديلات بالحالة الجافة أن موديلات التربة مع فجوات عميقة أو ضحلة مع موقع فجوة أفقي بالسالب(S/B=-8) تحمل أكثر من حالة الفجوة عند موقع أفقي موجب و كذلك اوضحت النتائج أن أشكال الفشل تكون مختلفة و تعتمد على الشكل الهندسي للمسألة. عادةً المقاومة للركائز المائلة اصغر من الركائز العمودية لحالة فجوة عند موقع (D/L=1 and S/B=0). كذلك لنفس موقع الفجوة تكون التأثيرات لموقع الحمل الأفقي عن سطح الأرض لحالة الركائز المائلة صغيراً جداً . الركيزة المحملة بحمل عمودي ساكن مقداره 228.6 (N) تحمل حمل أفقي اكبر من الركيزة غير المحملة عمودياً عند وجود فجوة، بينما هذا السلوك يكون معاكس عندما التربة لا تحتوي على فجوة. الفشل لا يمكن أن يحصل لحالة فجوة (D/L=0.5 and S/B=-8) مع معامل امان (F.S=0.8)، رغم ان مقدار الحمل الأفقي الساكن (209 N) يكون اكبر من قابلية تحمل الركيزة (169 N) عند مراقبة الإزاحات الأفقية للركيزة مع الزمن.

أوضحت النتائج للموديلات المختبرية مع وجود الماء إن جريان الماء باتجاه تسليط الحمل الأفقي تكون أكثر خطورة على استقرارية الركيزة من حالة وجود الماء بحالة ساكنة في الترب الغير حاوية على فجوات، ولكن حالة وجود الماء بصورة ساكنة تصبح خطرة جداً عند و جود الفجوات.

INTRODUCTION

The piles are often subjected to lateral loads, particularly in quay and harbor structures where horizontal forces are caused by the impact of ships during berthing and wave action, in offshore structures subjected to wind and wave action, in pile supported earth retaining structures, in lock structures, in transmission- tower foundations where earthquake prone areas as shown in Figure(1).

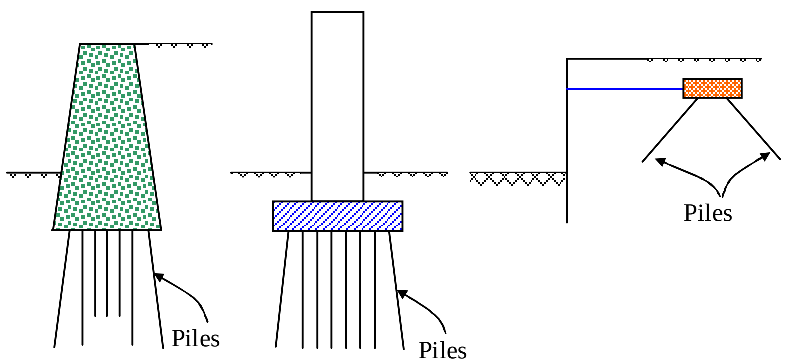
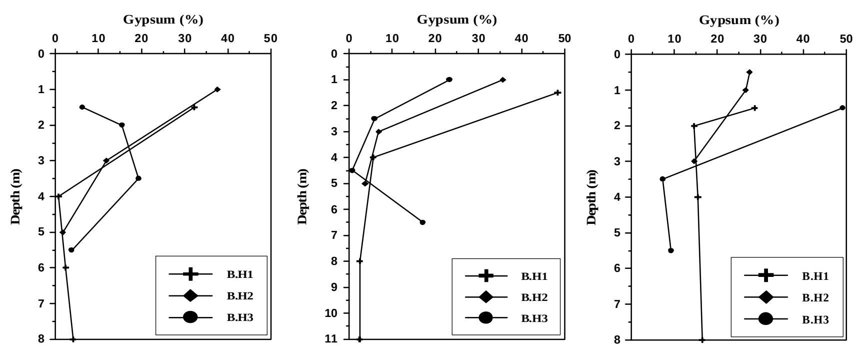


Figure (1): Examples of piles under lateral load.

In general, Najaf soil is mainly of fractured limestone with some gypsum. Figure (2) shows the percentages of gypsum for three different locations covering the region in Al-Najaf governorate. The gypsum content varies from (0.6) to (49.15) percent and the high percentages are concerned at the one meter below the ground surface level. These percentages of gypsum in soils can cause considerable more damage to structures and highways than other natural disasters combined.



(a). AL-Najaf Sea (b). AL-Wafa Region (c).AL-Jamia'a Region

Figure (2):Gypsum percentages versus depth for three different locations at AL-Najaf city (NCCLR, 2005).

Many existing gypsum are located in Al-Najaf soil and with continuous ground water movement, the gypsum dissolve and generate many cavities of different irregular shapes and at various locations below ground surface as

AIMS OF STUDY

The main objectives of the present study are:

1- To understand the behavior of a single laterally loaded pile embedded into sandy soil with cavity.

2- To study and understand the different factors (cavity locations in X and Z-directions, batter angle of pile, pulling height of lateral load and vertical dead loads) that influence the lateral movements , the rotations and the ultimate lateral resistance of the pile and the indication to the parameters that are responsible for pile stability.

3- To provide informations about the values of the horizontal and vertical creep of the single pile with time due to the formation of the cavity after the application of the lateral load (the presence of the structure during the cavity formation).

4-To study the effects of water states (water at rest and water flowing) and also to investigate the effect of flow direction on the response of laterally loaded pile with and without cavity

5-To present solutions which may be readily utilized in practice to obtain realistic estimates of lateral deformations and rotations of pile embedded into sandy soil with cavity, and to observe the deformations of the cavity sides.

REVIEW OF LITERATURE

Due to the review of literature indicates that there is no published information on the behavior of the pile foundations subjected to lateral loading for soils with the presence of cavities and/or water (i.e no previous results for soil with cavity presence under application lateral load testing are available, it is not possible to compare the results herein directly with available literature).

EXPERIMENTAL WORK

In this experimental study, the problem was treated as Two-Dimensional. This is due to the fact that the cavities are arranged in the form of Plain-Strain Condition.

