E-ISSN: 2528-388X
P-ISSN: 0213-762X

INERSIA
Vol. 19, No. 2, December 2023

Parametric Study on The Bearing Capacity of Down-hole Dynamic Compaction

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Keywords:
Down-hole Dynamic Compaction
Soil Reinforcement
Bearing Capacity

ABSTRACT

The DDC method is well known as Down-Hole Dynamic Compaction, an effective ground treatment method. DDC combines dynamic compaction and soil replacement methods to enhance bearing capacity, reduce settlement, minimize the potential for collapse, and mitigate liquefaction. DDC has been commonly used to stabilize collapsible soil, DDC basically forms a column inside the soil stratum which is similar to a stone column except DDC materials are put in sequence and then compacted by using DDC hammer, this is known as the self-tamping method. DDC is considered as a suitable method for soft soil improvement. This study modeled DDC as reinforcement for runway area which is predominantly soft soil in the study location. DDC is modeled with various dimension and spacing to assess its impact on bearing capacity and settlement, thereby simplifying the selection of suitable dimension during installation. The results show that the stress induced by external loads on Down-hole Dynamic Compaction (DDC) rises in correlation with the spacing between DDC installations. The peak stress was documented on a DDC unit with a 1-meter diameter positioned at a distance of 2.5 meters from the other DDC units, measuring 83.9 kN/m^2. The highest stress level was recorded in the soil surrounding a DDC unit with a 1.5-meter diameter, which was positioned 3 meters away from other DDC units, measuring 157.89 kN/m^2. The highest bearing capacity was achieved when a DDC with a diameter of 1.5 meters was positioned at a distance of 3 meters, resulting in a bearing capacity value of 1407.32 kN/m^2.

1. Introduction

The X International Airport project stands on land dominated by soft soil, which causes failure in the construction on it. Bearing capacity and settlement problems are often encountered when planning buildings in soft soil conditions [1]. Soil reinforcement is one proven approach to enhance the quality of soil properties, particularly by improving the shear strength parameter of the soil that supports a building structure, enabling it to withstand operational loads and its structural load based on permissible deformations [2].

Several soil improvement methods can be used based on geological conditions and existing problems, one of which is the Down-hole Dynamic Compaction (DDC) method. This method is still very rarely used in Indonesia, Martin Wijaya mentioned in his research that DDC, used as one of the soil improvement methods in Indonesia, has proven to be beneficial, especially when the on-site materials are oversized [3]. DDC is a combination of dynamic compaction and soil replacement methods that function to enhance bearing capacity and reduce settlement, minimize the potential for collapse, and mitigate liquefaction. DDC is often used in China to stabilize soils prone to collapsible loess [4]. Loess is a classic sediment mainly composed of fine particles formed from wind-blown dust accumulation [5]. Loess can be a primary cause of collapse due to its composition primarily consisting of fine particles that create pores or voids [3]. Collapsible loess is a condition when the loess is exposed to water, a portion of the loess undergoes conspicuous collapse rapidly under its own pressure from the overburden or additional load [6].

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https://dx.doi.org/10.21831/inersia.v19i2.65822
Received September 8th 2023; Revised December 29th 2023; Accepted December 31th 2023
Available online December 31st 2023

The impact of dropping a load from a height of 8-10 meters onto the ground generates stress waves that compress the loess framework and eliminate empty spaces between mud particles, thereby increasing soil density [6]. Down-hole Dynamic Compaction (DDC), also known as the dynamic compaction from within boreholes, stands as a soil reinforcement method in which holes are formed to a predetermined depth, and then filled with gravel material to shape sturdy columnar supports with substantial load-bearing capacity. Hard rock gravel is used as a filling material for reinforcing soft soils [7] and densely compacted soils in between the columns. DDC is built using the pre-boring method by drilling a hole before filling it with material and using a self-tamping method that focuses on dropping the hammer at the location of the hole until it reaches the desired depth [4]. This self-tamping method is commonly used because of its ability to generate dynamic lateral stresses that compact the surrounding soil. Especially if the soil is collapsible loess soil [8]. The self-tamping and pre-boring procedures can be observed in Figure 1 and Figure 2.

The Down-hole Dynamic Compaction (DDC) was used in this study as one of the ground improvement methods with three variations in diameter and spacing. The effectiveness of DDC will be analyzed, along with assessing the impact on bearing capacity resulting from the planned variations in diameter and spacing.

2. Method

DDC is constructed usually in an equilateral triangular pattern although a square pattern is sometimes used [9]. A typical layout of DDC in equilateral triangular and square patterns is shown in Figure 3 and Figure 4.

