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Enhancing stone column performance in peaty soil foundations through additive-induced stress reduction

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Abstract

This paper analyses the efficacy of dynamic compaction and the stone column method in enhancing the settlement of the peaty soil. Dynamic compaction was experimented on with the drop weight of 4, 6, and 8 kg and the drop height of 400, 600, and 800 mm, as well as with stone columns of one, two, and three units. The findings indicate that dynamic compaction significantly lowers the settlement compared to an untreated soil, and the greatest enhancement was realized at a weight of 8 kg and a drop height of 800 mm. The growth in settlement is in a 3-stage trend where in Stage I, settlement growth is slow with a reduction of 9.48% to 7.14%, in Stage II, growth is rapid with a reduction of 18% to 17.86%, and in Stage III, growth is rapid with a reduction of 72.41% to 75%. Stone column insertion provides even higher reduction in settlement, especially where the application of three columns has been used, and the extent of improvement is highest. These results demonstrate the effectiveness of each method to increase soil stability, and stone columns yield better outcomes, particularly in areas that are defined by soft, peaty soils, like those experienced in Iraq.

Keywords: Dynamic compaction, Settlement reduction, Soil stabilization, Drop weight, Drop height, Compaction efficiency, Geotechnical engineering

1. Introduction

The nature of peat and other organic soils makes them very difficult to deal with in terms of civil engineering construction because of their nature, i.e., extremely low shear strength, excessive compressibility, and a significant percentage of organic matter [1], [2]. The properties often cause significant settlement and stability problems, making them some of the most challenging ground conditions for foundations [3], [4]. Traditional foundation solutions on these problematic soils are usually costly and require many ground improvement methods [5].

Stone columns are one of the ground improvement techniques that have been commonly adopted and include low costs in order to increase the bearing capacity of the soft and compressible soils as well as to reduce settlement [6], [7]. Stone columns are effective in that they provide enhanced drainage routes, enhance the shear strength of the composite soil, and lower the overall and relative settlements [4], [7]. As a result, they reduce the bending moment, footing settlement, and vertical soil stresses, which contribute to a general enhancement of the foundation system performance [5].

Although stone columns have been proven to have a beneficial effect in numerous soft soils, their use in highly organic and peaty soils may be complicated due to the special fibrous nature and high compressibility of the peat [2]. In an attempt to maximize the performance of stone columns under such adverse conditions, the addition of additives to the column material or to the soil in the immediate vicinity of the column has received growing interest. These additives may alter the engineering properties of the stone column itself, or the connection between the stone column and the peaty soil, which may result in improved stress-transfer mechanisms and a decrease in the stress carried by the surrounding sensitive peat. This paper seeks to examine the effectiveness of using additives in enhancing the performance of stone columns with particular concentration on their capability of bringing about stress reduction in peaty soil foundations [8].

Peaty soils are found all over the world, but are notably prevalent in places like the southern Mesopotamian plain of Iraq. These soils present a big challenge to construction due to their low bearing strength inherent to them, high water content, and high compressibility. With the increase in urbanization, infrastructures are being located on soft peaty soils [9]. The scarcity of appropriate land around the cities and towns means that such areas must be used, and in most cases, they need to be improved significantly before building can take place [10]. Their low shear strength and high moisture content, which are normally between 60 and 90%, and compressibility are due to their high organic content and hence unsuitable for the normal road, canal, harbor, and railway foundations [11].

Various techniques of soil improvement have been reported in different parts of the world, such as dewatering, compaction, preloading (with or without vertical drains), grouting, deep mixing, stone columns, deep densification, and reinforcing agents. Stone columns and dynamic compaction are also among them and have always proved to be effective in improving the geotechnical behavior of peat and other weak soils. Such techniques will deal with the typical issues like higher bearing capacity, lessening of settlement, increment in slope stability, lessening liquefaction, and speedy primary consolidation [12]. Dynamic compaction involves the use of high-energy impacts that are provided through the use of heavy weights dropped on the site. This kinetic energy is lost to the ground that leads to a rapid increase in pore-water pressure, and a consequent decrease in shear strength [13]. Conversely, stone columns are implemented through cutting and placing hard vertical material made of hard stone. This process replaces the soil around it, leaving behind vertical columns that are strengthened by a stronger material. This makes the columns reduce settlement potential, increase stability in general by lowering the void ratios, and promote rapid pore-pressure dissipation in the surrounding soil matrix [13].

Peat is a very organic soil that is made up of decomposing vegetation in the presence of water. Its composition and structure are very distinct and unlike inorganic soils, which present serious challenges to geotechnical engineers [5]. Major factors that have made these challenges include: high compressibility and low shear strength. Peaty soils are extremely compressible and have very low shear strength [1], [2]. This results in huge and frequently long-term settlements, with major secondary consolidation, under applied loads [5]. The peat-based structures are therefore liable to overturning and over-differentiating settlements, which may threaten their stability and serviceability [6].

When the percentage of organic matter is high and the structure is fibrous, the mechanical behavior of peat differs greatly from that of mineral soils [5], [6]. Modification of strength behavior can be done by the fibers, and organic matter can undergo decomposition, resulting in continuous changes in volume [6]. It is directly associated with its low shear strength and high compressibility; peaty soil has a very low bearing capacity and is not suitable to support conventional foundations without ground improvement [1]. Peat has been found to exhibit non-linear mechanical behavior and a time-dependent loading response, with long-term predictions of the settlement process being complicated [3]. Under these daunting conditions, the development of civil engineering facilities on peaty subgrades requires the use of powerful ground improvement methods to stabilize the structures and minimize deformations [3].

Granular piles or the stone column technique is an established and commonly used method of ground improvement of soft cohesive soils and loose silty sands [9]. It started in the 1830s in France, but began to be widely applied in Europe since the 1950s [4]. The main aim of the stone columns installation is to enhance the engineering characteristics of weak strata; stone columns are stiffer and stronger than the surrounding soft soil, and thus a considerable part of the applied load is transferred to the whole of the bearing capacity of the composite ground [3], [4]. Stone columns can decrease the total and differential settlements by increasing the stiffness of the soil mass and offering better drainage [9]. They quickly lose the excessive pore water pressure that occurs when loads are applied [9].

Granular columns are highly permeable, which offers radial drainage channels, which increases the rate of consolidation of the surrounding fine-grained soil significantly [4]. Liquefaction potential may also be reduced in loose sandy soils by the use of stone columns [4]. Stone columns are built to have increased shear stresses and concentrated vertical stresses of the stiffer column material, and hence lower stresses are exerted on the weaker soil around it [5], [11]. The load on the footing is redistributed, and a large part of it is carried by the stone columns, which results in an observable ratio of stress concentration. The stone columns are usually built by hollowing or vibrating a hole in the loose ground and filling it with compacted crushed stone or gravel [12]. This technique has benefits over other approaches, like replacement approaches, since it is cost-effective, uses regular equipment, and is effective in expansive regions of soil stabilization [12], [13].

Although the use of stone columns is associated with significant advantages, their operation under even the most demanding conditions, like the use of peaty soil, which is highly organic, can be enhanced further. The idea of adding additives to the ground improvement schemes is to change the properties of the soil or column to give the ground engineering performance. As an example, in certain model tests, the cement has been incorporated in the backfill material of the stone columns to improve the qualities [5], [14].

Some of these additives, like cement or lime, react with the soil constituents to create cementing agents, which enhance the shear strength and stiffness of the treated soil or column material. Additives may be used to decrease compressibility of soft soils by changing their fabric or forming more powerful bonds between the particles [14]. There are additives that can be used to affect the permeability of the composite ground by improving drainage or by decreasing it where necessary. Here, additives may be used to increase the stiffness and the load transfer ability of the column, so that the redistribution of stresses is more effectively achieved. The stiffening and strengthening of the columns of stones can cause a higher ratio of load to be put upon and borne by the columns, and thus the weight that is transferred on the very compressible and weak peaty soil matrix can be lessened. This stress reduction induced by additives is essential in reducing settlement and in making sure that the stability of the structures on peaty foundations is achieved.

2. Research gap and study aim

The previous studies have demonstrated the usefulness of stone columns in the different conditions of soft soils and the difficulties of peaty soils in detail. Although the application of additives in overall soil stabilization is familiar, there is a particular necessity to explore the synergistic interactions between stone column technology and specific additives deeply to improve their performance, particularly in peaty soil foundations, with the major focus on achieving the optimal levels of stress reduction. It is important to have a thorough insight into the effects of various additives on the mechanical behavior of stone columns and the interaction between the columns and peat to come up with more reliable and sustainable solutions to foundation problems.

Thus, the purpose of the study is to examine and measure the performance of stress reduction by additives in improving the performance of stone columns installed in peaty soil foundations. In particular, it aims at determining the best types of additives. The peaty soils, especially in the southern Mesopotamian plain in Iraq, are of particular engineering challenges. The current paper aims at considering the techniques that can enhance the geotechnical performance of such soils, and the approaches to stone columns and dynamic compaction are considered as methods to enhance the bearing capacity and reduce settlement. The best method of improving the behavior of peat in this area will be discovered through experiments conducted in laboratories.

3. Equipment used

A purpose-made loading frame was made to exert vertical static loads on soil samples in a steel cylinder with a 600 mm diameter and 500 mm height. A circle of steel plate (diameter=110mm) was used as the specimen base, and stone columns were built using hollow plastic pipes that had a diameter of 30 mm. Simulation of dynamic compaction was done on drop weights of 4 kg, 6 kg, and 8 kg, and these were dropped on the soil samples in sequence.

