



Optimization of Dynamic Compaction Procedure for Sandy Soils

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ABSTRACT: Dynamic Compaction (DC) is employed as a simple and economical method to improve weak soils in the last few decades. DC is usually applied for granular soils by falling a heavyweight (up to 40 tons) from a height (up to 40 m) at regularly spaced intervals. Significant issues in DC are the weight and height of the tamper, compaction pattern and the distance between tamping locations. Incorporated innovation in this paper is to introduce an analytical approach to optimize the compaction pattern and DC variables regarding regular constraints. The required energy for compaction is evaluated for square and diamond patterns. DC optimization is a non-linear and non-convex problem due to nonlinear equations in soil compaction behavior. Thus, a metaheuristic approach (Genetic Algorithm) is employed to find global optimum. The optimum answer presents the minimum compaction energy in each pattern. Results indicated that the maximum allowed values of tamper mass and the number of tamper drops were required to minimize compaction energy. The ratio of compaction energy at diamond pattern to square one was also found to be about 0.75 to 0.90 for the same compaction conditions.

Keywords: Dynamic Compaction, Ground Improvement, Optimization, Sandy Soils.

1. Introduction

Soil improvement techniques improve the engineering properties of soil, like strength, stiffness, and permeability (Anand and Sarkar, 2021; Ghanbari and Bayat, 2022; Sahlabadi et al., 2021; Haghbin and Ghazavi, 2016; Salehi et al., 2021). Soil compaction is widely used in geotechnical projects to reduce the foundation and construction and/or any unexpected risks. During civil projects, geometrical compaction is essential in reducing the

inter-granular porosity to reach a high relative density (Ghassemi and Shahebrahimi, 2020; Mehdipour and Hamidi, 2017; Paranthaman and Azam, 2022; Raja and Thyagaraj, 2020; Silveira and Rodrigues, 2020). Dynamic Compaction (DC) is a relatively traditional and old-fashioned method introduced by Menard and Broise (1975) and was applied to improve the granular soils only. The DC technique is a type of ground improvement method that involves the repeated high-energy impacts to the soil surface using a

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heavyweight (up to 40 tons) with drop heights from 10 m to 40 m. Previous studies revealed that DC technique could be widely used to stabilize loose granular materials and waste landfills to its ease of implementation, economically competitive and environmentally safe (Gu and Lee, 2002). Obtaining soil improvement in quantitative engineering units during the DC has been a challenge with various techniques used in previous studies (Adam et al., 2007).

Feng et al. (2000) used a conical-based pounder to improve the efficiency of DC. The results of laboratory DC tests showed that the efficiency of the used DC method depends on both the grain size distribution and the volumetric response of the sand. The same results have been reported for a conical pounder by Arslan et al. (2009). Hu et al. (2001) studied the effect of DC on the shear strength characteristics of loess. The experimental results revealed that the shear strength of loess increased with the number of drops and after a peak value, the shear strength decreased. Shen et al. (2018) studied the influence of DC on liquefaction potential of silty sand. The effect of DC on liquefaction potential was evaluated using CPTs before and after DC. There is nowadays a renewed interest in DC due to its advantages over other types of soil improvement techniques (Feng et al., 2010, 2015; Ghassemi et al., 2010; Li et al., 2011; Wang et al., 2013; Zhang et al., 2019).

Feng et al. (2017) presented a method of modeling preloading consolidation with drains and dynamic compaction in a centrifuge using a 3D printing technique. This method performed well in predicting the surface settlement, excess pore pressure and effective pressure, number of drops, and improvement depth by DC. So far, several models have been introduced for DC technique in the previous studies which were developed primarily based on several in situ experiences and physical modeling tests (An et al., 2020; Chen et al., 2019). However, previous studies mainly focused on the research of single-location tamping

but the influence of adjacent tamping locations and the multi-location tamping has not been widely considered (Feng et al., 2010, 2013; Ménard and Broise, 1975; Wang et al., 2013). Experimental studies of multi-location tamping consider the interaction between the adjacent tamping locations, which helps understand the soil behavior in response to the impact of tampers during DC procedure.

The effective depth of DC or the depth of improvement as the affected depth during compaction is a key parameter for designing the DC procedure. The improvement depth was usually predicted using empirical correlations in the practical design procedure (Scott et al., 2021). Ménard and Broise (1975) proposed Eq. (1) to estimate the improvement depth based on the energy per drop.

$$Z = n\sqrt{MH} \quad (1)$$

where n : is an influential factor in the sense of depth of improvement. Also, M , H and Z : are tamper mass, drop height and improvement depth of soil. This equation was modified later by other researchers.