Consider the ultimate strength of either a square of infinitely long rigid concrete footing on the surface of a cohesive soil reinforced with DDC, as illustrated in Figure 5. Assume the foundation is loaded quickly so that the undrained shear strength is developed in the coherent soil, with the angle of internal friction being negligible. And then, neglect cohesion in DDC. And for now, assume the full shear strength of both the DDC and cohesive soil is mobilized [10].

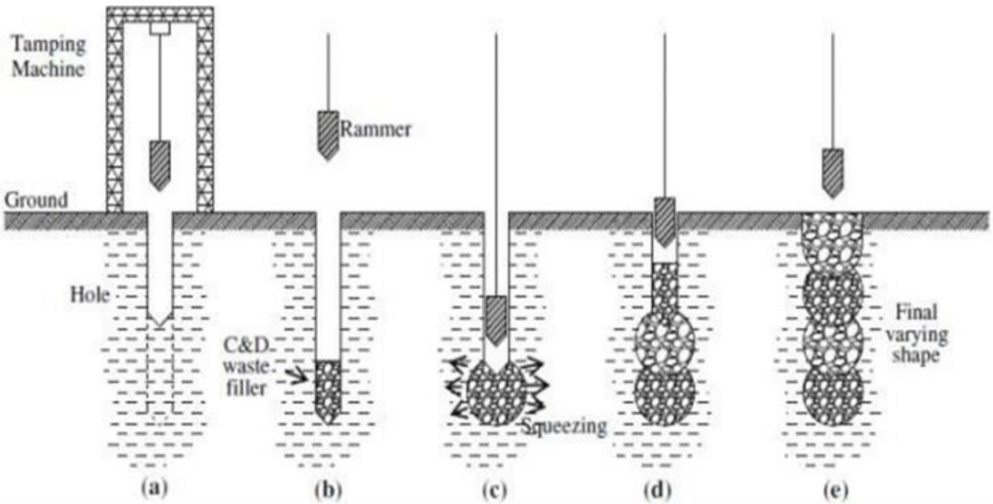


Figure 1. Self-tamping procedure

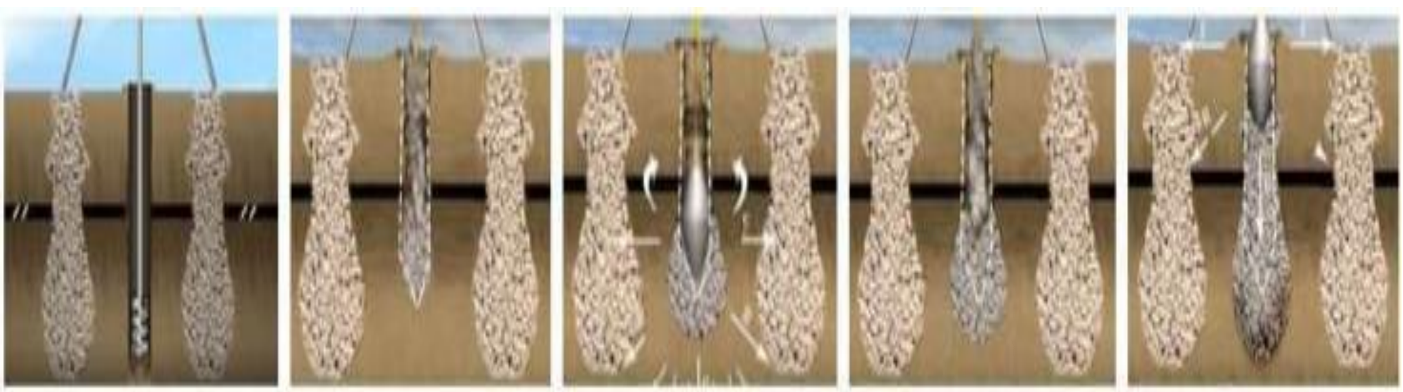


Figure 2. Pre-boring procedure

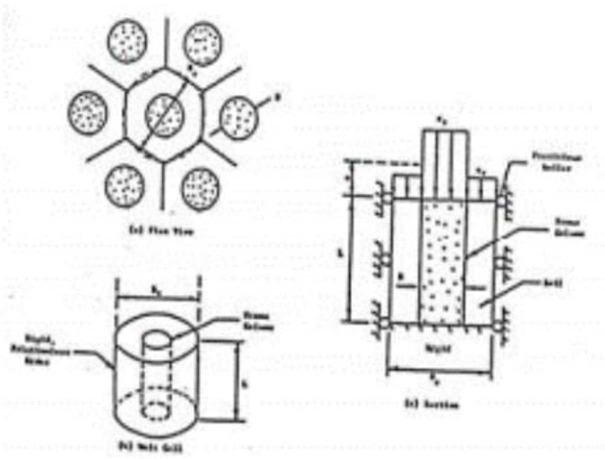


Figure 3. Unit Cell.