In the case of peaty soils, a classification system that is based on their consistency, organic content, and physical properties would have different characteristics as compared to the clays, due to the nature of peat. The following is a classification scheme that I will suggest be applied to peaty soils. As mentioned earlier, peaty soil deposits are highly concentrated in different parts of the world, especially the wetlands and coastal areas.

Peaty soils occur in a wide range of geographic locations all over the world, such as the Nordic nations (except Denmark), Canada, and parts of Northern Europe. These regions are famed for large deposits of organic-rich peaty soils, which are usually deposited in wetlands and coastal areas. The occurrence of thick deposits of over 100 m is common in areas with a lot of precipitation and poor drainage, and results in the accretion of organic matter. The soils can be described as usually having a high organic content, a low shear strength, and high compressibility, and are often called organic soils in many geotechnical works. Other regions of Europe, including the Netherlands, some parts of the UK, India, and Japan, also have peaty soils, which do not always behave in the same way depending on the climatic conditions and the particular processes of soil formation.

The geography of Iraq has large deposits of peat, especially those found in the Mesopotamian plain to the south. Peat is highly represented in the marshlands and the wetlands. These historically rich ecological systems possess large amounts of peaty soils that are difficult to construct because of low strength, high compressibility, and high organic content. The Tigris and Euphrates rivers, which have a history of forming vast wetland lands, have significantly impacted the allocation of peaty soils in Iraq. With time, the changes in the path of the river Shatt al Arabs and its surroundings have led to the deposition of soils of an organic nature in the marshlands that are presently covering large portions of peaty soils.

This area may be divided into two major types of peaty soils:

1. Young peaty soils: These soils are usually present on the existing riverbanks (e.g., Abu-Flus and Fao regions) and are usually rich in organic matter and loosely consolidated.

2. Aged peaty soils: These soils are found both along the former river channels (e.g., Umqasr, Khor Al -Zubair) and are older than the others and have undergone some consolidation.

The southern Mesopotamian plain is geomorphologically split into a number of distinct units, as shown in Figure 1 (IPA, 1977). These units are of different soil formations, such as peaty soils, and they include:

1. Levees and silted river levees
2. Estuary river levees
3. Silted tidal flats
4. Tidal flats
5. Horses and marshes
6. Alluvial fans
7. Sand dunes (Aeolian Landform Unit).

This unit stretches along the rivers Euphrates and Tigris. These levees are slightly raised above the plain and slope unevenly towards the marshes and the lowlands around it. The soil in this region is mainly a combination of clay and peaty soils, which have large amounts of organic material; hence, they are very compressible and cannot be used directly without significant treatment or improvement of the soil.

The Mesopotamian Marshlands are depicted as the cartographic area of southern Iraq, which historically had been composed of rich organic, peaty soils, mainly covering the floodplains of the rivers Euphrates and Tigris. The Central Marshes, Hammar Marshes, and Hawizeh Marshes are of special significance in this geomorphic context because they represent the locations that have been subject to the accumulation of deep peaty sediments for millennia, caused by continually high-water tables, a lack of drainage routes, and rich vegetation cover. Such soils that are rich in organics are highly compressible, have low shear strength, and are prone to high settlement rates under the imposed loads, which makes these soils a nightmare to civil engineering activities unless proper soil improvement methods are used.

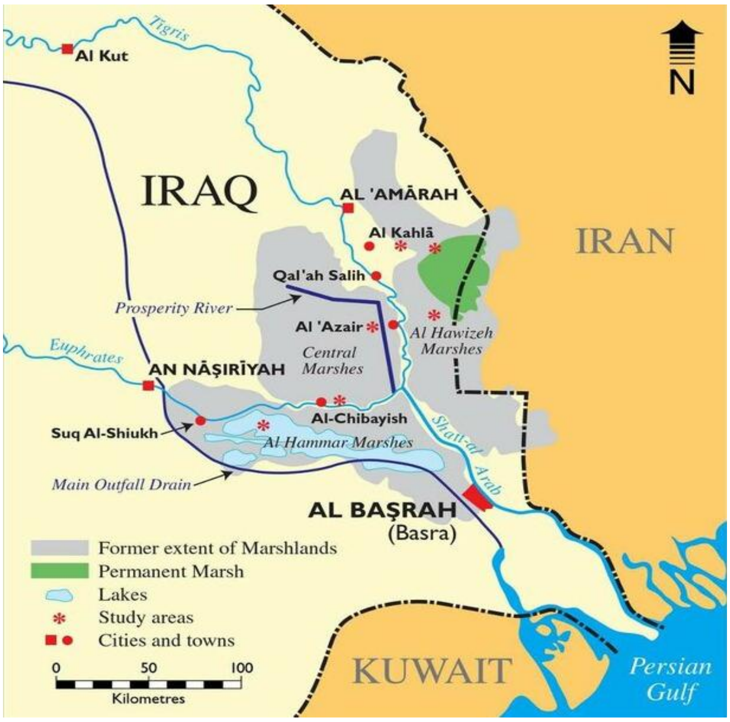

Figure 1. Map showing the extent of the Mesopotamian Marshlands and wetland areas in Southern Iraq

The map also sheds some light on the historical extent of these marshlands, highlighting the importance that they play in shaping the topography of the region and the dominant soil properties. Particularly of interest is the region between Basrah, Fao, and Umqasr, which contains a dual of young and old peaty soils, which are distinguished according to their history of consolidation, an aspect that directly influences their mechanical behavior. The occurrence of these peaty soils in the marshland matrix in the southern part of Iraq creates a unique group of issues related to geotechnical engineering, especially in terms of designing and building infrastructure, such as building foundations, roadways, and canals. Engineered solutions such as stone columns and dynamic compaction are necessary to overcome these problems because they can reduce the compressibility of soils and increase the overall strength, and make the previously unstable subgrades viable to be developed. Marshlands indicate regions historically associated with high organic/peaty soils formed by prolonged waterlogging and vegetation accumulation [11]. This zone can be divided into two major types of peaty soils:

1. Young peaty soils: These soils are found on the existing river banks [14] and are characterized by a recent origin, fat organic matter, and low consolidation.
2. Aged peaty soils: These are soils found along the previous course of rivers [15], which are relatively old, have partially consolidated, but are still very compressible and low in shear strength.

Depending on the genesis of soils and the hydrological characteristics of the territory, the geomorphological units of the southern Mesopotamian plain may be divided into a few distinct types. Such units include regions that are mainly covered with peaty and other organic soils. The estuary river levees occur in the form of a thin belt along the Shatt Al-Arab. The lands bordering the river are seasonally flooded slightly above the tidal plain and Hor. Tidal forces modify the estuary levees, and the water flow is bi-diurnal, developing clayey to fine silty soils. These are soils that usually have a high content of organic matter and share properties characteristic of peaty soils, especially high-water retention and low shear strength.

Silted tidal flats soils are located in the space between the eastern embankments of Shatt Al-Arab and protect the land against flooding. The land has, over time, been changed into silted tidal flats as a result of sedimentation, which has been greatly influenced by the years of irrigation. The soils are fine-grained, stratified, and rich in organic content. They tend to be very salty and alkaline, and the level of groundwater differs depending on the location. These soils can be cultivated in areas with well-drained conditions and reclaimed environments, but in the current situation, they have poor engineering characteristics and cannot be used in constructions without remediation. The tidal flats extend north-westwards along the western side of Shatt Al-Arab between Basrah and Fao and are cut up by tidal creek patterns that are irregular in appearance and thus susceptible to yearly flooding. The soils are extremely salty and alkaline, and tend to be moist due to the capillary action of deep groundwater, which is salty and alkaline. Their form is not well-developed and is fragile, which does not allow agricultural practices without serious reclamation.

Horses and marshes are located between Basrah and Qurna on the western bank of Shatt Al-Arab; the marshes therein are flooded periodically. The very common soils are peaty, which are a result of continuous buildup of organic matter. The groundwater is not deep because of the high rate of evaporation, and seepage processes help in the salinization of some regions. The common soils are fine-textured and are usually cracked, and are highly saline and alkaline. Alluvial fans are the Al-Batin fan, which is enclosed by Hor Al-Hammar. It is located between the Euphrates fault and Hammar to the north, Khor Al -Zubair to the southeast, and Dibdibba plain to the southwest. The soils in this area are normally mineral-rich, and yet they have the features of organic-rich soils due to their closeness to marshlands.

Stone columns construction is a process that is carried out by excavation of vertical boreholes, which are usually 600-800 mm in diameter and excavated to a specified depth (Ls) of 5 8 mm. The boreholes are then sealed with gravel or crushed rock, hence creating stone columns that are bounded by the soils that are found in the area. Various techniques are used to build stone columns, such as the rammed method, wet-top feed, and dry-bottom feed, each with its own benefits and specific use.

The rammed granular piles installation is carried out through the use of traditional piling apparatus similar to that of bored cast-in-situ piles. This technique has been found to work in field tests, especially in regions that have peaty soils which are soft and compressible.

The wet-top feed method uses jetting water to push off soft material in the borehole and stabilize the probe. The procedure guarantees that the stone backfill is taken to the tip of the vibrator. It is very popular because of its high productivity and cost-efficiency. It has the capacity to fill bigger stone sizes (up to 130 mm in diameter), and can treat soils of high moisture content, such as in the wetland areas, which is frequently experienced. This method is especially skillful to reach tighter ground conditions and deeper grounds in wet conditions.