Over the last several years, there have been quite extensive studies to identify appropriate values of n , ranging from 0.3 to 1 depending soil types (Mostafa and Liang, 2011). Zou et al. (2008) proposed an equation to estimate Z depending on the tamper mass and area, the falling height, the number of tamper drops, the dry unit weight and water content of soil. Oshima and Takada (1999) conducted a series of centrifuge tests to analyze Z values. Based on the results of centrifuge tests, Z was considered as the depth at which the relative density (D_r) of the soil increases by more than 5%. Oshima and Takada (1999) carried out a series of geotechnical centrifuge tests to evaluate the compacted areas of multi-location tamping. Based on the test results, the soil-improvement zone with depth Z and radius R was defined according to Figure 1.

The depth and radius of the soil-improvement zone were described by Eqs. (2) and (3) proposed by Oshima and Takada

(1999).

$$\begin{aligned} Z &= a_z + b_z \log(M \times \sqrt{2gH} \times N) \\ &= a_z \\ &\quad + 0.434b_z \ln(M \\ &\quad \times \sqrt{2gH} \times N) \end{aligned} \quad (2)$$

$$\begin{aligned} R &= a_R + b_R \log(M \times \sqrt{2gH} \times N) \\ &= a_R \\ &\quad + 0.434b_R \ln(M \\ &\quad \times \sqrt{2gH} \times N) \end{aligned} \quad (3)$$

where N and g : are the number of tamper drops and earth gravitational acceleration. Also, a_z , b_z , a_R and b_R : are the empirical constants.

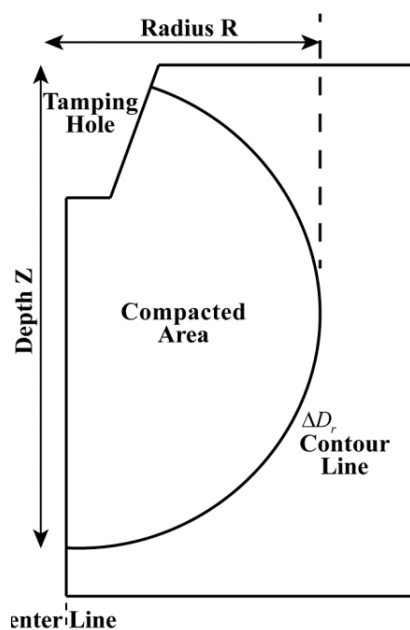


Fig. 1. Dimensions of the soil-improvement zone (Oshima and Takada, 1999)

Earlier studies mainly focused on the test results such as shear wave velocity measurement (V_s), Standard Penetration Test (SPT), and Cone Penetration Test (CPT) before and after DC which were applied widely in the site investigation (Du et al., 2019; Feng et al., 2010; Ménard and Broise, 1975). For example, Chow et al. (1992) studied the effect of print spacing (distance between tamper locations) on the degree of improvement in DC. Based on the results, an approach to estimate the improvement radius of the soil-improvement zone was presented based on assessing the degree of improvement by the increase in friction angle of granular soils.

The estimation of the friction angle was derived from indirect empirical correlation with CPT measurement.

Optimization techniques in Civil Engineering for reducing the time and cost of projects have attracted the interest of many researchers worldwide (Bağrıaçık et al., 2020; Biabani et al., 2022; Fazli, 2022; Hosseini et al., 2022; Kalantary and Kahani, 2019; Kaveh and Zaerreza, 2022). In recent years, many studies have been conducted on optimizing dynamic compaction design using various methods such as fuzzy logic and artificial intelligence (Pasdarpour et al., 2009). In the field of optimization approaches, the Genetic Algorithm (GA) is a well-known optimization method initiated by Holland (1992) and developed by Goldberg (1989). As a member of the family of metaheuristic algorithms, GA is constructed based on the Darwinian evolution theory. It is appropriate especially for non-convex and non-linear optimization problems, where traditional gradient-based algorithms do not have a satisfactory performance to find global optimum. Details of GA procedure may be found in many literature (Holland, 1992). Pasdarpour et al. (2009) presented a fuzzy-GA methodology for the optimal design of soil dynamic compaction. The results indicated that the GA produced the optimal design of soil dynamic compaction. An et al. (2020) studied the optimization of DC design to minimize the remaining compaction time using a Compaction Process-Dynamic Optimization Method (CPDOM) based on the GA. The results proved that CPDOM may be employed for civil engineering projects. Wang and Yin (2020) presented a model to predict the soil compaction parameters using Multi-Expression Programming (MEP). The validity analyses of the model indicated that the proposed model could be used for various soil types with high accuracy.