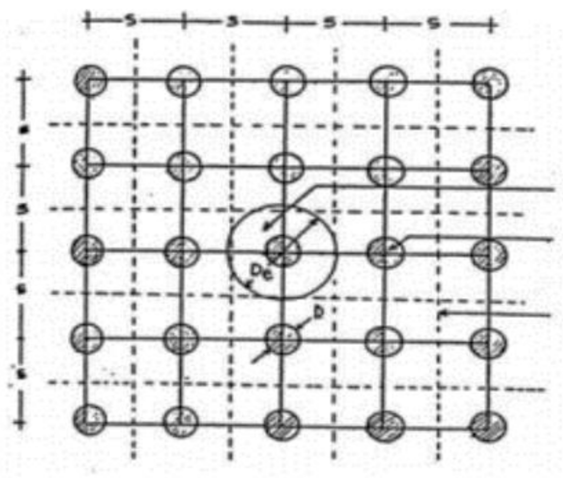


Figure 4. DDC Uuing Square Arrangement Pattern.

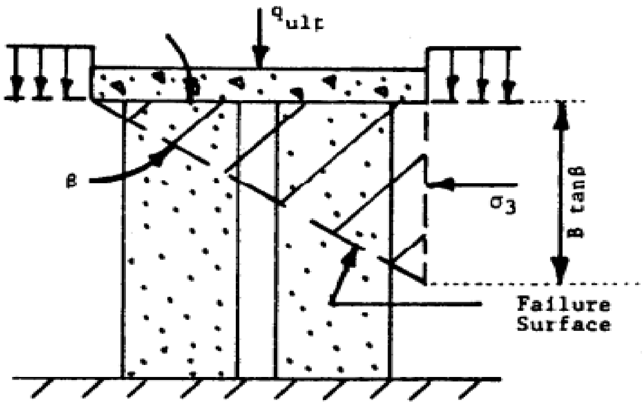


Figure 5. Failure mechanism of a group of DDC columns in cohesive soil .

The ultimate bearing capacity (q_u) of the group can be determined by approximating the failure surface by two straight rapture lines as Equation 1.

$$q_u = \sigma_3 \, tg^2\beta + 2 \, c_{av} \, tg \, \beta \quad (1)$$

where σ_3 is the average lateral confining pressure from Equation 2.

$$\sigma_3 = ½ \, \gamma_c \, B \, tg \, \beta + 2c \quad (2)$$

where γc is the saturated or wet unit weight of cohesive soil, B is foundation width, c is undrained shear strength within the unreinforced cohesive soil, and β is the inclination of the failure surface as given by Equation 6.

As shown in Figure 5, the average shear resistance of composite soi would be developed on the failure surface. The ultimate stress q_{ult} that the composite soil can withstand is dependent upon the lateral, ultimate resistance σ3 of the block to movement, and the composite shear resistance developed along the inclined shear surface. From a consideration of the equilibrium of the block, the average shear strength parameters within the block are:

$$C_{av} = (1 - as) \, c \quad (3)$$

whereas is the area replacement ratio and μs is the stress concentration factor for DDC, as defined by Equations 4 and 5.

$$as = 0{,}785 . \left(\frac{D}{S}\right)^2 \quad (4)$$

and

$$\mu s = \frac{n}{(1+(n-1)) \, x \, as} \quad (5)$$

where D is the diameter of DDC, S is the spacing of DDC, and n is the stress concentration ratio. Based on the FHWA (Federal Highway Administration) the stress concentration is around 2-5 [12].

As mentioned previously, the strength components due cohesion of DDC and friction of the clay are neglected in this derivation. The failure surface makes an angle an β with the foundation. Where β for the composite soil is calculated as Equation 6.

$$\beta = 45° + \frac{\varphi_{av}}{2} \quad (6)$$

and

$$\varphi_{av} = \text{arc tg} (\mu_s \text{ as tg } \varphi_s) \quad (7)$$

The stress distribution that occurs on the DDC and existing ground is different even though the total working stress is designed to be the same for all areas. The stress distribution on the DDC will be higher because the stiffness of the DDC is higher than that of the surrounding soil [9]. Figure 6 shows an illustration of the stress distribution in composite soil and DDC.

$$\Delta\sigma z = \Delta\sigma s\ (1 - as) + \Delta\sigma c \text{ x as} \quad (8)$$

where as is the area replacement ratio in DDC by Equation 4 and Δσs is the stress that occurs in the soil, Δσc is the stress that occurs in DDC which can be calculated using the Equation:

$$\sigma_s = \mu s \text{ x } \sigma \quad (9)$$

and

$$\sigma_c = \mu c \text{ x } \sigma \quad (10)$$

$$\mu c = \frac{1}{(1+(n-1))\ x\ as} \quad (8)$$

where σ is the vertical load received by the soil, and μc is the stress ratio that occurs in the soil around the DDC.

