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Soft Clay Soil Improvement Using Stone Columns and Dynamic Compaction Techniques

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Abstract

Soft clays are widely spread in Iraq particularly in its southern Mesopotamian plain. As many sites within these regions may be used for vital projects; an adequate solution has been found out to improve such clays using stone column and dynamic compaction methods. For this purpose, the present paper has presented the laboratory measurements of the properties of such clays and their settlements at different applied stresses. Thirteen soil model tests have been made, at 27% water content and 9 kPa undrained shear strength, to examine their behaviors under loading .The tested models include : (1) model for untreated soil ; (3) models for soil treated with stone columns (1,2 and 3 columns) with 30mm in diameter and 180mm length ; (9) models for soil treated with dynamic compaction using drop weights 2 , 3 and 5kg at three different drop heights (500 , 750 , and 1000mm) . For dynamic compaction, the behavior of soil stress - settlement reflects two stages for 2 and 3 kg drop weights with slow and rapid settlements respectively. Whereas , three stages were identified using 5kg drop weight with slow, medium and quick settlements. No considerable effect of drop height and no noticeable improvements have been indicated with soil model treated by dynamic compaction except for weight drop of 5kg but with less improvement ratio compared with stone columns model test. Whereas, the behavior of stress-settlement using stone columns reflects three stages with slow, rapid and slow (again) settlements . In comparison with untreated soil, the maximum cumulative settlement improvement ratios were 69% and 178% at applied stress of 30 kN/m^2 for soil models treated with dynamic compaction (5kg drop weight) and 3 stone columns respectively .

Keywords : Soft clay ; Stone column ; Dynamic compaction .

تحسين التربة الطينية الضعيفة باستخدام تقنيتي الأعمدة الحجرية والرص الديناميكي

الخلاصة

تنتشر الترب الطينية بشكل واسع في العراق وخصوصا في السهل الرسوبي الجنوبي .و لمـــا كان العديد من المواقع ضمن هذه المناطق يمكن استخدامها لاقامة المشاريع الحيوية , لذا لا بـــد من ايجاد حل ملائم لتحسين خواص هذه الترب ومنها استخدام طريقتي الأعمدة الحجرية والرص الميكانيكي . لهذا الغرض أجريت في البحث الحالي قياسات مختبريـــة لـــصفات هـــذه الأطيـــان وهطولها تحت اجهادات مسلطة مختلفة. حضرمختبريا 13 نمـــوذج تربـــة بنـــسبة رطوبـــة 27%واجهاد قص غير مصرف 9kPa لفحص سلوكها تحت التحميل . تضمنت نماذج الفحص: نموذج واحد لتربة بدون معالجة ؛ 3 نماذج لتربة معالجة بالأعمدة الحجرية (1, 2 , 3 أعمدة) بقطر30mm وطول 180mm ؛ 9 نماذج لتربة معالجة بالرص الديناميكي بـــأوزان اســـقاط 2 و3 و 5 كغم وبثلاث ارتفاعات اسقاط مختلفة (500 و 750 و1000 ملم) . بالنـــسبة للـــرص

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الديناميكي (لاوزان اسقاط 2 و5 كغم) , عكس سلوك اجهاد – هطول التربة مرحلتين واظهرت فيهماهطولا بطيئا ثم سريعا. بينما ميزت ثلاثة مراحل باستخدام وزن اسقاط 5 كغم ذات هطول بطيء ثم متوسط فسريع . ولم يلاحظ أي تأثير لارتفاع الاسقاط ولا تحسينات معتمـدة للرص الديناميكي ماعدا لوزن اسقاط 5 كغم ولكن بنسبة تحسين أقل مقارنة مع فحص نمـوذج الأعمدة الحجرية .بينماعكس سلوك اجهاد – هطول التربة باستخدام الأعمـدة الحجريـة ثلاثـة مراحل ذات هطول بطيء ثم سريع فبطيء (مرة اخرى) . وبالمقارنةمع التربة غير المعالجـة وجدت نسب تحسين الهطول التراكمية القصوى بحدود 69% و 178% تحت اجهـاد تحميـل $30kN/m^2$ لنماذج التربة المعالجة بالرص الديناميكي (لوزن اسقاط 5 كغـم) وباسـتخدام 3 أعمدة حجرية على التوالي.

Introduction

In most cities of the world and as a result of fast development and urbanization, infrastructure projects are gradually more located on soft soil. Recent problem concerning land scarcity in the vicinity of existing urban areas often necessitates the use of some sites with soil of low quality (such as soft clays), untreated soils in their virgin state may be unsuitable for short or long term construction activities and so their properties must be improved before use. Soft clays are present in different parts of the world and extensively found in many locations particularly in coastal areas in Iraq such as the southern part of Mesopotamia in Iraq especially between Basrah and Fao. The construction of buildings, roads, canals, harbors and railways on soft clay has always been associated with problems of stability and settlements. Soft clays are usually characterized by their poor strength, high water content and high compressibility [1].

Many methods for soil improvement are available around the world including, dewatering, compaction, preloading with and without vertical drains, grouting, deep mixing, stone columns, deep densification and soil reinforcement. Many of these techniques have been used for many years, while others (deep dynamic compaction, compaction piles) show rapid advances in recent years [2].

The use of stone columns as a technique of soil reinforcement is frequently implemented in soft cohesive soil and have been successfully used to support isolated footing, large raft foundations and embankment. Besides, their use in soft clays has been found to provide moderate increases in load carrying capacity accompanied by significant reduction in settlement .Being granular and freely drained material, consolidation settlement is accelerated and post construction settlement is minimized [3,4].

Stone columns may have particular application in soft soils, they are generally inserted on volume displacement basis excavating a hole with specified diameter and desired depth.

The lateral expansion of column due to ramming will induce pore pressure in clay, but is rapidly dissipated back into the much large voids in the granular column. The net effect is to produce a rigid vertical stone mass surrounded by stronger material,

which has a slightly reduced void ratio . It has also been reported that the stone columns have increased the tendency to resist the liquefaction potential in the subsoil , and provide sufficient safety for slope stability [5,6].