Soil used

Due to the soil morphology of Al-Najaf city, many samples at different depths were brought representing locations covering the region in Al-Najaf governorate. The site characteristics of Al-Najaf city are determined to be used in the laboratory model tests and to be used as required parameters (input file) in the finite element program. These characteristics include soil properties, chemical properties of soil and water, pile material properties, and the properties of the interface between the pile and soil. Three regions are designated as (A,B and C), these regions correspond to Al-Jamia'a region, Al-Najaf Sea and Al-Wafa region in chapter one respectively.

It was found that type (A) exists extensively in Al-Najaf governorate, so this type was used in the present work.

Steel box

Figure(3) shows a photographic view of the steel box (container) with inside dimensions of (175 mm) in width, (610 mm) in length and (550 mm) in height. It consists of three compartments, the middle one is used for the preparation of the bed of soil while the outside compartments are used as reservoirs for upstream and downstream levels. The dimensions of the middle compartment is of (350mm) in length, (550mm) in height and (175 mm) in width. This compartment is made of three plates welded to each other with one side portable in the longitudinal direction. The two transverse sides (in the width direction) contain holes at different levels (filter screens with opening 10 mm) in order to allow for the flow of water through the soil. The two outside compartments are (130mm) in length, (550mm) in height and (175mm) in width. The water level was controlled by the vertical holes which are located at various levels in the transverse side of the two outer compartment.

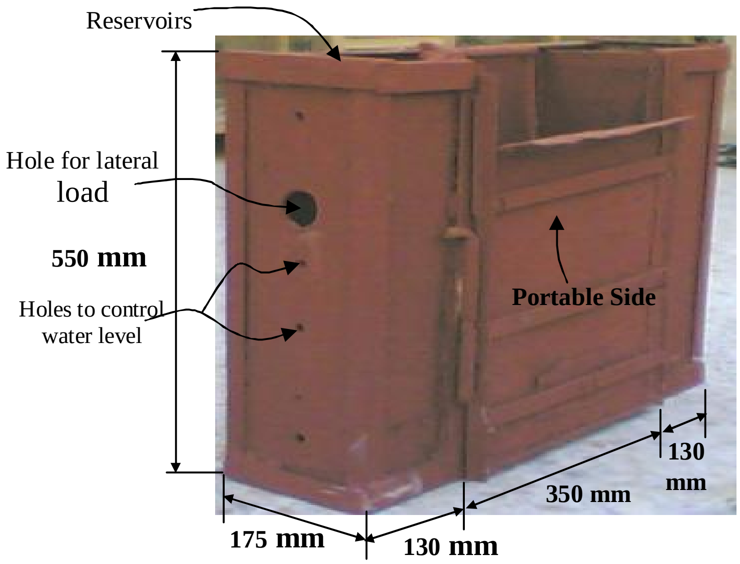


Figure (3): Steel container diagram

Model pile

Steel model solid square pile was designed with dimensions (B=11 mm) in width, jacked (L=160 mm) into a soil mass. The pile length is constant for all model tests. The free length of the pile above the bed of the soil surface level is (g=40 mm).

Model preparation

In all the model tests, the soil samples are prepared by mixing dry soil with water in percent corresponding to natural moisture content, then spreading the soil inside the middle compartment of the container in four layers. Each layer is compacted to a unit weight equal to the natural wet unit weight in the field (19.4 kN/m3). The thickness of the first layer is (35 mm), but it is (80 mm) for the other three layers. The under compaction process was selected to produce homogeneous sample that could be used for a parametric study in a laboratory testing program. The dimensions of this homogenous sample are (H=275 mm) in height, (175 mm) in width and (350 mm) in length.

The cavities were prepared by placing a block of wood with dimensions corresponding to the cavity dimensions. These dimensions are constant for all model tests in which, the height and the width of the cavity are (h=80 mm) and (W=75 mm) respectively. Following the placement of the required wood block, compaction continued till the final level of the bed of soil (ground surface level). The model pile was jacked into the soil to the required depth (i.e pile length), then the front side is removed and the wood block is pushed slowly and the front side is placed again in its original position as shown in Figure (4).

(a).During compaction (b). After cavity forming

Figure (4): Stages for the preparation of the model test.

Pile installation

When testing model pile system a major difficulty was to start with the installation of a pile in a sand soil layer. In model of pile studies, it is usual to push the pile into the sample by handle jack with a rate of (1.2 mm/sec). Three methods are there to jack pile depending on the initial angle of inclination of the pile during its installation as illustrated in Figure (5). For all model tests, the pile is installed at the center of the middle compartment of the steel container.

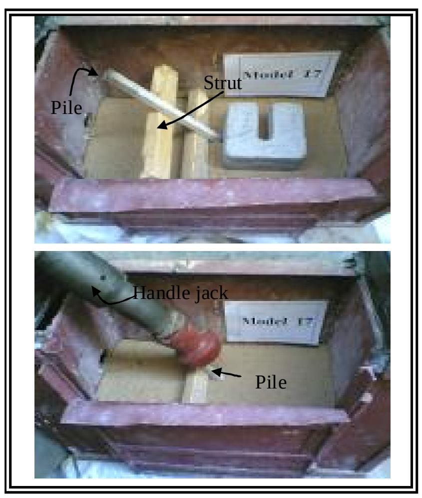


Figure (5): Methods of pile installation.

Model testing

The schematic diagram of the test setup, loading arrangement, and model single pile is shown in Figure (6). Two dial gauges were fixed in positions which measure the displacements in X-direction (lateral) and in Z-direction (axial). The dial gauges having a sensitivity of (0.01) mm. The initial readings of the dial gauges are recorded prior to any loading.

The lateral load was applied to the single pile head through a pulley arrangement with flexible wire was attached to the pile head. The other end was attached to the loading pan. The loads were applied by dead weight over the loading pan starting from the smallest with gradual increase in stages. This lateral load was applied to the pile in an incremental manner so that the non-linear load versus displacement curve could be adequately defined. The load was maintained for a period of time for each load increment to allow displacement readings to stabilize with no movement. Rotation of the pile was determined from the corresponding lateral and axial displacements.