2.1. Soil Data

Soil data was obtained from the X International Airport project. Some of the data was correlated by using a correlation table [11]. The parameters that would be used in calculating the DDC bearing capacity value can be seen in Table 1 to Table 4.

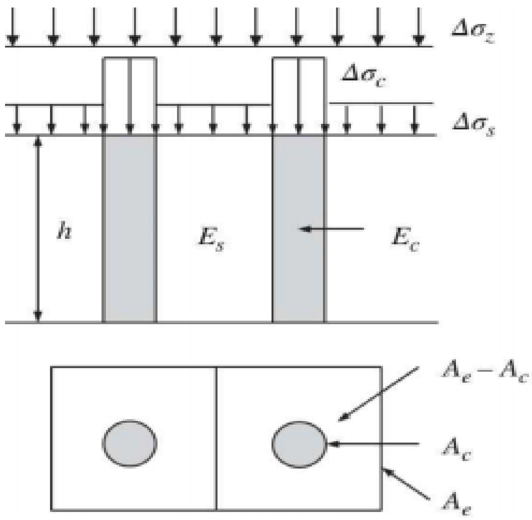


Figure 6. Stress distribution model

Table 1. Soil parameters

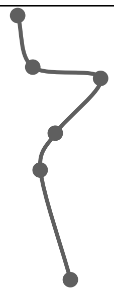
Layers	Soil Type	Soil Description	N-SPT
Layer 1	CH	Fat Clay	
Layer 2	ML	Sandy Silt	
Layer 3	MH	Andesitic Boulder	
Layer 4	CH	Elastic Silt	
Layer 5	ML	Fat Clay	

Table 2. DDC parameters

γ	C	ϕ	v	E	k
kN/m^3	kPa	°		kPa	m/day
22	2	43	0.2	150000	8.64

Table 3. Load data on runway area

Description	Thickness m	Unit Weight kN/m^3	Load kN/m^2
AC - Base	0.085	10.4	0.884
AC - BC	0.09	24.2	2.178
AC - BC	0.075	24.2	1.815
AC - WC	0.06	23.1	1.386
Aircraft Load			5.551
Embarkation Load			82.63
Total			94.44

Table 4. Variations in DDC diameter and spacing

Diameter m	Spacing m
1	2.5
1.2	2.7
1.5	3

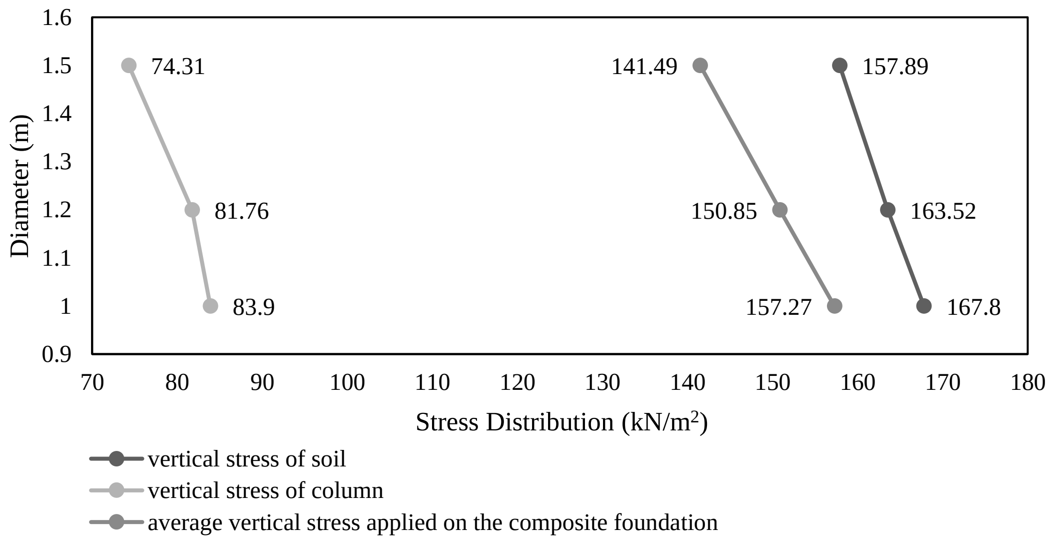


Figure 7. Stress distribution graph

3. Results and Discussion

By using Equations 9, 10, and 11 as previously explained, the results of stress analysis occurring in DDC with variations of 1 m diameter at 2.5 m spacing and 1.2 m diameter at 3 m spacing are presented in Figure 7.