Soil densification by dynamic compaction (DC), also called heavy tamping or dynamic consolidation , is a well–known compaction method . Soil is compacted by repeated , systematic application of high energy using a heavy weight (pounder) . The imported energy is transmitted from the ground surface to the deeper soil layers by propagating shear and compression waves types which force the soil particles into a denser state . In order to assure the effective transfer of the applied energy , a stiff layer of 1 to 2 m in thickness usually done to cover the ground surface . Pounders can be square or circular in shape and made of steel or concrete . Their weights normally range from 5 to 25 tons and drop heights of up to 25 m have been used . Heavier weights and larger drop
weights are used for compaction of deeper soil deposits but are not very common . The imposed energy is dissipated through the ground and rapid excessive pore water pressure is developed and immediate loss of shear strength occurs [7].

Stone columns and dynamic compaction are techniques used to improve the geotechnical properties of soft saturated soil . These techniques proved efficiency in the following points :

1- Improving bearing capacity .
2- Reducing total and differential settlement .
3- Improving slope stability .
4- Reducing the liquefaction potential in the subsoil.
5- Accelerating the stage of primary consolidation.

The choice of any technique depend upon several factors related to soil type and its initial properties , material and equipment available , structure type , time available and economy . For the above reasons as well as soft clays are spread over large areas in Iraq specially in its southern Mesopotamian plain and for the necessity of using such sites for future projects ; an adequate solution might introduce to improve these sites .

This paper has presented the laboratory measurements of the properties of soft clay and its settlements at different applied stresses to improve such clays by means of stone columns and dynamic compaction methods by performing several laboratory models .

Experimental Work

Soil Used

A brown clayey soil with natural water content of 2.1% was brought from a site east of Baghdad . Several trial tests have been carried out to prepare soft clay with a water content of 27% from the natural one, as discussed later . Standard tests were performed to determine the physical and chemical properties of the soil (Table 1). Grain size distribution of the soil used revealed 3.3% sand , 31.7% silt and 65% clay and the soil is classified as CL according to ASTM [8].

Crushed Stone Used

The crushed stone used was limestone with size range of 2-8 mm in diameter (Fig. 2) . This range was chosen according to a recommendation suggested by Al-Shaikhly, 2000 [9] who found that the optimum results of improvement are obtained when the ratio of average diameter of crushed stone to stone column diameter is in the range between 0.11-0.17 . Some physical properties of the crushed stone are given in table 2 .

Equipments Used

A special loading frame was used to apply vertical static load to the soil molded in a steel container (Fig. 3) . The steel container of 4 mm in thickness and its internal dimensions of 600 mm in diameter and 500 mm height provided with a movable base. The container was sufficiently rigid and exhibited no lateral deformations during the tests . Circular steel plate of 10 mm in thickness and 110 mm in diameter was used as a foundation in all tests. Hollow plastic pipes with diameter of 30 mm were used in the construction of stone columns . Drop weights of 2 , 3 , and 5Kg were used in performing the dynamic compaction. A steel arm fixed in the wall was used to drop weights.

Control Tests

Prior to the stage of preparation of the bed soil, trial tests were performed to control the efficiency of the applied method . These control tests were carried out to check two main points of vital importance regarding the preparation of homogenous soft bed of soil. First is determining the variation in shear strength at different liquidity indices. The shear strength of soil decreases with increasing value of the liquidity index, giving a value of 9 kPa for 0.5 liquidity index as shown in figure 4 . The second point is determining the variation in shear strength of the soil versus time after mixing .These tests provide the time required for remolded soil to regain strength after rest period following the mixing process (Fig.5). To accomplish this point, eight individual samples were prepared individually and placed in three layers inside CBR molds. Each was tamped gently with special hammer to extract any entrapped air. The samples were then covered with polythen sheet and left for a period of eight days.. Each day, the undrained shear strength was measured by vane shear device.

The Bed of Soil

The following steps were used in preparing the bed of soil in the steel container:

1- The soil used was first crushed with a hammer to small size and then left for 24 hrs for air–drying, further crushing was carried out using the crushing machine.

2- The air –dried soil was subdivided into groups, each group contains 25 kg of air-dried soil mass.

3- Each group was mixed gradually and thoroughly with sufficient amount of water corresponding approximately to the water content of 27%. This water content provides a shear strength value of 9 kN/m^2 as stated in previous section and figure 4. The mixing operation conducted using a large machine (120 liters) manufactured for this purpose .

4- After thorough mixing , the soft soil lumps were spread into the container in layers of 50 mm thickness, and tamped with a special tamping tool. The process was continued until the required bed thickness of 350 mm was achieved.

Construction of the Stone Column

Three arrangements of stone columns were constructed. The first is single stone column then group stone columns (2 and 3). The length and diameter of stone columns used in all tests were respectively 180 and 30 mm with L_s / D_s ratio 6 , while the area replacement ratios (A_r) were 0.074 , 0.148 and 0.225 respectively . Details of each are given below. At the end of curing period, the following steps were used in construction of stone columns:-

1- The top surface of the bed of the soil was leveled.

2- A number of holes were made, in the first test the hole was made at the center of the container and in the second test at longitudinal direction, whereas in the third test at trianglular shape . The space between stone columns was 2D center to center. The hole was made by pushing a hollow plastic (PVC) pipe, with external diameter of 30mm, into the bed of soil. This process was carried out gradually in several lifts to ensure complete hole depth .

3- The soil was removed from tube and samples of soil at different depths were taken for water content measurement.

4- The crushed stone was poured into the hole as layers and each layer was completed gently by tamping rod until a complete full depth was achieved.

5- Finally, each test model was subjected centrally to different loading, and settlements have been recorded by dial gauges simultaneously at each load.

Construction of Dynamic Compaction

Nine dynamic compaction tests were carried out . Details of this construction are given below :

1- Dropping different weights of 2,3 and 5kg from different heights 500,750 and 1000mm for each load . In the first test , a 2 kg weight was dropped at different heights 500,750 and 1000mm. In the second and third tests 3 and 5 kg weight were dropped respectively with the same heights. For all tests, the number of drops was 50 blows This stage is shown in figure 6 .