The relationships between the lateral load versus horizontal displacements and pile rotations are measured under the following four different conditions

1- The influence of the cavity locations(D/B and S/B), pile slopes(θ), pulling height distance of lateral load above soil surface level (e) and vertical dead load (P_v) are conducted on model pile tested immediately after compaction of soil and removing of the wood block(cavity formation).
2- The study of time effect when the lateral load (corresponding to factor of safety) is applied at first, then the forming of the cavity perform (removing of wood block).
3- The effect of the water at rest state is when the water is raised upward through the bed of soil after the removing of the wood block.
4- When the water flowing laterally underneath and adjacent the pile.

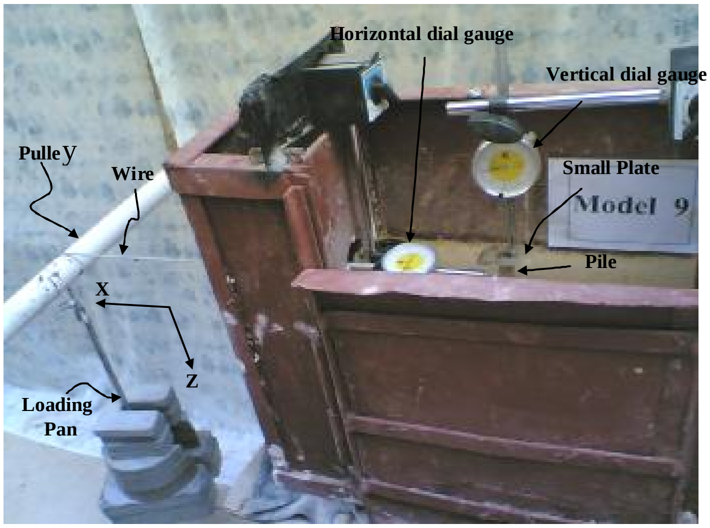


Figure (6): Experimental set-up

Discharge measurement

For water flowing state, the flow rate through the soil sample under the constant hydraulic gradient of (I=0.63) was measured by collecting of the existing water from the downstream zone (one reservoirs) in jar as seen in Figure (7). To maintain the water head in the upstream zone, the source of the water will continue adding water to the top of the upstream reservoir.

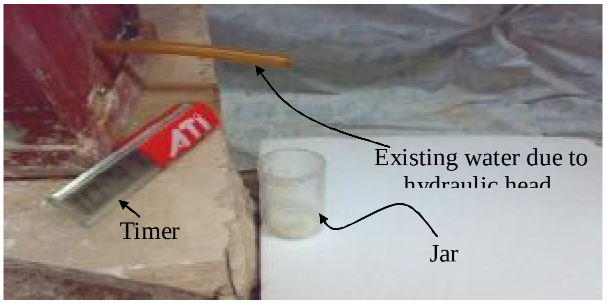


Figure (7): measurement of discharge

Repeatability of Laboratory Tests

The ability to reproduce test results for models with similar compositions was evaluated during the laboratory experiment. The purpose of repeating the laboratory tests is to determine the variability of the test procedures and materials. The results for the model tests are the averages for a number of test results(average of two tests results).

PRESENTATION AND INTERPRETATION OF LATERAL TEST RESULTS

The interpretation of the test results generally involves two phases, firstly showing the relationship between lateral load and horizontal displacement and the individual pile rotation. Secondly, illustrating the observation of lateral pile displacement with time.

Forty-seven model tests were performed and the testing program comprised the following seven separate broad series as below:

Influence of Changing Cavity Location

This series involves thirteen tests on model free head vertical pile with pulling height distance (e/L= 0). This pile is pushed into the compacted sandy soil with rectangular cavity (h/w=1.06). Single piles were tested, installed at the container center. The cavities were prepared at various offset from the pile centerline and to the depths mentioned below.

In this phase, the model tests are divided into four parts as below:

1 Model tests with (D/L=1) and (S/B= -8, 0 and +8)
2 Model tests with (D/L=0.75) and (S/B= -8 and +8)
3 Model tests with (D/L=0.5) and (S/B= -10.25, -8, 0,+8 and +10.25)
4 Model tests with (D/L=0.25) and (S/B= -8 and +8)

Stability analysis of pile with cavity presence

The effect of the presence of a cavity on the ultimate lateral resistance, normalized with respect to the no cavity condition (the reduction in lateral resistance due to the presence of the cavity) is presented in Figure(8). The figure illustrates the variation (P/P_o) versus (D/L) at a different (S/B) ratio. As (D/L) increases, the effect of the presence of the cavity decreases, and the value of the (P/P_o) is approximately equal to (1). The value of (P/P_o) for the case (D/L= 0.25 and S/B= -8) is irregular. The ratios (P/P_o) for the cases of the cavity with (D/L=1and S/B= -8), (D/L=1and S/B= 0) and (D/L=1and S/B= +8) are approximately equal. At depth ratio (D/L=0.5), the peak value of the ratio (P/P_o) is observed for the case (S/B=-10.25), this ratio becomes minimum at zero distance ratio (S/B=0).

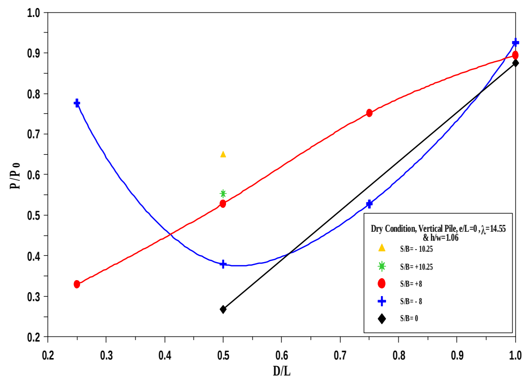


Figure (8): Effect of horizontal location and depth of cavity on ultimate lateral resistance.

Effect of Angle of Batter on the Behavior of Pile

Battered pile is widely used in deep water or scour region to resist large lateral loads such as ship impact (ocean structures), towers, earthquake, etc……

Nine model tests were conducted with different angles of pile inclinations such as the pile battered reverse (Negative Pile), the vertical pile and the pile battered forward (Positive Pile). These tests are divided into three categories based on the presence of the cavity within the soil mass as the following.