Wang et al. (2013) based on the experimental results indicated that DC frequency was an important parameter in soil densification. Wu et al. (2020) carried

out a large-scale field test to study vibration velocities from dynamic compaction of granular soil. The results indicated that the soil-improvement zone was roughly cylindrical with the same diameter as the tamper, located immediately beneath the tamper.

As mentioned, DC has been studied a lot during the past decades. However, this study aims to introduce an innovative approach to optimize the pattern and design variables incorporated in DC. Required relations for the simulation of DC were employed based on the proposition of Oshima and Takada (1999) according to Eqs. (2) and (3). The optimization problem consists of minimizing the required energy for DC by properly selecting patterns and related variables since certain practical constraints must be satisfied.

2. Materials and Methods

Proper simulation of soil compaction is essential to optimize the pattern and related variables of DC. The proposed equations by Oshima and Takada (1999) were employed in this study. The equations were presented to determine both of the depth and radius of the compacted zone. The compacted bubbles inside the soil were estimated for any combination of tamper mass, drop height and the number of drops. Proper choosing of the pattern and distances between tamping locations is needed for efficient and economical DC operation.

The intersection of adjacent compaction bubbles is presented in Figure 2 to consider the compacted zone between two adjacent tamping locations. This study assumes that the compaction characteristics at all tamping locations are the same. The intersection of two bubbles is taken place in the depths equal to Z' and Z'' according to Figure 2, where the common zone between bubbles has enough compaction. As shown by Figure 2, Z' and Z'' are the distance of the ground surface from the intersection point of the two bubbles at the bottom and upside of the bubbles, respectively. Evidently, the depths of Z' and Z'' depend on the horizontal

distance between tamping locations (KR). These depths may be determined in terms of KR , where K is a coefficient between 1 and 2 theoretically and R is introduced in the previous section. The values below about 1.2 for K is not economical while “ $K = 2$ ” means two adjacent compaction bubbles are tangent to each other.

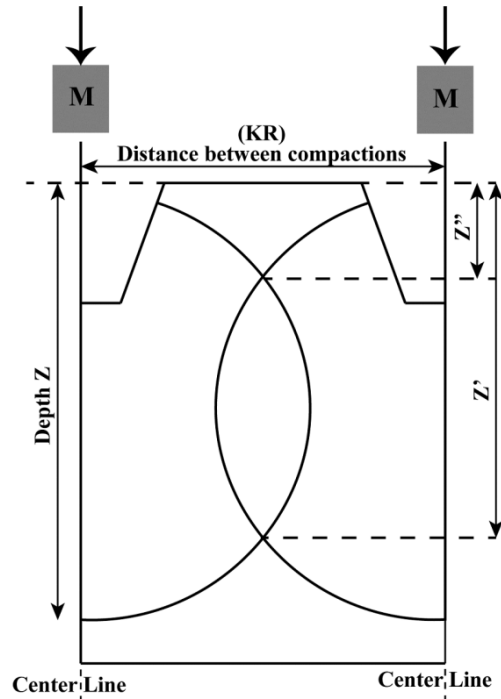


Fig. 2. Intersection of adjacent compaction bubbles with distance KR

Intersection points on the boundary of bubbles were employed to estimate the values of Z' and Z'' in terms of KR . For this purpose, 15 different values were chosen for K between 1.2 and 2 and the adjacent bubbles were drawn for each case. The values of Z' and Z'' were measured for each value of K and, as a result, 15 pairs of (K, Z') and (K, Z'') were obtained. After eliminating R in relations among KR , Z' and Z'' , the equations are estimated by fitting a quadratic function on the results. Finally, the relation of K' and K'' versus of K were calculated by Eqs. (4) and (5), respectively. These equations are required during the optimization procedure.

$$K' = -1.47K^2 + 4.14K - 1.35 \quad (4)$$

$$Z' = K' \times R$$

$$K'' = 1.54K^2 - 4.33K + 3.55 \quad (5)$$

$$Z'' = K'' \times R$$

Another issue during DC is the compaction pattern. Generally, two patterns of square and diamond were employed in this study according to Figures 3 and 4.