2-The top surface of the bed of the soil was leveled and left for 2 days as a curing period .

3- Finally, each test model was subjected centrally to different loading, and settlements have been recorded by dial gauges simultaneously at each load.

Results and Discussion

For soil treated by dynamic compaction (drop weights 2 and 3 kg) with drop heights of 500,750 and 1000mm (Figs. 7 and 8) , the stress-settlement behavior for untreated and treated soils are the same. The settlement is less for treated soil especially with larger drop heights reflecting two stages (I and II) in their behaviors, with slow and quick increase for the two stages respectively .The percentage of the settlement ratio over the total settlement associated with the two stages are respectively 10.34 – 89.66 %. The corresponding values of the percentage ratio of the settlement per 1 kN/ m^2 are 0.858 – 2.72 % for the two stages. Thus, no considerable improvements have been indicated . But, in case of using 5kg drop weight (Fig.9), the treated soil shows larger reduction in settlement than soil treated with 2 and 3 kg drop weight and untreated soil reflecting higher reduction with larger drop height .In addition, the curve behavior shows three stages (I , II and III) in which the settlement increases slowly , medium and quickly for the three segments respectively . The percentage ratios of the settlement over the total settlement for the three stages (and for 500,750 and 1000mm drop heights) are 9.48 - 7.14 , 18 - 17.86 and 72.4 – 75 % respectively . The corresponding values of the percentage ratio of the settlement per 1kN/ m^2 for the three stages and drop heights are 0.79 – 0.59 , 1.8 – 1.9 , 3.14 – 3.2 % respectively .Comparing figures 10 , 11 and 12 , it is obvious that there is no considerable change in the stress – settlement behavior except the reduction in the settlement for drop weight 5kg and drop height of 1000mm especially at stress 22kN/ m^2 . Low improvement may be due to the un removal of the topsoil bed which is damaged by the effect of weight dropping. Besides , it is well noted that the higher compaction energy level results in slightly higher reduction in settlements.

By considering stress-settlement for soil treated using different numbers of stone columns (1 ,2 and 3 columns) (Fig.13) , three stages are identified with settlement increases slowly , quickly and slowly again at the different stages (I , II and III). The percentage ratios of the settlement over the total settlement for the three stages are respectively 4.65 – 9.3 , 68.5 - 74.46 and 19.19 – 23.26 % . The corresponding values of the percentage ratio of the settlement per 1kN/ m^2 for the three stages are therefore 0.27 – 0.75 , 2.85 – 4 , 2.13 – 2.46 % respectively. Referring to figures 14, 15 and 16, it is clearly shown that the higher reduction in settlement is provided by using 3 stone columns compared with other soils treated with the other used stone columns or that treated by dynamic compaction. Besides, the settlement increases quickly in stage III for soil treated by dynamic compaction (drop weight 5kg), whereas it increases in stage II for soil treated by stone columns.

In view of the whole deformation process , the settlement curves are non linear but the curves are close linear with each individual stage. They are consistent with the following regression equations for the curves between settlement (S) and applied stress (σ).

For the entire curve :

$$S = a\sigma^2 + b\sigma + c \qquad ...(1)$$

For an individual stage :

$$S = b\sigma + c \qquad ....(2)$$

where a , b , and c = regression coefficients.

The settlements in untreated and treated soils have been determined at stresses 10 , 20 and 30 kN/ m^2 from the entire curves using regression equation 1 . Then the ratio of improvement in settlements percentage have been determined from the cumulative results of the settlements for each model test and at each stress. The percentage of improvement ratio in settlements (SIR%) have been calculated using the following equation;

$$SIR\ \% = (S_{unt} - S_t) / S_{unt} \quad ....(3)$$

Where S_{unt} , S_t settlements in untreated and treated soils .

Tables 3 and 4 summarize the cumulative improvement ratio in settlements using dynamic compaction and stone columns methods respectively. For dynamic compaction, the minimum cumulative improvement ratio in settlement is obtained using 2kg drop weight and 1000mm drop height at stress 10 kN/ m^2 which is about 8%, whereas the maximum ratio is obtained using 5kg drop weight and 1000mm drop height at load 30 kN/ m^2 which is about 69 %. For stone column, the minimum ratio in settlement is obtained by using 1 stone column at stress 10 kN/ m^2 which is about 16%, while the maximum cumulative improvement ratio is obtained using 3 stone columns at stress 30 kN/ m^2 which is about 178 %.

Conclusions

From the above model tests the following points may be drawn:

1-For stone columns tests:

a-The soil settlement can be classified into three stages where the settlements increases slowly, quicklyand slowly (again) with different stages (I, II and III) respectively.

b-Minimum cumulative improvement ratio in settlement is obtained by using 1 stone column at stress 10 kN/m^2 which is about 16%, while the maximum is obtained using 3 stone columns at stress 30 kN/m^2 which is about 178%.

2-For dynamic compaction:

a-The soil settlement can be classified into two stages (except for weight drop 5kg) where the settlement increases slowly and quickly . Whereas, for model tests using 5 kg drop weight (at different drop heights), three stages have been identified with slow , medium and quick settlement increase with different stages I, II and III respectively.

b-Minimum cumulative improvement ratio in settlement is obtained using 2kg drop weight and 1000mm drop height at stress 10 kN/ m^2 which is about 8%, whereas, the maximum cumulative ratio is obtained using 5kg drop weight and 1000mm drop height at stress 30kN/m^2 which is about 69%. c-No considerable effect of drop height on settlement is noticed for drop weight of 2 and 3 kg except , to some extent , for 5 kg.

3- In view of the whole deformation process, the settlement curves are non linear, but the curves are close linear lines with each individual stage.

4-Less improvement is noticed for soil treated by dynamic compaction compaed with stone columns.

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Table (1) Physical and chemical properties of soil used.