5-2-1 Model tests of pile slopes with(q = - 30, 0 and +30 deg.) for no cavity condition.

5-2-2 Model tests of pile slopes with(q = - 30, 0 and +30 deg.) for cavity with depth ratio (D/L=1) and distance ratio (S/B=0).

5-2-3 Model tests of pile slopes with(q = - 30, 0 and +30 deg.) for cavity with depth ratio (D/L=0.5) and distance ratio (S/B=0).

The effect of both the cavity presence and pile slope

The reduction of the ultimate lateral resistance due to cavity (P/Po) is plotted as a function of cavity depth ratio (D/L) and pile inclination (θ) as shown in Figure(9). It can be seen from the figure that the pattern of the upper curve for cavity deep depth ratio (D/L=1) is not similar to lower curve for cavity shallow depth ratio (D/L=0.5). The effect of the presence of the cavity on the ultimate lateral resistance is much more significant for the cavity depth ratio(D/L=0.5) than for cavity depth ratio (D/L=1).The influence of both cavity presence and pile inclination on the lateral load resistance at failure is presented in Figure(10). In this plot, the ultimate lateral load resistance decreases with increasing pile inclination and with decreasing cavity depth ratio.

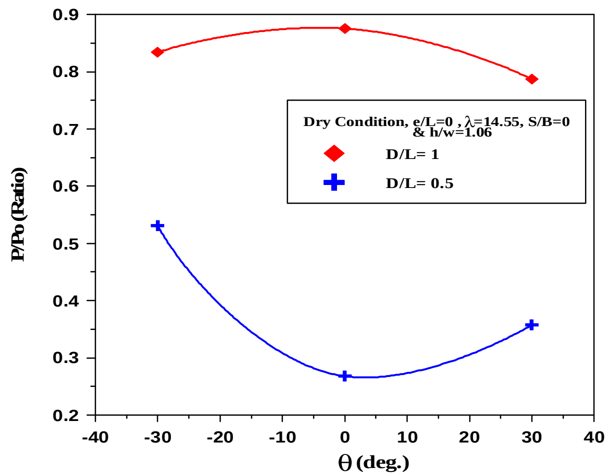


Figure (9): Relationship between reductions of ultimate lateral load resistance with pile slopes.

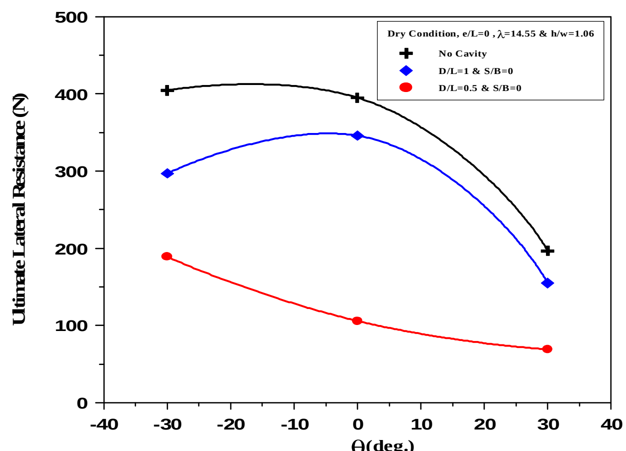


Figure (10): Effect of cavity depth (D/L) and pile inclination on ultimate lateral load resistance.

Influence of Position of Applied Lateral Thrust

In case of a single pile used as an anchor or tieback as in an anchored bulkhead installation, lateral load or moment , or both are applied on the head of the single pile and other examples, such as overhead catenary systems carrying electric power in railway network, transmission towers, advertisement and waterfront construction ship.

Six model tests were performed when the height of the load application equals (25 mm) above the bed of the soil. In this section must be emphasize, the values of the lateral displacements of the pile head are measured with the ground surface level.

1 Model tests of pile slopes with (q = - 30, 0 and +30 deg.) for no cavity condition and pulling height ratio (e/L >0).

2 Model tests of pile slopes with (q = - 30, 0 and +30 deg.) for cavity condition(D/L=1 and S/B=0) and pulling height ratio (e/L >0).

Effect of pulling height (e/L) and initial pile slope(q).

To give sufficient idea about the variability of pulling height ratio of the pile, the Figures(11 and 12) are plotted in terms increase in displacement, it can be denoted that as the difference in displacement between the cases of (e/L=0 and 0.156) as a percent of the case(e/L=0). For no cavity condition, the maximum increase in displacement occurred at positive batter pile (θ=+30 deg.), while the peak increase in displacement is observed with vertical pile for cavity condition.

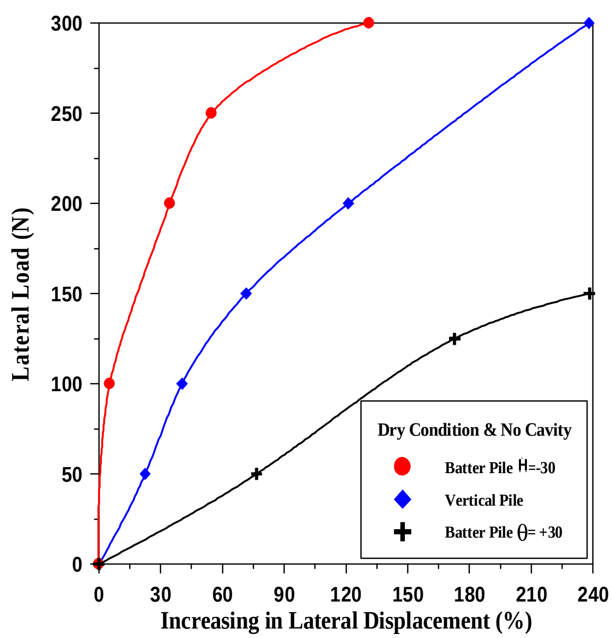


Figure (11) Model tests for no cavity condition.