The distances between tamping locations in Figures 3 and 4 were selected so that the maximum distance between adjacent tamping locations was KR and, as a result, required compaction was met for any point of the land along of the X or Y direction. For each square or diamond pattern case, all distances between tamping locations were depicted. The number of tamping locations inside the land was also calculated according to Eqs. (6) and (7) for the square and diamond patterns, respectively. These numbers were required to compute the total compaction energy in each pattern. It is obvious that “NC” is a nonlinear function in terms of “R” and “K” in both cases of

square or diamond patterns. Eqs. (6) and (7) were obtained employing Figures 3 and 4 by multiplying the number of rows and columns of tamping locations. The number of rows and columns is calculated by dividing the total length of land in any direction by distances between tamping locations. In square pattern, a distance equal to $0.5KR$ exists between tamping locations and the boundary of land. The distance value on each side should be subtracted from the total amounts of X or Y before division. In the diamond pattern, the available distance is different for hollow and solid circle signs and is indicated precisely in Figure 4. It is essential to remember that solid and hollow circle signs are the same regarding compaction properties and the distinction is just for facilitating their enumeration.

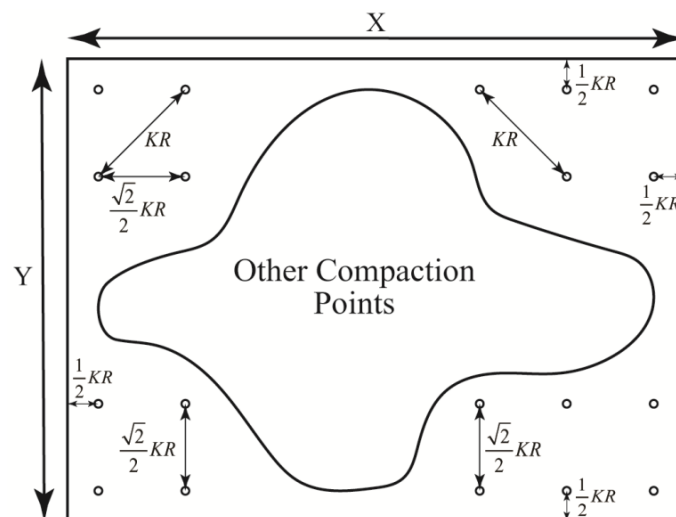


Fig. 3. Square compaction pattern and the distances between tamping locations

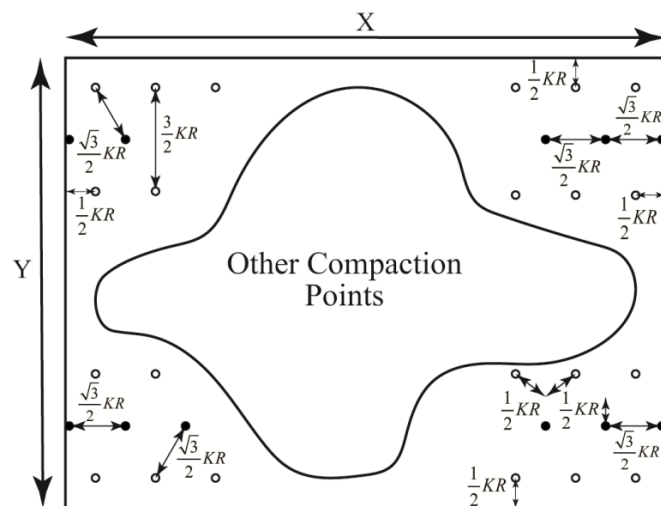


Fig. 4. Diamond compaction pattern and the distances between tamping locations

$$\begin{aligned}
NC_{Square} &= n_1 \times n_2 \\
&= \left(\frac{Y - KR}{\frac{\sqrt{2}}{2}(KR)} + 1 \right) \times \left(\frac{X - KR}{\frac{\sqrt{2}}{2}(KR)} + 1 \right) \quad (6)
\end{aligned}$$

$$\begin{aligned}
NC_{Diamond} &= n_1' \times n_2' + n_1'' \times n_2'' \\
&= \left(\frac{Y - KR}{\frac{3}{2}KR} + 1 \right) \times \left(\frac{X - KR}{\frac{\sqrt{3}}{2}(KR)} + 1 \right) \\
&\quad + \left(\frac{Y - 2\left(\frac{5}{4}KR\right)}{\frac{3}{2}KR} + 1 \right) \times \left(\frac{X}{\frac{\sqrt{3}}{2}(KR)} + 1 \right) \quad (7)
\end{aligned}$$

In this paper, the objective function is assumed to required energy (or cost, equivalently) of DC according to Eq. (8). The decision variables in the optimization problem are tamper mass (M), drop height (H), the number of drops in each point (N) and the number of tamping locations in the whole land (NC).

$$\text{Minimize}(F = NC \times N \times M \times g \times H) \quad (8)$$

where H , M and N are forced to be integer numbers in this study according to practical applications. Value of N is restricted to 120 to facilitate the optimization procedure; however, there is no limitation in practical applications.