No.	Index property	Index value
1	Natural water content (w_c)%	2.1
2	Liquid limit (LL)%	35.0
3	Plastic limit (PL)%	19.0
4	Shrinkage limit (SL)%	14.0
5	Plasticity index (PI)%	16.0
6	Activity (At)	0.45
7	Specific gravity (G_s)	2.69
8	Gravel (larger than 2mm)%	0
9	Sand (0.06 to 2mm)%	3.3
10	Silt (0.06- 0.002mm) %	31.7
11	Clay (less than 0.002mm)%	65
12	Total dissolved salt (TDS)%	2.92
13	Gypsum content (G.C) %	4.7
14	SO_3 content %	1.36
15	Organic material (O.M)%	0.44
16	pH value	8.9
17	Unified Classification	CL

Table (2) Physical properties of crushed stone used.

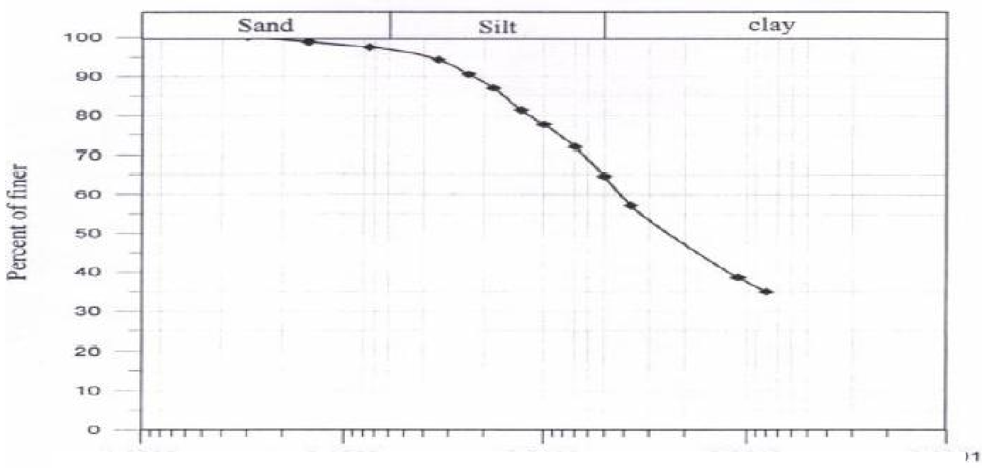
No.	Index property	Index value
1	Max. dry unit weight (kN/m^3)	15.7
2	Min. dry unit weight (kN/m^3)	13.5
3	D_{10} (mm)	4.66
4	D_{30}(mm)	5.0
5	D_{60}(mm)	5.12
6	Specific gravity (G_s)	2.64
7	Coefficient of uniformity(C_u)	1.02
8	Coefficient of curvature (C_c)	1.05
9	Relative density (D_r)%	71

Table (3) . Cumulative Improvement ratio in settlement using dynamic compaction.

Applied stress (kN/m ^{2})	10			20			30		
Weight (kg)	Improvement Ratio %			Improvement Ratio %			Improvement Ratio %		
	500mm	750mm	1000mm	500mm	750mm	1000mm	500mm	750mm	1000 mm
2	7.70	10.73	13.42	12.86	17.87	22.04	16.12	22.32	27.08
3	15.24	16.64	19.10	25.21	27.61	31.56	31.24	34.34	39.06
5	28.69	30.09	34.20	49.35	49.50	56.35	59.20	60.93	69.46

Table (4) Cumulative Improvement ratio in settlement using stone columns .

Applied stress (kN/m ^{2})	10	20	30
	Improvement Ratio %	Improvement Ratio %	Improvement Ratio %
1 stone column	16.41	29.62	40.45
2 stone columns	74.23	110.74	138.17
3 stone columns	78.22	135.92	178.32



Figure(1) Grain size distribution of soil used .

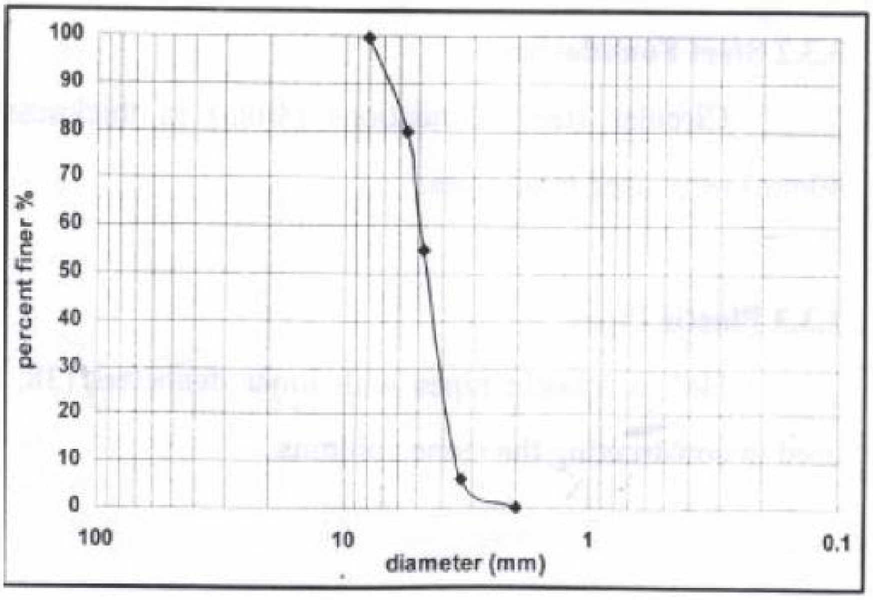


Figure (2) Grain size distribution of crushed stone used.