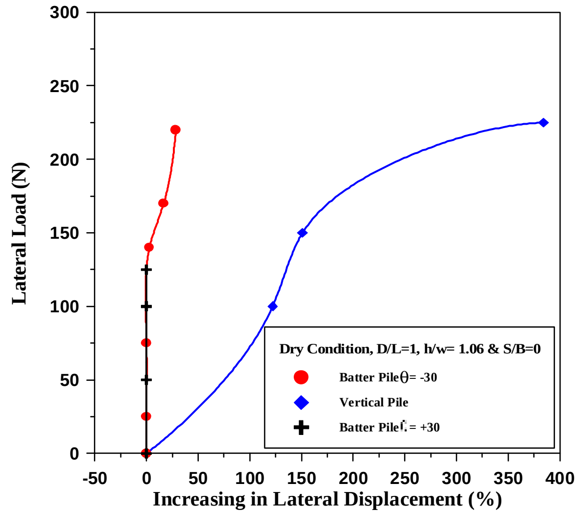


Figure (12) Model tests for cavity (D/L=1andS/B=0).

Effect of cavity presence and pile slope

The effect of the cavity on the ultimate lateral resistance of the pile reduces with increasing pulling height ratio (e/L) for negative and positive batter pile. Reversed behavior can be noted for vertical pile case (θ=0 deg.) as shown in Figure(13). In other means, the ratio (P/P_o) is reduced with the increase in the ratio (e/L) for vertical pile case. This behavior can be explained as the fact that, by increasing (e/L)(combined effect of the generated moment and lateral load at ground surface) more soil particles must be displaced for with and without the cavity presence during the application of the load increments.

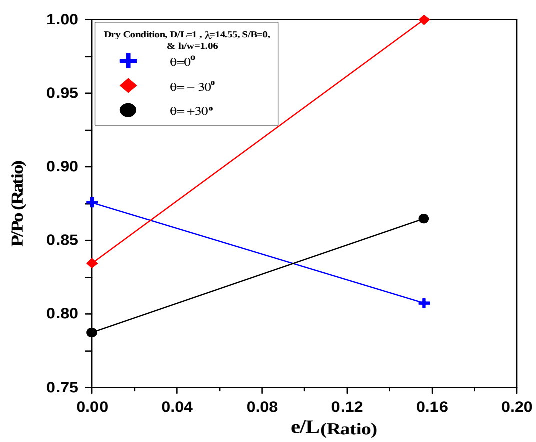


Figure (13): Ultimate lateral resistance (percent of no cavity condition) of pile versus pulling height ratio at various pile slope.

Effect of Changing Vertical Dead Loads

Generally, pile foundations for buildings and bridges are often subjected to vertical and horizontal loads simultaneously. Yet, the axial and lateral responses of piles are often evaluated (by using different theoretical methods) separately without considering their possible interactions (Zhang et.al.,2002).

The vertical dead load is applied on the vertical pile head by loading pan. This load remains constant during the application of the lateral load increments. The position of the horizontal thrust is close to the bed of the soil surface level (e/L=0). The pan of the vertical dead load is welded to pile head. This dead weight does not cause any bending moment on the pile laterally loaded.

Six model tests are conducted with different vertical dead loads of the two cases for cavity and no cavity conditions as below.

5-4-1 Model tests for no cavity condition at vertical dead load (0, 98.1 and 228.6 N)

5-4-2 Model tests for cavity with (D/L=0.5 and S/B=+8) under vertical dead load (0, 98.1 and 228.6 N).

Combined effect of cavity presence and vertical dead loads.

The relationship between the ratio (P/P_o) and the vertical static weight (P_v) is presented in Figure(14). It can be noted from this figure that the ratio (P/P_o) decreases due to the increase in vertical dead load until it reaches to a minimum value, beyond which the (P/P_o) increases with increasing of the vertical load. Based on the results of the figure, the effect of the presence of the cavity is much more significant for the vertical dead load of (98.1 N).

The influence of both the cavity presence and vertical dead load on the lateral load resistance of the pile at failure state is presented in Figure(15). It can be noted that the ultimate lateral resistance increases due to the increase in vertical static weight (P_v) for cavity condition. For no cavity condition, the resistance decreases at high dead load. At vertical dead load of (98.1 N), the value of the ultimate lateral resistance of the pile is minimum for cavity condition and it becomes maximum for no cavity condition.

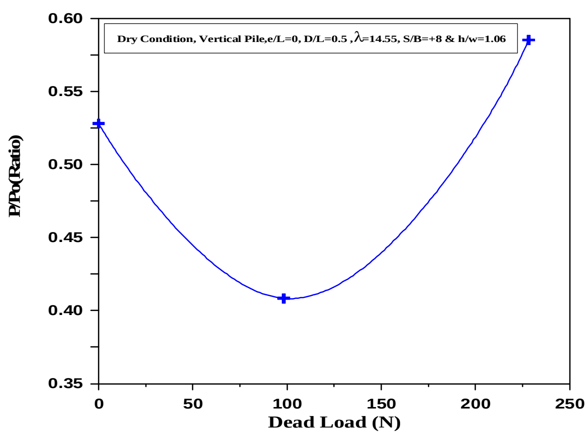


Figure (14): Relationship between reduction in ultimate lateral resistance of pile due to the cavity presence and vertical dead load.

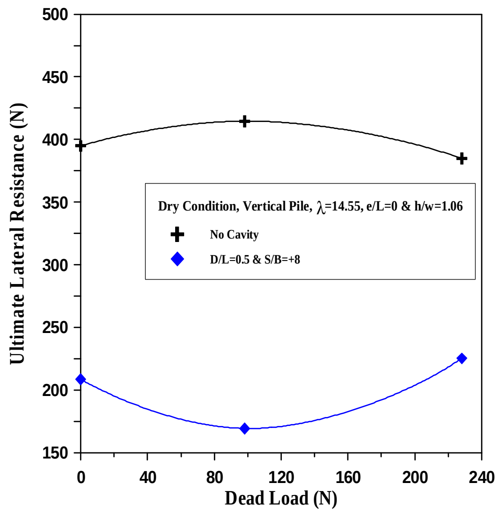


Figure (15) : The combined effect of vertical dead load and cavity presence on the ultimate lateral resistance of pile.

Displacement-Time Predictions Under Constant Lateral Load

There are two types of cavity problems that can be observed in the field. In the first, a cavity exists initially in the soil mass and then the lateral load applied on the pile head. In the second, there is initially no cavity in the soil mass, but after the application of the lateral load, the cavity will form into the soil mass.