Regular constraints incorporated in optimization problems are according to Eqs. (9) to (15).

$$Z'' \leq Z' \leq Z \quad (9)$$

$$\text{Reiured Depth for Compaction} \leq Z' \quad (10)$$

$$0.5m \leq Z'' \leq \text{Foundation Depth} \quad (11)$$

$$5\text{tons} \leq M \leq 40\text{ tons} \quad (12)$$

$$10m \leq H \leq 40\text{ m} \quad (13)$$

$$N \leq 120 \quad (14)$$

$$1.2 \leq K \leq 2 \quad (15)$$

where *Foundation Depth*: is the depth that the foundation is constructed and the *Required Depth for Compaction*: is the

depth that a specified amount of compaction (ΔD_r) is required and is undoubtedly more than the foundation depth. The study driven by Oshima and Takada (1999) is one the few ones that considered the influence of “ M ”, “ N ” and “ H ” on the dimension and degree of compaction in sandy soils. The dimensions of compacted bubbles and the degree of compaction in terms of different values of “ R ” and “ Z ” are investigated. This study was performed experimentally and the results were assumed valid for our study.

Solving the optimization problem within Eqs. (8) to (15) requires efficient algorithms to conquer the non-convex and non-linear nature of the problem. As a well-known metaheuristic optimization method, GA is one of the best choices. This research used Solver Add-in in Microsoft Excel package to implement GA where required parameters were adjusted before starting the solution. Objective function and constraints were defined in solver, while the population size in each generation and other GA parameters were regulated. Population size and mutation rate were equal to 200 and 0.075, respectively.

The main advantage of the GA is moving toward the global extremum in a non-convex problem. However, there is no guarantee to achieve the global extremum, exactly. As a result, a gradient-based algorithm is required to get the GA answer as an initial guess and continue the search process. In the current study, Generalized Reduced Gradient (GRG) method available again in Solver Add-in was employed to improve the GA results. GRG gets the near-optimum answers obtained by GA and converges to exact value of global extremum. Initial GA cooperation is essential because GRG needs help finding global extremum. Generally, gradient-based algorithms like GRG may be trapped in local extremum without support of metaheuristic algorithms. This paper’s main objectives are to examine the proposed method’s effectiveness and compare the square and diamond compaction patterns.

For this purpose, four square lands with dimensions of 30 m, 50 m, 100 m and 200 m were assumed, and the total required compaction energy was calculated.

Sensitivity analysis was also performed according to Eqs. (16) and (17) to show the influence of different parameters on the depth and radius of the compaction zone. Differentiating of Z and R in terms of M , N and H is performed by applying Eqs. (2) and (3).

$$dZ = \frac{\partial Z}{\partial M} dM + \frac{\partial Z}{\partial N} dN + \frac{\partial Z}{\partial H} dH$$

$$= 0.434b_z \left(\frac{dM}{M} + \frac{dN}{N} + \frac{dH}{2H} \right) \quad (16)$$

$$dR = \frac{\partial R}{\partial M} dM + \frac{\partial R}{\partial N} dN + \frac{\partial R}{\partial H} dH$$