Based on the graph above, the stress experienced by the Down-hole Dynamic Compaction (DDC) due to external loads is directly proportional to the spacing between DDC units. The larger the spacing between DDC units, the greater the stress absorbed by the DDC. The stress experienced by the soil surrounding the Down-hole Dynamic Compaction due to external loads is also directly proportional to the spacing between DDC units. The smaller the spacing between DDC units, the lower the stress transferred to the soil. The minimum stress experienced by the soil surrounding the DDC occurs in the case of a DDC with a diameter of 1.5 m and a spacing of 3 m.

By using Equation 16, the results of the bearing capacity analysis for the Down-hole Dynamic Compaction (DDC) with variations in diameter and spacing between columns are presented in Figure 8.

The value of the bearing capacity is impacted by changes in DDC diameter and spacing between units; greater spacing leads to a reduction in the obtained bearing capacity. According to the analysis based on Barksdale and Bachus theory (1983), the most critical bearing capacity value arises in the DDC with a diameter of 1 m and a spacing of 2.5 m, measuring 1102 kN/m².

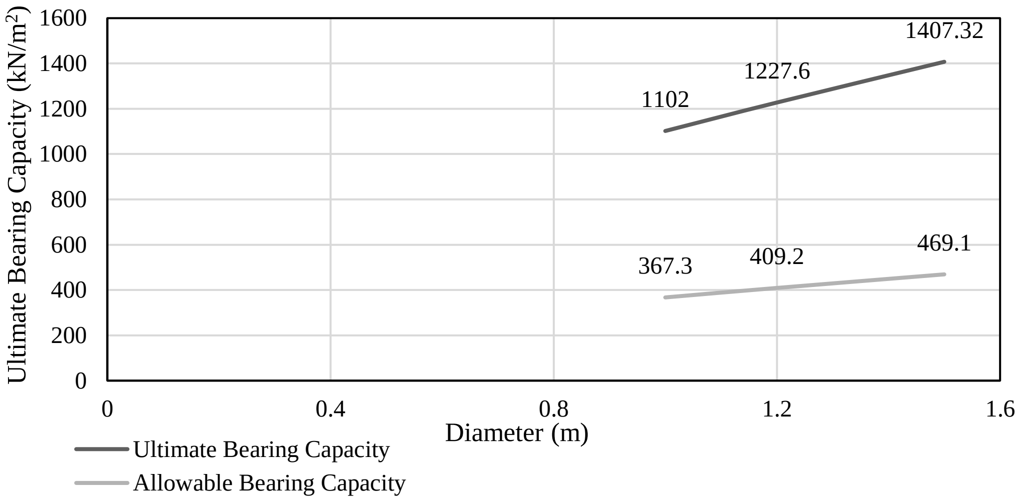


Figure 8. Bearing capacity analysis graph

4. Conclusion

The stress induced by external loads on Down-hole Dynamic Compaction (DDC) rises in correlation with the spacing between DDC installations. To put it simply, as the separation between the DDCs grows, so does the level of stress endured by the DDCs. The peak stress was documented on a DDC unit with a 1-meter diameter positioned at a distance of 2.5 meters from the other DDC units, measuring 83.9 kN/m^2.

The stress encountered by the surrounding soil as a result of external loads and the use of Down-hole Dynamic Compaction (DDC) is in direct correlation with the distance between DDC installations. To put it simply, when the spacing between DDCs increases, the ground undergoes greater stress. The highest stress level was recorded in the soil surrounding a DDC unit with a 1.5-meter diameter, which was positioned 3 meters away from other DDC units, measuring 157.89 kN/m^2.

Variations in both DDC diameter and the spacing between DDCs have an impact on the bearing capacity value. As the diameter of DDC increases, so does the bearing capacity value. The analysis results are consistent with the theory presented by Barksdale and Bachus in 1983, indicating that the highest bearing capacity was achieved when a DDC with a diameter of 1.5 meters was positioned at a distance of 3 meters, resulting in a bearing capacity value of 1407.32 kN/m^2.

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