Experimental models, which take into consideration the load of the structure (lateral load) during/after the formation of the cavity are tested. In other words, this section gives an idea about the behavior of the single pile laterally loaded when it is embedded into soil without cavity at first stage. In the final stage, when the lateral load reaches to constant value (corresponding to factor of safety) and after the measured displacements of ground surface adjacent to pile had become stable, the wood block is pulled slowly (wood block is corresponding to the cavity i.e cavity is formed) from the bed of the soil and the lateral and vertical displacements reading of the pile will be recorded with time(the effects of the time have been taken and hence the corresponding lateral and vertical displacements are measured).

Model tests for cavity with (D/L=0.5 and S/B=+8) at constant lateral load.

In this category, four model tests were conducted on single pile under different static lateral load conditions for cavity with (D/L=0.5 and S/B= +8).

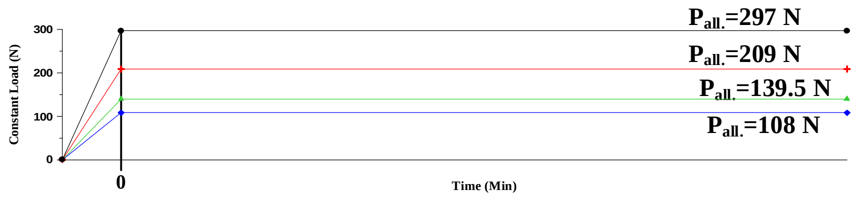
Figure(16a) shows the variation of lateral load increment with time and then the load is kept constant. In these four model tests, the piles were initially loaded incrementally up to a load of (108, 139.5, 209 and 297 N), these loads represent a working load corresponding to factor of safety equal to (2.0, 1.5, 1.0 and 0.7) respectively.

The family of the lateral displacement-time curves is presented in the Figure (16b). As expected and as judged from this figure, it can be noted that the lateral displacements increase with time. The decrease in factor of safety is very effective in increasing the lateral displacements with time.

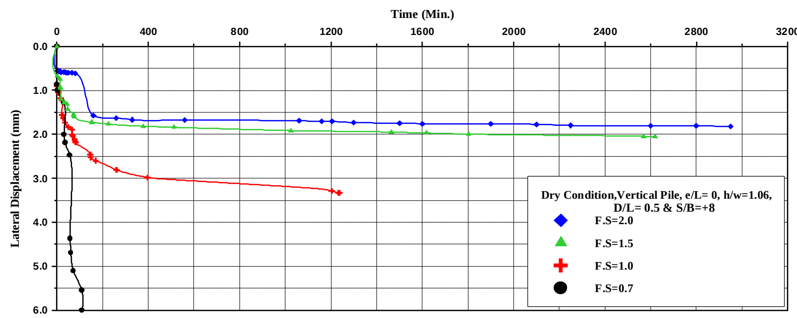
For cases (F.S= 2.0 and 1.5), the lateral displacement increases rapidly with time at first (sharp increase in displacement was noticed during the first of 155 min). After that, the pile is in a state of equilibrium and the increase in displacements can happen at a uniform small rate.

When the constant lateral load is equal to the ultimate lateral resistance of pile (F.S=1.0), the lateral displacement starts to occur rapidly up to (400 min) and continue to develop but at a slow rate. No sudden collapse occurs for the three previous cases. The lateral displacement of the pile for the case of (F.S=0.7) (the value of the constant lateral load greater than the ultimate lateral resistance) is observed with a very rapidly rate and then collapse take place after (85 min). In other words, the failure does not occur suddenly.

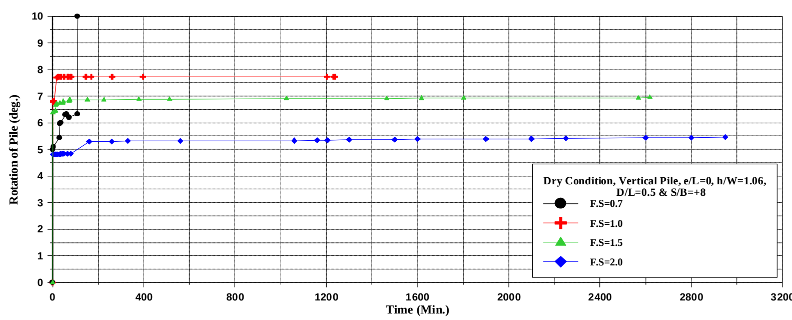
Immediately after the completion of the forming of the cavity, the values of the rotation of the pile are very high (at time equal to zero) and then it reaches to constant values as shown in Figure(16c).These cases have similar behavior except the case for (F.S=0.7) when failure happens (at early time, the values of the pile rotations for (F.S=0.7) it is smaller than those for two cases (F.S= 1.0 and 1.5).



(a). Relationship between the lateral load and time



(b). Observed of surface lateral displacements with time due to the formation of the cavity under constant lateral loads



(c). Pile rotations with time due to the forming of the cavity under constant lateral loads

Figure (16): Results of model tests at different static lateral load for cavity with (D/L=0.5 and S/B=+8)

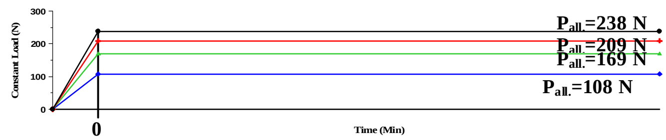
Model tests for cavity with (D/L=0.5 and S/B= -8) at static lateral load

In Figure(17a), the lateral load increased in several stages with time, then the load remained constant, these values of constant lateral load were (108, 169, 209 and 238 N), the corresponding factor of safety were (F.S=1.5, 1.0, 0.8 and 0.7).