The dry-bottom feed method is only applied to sensitive areas in the environment, e.g., near fish-bearing streams. The use of vibrator probes, a hopper, and a supply tube is used to deposit the stone directly to the tip of the vibrator, avoiding the use of jetting water. This destroys the formation of spoils, making it appropriate in limited locations and where water consumption is limited. This technique is capable of treating peat soils that are 80 feet deep, even where there is a variation in the groundwater levels, and provides a cleaner and more efficient option than wet-top feed. Three main failure modes can occur when a single stone column is in the state of loading [15]:

1. Punching failure: This type of failure is common when the column bearing at the end is resting on a weak stratum and the length-to-diameter ratio is in the range of 2 to 3, which occurs before bulging failure.
2. Bulging failure: This happens in peat-saturated layers which are over solid material; bulging happens when the column length is more than 4-6 times its diameter.
3. General shear failure: This takes place when the column or trench width is greater than three times the loaded area width, and is based upon the short-column behavior of Prandtl on firm supports.

Dynamic compaction (DC), also known as heavy tamping or dynamic consolidation, is a common technique used to improve the properties of soils [16]. The method conveys high-energy strikes to the ground by dropping a heavy weight (pounder) down on the ground many times and at considerable heights. This transfers gravitational energy to the deeper strata and compresses particles of the soil, making it denser. This technique works well, especially in peat soils, which are very compressible and vulnerable to excessive settlement [17]. The pounder is lowered over and over in a known grid pattern during every pass. The compaction is to compact near-surface layers and reduce the disturbance of deeper horizons [18]. The achievable degree of compaction is affected by the following factors: soil type, drop height, and pounder mass.

Table 1. Physical and chemical properties of soil are used according to the ASTM (2002)

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 0.005 mm %	31.7
11	Clay (less than 0.002mm) %	65
12	Total dissolved salt (TDS) %	2.92
13	Gypsum content (Gs) %	4.7
14	SO_3 content %	1.36
15	Organic material (O.M) %	0.44
16	pH value	8.9
17	Soil symbols	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	Coeff. of uniformity (C_u)	1.02
8	Coeff. of curvature (C_c)	1.05
9	Relative density (D_r)%	71

4. Methodology

The study used an experimental program of laboratory scale to investigate the effectiveness of stone columns and dynamic compaction in mitigating peat-based foundations. The methodology includes a description of the special equipment, careful preparation of the peat bed, creation of different stone-column models, and carrying out dynamic compaction experiments.

The experimental setup aimed at stimulating the geotechnical environment, as was common in the testing of the soft soil foundations. Key instruments include:

- Steel container: The experiments were carried out in a strong steel container with inner dimensions of 600 mm in diameter and 500 mm in height. The container is made out of 4 mm-thick steel plates to maintain structural integrity during testing, and a mobile base is added to allow for experimental variability.
- Circular steel foundation: The loading footplate was made of a 10 mm thick plate of steel, which was 110mm in diameter. It plays a central role in conveying the vertical loads that simulate the condition of the field that stone columns are subjected to in peat-rich environments.

Plastic pipes: The hollow polyethylene pipes, with a 30 mm outer diameter, were used to create a clean and specific annular space in which the stone columns would be built. Their application makes it easier to delineate the column well and control backfilling of granular material, hence maintaining the integrity of the surrounding peat.

- Steel arm: A steel arm mounted on the wall was used to make dynamic compaction experiments. It allowed controlled lowering of the compaction weights at specific frequencies and heights, which mimics dynamic loading and thus allows evaluation of its effect on the geotechnical properties of peat.
- Steel weights: Dynamic compaction was done by attaching steel weights of 4 kg, 6 kg, and 8 kg to the steel arm. This mass variation can be simulated to have different loading conditions, and improvement in peat can be evaluated, which is known to have low shear strength and high compressibility.

Model preparation and testing: The experiment programme entailed the preparation of a peat bed, stone columns, and dynamic compaction. Bed of soil preparation: The bed preparation involved a series of controlled processes that would result in homogeneity and uniform initial conditions of all tests performed [19].

Figure 2. A steel arm is used in dynamic compaction to drop the weight

Control tests were conducted before determining the main bed to determine the best homogeneous peat conditions, with special attention to the variation of shear strength.

Variable shear strength at liquidity indexes: Preliminary experiments were conducted on the correlation between peat shear strength and liquidity index. Results, as shown in Figure 6 of the original article, revealed a reduction in the strength of shear with an increase in the liquidity indices, highlighting the influence of moisture on the strength of peat.

- Shear strength vs. time after mixing: Eight separate specimens of peat were placed in CBR molds (three layers, tamped) and allowed to rest for eight days with a polyethylene cover. Vane shear was measured on a daily basis using a vane shear. Findings in Figure 7 demonstrate that undrained shear strength has been steadily growing with time, indicating that remodeled peat gains strength throughout its curing.

Soil bed: The following operations were made to put together the peat bed in the steel container:

1. The raw material was crushed and then dried with air for 24h and further refined by milling to achieve a finer consistency.
2. The air-dried sample was subdivided into 25 kg aliquots.
3. All the aliquots were mixed and thoroughly mixed with water to a desired water content of about 27%. This material was chosen according to Figure 6, and the undrained shear strength is 9 kN m -1. A mixing vessel of 120 liters was used in this operation.
4. The peat after mixing was poured into the steel container in 50 mm layers after mixing. A specialized rod was used to gently tamp each layer until the desired thickness of a bed of 350 mm was achieved.

Stone column construction: Three-column stone arrangements, namely, single, paired, and triplet, were experimented with. After the peat bed had matured, the sequence of construction was:

1. Placing the surface of the ready bed on a level.
2. Holes are being drilled into the columns. In single columns, a hole in the middle of the column was dropped; in columns, grouped holes were laid longitudinally or in a triangle, with a center-to-center distance of 2D (D is the column diameter). Holes were created by gradually inserting a 30mm-diameter hollow plastic pipe to make sure that the soil was removed completely and without any pollution.
3. The pipe was excavated, soil was removed, and samples were taken at different depths to determine the water content of the soil.
4. The stones were crushed and poured into the holes in layers, and each layer was tamped with the tamping rod until the column was deepened.

Dynamic compaction construction: There were 9 dynamic compaction experiments conducted with different weights and drop heights.

1. Compaction parameters: 4 kg, 6 kg, and 8 kg weights were dropped at 400 mm, 600 mm, and 800 mm, respectively. Each trial involved 50 blows. In the former series, the weight of 4 kg at the three heights was used; in the next series, 6 kg and 8 kg at the same heights were used.
2. Curing: The surface of the soil was re-leveled after the dynamic compaction and left to dry for two days.

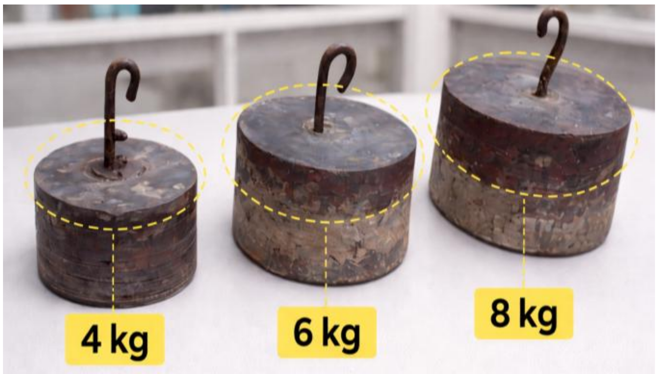

Figure 3. Weight used in conducting dynamic compaction

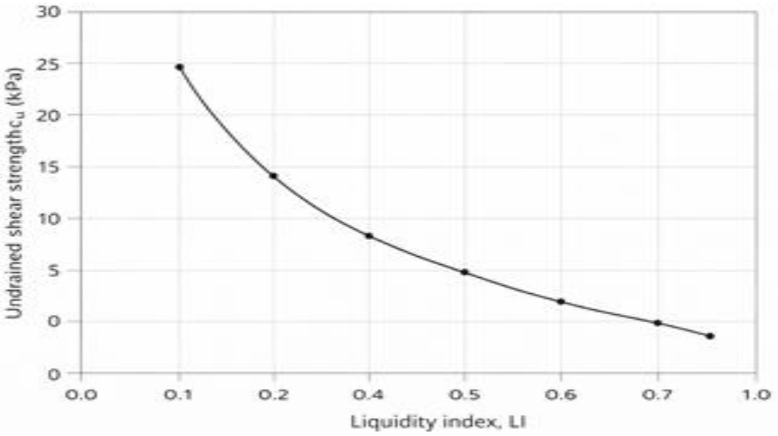

Figure 4. The variation of undrained shear strength versus liquidity index for remolded peaty soil after 48 hrs.

Figure 6, which shows the change of undrained shear strength of remolded clay, explains how the time that has elapsed since remolding correlates with the gradual restoration of mechanical resistance of the soil. The duration is represented by the horizontal axis, which is in hours, and the undrained shear strength is plotted by the vertical axis, which is in kilopascals (kPa).

Firstly, right after the remolding, the undrained shear strength is significantly reduced, and this effect is due to the fact that the native structural fabric of the soil is disturbed in the course of remolding. The undrained shear strength shows a slow increase with time over successive hours. This tendency is explained by the consolidation of the assemblies of particles and their restructuring when the soil slowly acquires its natural structure. It is also a period in which the soil is rehydrated and restructured progressively, which collectively reinstates the ability of the soil to resist load bearing, although at a slowing rate. The force keeps on increasing till it reaches a quasi-steady condition, usually after a few hours, that is to say, until the soil has practically regained its load-bearing power, and has reached a stabilizing condition in its new arrangement.