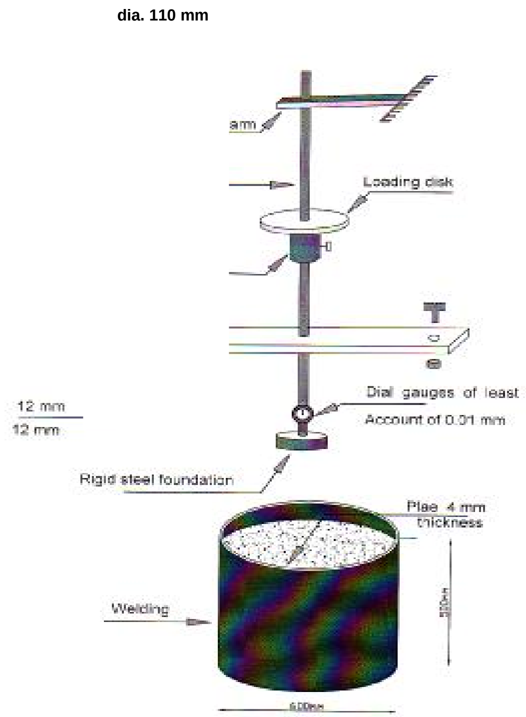


Figure (3) Steel container and loading assembly used in the tests.

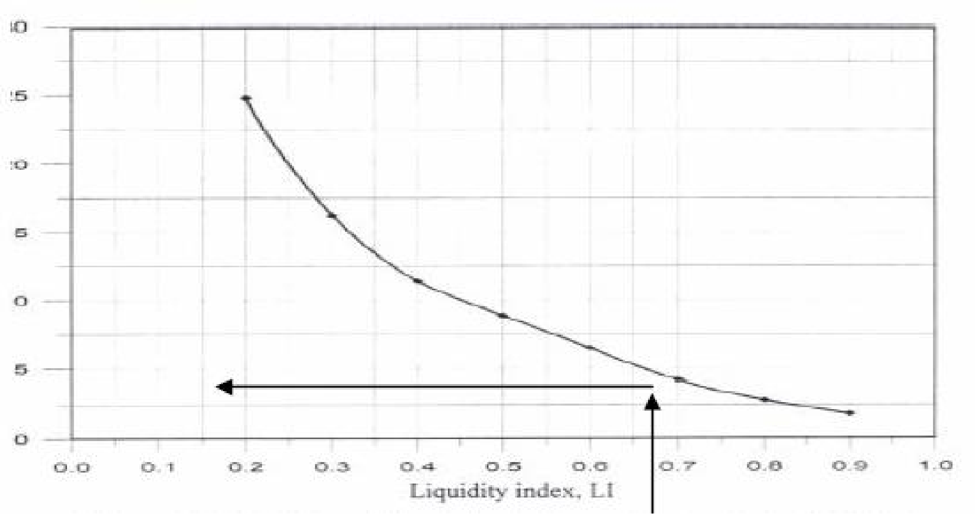


Figure (4) . Variation of undrained shear strength versus liquidity index forremolded clay after 48 hrs.

9kPa

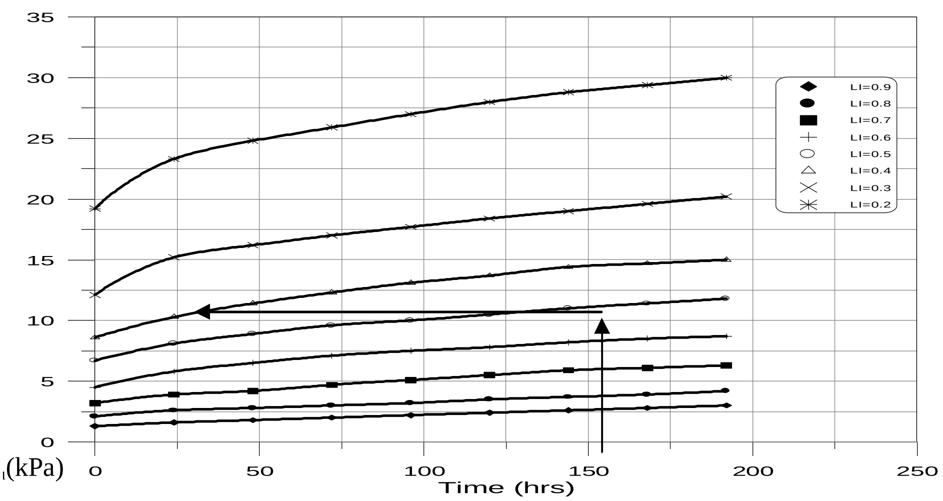


Figure (5) Variation in untrained shear strength versus time for remolded clay.

weight

Figure (6) Construction of dynamic compaction.

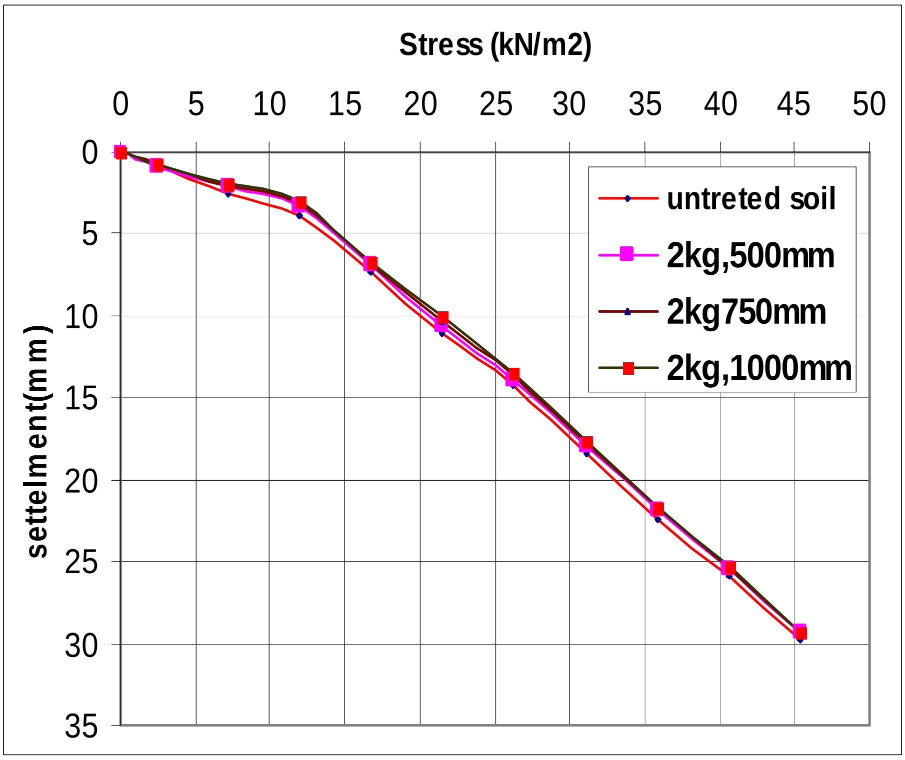


Figure (7) Stress-settlement curve for untreated and treated soil using dynamic compaction(weight 2kg, heights of drop 500,750,1000mm).