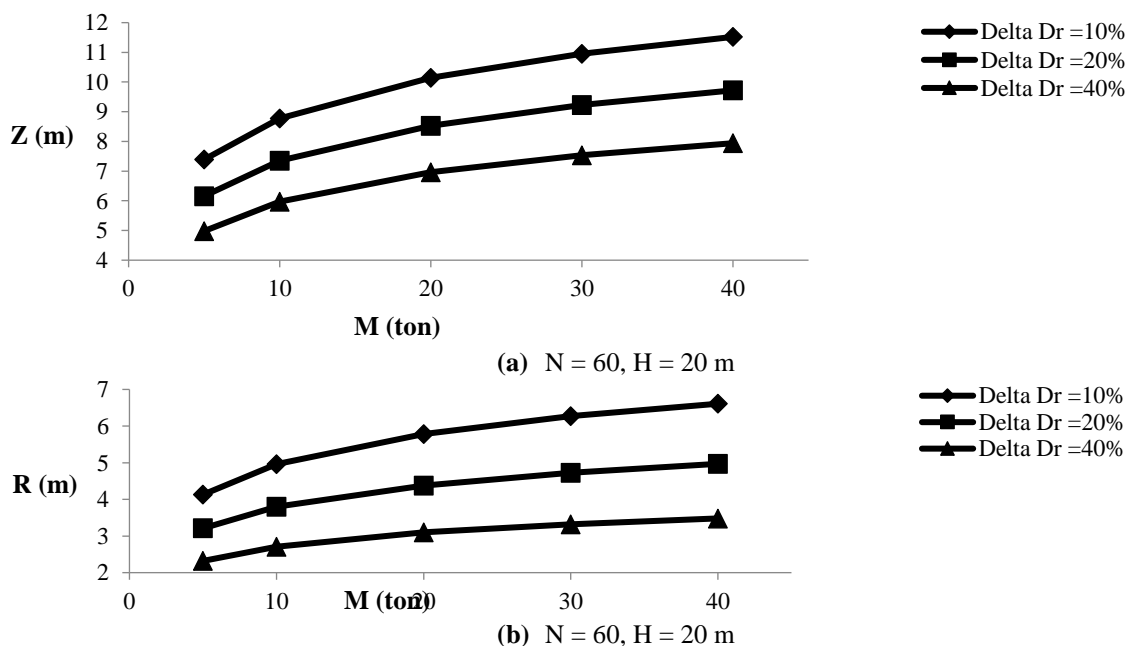
$$= 0.434b_r \left(\frac{dM}{M} + \frac{dN}{N} + \frac{dH}{2H} \right) \quad (17)$$

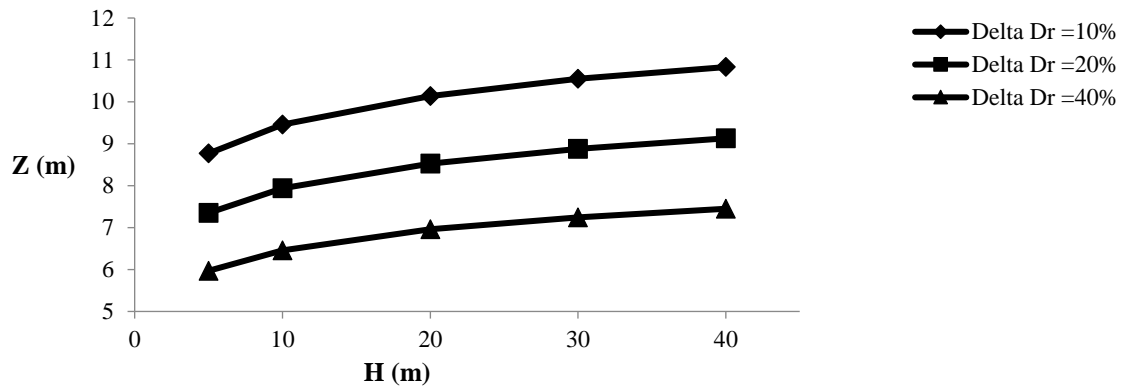
3. Results and Discussion

Before considering the optimization results, it is appropriate to analyze the variation of Z and R in terms of three influential variables of M , H and N . This analysis specifies each variable's impact on the compacted zone's depth and radius. Figure 5 is drawn according to Eqs. (2) and (3) for

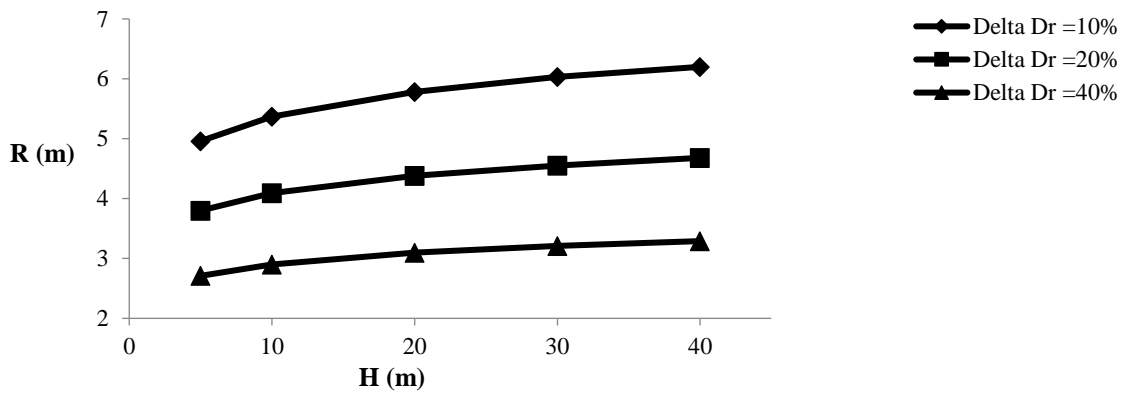
cases ΔD_r equal to 10%, 20% or 40%. The values of a_z, b_z, a_r, b_r are based on the proposed values by Oshima and Takada (1999). As expected, the least required compaction ($\Delta D_r = 10\%$) results in the largest amounts of Z and R and vice versa.