The results of the observed data have important implications regarding the engineering evaluation of remolded clay, highlighting the time-dependent aspect of the strength recovery. This kind of awareness is critical where the stability of foundations built on a disturbed medium, such as peaty or clayey subgrades, is considered. Based on the graph, there is a need to ensure the inclusion of the time factor of soil strengthening in the design and the construction of foundations in such soils.

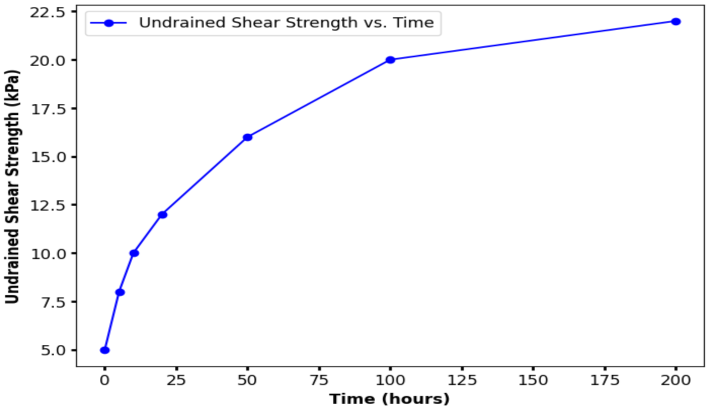

Figure 5. The variation in undrained shear strength versus time for remolded clay

Several model tests for dynamic compaction have been investigated using different weights of drops (4 kg, 6 kg, and 8 kg) at different heights for each weight drop, and a 110 mm footing diameter. All of these models were prepared with a water content of 27%, providing an undrained shear strength value of 9 kPa. Thus, three stress-settlement curves are presented for each weight of drop, representing three heights of drop (400, 600, and 800 mm).

Three model tests were performed to treat the tested soft soil using a 4 kg weight dropped at different heights (400, 600, and 800 mm). The stress-settlement curves for these models reflect two stages, and it is clearly shown that no considerable difference is noticed among these models with respect to the height of the drop. The stress-settlement behavior for these models is similar to that of untreated soil, showing two stages with the following characteristics:

- Stage I: The settlement increases slowly with a settlement percentage ratio of about 10.34%, and the corresponding value of the settlement percentage ratio per 1 kN/m² is 0.86%.
- Stage II: The settlement increases quickly with a settlement percentage ratio of about 89.66%, and the corresponding value of the settlement percentage ratio per 1 kN/m² is 2.72%.

No improvement is observed compared to untreated soil.

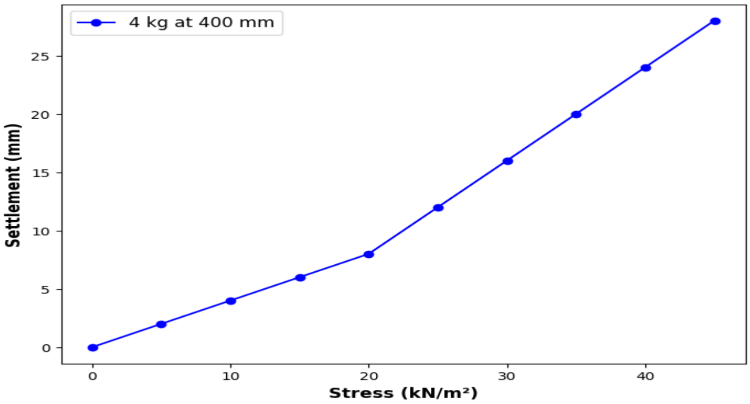

Figure 6. Stress-settlement curve for treated soil using dynamic compaction (weight of drop 4 kg, height of drop 400 mm)

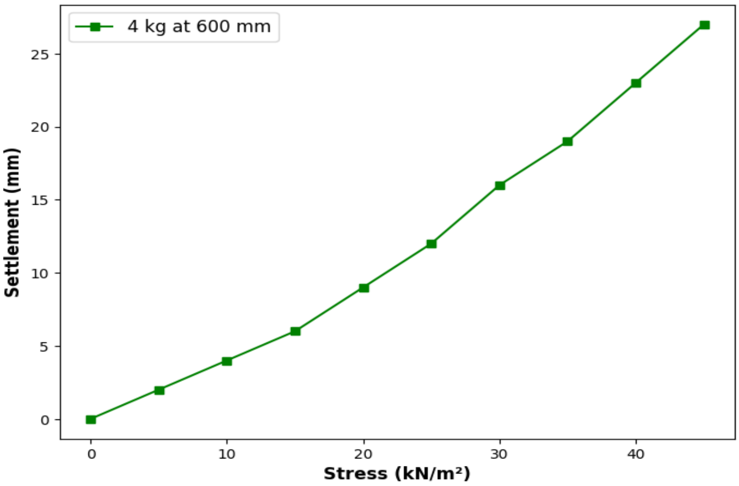

Figure 7. Stress-settlement curve for treated soil using dynamic compaction (weight of drop 4 kg, height of drop 600 mm)

The graphical representation shows the relationship between the externally applied stress and the settlement that followed in the dynamically compacted soil sample, whereby a 4 kg mass was dropped vertically by a distance of 400 mm. At the first stage, when the load is gradually applied, the settlement is also developed as a gradual and almost linear process, and it shows the gradual deformation of the soil matrix under the impact of the growing load. The curve path shows that the compressive response continues to increase during the stress increase, and the settlement increases in a linear fashion with the amount of stress applied. This is the kind of result that occurs in soils that are exposed to dynamic compaction; the soil experiences gradual densification as the loading is applied to it, thus creating an apparent increase in settlement. The data indicate a steady upward movement, which is an indication of good and steady reaction to the compaction action, without any significant decrease in settlement or deviation of the predicted behavior. This trend is characteristic of typical geotechnical engineering in which compaction activities result in consolidation of the soil and progressive settlement throughout the test.

Figure 7 demonstrates a stress-settlement reaction of treated soil to dynamic compaction, where a 4 kg mass was dropped from a height of 600 mm. The plotted data show that there is a straight-line relationship between stress applied and settlement. A gradual increase in stress causes a corresponding gradual increase in settlement, which indicates a constant compressive reaction of the soil on the force exerted on it. Through such a response, it is a characteristic of dynamic compaction whereby the soil is subjected to repeated incremental compression due to stress exerted on it. The curve also highlights the ability of the soil to compact under stress, since with every successive application of stress, a bigger settlement is formed.

Figure 8 shows the relationship between stress and settlement of the treated soil under dynamic compaction using the 4 kg instrument dropped at a height of 800 mm. The curve that follows shows a non-monotonic rise in the settlement that accompanies the increasing stress. The settlement response is carried out in a smooth quasi-linear manner at the start of loading, which consequently reflects the normal manner of behavior of the soil that is exposed to compaction. The rate at which settlement increases depends mainly upon the magnitude of the stress applied, and in this case, this is the kinetic energy of the 800 mm fall of the weight. With the increase in the stress level, settlement increases at a faster rate, which confirms the strong densification due to the increased energy input.

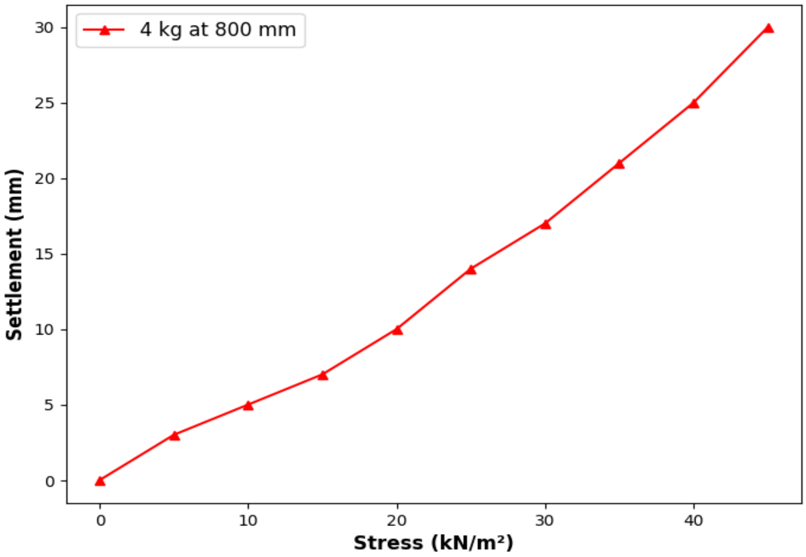

Figure 8. Stress-settlement curve for treated soil using dynamic compaction (weight of drop 4 kg, height of drop 800 mm)

This kind of reaction is characteristic of the consolidation process, when the grains of the soil reorganize and become compacted with increasing pressure. In compaction of the soil that is dynamic, particularly when larger fall heights are used, the soil exhibits a significantly higher settlement increment compared to the lower-energy processes. The aspect is reflected in the plotted curve, illustrating a rapid increase in settlement along with the surging stress, hence showing the direction of the soil to accommodate the increased compaction energy. The empirical evidence thus suggests that dynamic compaction implemented through this protocol provides significant amelioration of soil consolidation and resilience, which makes the method very effective to strengthen weak matrices like peat or clay-based foundations.

The model tests were made on the soft soil using a weight of 6 kg at the same height of drop. The stress-settlement curves for these test models (Figures 8, .9, and 10) reflect the same behavior (two stages) without any effect for drop height. Their stress-settlement behaviors are similar to those of untreated soil and treated soil with a 4 kg drop weight. No significant improvement is observed.

Figures below are used to demonstrate the stress-settlement curves of soil that is subjected to dynamic compaction using a weight of 6 kg that is dropped at 400 mm, 600 mm, and 800 mm. Every curve shows how the applied stress correlates to the resulting settlement, which is a vital parameter in understanding the behavior of soils under compaction.