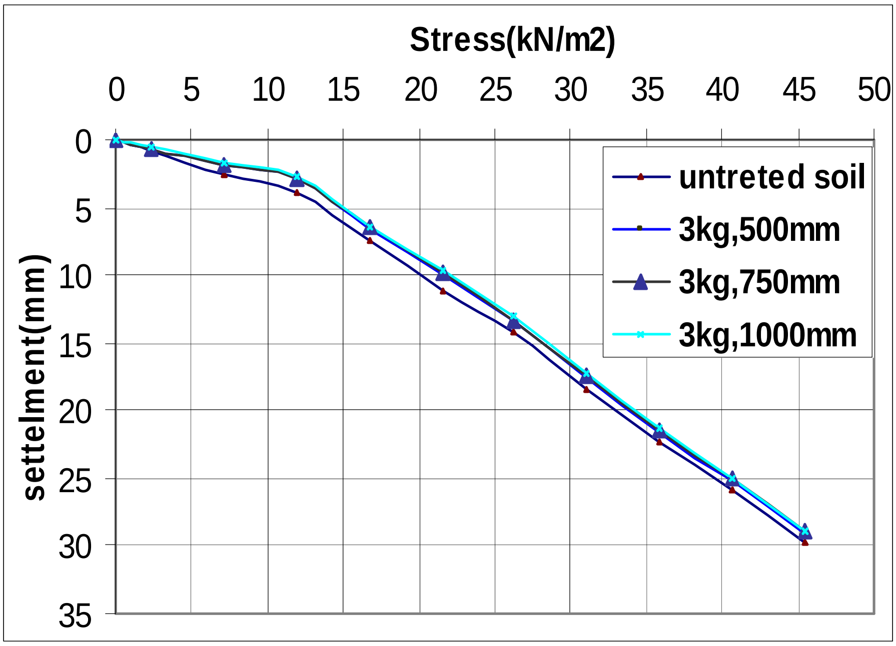


Figure (8) Stress-settlement curve for untreated and treated soils using dynamic compaction (weight 3kg , heights of drop 500,750,1000mm).

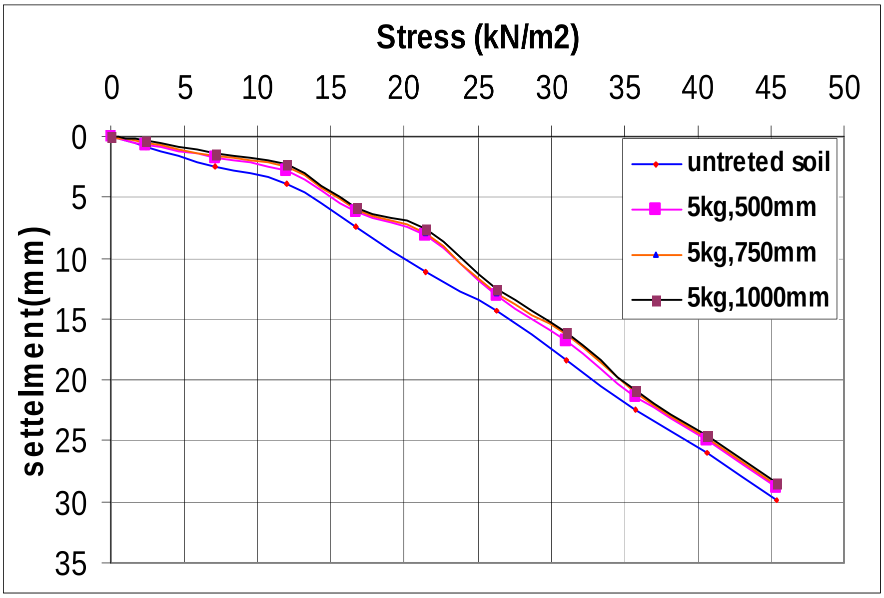


Figure (9) Stress-settlement curve for untreated and treated soils using dynamic compaction (weight 5kg heights of drop 500,750,1000mm).

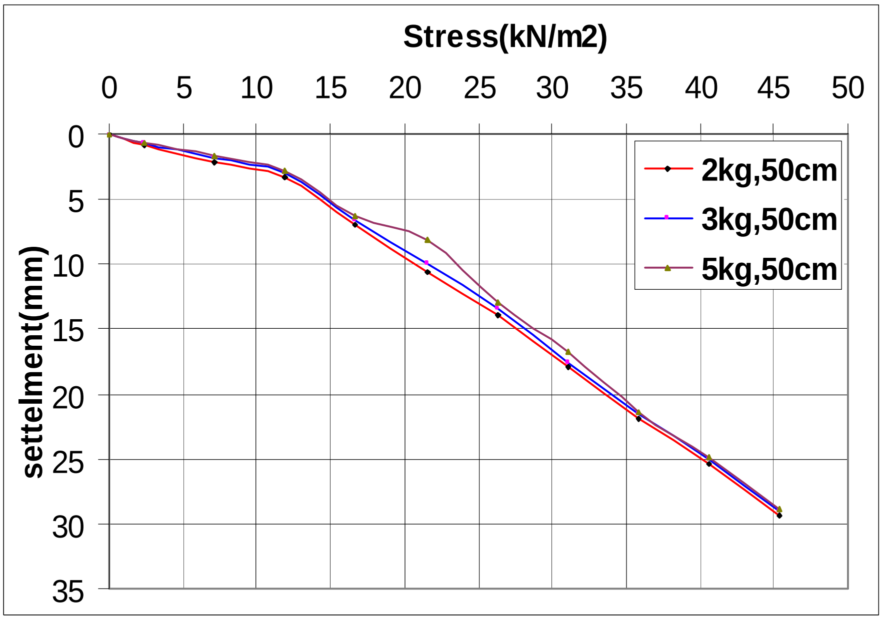


Figure (10) Stress-settlement curve for untreated and treated soils using dynamic compaction (weight2,3, 5kg heights of drop 500mm).