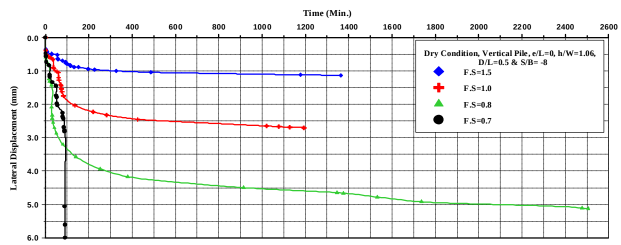
Figure (17b) depicts the evolution of the lateral displacement of the pile during/and after removing of the block wood (cavity formation). It can be noted from this Figure that the observed lateral displacement increases with time and decreases with increasing of factor of safety. Furthermore, these displacements increase sharply up to certain values of (225,425,910 and 90 min) for (F.S=1.5, 1.0, 0.8 and 0.7) respectively, beyond which the rate of the displacements reduces significantly.

In spite of that the constant lateral load is greater than the ultimate lateral resistance of (F.S=0.8), failure does not occur. While for the case of (F.S=0.7), the reduction of factor of safety results in a collapse of the soil adjacent to the pile and also to the cavity, which quickly propagated laterally and vertically throughout the soil mass. The failure occurs after a period of (90 min) after cavity formation.

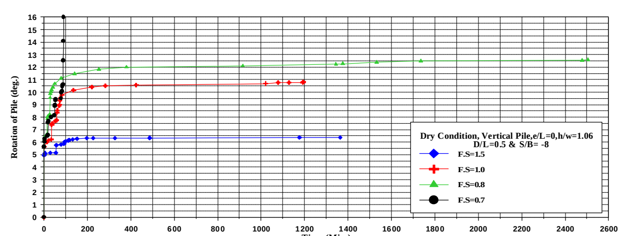
The family of the pile rotations-time curves are presented in Figure (17c). As expected the instantaneous rotation is rather high during the early time (at zero time), while an essentially approximation constant rotation rate is attained after (100-400 min) for all cases.



(a). lateral load versus time.



(b). Predicted lateral displacements at pile head due to the formation of the cavity versus time for different constants lateral loads



(c). Pile rotations versus time due to the forming of the cavity under constant lateral load

Figure(17): Results of model tests for several static lateral load for cavity with (D/L=0.5 and S/B=-8) condition.

Influence of Rising Water Level (Water at Rest State)

The location of the ground water table has an effect on how laterally loaded pile behaves. In order to study the water effects, five models are tested in the laboratory.

In all model tests of this category, the water table rises from the bottom of the container model to the top surface of the soil bed. It is increased in three equal lifting of the water and referred to the initial ground level of Al-Najaf city. For each lift, the water head is maintained by adding the water to reservoirs (upstream and downstream) from the source.

Model tests for no cavity condition at different pile inclinations

Model tests for vertical pile at various cavity locations

Effect of water presence and pile inclination for no cavity condition

In general, the presence of a water table around a pile reduces the effective shear strength of a granular soil and, hence its ultimate lateral resistance of the pile (failure occurred faster). Also, the water accelerates the development of the lateral displacement of the pile. This will lead to an increase in displacement. The change in lateral displacement due to the presence of the water denoted as the difference in displacement between the dry state and water at rest state as a percent of the dry state. This increase can be plotted as a function of the lateral load and pile inclination as in Figure(18). The figure appears that the increase in displacements are high when the angle of the pile inclination (θ= +30 deg.), while they are very low at vertical pile.

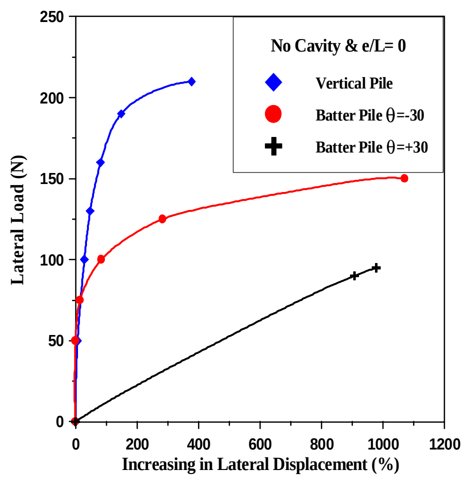


Figure (18): Relationship between lateral load and increasing in lateral displacement (due to the water presence).

Influence of water presence and cavity location for vertical pile

The effect of varying the lateral distance ratio (S/B) on the ultimate lateral resistance of the pile is constant for the water state as shown in Figure(19). These figures show very small increase in the ultimate lateral resistance with the increase in (S/B) ratio for dry state.

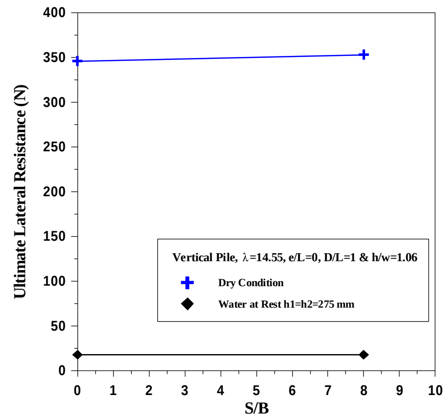


Figure (19): Comparison between results of ultimate lateral resistance of pile for dry and water at rest states.

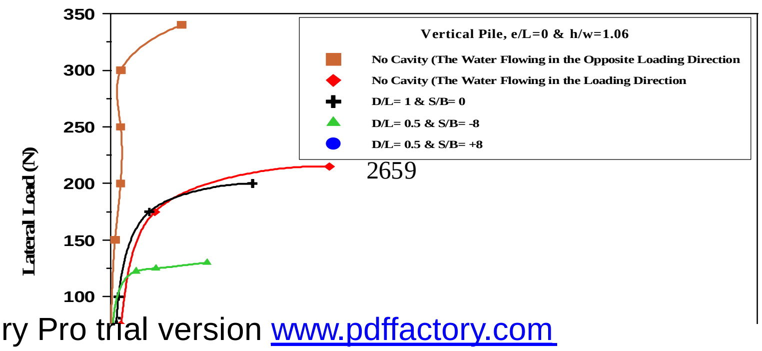
Influence of Water Flowing Laterally

This section is divided into two parts, one for comparing the results from two model tests for no cavity condition (the effect of the direction of flow) and the second part explained the combined effect of the water flowing and the presence of the cavity.