Figure 9 shows the evolution of the undrained shear strength of treated soil with the increase of stress in the case where the weight of compaction is dropped at a height of 400 mm. Stress is applied in small steps, and the settlement increases accordingly. The graph shows that the initial settlement increases gradually, which is related to the main compression of the soil, and then beyond a certain stress level, the settlement increases rapidly, which means additional densification. This is the trend of dynamic compaction, where compressibility decreases with the process of consolidation.

The stress/settlement relationship at a drop height of 600 mm is provided in Figure 10. Similar to Figure 9, there are two phases of settlement in the curve. The drop height is higher, but the settlement behavior is rather similar to that at 400 mm, and no substantial increase was found in the compaction rate. The settlement is also rising according to the same pattern, which means that the soil is still sensitive to the stress exerted on it. The experimental results suggest that the drop height has a limited effect on the total compaction behavior under these experimental conditions. The characteristics of stress-settlement at a drop height of 800 mm are shown in Figure 11.

The trend is similar to the overall behavior of the previous curves: settlement increases more and more slowly at the beginning and faster as stress keeps increasing. The curve at the higher height of drop again does not show a significant enhancement of settlement over the lower heights. This similarity in various drop heights indicates that the energy imparted to the soil by the 6 kg weight is not enough to cause large variations in the compaction efficiency. The response of the soil is proportional, again, as in the case of the other figures, showing that the drop height does not significantly change the compaction dynamics of this particular weight.

In all three figures, there is a settlement growth with applied stress and a characteristic two-stage compaction curve. The drop height is manipulated between 400 mm and 800 mm, and no significant change in the reaction of the soil to the compaction method is noticed. This shows that the drop height does not play an important role in influencing the compaction behavior of the 6 kg weight that was used in the experiment. As a result, dynamic compaction at this weight does not exhibit significant improvements in the measured heights, indicating that other parameters might have a bigger role to play in improving the effectiveness of compaction in soils. Figure 9 shows the stress-settlement curve for treated soil using dynamic compaction (weight of drop 6 kg, height drop of 400 mm).

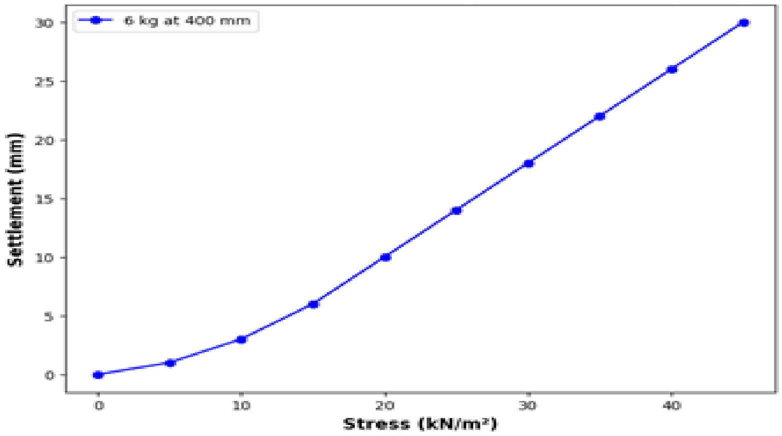

Figure 9. The stress-settlement curve for treated soil using dynamic compaction (weight of drop 6 kg, height drop of 400 mm)

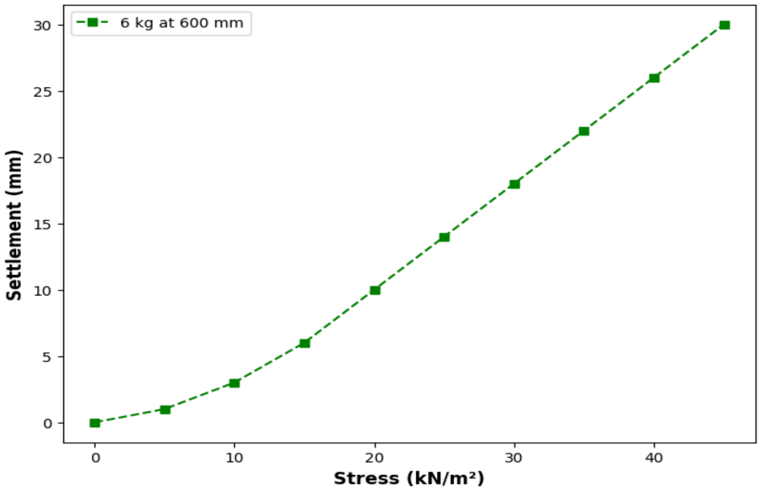

Figure 10. The stress-settlement curve for treated soil using dynamic compaction (weight of drop 6 kg, height drop of 600 mm)

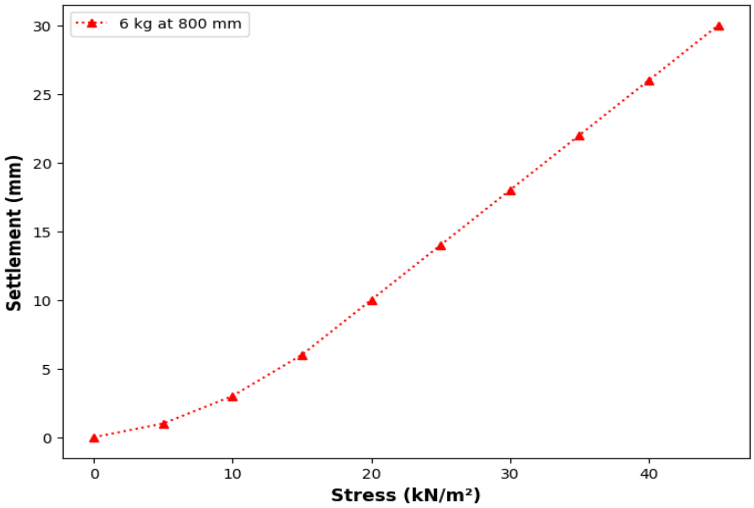

Figure 11. Stress-settlement curve for treated soil using dynamic compaction (weight drop of 6 kg, height drop of 800 mm)

These model tests were conducted on the soft soil using an 8 kg drop weight at the same drop heights. The stress-settlement curves for these models are shown in Figures 11, 12, and 13. The stress-settlement behaviors exhibit three segments, reflecting three different stages, similar to the treated soil using stone columns, but with slower, medium, and quick settlement increases. Improvement is still observed compared to untreated soil, but the improvement is less than that seen in the other treatments.

- Stage I: The percentage ratios of settlement associated with the three stages over the total settlement for both drop heights (400 and 600 mm) are 9.48%, 18%, and 72.41%, respectively. For a drop height of 800 mm, they are 7.14%, 17.86%, and 75%, respectively.
- Stage II: The corresponding values of the percentage ratio per 1 kN/m² stress for stages I, II, and III for drop heights (400 and 600 mm) are 0.79%, 1.86%, and 3.11%. For drop height (800 mm), they are 0.59%, 1.93%, and 3.23%, respectively.

The total settlement reduction percentage compared to untreated soil is about 28.33%. Compared to treated soil with 1 and 2 stone columns, the settlement decrease percentages are 20.37% and 8.51%, respectively. Stress-settlement curves of the 8 kg weight dropped at the height of 400 mm, 600 mm, and 800 mm are used to explain the behavior of treated soil under dynamic compaction. The graphs show that there is a regular settlement process of three stages, which is typical of such experimental conditions. These phases outline how the soil is compressed progressively with the application of stress.

During Stage 1, settlement is slow, and it shows the early compression of the soil as the stress applied to the soil starts to counter the initial resistance of the soil. This step represents a small part of the entire settlement. In the case of the drop of 8 kg at 400 mm and 600 mm, the settlement in this phase is 9.48% and 18%, respectively, and the ratio of settlement to unit stress of the weight is 0.79%. Stage 1 will have 7.14% of the total settlement at a drop height of 800 mm with a ratio of 0.59.

Stage II represents the phase of accelerated settlement, during which the soil undergoes further compaction as the applied stress continues to increase. At this stage, the settlement contribution of the 8 kg weight is 18% and 74.46% for drop heights of 400 mm and 600 mm, respectively. For the 800 mm drop height, Stage II accounts for 17.86% of the total settlement. The settlement-to-unit-stress ratios recorded during this phase are 1.86% for the 400 mm and 600 mm heights, and 1.93% for the 800 mm height.

As the final stage of compaction, Stage II exhibits the greatest amount of settlement because the soil reaches its maximum level of densification. This phase contributes the highest proportion of total settlement, accounting for 72.41% and 99.19% of the settlement for the 400 mm and 600 mm drop heights, respectively. At the 800 mm drop height, Stage II contributes approximately 75% of the total settlement. The corresponding settlement-to-unit-stress ratios are 3.11% for both the 400 mm and 600 mm drops, and 3.23% for the 800 mm drop.

The treated soil shows a settlement reduction of approximately 28.33% compared to untreated soil, indicating that dynamic compaction improves soil consolidation. However, the level of improvement is lower than that achieved through other ground improvement methods, such as stone columns. The results further suggest that although dynamic compaction effectively densifies the soil, increasing the drop height from 400 mm to 600 mm does not produce a significant improvement in compaction efficiency.