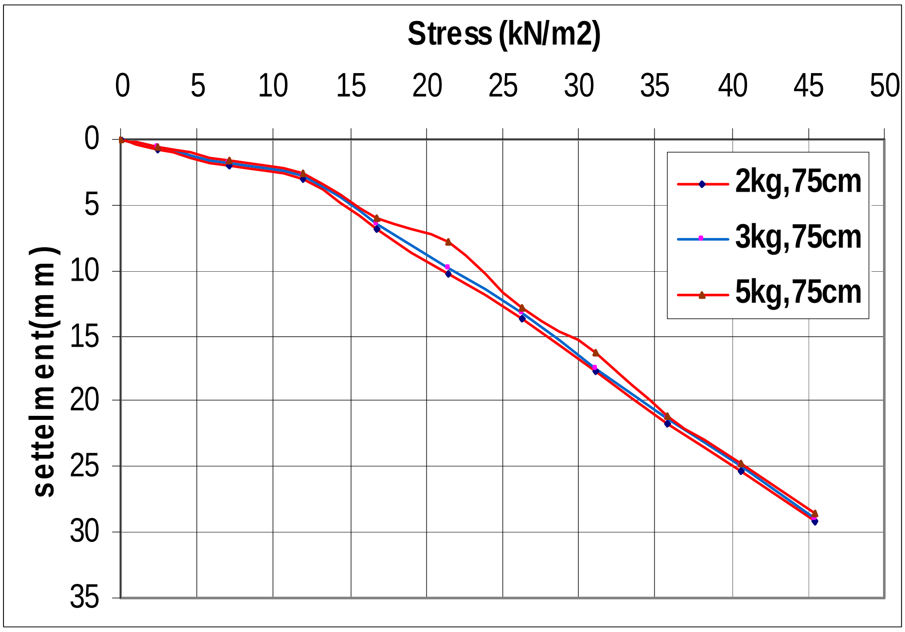


Figure (11) Stress-settlement curve for untreated and treated soils using dynamic compaction (weights 2,3, 5kg heights of drop 750mm).

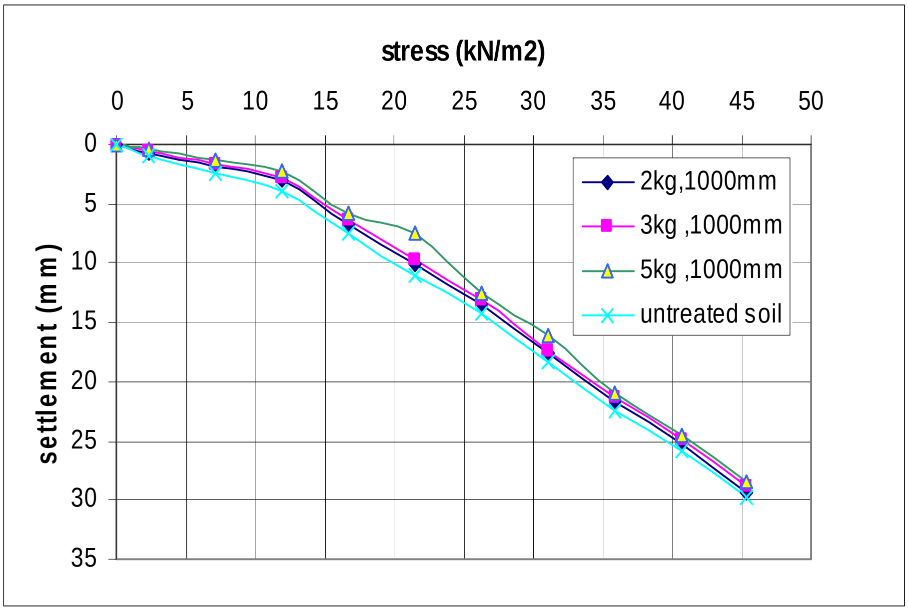


Figure (12) . Stress-settlement curve for untreated and treated soils using dynamic compaction (weights 2,3, 5kg heights of drop 10000mm).

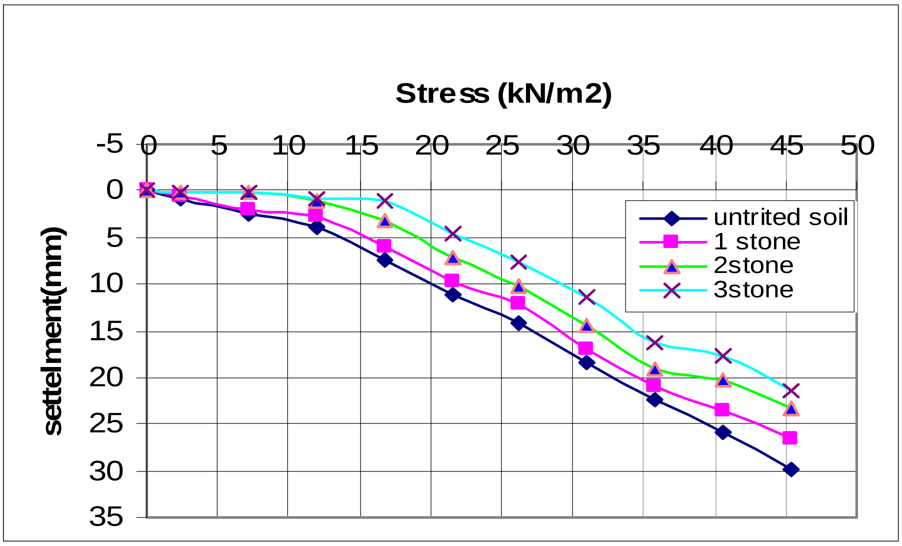


Figure (13) Stress-settlement curve for untreated and treated soils using stone columns (1 ,2 and 3 stone columns).