Figure 5 indicates that H has a minor influence on the depth and radius of the compaction zone when compared to other variables. This is induced regarding the relatively horizontal curves for variation of Z and R versus H in Figures 5c and 5d which also is concluded from the results of sensitivity analysis obtained by Eqs. (16) and (17). The reason is the small value for the coefficient of dH in Eqs. (16) and (17) because of the presence of "2" in the denominator of the coefficient. On the other hand, variables M and N are more effective than H to increase the depth and radius of compaction zone. The steep curves of Z and R versus M and N indicate the influential nature of these variables in improving the compaction zone. Considering Eqs. (16) and (17), it is concluded that M is even more effective than N . The reason is that usually, dM has a larger coefficient than dN . In other words, the values of N are normally more than M (in terms of tons) and thus $(1/M > 1/N)$. However, the tamper mass M may have some limitations to implement in practical applications.

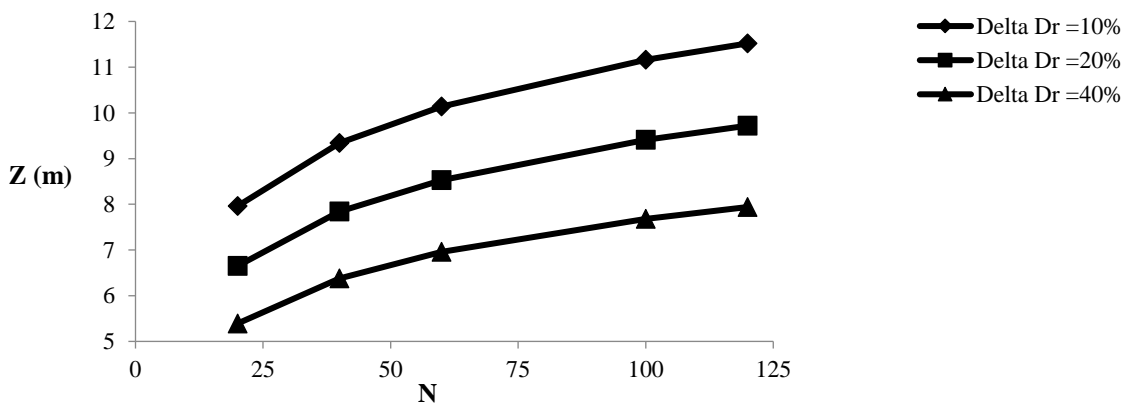




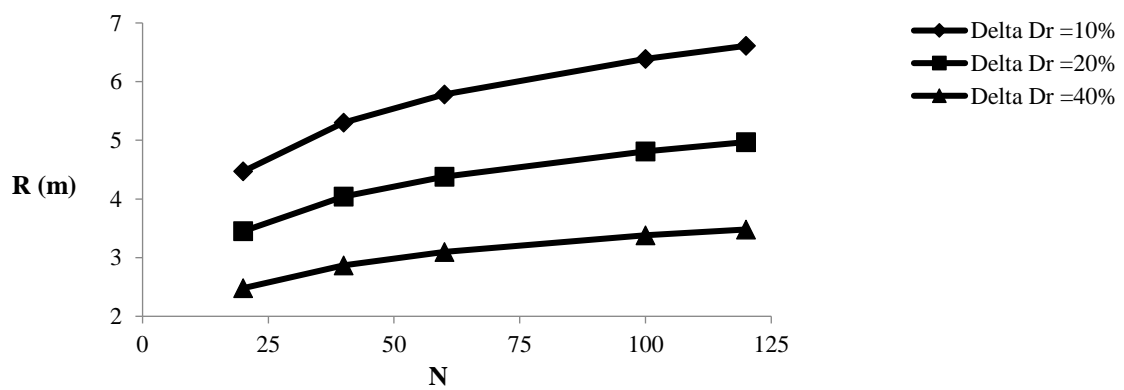
(c) $N = 60, M = 20$ t



(d) $N = 60, M = 20$ t



(e) $M = 20, H = 20$ m



(f) $M = 20$ t, $H = 20$ m

Fig. 5. Variation of depth and radius of compacted zone in terms of the effective DC variables: a) Z vs. M ; b) R vs. M ; c) Z vs. H ; d) R vs. H ; e) Z vs. N ; and f) R vs. N