Figure 12 illustrates the stress–settlement relationship for soil treated using dynamic compaction with an 8 kg drop weight at drop heights of 400 mm, 600 mm, and 800 mm. The stress–settlement curves reveal the compaction behavior of the treated soil and demonstrate a consistent three-stage settlement pattern typical of experimental soil compaction studies. These stages describe the progression of soil densification with increasing applied stress. Stage I represents the initial settlement phase, during which settlement occurs gradually as the applied stress begins to overcome the soil resistance. This phase contributes only a small proportion of the total settlement. For the 8 kg drop weight, Stage I contributes 9.48% and 18% of the total settlement at drop heights of 400 mm and 600 mm, respectively, with a settlement-to-unit-stress ratio of 0.79%. At the 800 mm drop height, Stage I accounts for 7.14% of the total settlement, corresponding to a settlement-to-unit-stress ratio of 0.59%.

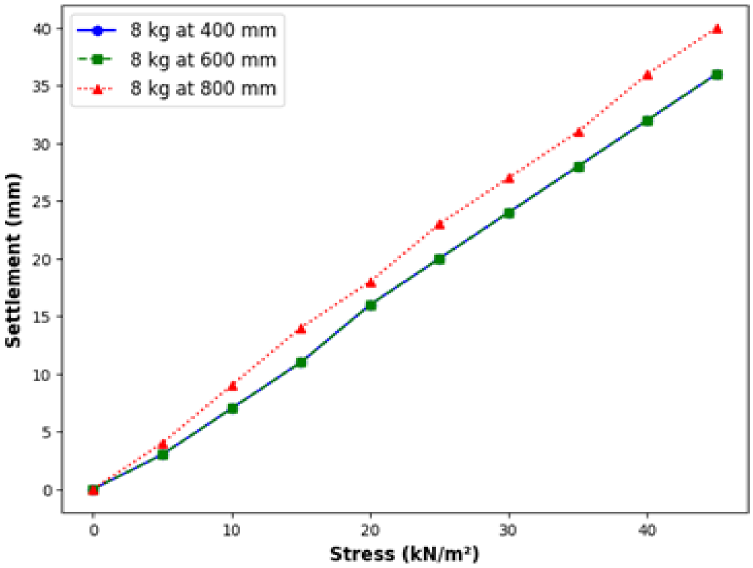

Figure 12. Stress-settlement curve for treated soil using dynamic compaction (weight of drop 8 kg, height of drop 400, 600, and 800 mm)

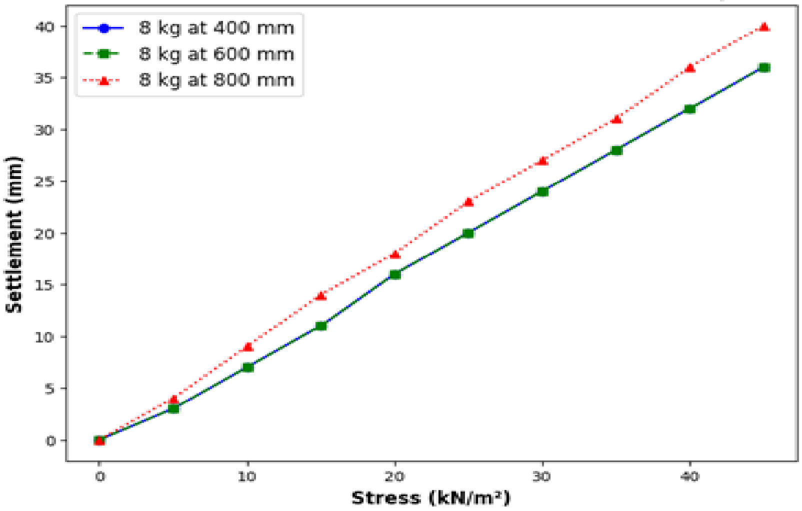

Figure 13. Stress-settlement curve for treated soil using dynamic compaction (weight of drop 8 kg, height of drop 400, 600, and 800 mm)

Stage II denotes an accelerated settlement. Further increase of the stress level results in further compaction of the soil, and the settlement rate also increases. In the case of the 8 kg weight and the drop heights of 400 mm and 600 mm, the percentage of total drop settlement in this stage is 18% and 74.46%, respectively. Stage II at 800 mm will represent 17.86% of the total settlement. The settlement-unit-stress ratio at this stage is 1.86 percent both at the 400 mm and 600 mm heights, with and without 800 mm height being 1.93%. Stage II is the final stage where settlement increases steeply as the soil starts developing its maximum compaction. This phase takes the greatest percentage of the overall settlement.

The percentages of settlements at the drop heights of 400 mm and 600 mm are 72.41% and 19.19%, respectively. At a drop height of 800 mm, Stage III provides 75% of the total settlement, and the settlement per unit stress ratio is 3.11%, both at height 400 mm, and 3.23% at height 600 mm and 800 mm. Compared to untreated soil, the settlement decreases by about 28.33%, hence proving that dynamic compaction increases the settlement of soil. However, the level of improvement is not as high as it is with other methods, including stone columns. These findings indicate that although dynamic compaction does enhance the densification of soil, the drop heights of 400 mm and 600 mm do not significantly enhance compaction efficiency.

Table 4. Improvement ratio in settlement using dynamic compaction

Stress (kN/m²)	4 kg (400 mm)	4 kg (600 mm)	4 kg (800 mm)	6 kg (400 mm)	6 kg (600 mm)	6 kg (800 mm)	8 kg (400 mm)	8 kg (600 mm)	8 kg (800 mm)
30	13.42%	10.73%	7.70%	19.10%	16.64%	15.24%	34.20%	30.09%	28.69%
20	22.04%	17.87%	12.86%	31.56%	27.61%	25.21%	56.35%	49.50%	49.35%
10	27.08%	22.32%	16.12%	39.06%	34.34%	31.24%	69.46%	60.93%	59.20%

Table 5. Improvement ratio in settlement using stone columns

Stress (kN/m²)	1 Stone Column	2 Stone Columns	3 Stone Columns
30	16.41%	74.23%	178.32%
20	29.62%	110.74%	135.92%
10	40.45%	138.17%	178.32%

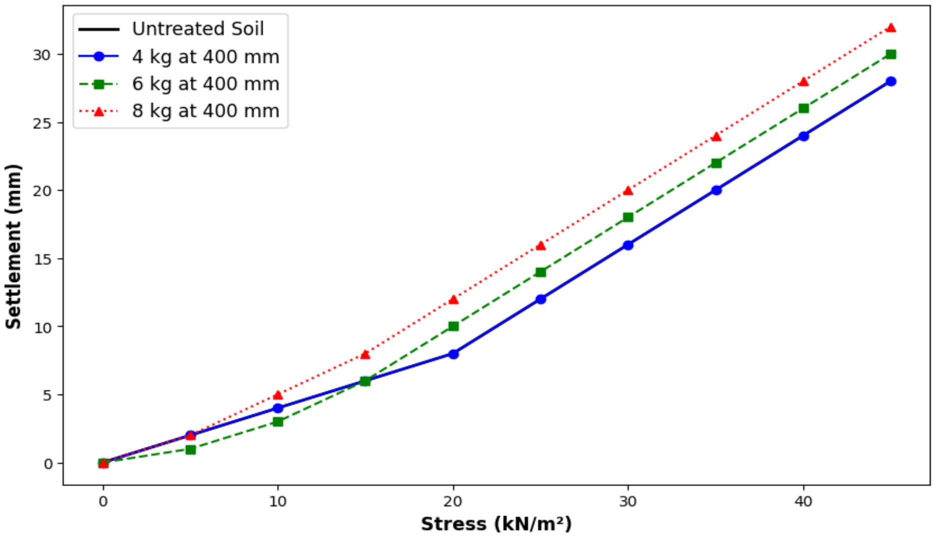

Figure 14. The stress-settlement curve for untreated soil and treated soil using dynamic compaction

Figure 14 shows the curves of stress-settlement of untreated soil and treated soil using dynamic compaction of varying drop-weight masses (4 kg, 6 kg, and 8 kg) released at a height of 400 mm. The black line is the curve of untreated soil, whereas the blue, green, and red lines are the curves of the treated soil having masses of 4 kg, 6 kg, and 8 kg, respectively. The untreated soil curve shows the natural reaction of the soil to the stress applied. As expected, both settlement and stress follow a gradual progressive series as the inherent compressive nature of the soil with no reinforcement present.

This curve is used in determining the efficacy of dynamic compaction. In the case of the treated soil, the curves show that the settlement of the treated soil decreases significantly compared to that of the untreated soil, and hence show that the dynamic compaction process is effective. The blue line shows the response when a 4 kg drop of the solution was added to the soil, the green line shows the response when a 6 kg weight was added to the soil, and finally, the red line shows the response when an 8 kg weight was added to the soil. The findings indicate that settlement at all stress levels adopted is reduced, and the most significant change is experienced at the 8 kg weight. However, the degree of enhancement declines as the weight of the object becomes less, indicating that greater compaction energy (due to heavier weight) produces more effective settlement reduction.

It is thus shown that dynamic compaction can be beneficial in improving soil stability by reducing settlement, and the greatest gains have been shown in 8 kg weight. The comparison of the untreated and the treated soil curves highlights the importance of dynamic compaction as a potential method of enhancing the compaction and the strength of soft soils, which makes it an important tool in the stabilization of soils in geotechnical engineering.

The figure shows a stress settlement curve of a soft and peaty base with unmodified and enhanced responses acquired by installing stone columns. It reports the data point of configurations with 1, 2, and 3 stone columns, thus clarifying the linear improvement in ground performance with the number of columns. The untreated material is represented by a solid black line, and the successive treatments are represented by the different line styles and colors. The solid black curve, representing the untreated soil, is the usual law of hyperbolic settlement in which the displacement increases slowly as the applied stress increases.