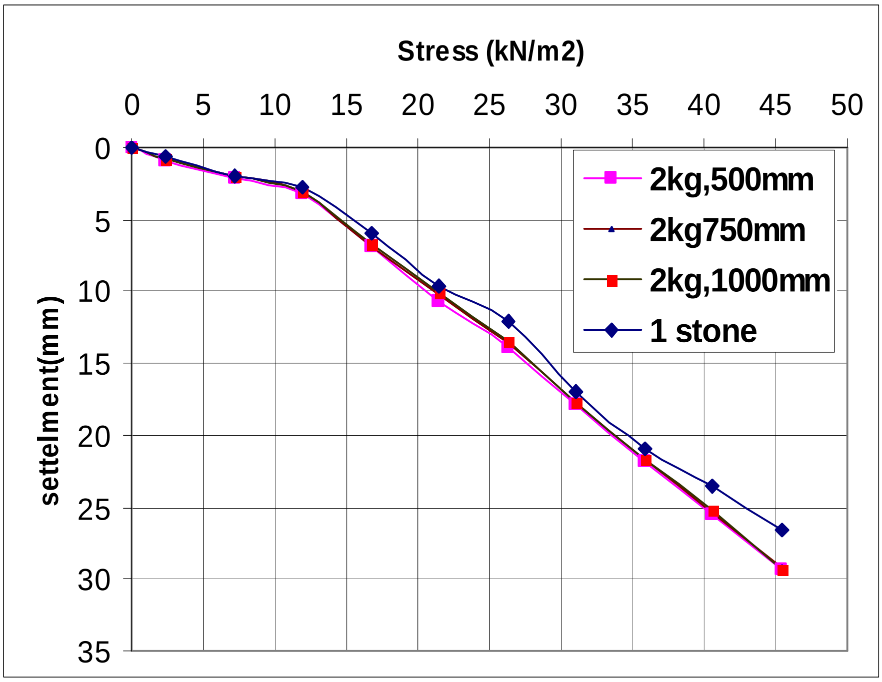


Figure (14) Stress - settlement curve for treated soil using 1stone column and dynamic compaction(weight 2kg , heights of drop 500,750,1000mm).

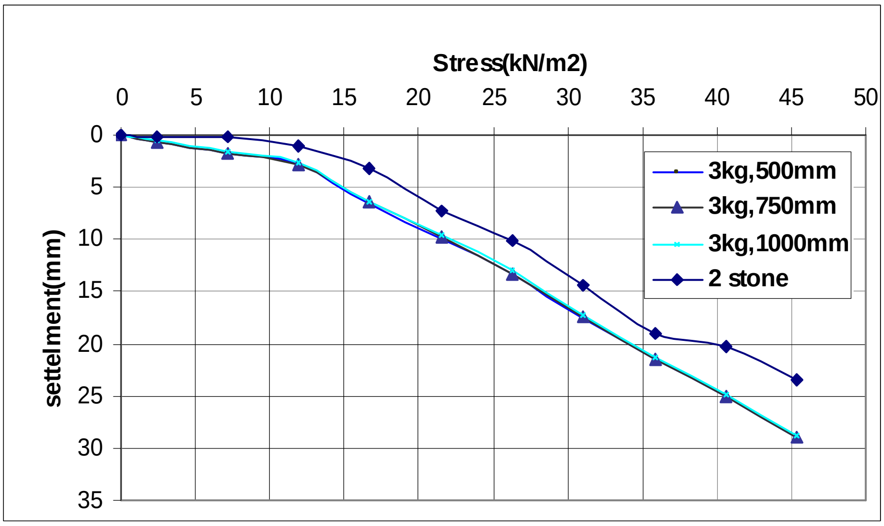


Figure (15) Stress-settlement curve for treated soil using 2 stone columns and dynamic compaction (weight 3kg , heights of drop 500,750,1000mm).

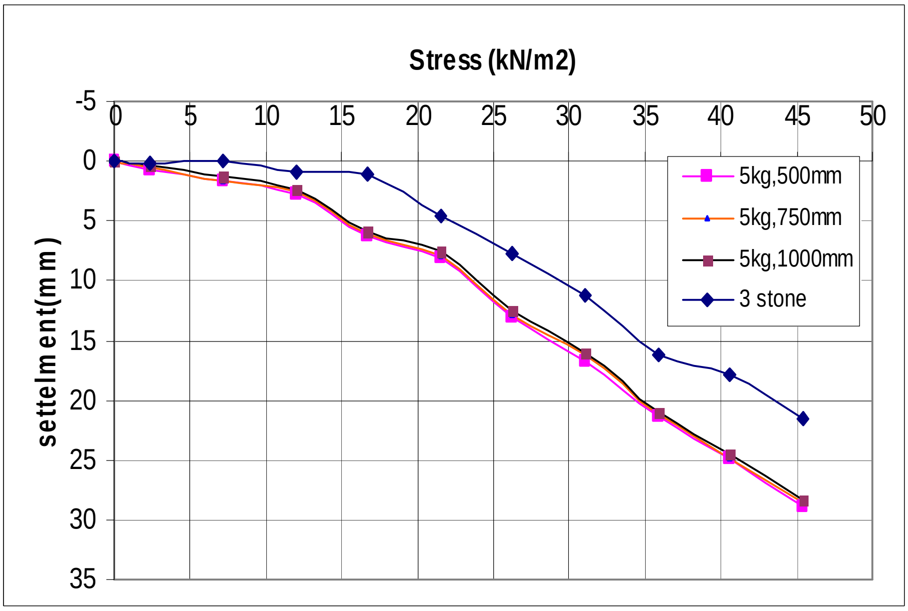


Figure (16) Stress-settlement curve for treated soil using 3 stone columns and dynamic compaction (weight 5kg , heights of drop 500,750,1000mm).