Calculating the minimum required energy for compaction in each square and diamond pattern case and comparing them is another objective of this study. It is apparent that compaction energy is dependent on parameters like Z' , Z'' and ΔD_r , where more values for parameters Z' or ΔD_r cause more required energy. Small value of Z'' on the other hand needs more tamping locations and thus more energy. However, a minimal value of Z'' may cause an infeasible situation in the solution procedure. Generally, infinite combinations of Z' , Z'' and ΔD_r may occur. As a typical example, Table 1 indicates the obtained values of DC optimization for $Z' = 6$, $Z'' = 2$ and $\Delta D_r = 40\%$. The results show that the preferred value for M is the maximum practical (40 tons here). The optimum value for N is also the maximum assumed value in the problem. However, in some cases, the value for N has a slight deviation from the maximum. It seems it is taking place because only integer values for M , N and H are allowed. The optimum values of M and N are the maximum allowed ones because of the larger coefficients of dM and dN to improve dZ and dR in Eqs. (16) and (17).

Another important point regarding Table 1 is the efficiency of the diamond pattern compared with square one. Results indicate that ratio of the required energy of diamond to the square pattern is between 0.75 and 0.9; however, no regular trend is observed in terms of land dimension. It seems that the diamond pattern is more effective than the square one due to better interlock of compaction bubbles in each other.

The proposed approach in this study is

quite analytical and is performed based on the empirical equations obtained by Oshima and Takada (1999). As a result, the verification phase has no sense here, and optimization results are valid for all cases.

4. Conclusions

This paper presented an innovative method to implement dynamic compaction so that minimum compaction energy is consumed while required constraints are satisfied. For this purpose, the DC problem was formulated regarding all physical and practical constraints. The depth and radius of the compacted zone were estimated for a single tamper. Then, extra equations were developed to determine the intersection points of compaction bubbles. Afterwards, the best values for horizontal distances between tamping locations were determined to satisfy compaction requirements specified by the operator. Obtaining the best horizontal distances needs to solve a non-linear and non-convex optimization problem. Generally, finding the global optimum in a non-convex problem is a challenge. To overcome this challenge, a combination of metaheuristic (GA) and gradient-based (GRG) algorithms was employed. All calculations were performed for two compaction patterns of square and diamond. A sensitivity analysis was also performed to identify the impacts of influential variables on the DC procedure. The impacts of variables were compared and some discussion about the range of each one was presented. Finally, the main obtained points are as follows.

Table 1. Obtained DC variables for various land dimensions for $Z' = 6$, $Z'' = 2$ and $\Delta D_r = 40\%$

Land dimension (m × m)		30×30	50×50	100×100	200×200
Square pattern for DC	K	1.483	1.476	1.448	1.455
	N	120	119	120	117
	H (m)	19	19	18	19
	M (ton)	40	40	40	40
	F (MJ)	32197	107316	488042	2093690
Diamond pattern for DC	K	1.469	1.429	1.487	1.467
	N	118	119	120	118
	H (m)	19	18	19	19
	M (ton)	40	40	40	40
	F (MJ)	25504	96627	374740	1602377

Tamper mass (M), drop height (H) and the number of drops in each tamping location (N) affect the radius and depth of the compacted zone. The compaction energy is enhanced by increasing each of these variables. However, the tamper mass and the number of drops in each tamping location are the most effective variables for increasing the radius and depth of compacted zone while the drop height is the least effective one. It is required to note that tamper mass and drop height have some practical limitations, while the number of drops has no such limitation. The required energy (or equivalently cost) for DC in a diamond pattern is about 75% to 90% of the energy of a square pattern, for the same conditions of compaction. Applying the following results may benefit operators economically during DC, especially in large projects.

- The optimum value for K is between 1.4 and 1.5 in all cases.
- The optimum value for M is the largest practical value in all cases.
- The optimum value for N is the largest allowable value. However, in some cases the maximum values of N are not obtained due to the integer variables incorporated in the problem.
- The optimum value for H is about 18 m to 19 m for DC operations with dimensions near to the values of this study. This value is almost half of the maximum allowed value for H . It seems the reason is the presence of number "2" in the denominator of the coefficient of dH within sensitivity analysis equations.

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