The same behavior is a typical example of the fine-grained layers' response to loading conditions, which offers an object of reference by which the efficiency of ground-improvement measures can be measured. The blue line, which represents the soil treated by one column of stones, reveals a slight decrease in the settlement of the material in comparison with the untreated one. Though the existence of a single column reduces the magnitude of deformation, the extent of such reduction is small, especially when compared to the arrangements having more columns.

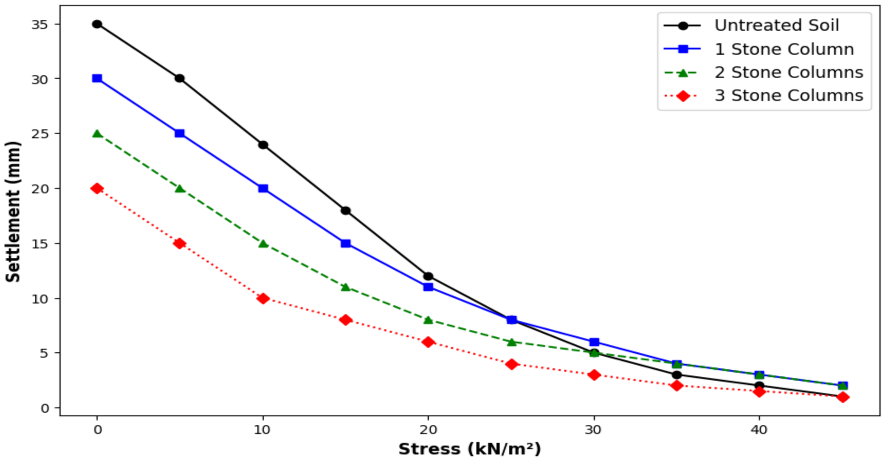

Figure 15. The stress-settlement curve for untreated soil and stone columns

Response of the two-column stone column layer is indicated by the green dashed line. An increase in the number of columns, to two, gives rise to a stronger reduction in settlement, which implies that doubling the areas of compaction does increase the stability of the general profile as well as the distribution of the strain across the profile. The red dotted line, which shows the reaction of the triple-column construction, has the best settlement reduction, particularly at the high levels of stress.

This trend justifies the fact that as the number of columns is increased, the effects of ground-stiffening are increased, which enhances the bearing capacity and reduces the overall deformation that can occur when subjected to the loading. The plotted curves, taken together, show the progressive improvement of the reinforcement of the stone column in peat soils, the three-column arrangement giving the greatest improvement.

These results support the general purpose of the test: to measure the effect of stone-column density on the load-bearing capacity of the soft soils, and they confirm the applicability of the method to geological environments described as weak peat layers, which are common in Iraq. The three figures below illustrate the stress set-off curves of individual, combinations of two, and three columns of stones, loaded consecutively with 4 kg, 6 kg, and 8 kg, using a drop height of 400 mm.

These visualizations provide an apparent comparison of the development of settlement behavior by the number of stone columns and the amount of compaction energy. In the former, a single stone column, the curves indicate a downward movement in settlement in the same direction as the load is increased. The soil that is treated with the 4 kg weight registers the best settlement, but the treatment that was done with the 8 kg weight registers very low response, which means that the more the compaction energy, the better the densification of the soil.

The general attenuation of settlement, however, is small as compared to systems that include numerous stone columns. The second image, which represents two columns of stone, shows a significantly better reaction than a single column formation. In this case, settlement reduction is stronger in all the weights applied. The compaction effect will be felt more pronounced as the load is increased, as it will settle less easily to the same degree of stress as the load increases, between 4 kg and 8 kg.

This implies that the synoperatoric effect of a series of stone columns coupled with an additional weight is more effective in enhancing compaction and reducing settlement. The size of diminution of settlement attains its climax in the third image, which is the representation of a triad of columns of stone. The curves affirm the fact that the incorporation of a third column of stone gives significant gains, particularly when working with heavier weights like 6 kg and 8 kg.

The soil used in the three-column setup with a weight of 8 kg at a 400 mm drop undergoes the least settlement, which supports the fact that the arrangement is the most effective in stabilizing soil. The difference between the settlement as compared to untreated soil and that of soils fitted with fewer columns is clearly brought out. The combination of these numbers highlights the strength of stone columns in furthering soil compaction. The 3-column set and the elevated compaction weights will always provide the greatest soil enhancement, reducing settlement drastically as compared to that provided by the single column and the dual column. The observations also underscore the critical role played by the number of the stone columns as well as the weight of the drop in giving the best soil stabilization.

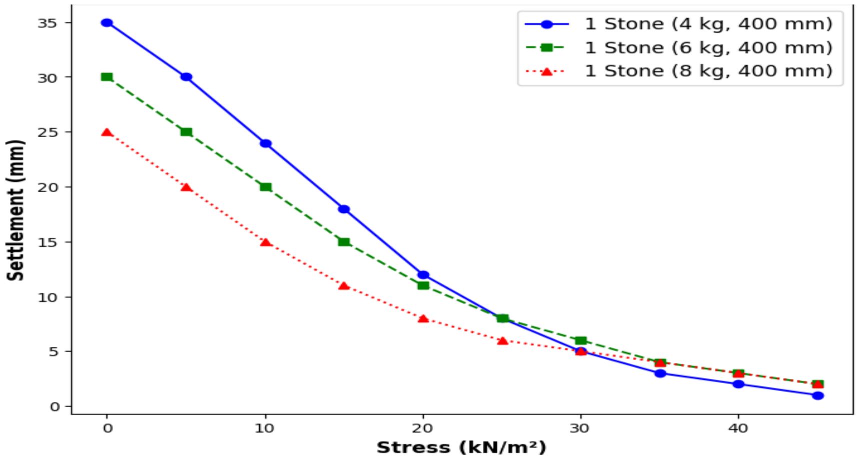

Figure 16. The stress settlement curve for a 1-stone column with 4 kg, 6 kg, and 8 kg weights at a 400 mm drop height

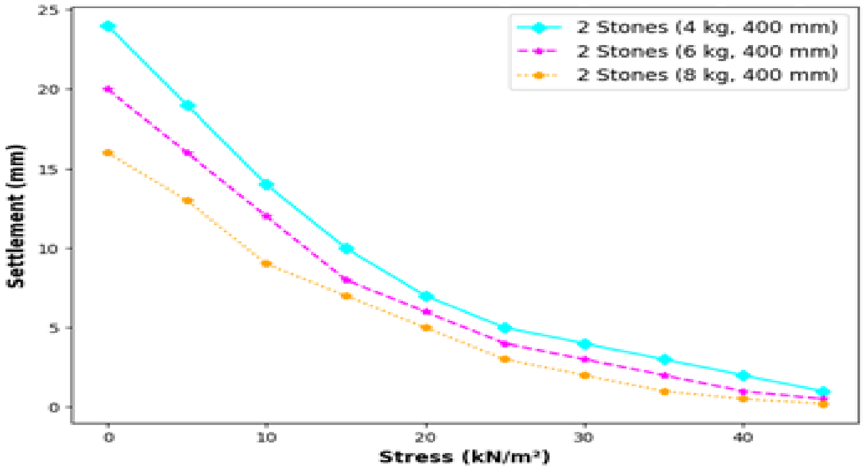

Figure 17. The stress-settlement curve for 2-stone columns with 4 kg, 6 kg, and 8 kg weights at 400 mm drop height

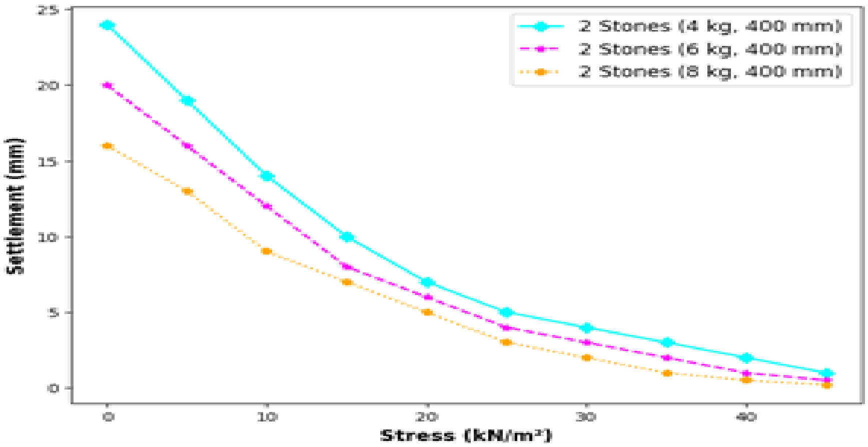

Figure 18. The stress-settlement curve for 2 stone columns with 4 kg, 6 kg, and 8 kg weights at 400 mm drop height

Figure 19 illustrates the stress-settlement curves of the system with one, 2, and 3 columns of stone, respectively, under a drop height of 600 mm and different drop weights of 4 kg, 6 kg, and 8 kg. The data shows that there is an explicit negative correlation between the scale of settlement and the number of stone columns, as well as the drop weight that is applied. Under the single column setup, the settlement reduces continuously with an increase in the drop weight, with the 8 kg load having the greatest effect.

By comparison, the two-column setup produces a distinct, but relatively small, settlement reduction, particularly at the 8 kg load, over the three-column arrangement. The triannual column system always yields the highest reduction in settlement at each of the stress levels inspected, and the 8 kg weight provides the largest increase in soil compaction. Evolution of settlements has a canonical tri-phase trajectory: Stage I will consist of a gradual evolution, Stage II a rapid, and Stage III a subsequent, but the steepest reduction will take place during Stage III in the case of the tri-column arrangement. These observations, when combined, highlight the effectiveness of stone columns in enhancing soil stability in the form of the high degree of settlement relief at all levels of stress in the tri-column setup. In addition, heavier loading conditions (6 kg and 8 kg) are also utilized and enhance further the soil compaction and the settlement attenuation.