The model tests were conducted when the flow through the soil mass is under a constant hydraulic gradient of (I=0.63). It should be emphasized that these tests were only achieved through steady state flow conditions. The location of the phreatic line depends upon the time and the location of the cavity.

Model tests for no cavity condition with water flowing
Model tests for cavity presence at different locations
Influence of water flowing at different cavity locations

The water flowing through soil mass leads to an increase in lateral displacement, this increase is plotted as a function of the lateral load and the cavity locations in Figure(20). The slope of the load – increase in displacement curve of the no cavity condition is very steep when water is flowing in the opposite of load direction, while for cavity with (D/L=0.5 and S/B=+8), the slope is very flat. Other curves family for no cavity condition, cavity with (D/L=1 and S/B=0) and cavity with(D/L=0.5 and S/B=-8) are merged together in the initial stage, and at high lateral load, the increase in displacements for the case (D/L=0.5 and S/B=-8) are higher than those for the cases no cavity and (D/L=1 and S/B=0).



A Comparison of the ultimate lateral resistance values at cavity depth (D/L=0.5) for different test states is presented in Figure(21). The ultimate lateral resistance values are high at negative horizontal distance ratio (S/B=-8), while this resistance becomes low at positive lateral distance ratio (S/B=+8) for the water flowing state. This is mainly because, water flowing is very effective on the cavity with ratio (S/B=+8). For dry state, the lateral load at failure increases with the increase in the lateral distance ratio (S/B) as seen in Figure (21).

Comparison Among Dry, Water at Rest and Water Flowing States

The results of the ultimate lateral resistance of pile for the three states are listed in table(1). It can be seen that for all states, the values of the ultimate lateral resistance of the pile are not equal. Generally, the reduction in ultimate lateral resistance of the pile due to the presence of the water are (48%) for no cavity condition, while for cavity with (D/L=1 and S/B=0), the drop become (41%) and (94.9%) for the water flowing and water at rest states respectively.

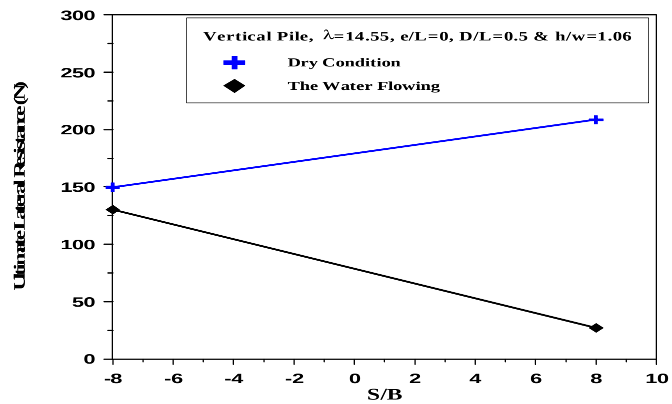


Figure (21): Relationship between lateral load at failure (P_u) and lateral distance ratio (S/B) for two different states.

Table (1): Values of the ultimate lateral Resistance of pile (N).

Soil State	No Cavity Condition	Cavity (D/L=1 and S/B=0)
The dry state	395	346
The water flowing in the load direction state	204	202.5
The water flowing in the opposite load direction state	346	-----------
The water at rest	204	17.5

CONCLUSIONS

The following main conclusions can be drawn from the experimental and theoretical results presented in this research

Experimental study

Soil is in dry state

1- For very deep or shallow cavity, the pile with negative distance ratio (S/B=-8) carries more load than that with positive distance ratio (S/B=+8).

2- The lateral resistance of the pile increases with the increase of cavity depth (D/L) for model tests with (S/B=0 and +8), while for model tests with (S/B=-8), the resistance of case (D/L=0.25) is high than the cases of (D/L=0.5 and 0.75).

3- At (e/L=0), the soil resistance without cavity decreases with increasing the initial angle of the pile inclination, while the resistance of the batter pile are generally smaller than that of the vertical pile case for deep cavity .

4- For high vertical dead load of (228.6N), the lateral displacements of the pile are the lowest at a small lateral load increments and becomes the highest at large lateral load increments for no cavity condition.

5- For cavity condition, the pile with dead load of (228.6 N) carries more load than the pile with no vertical load.

6- Under constant lateral load, the decrease in factor of safety is very effective in increasing the observed lateral displacements and rotations with time.

7- In spite of the fact that the constant lateral load (209 N) is greater than the ultimate lateral resistance (169 N) of the case of (F.S=0.8), failure does not occur even for long time when the cavity condition is located at (D/L=0.5 and S/B=-8).

Water at rest state

1- The slope of load-displacement curve for vertical pile into soil without cavity is steeper than that for batter pile (positive or negative).

2- The differences between the pile rotation curves of the two states (dry and water at rest) increase with increasing pile inclinations.

3- The rate of pile rotation is very high for the water at rest state at any pile slopes.

4- For cavity condition and before the application of the lateral load, hairline crack around the pile is formed due to the presence of the water when the distance ratio (S/B=0).
5- Generally, the load-displacement and rotation curves for cavity condition have an approximately horizontal slope (very flat).

Water flowing state

1- The location of the phreatic line (due to water flowing laterally) depends upon time and cavity position.
2- For all cases of cavity and no cavity conditions, the flow rate is rapid at the beginning until it reaches a maximum value, then it decreases when the flow time increases. For long time period, the curves of the flow-time become horizontal lines
3- The case of water flow in the load direction through the soil mass without cavity is more dangerous than the flow in the opposite load direction
4- Water flowing is more dangerous on the pile stability than water at rest state for no cavity condition, but the water at rest state becomes very dangerous state for any cavity location.

RECOMMENDATIONS FOR FUTURE WORK

1- Investigating the effects of the method of the pile installation on the response of laterally loaded piles executed in soils has cavities.
2- Determining of the response of pile group or pile raft laterally or vertically or oblique loading when the soil mass containing with cavities.
3- Finding design charts for a single pile embedded in soil with cavity when the pile is loaded laterally or vertically or oblique.
4- Prediction of the single pile response when the cavity has inclinations in Y-direction.
5- The monitoring of the lateral displacement when the volume of the cavity varies with time.

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