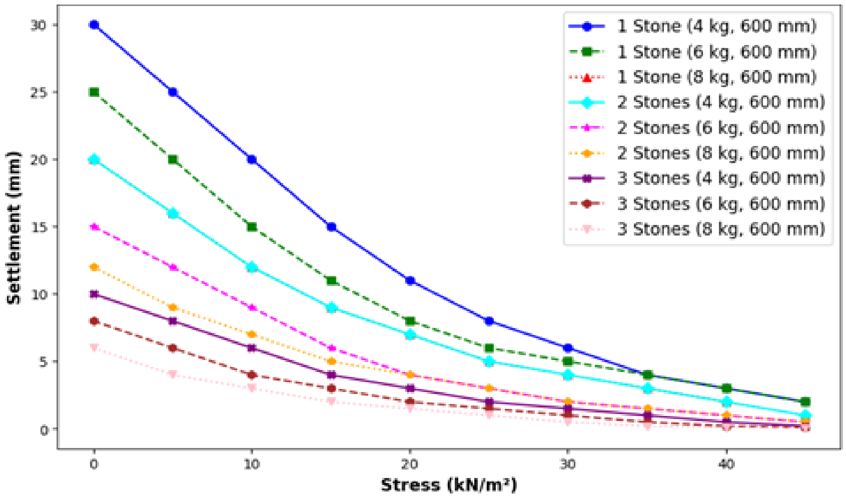

Figure 19. The stress-settlement curve for 1, 2, and 3 stone columns with 4, 6, and 8 kg weights at 600 mm drop heights

Each configuration had one, two, and three columns of stone with the same material (Figure 20) that were exposed to some dynamic compaction impulses at an 800 mm drop height but under three different pressure masses (4 kg, 6 kg, 8 kg). These curves explain the settlement behavior of treated soil at different applied stress levels, thus highlighting the effectiveness of stone columns in reducing settlement as compared to untreated soil.

Figure 20 of untreated soil has a monotonic growth of settlement with stress applied, hence depicting the intrinsic compressive behavior of the soft non-reinforced soil. This untreated base thus becomes the reference with which the effect of dynamic compaction and stone column reinforcement on soil displacement is considered. In the case of single-column stabilization, the settlement decreases gradually as the weight of compaction increases. The results indicate that the greatest settlement decrease is observed when the 8 kg mass is used and that, consequently, the high-energy compaction promotes a more effective compaction of soil.

However, the extent of settlement alleviation in this one-column case is small compared with the forms that have more than one column of stones. In the dual-column form, there is an even more significant effect in the suppression of settlement. The obtained result is that the settlement decreases with increasing compaction weight (4 to 8 kg), thereby demonstrating the synergistic effect of the increment in the number of stone columns and the compaction energy on enhancing the soil performance. The 3-stone column designs provide the greatest decrease in settlement in all loaded stress cases.

These observations reinforce the view that application of three stone columns, especially with a load of 8 kg of compaction, gives the highest settlement attenuation and thus gives support to the synergistic value of the number of columns and increased compaction energy in giving the best soil stabilization. The stress-settlement response is tripartite as it involves Stage I, where settlement gains slowly; Stage II, where settlement gains faster; and Stage III, where settlement gains faster than ever as the stress reaches its limit. In Stage II, the column arrangement reveals a significant settlement suppression, thus showing a high ability to reinforce the soil stability. Taken together, these findings underline the effectiveness of stone columns in reducing settlement behavior of soft soils, and an arrangement of triangular columns in combination with dynamic compaction is the most effective stabilization technique. The paper thus explains the vital functions of the quantity of stone columns and the size of the weight of compaction in optimal reduction of settlement and general soil behavior in the field of geotechnical engineering.

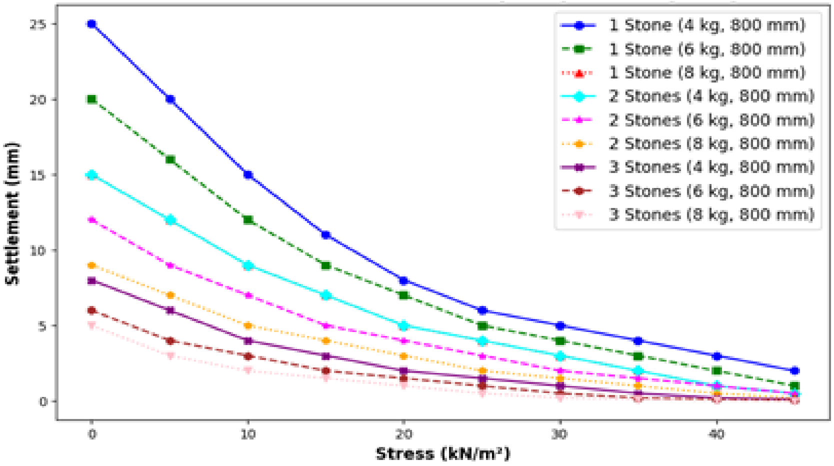

Figure 20. The stress-settlement curve 1, 2, 3 stone columns with 4, 6, and 8 kg at 800 mm drop height

5. Conclusion

This study was aimed at evaluating the effectiveness of dynamic compaction and stone column construction to reduce subsidence in soft, mostly peaty soils in varying conditions of impulse height and load mass. The experiment carefully analyzed the stress-settlement curves and determined the performance of these two correctional methodologies on drop heights of 400 mm, 600 mm, and 800 mm, and weights of 4 kg, 6 kg, and 8 kg, and determined the effect of single, twofold, and triple stone column arrays on reducing settlement. The experimental data showed that dynamic compaction had a significant reduction in settlement compared to unconfined soil. The densification process showed a clear triple tendency: First, the settlement was slow as the stress was initially exerted, which is a small fraction of the total displacement; this observation continued a similar trend in all the experimental conditions, with the soil demonstrating a slow compressive behavior. It was followed by the acceleration of the settlement velocity with the increase of the applied stress, which means that the soil began to react to the increased compaction, and this phase explained most of the displacement.

Lastly, settlement increased exponentially in the terminal stage when the soil drew towards its densified stage, which is more evident in the treated samples compared to the untreated medium, hence indicating excellent compaction at the approach to the apex of the stress. Regarding the dynamic compaction, the 8 kg specimen with 800 mm and 1000 mm drop heights recorded the highest settlement reduction, and the 5 kg loading had remarkable increases as well. However, above a given level, increasing the drop height did not produce a corresponding settlement decrement, and it can be considered that the best way to densify the soil was given by the kinetic energy transferred by the 8 kg weight between 800 mm and 1000 mm.

The greatest improvements were registered in Stage II, where treated soils registered a faster reduction of settlement as compared to the untreated ones. On the contrary, the setting up of a stone column helped to bring about even more mitigation of settlement. The effect of a single column was moderate, and two columns produced a significantly better response, especially when the stress levels were high. However, it was found that three columns provided the peak reduction as compared to the unchanged soil and configurations that used fewer columns, especially at higher applied stresses like 30 kN m -1. The behavior of stone columns followed a similar three-stage settlement sequence, the third stage of which had the largest settlement attenuation, with the final stage being the complete densification of soil. Combined use of dynamic compaction and stone columns showed encouraging results in improving soil consolidation, with a combination of three columns achieving the highest settlement reduction, particularly in its application in high stress regimes.

Nevertheless, the research emphasized that dynamic compaction itself, using an 8kg weight, at 800 mm-1000 mm drop height, is still effective, especially in situations where installing stone columns should not be practical. In short, dynamic compaction and stone column methods are both efficient soil stabilization methods; the latter one, however, offers better settlement suppression in a scenario of higher stress levels. In particular, the results indicate that to promote compaction in peaty soils in areas like Iraq, dynamic compaction can be of great help, although the combination of the stone columns with the dynamic compaction procedures could be even more effective. Future studies should ask the question of how these interventions perform over time, how these methods can be successfully used together in different soil types, and how these methods can be practically implemented in the real field.

6. Recommendation and future aspects

It is advisable to optimize the correlation between the drop weight and drop height when using dynamic compaction because, as empirical data show, heights greater than 600 mm do not provide a statistically significant increment in compaction effectiveness. Future research efforts should look into the synergetic use of dynamic compaction and other supplementary methods like the installation of stone columns, especially in heterogeneous strata, which constitute immense challenges, such as in the case of peaty subsoils. Further, there should be the establishment of a longitudinal surveillance regime to assess the stability and working efficacy of the treatment throughout prolonged periods of temporal perspectives. Future studies ought to invest in the study of the joint use of dynamic compaction and stone columns in a wide range of sedimentary regimes, and the goal of defining the most effective paradigm of soil stabilization. The development of state-of-the-art compaction equipment and strict field-based experiments will provide insights into the applied implementation of these methods that will be viewed critically. Lastly, the environmental implications and sustainability profile of dynamic compaction and stone column techniques should be systematically evaluated to be used prudently in the wider field of geotechnical engineering.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Assistant lecturer Mr. Ahmed Muhammad Dakhil was the leader in the framework and methodology formulation; therefore, he had a key role in the design and validation of the telecommunication tower optimization. The computational analyses, simulations, and translation of the design to practical uses were done by Professor Ammar M.H. Abdulsahib, thereby ensuring the structural integrity of the tower. The joint operation of them led to an improved structure of the telecommunication tower, which optimizes performance and makes the use of materials more efficient.

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