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Manuscript Title:

Effective usage of poker vibrator for compacting quarry dust: An application to ground improvement in shallow foundation design

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Abstract

Appropriate ground improvement is required to stabilize soil under shallow foundations when there is a high groundwater table or weak soil. In such situations, a granular material like sand or quarry dust is widely used in the construction industry as a filling material to achieve higher bearing strength and to minimize settlement underneath foundations. Quarry dust, which is a waste product of the crushing process, is more economical and environmentally friendly. According to existing studies, quarry dust can be easily compacted by providing a vibration effect and a poker vibrator is a practical approach that can be used to achieve high degrees of compaction in quarry dust. However, as this technique is still quite novel to the industry, the expected results, in terms of degree of compaction, cannot be guaranteed. This is basically due to inappropriate practice and lack of guidance in the application of poker vibration. It is therefore essential to eliminate inappropriate practice by carrying out laboratory experiments on optimum poker vibration application techniques.

The aim of this study was to optimize the effectiveness of poker vibrator in shallow foundation design by studying various factors affecting it, including time of application, shape of the foundation, preferable layer thicknesses and patterns of application of poker vibrators. This was done by conducting a series of poker vibration compaction experiments in circular and square containers and then by assessing the variation of degree of compaction in each trial. According to the test results, the most effective period of compaction for poker vibration comes at around 30 s after the compaction commences and lasts up to around 10 s. Degrees of compaction (DOC) in both circular and square containers increase with increasing application points, because the higher the number of vibration points, the more the compaction process is enhanced. The application of vibrator at the middle gives a relatively higher DOC than application at corners, because the vibration of middle area affects a greater area in the quarry dust fill compared to vibrating from a corner. DOC reduces with increasing

initial layer thickness, regardless of pattern, because reduction of the layer thickness causes the vibration applying dust thickness to be reduced, which causes more vibration to the dust in the entire layer. The best poker vibration application pattern was also investigated.

Keywords: *Ground Improvement, Shallow Foundation, Quarry Dust, Poker Vibrator, Degree of Compaction (DOC)*

1 Introduction

Since shallow foundations are greatly affected by the properties of the underlying soil, an important part in the construction of shallow foundations is the improvement of the underlying soil profile. Ground improvement is defined as the in-place controlled enhancement of ground materials to form part of the geotechnical construction system (Welsh, 1991). However, this should be carefully done, in order to satisfy two design criteria: 1) soil settlement should be within the acceptable range, and 2) weak soil layers should be strengthened sufficiently to safely bear the transferred load from the superstructure (Schmertmann, 1970). Several procedures or techniques are available for the interpretation of the bearing capacity and settlement behaviour of saturated soils (Poulos and Davids, 2005).

The technique, which can be used to improve the ground profile, is dependent on various factors, including soil type, level of groundwater table and foundation type. To date, many ground improvement techniques have been utilised, including consolidation and pre-loading, chemical treatment, static and dynamic compaction (Chu and Yan, 2005). However, dynamic compaction is probably the most preferred ground improvement technique in granular soils, as it is usually the most economical solution (Mitchell and Katti, 1981).

According to existing findings (Shahriar et al., 2013), a major problem in the process of ground improvement in shallow foundation design is the presence of soil layers with low strength parameters and high water tables close to the surface. In order to overcome the issue of weak soil layers, weak soil layers should be removed to a sufficient depth and the space should then be filled with a suitable cohesion-less high-strength granular soil under sufficient compaction (Das, 1988). To find the solution for the latter case, dewatering should be carried out to lower the water table during the construction period, and techniques such as water-tight structure systems can be used to minimize the vulnerability of the structure to water (Barry and Roy, 2013).

Apart from the traditionally used techniques, currently an effective and economical novel method is being adopted in the construction industry to overcome the issue of weak soil layers in shallow foundation construction; replacement of the upper soil layers with a granular material (Tiwari and Kumawat, 2014) like sand or quarry dust. According to Satyanarayana et al. (2013), both quarry dust and sand particles have more shear strength under a wider range of moisture contents and they can achieve higher dry densities. Hence, they can withstand high strengths and can be used as fill and sub-grade material.

However, since there is a scarcity of sand due to rapid construction, quarry dust may be a better replacement material in the ground improvement process (Ilangovana et al., 2008). Quarry dust is an eco-friendly and economical granular material, as it is a waste product of the crushing process, and can be used successfully to improve the ground profile without compromising the strength characteristics (Vijayabharathi et al., 2013). According to Onyelowe et al. (2012), quarry dust with appropriate moisture content and compaction, can achieve a greater degree of compaction, due to the rough, sharp and angular particles. These lead to the creation of a higher degree of compaction (DOC) through the better interlocking between particles. Sridharan et al. (2006) also identified that quarry dust has high shear strength and this is beneficial for its use as a geotechnical material.

After replacing the weak soil layers with quarry dust, that layer should be effectively compacted to allow minimum settlement. According to Drnevich et al. (2007), this cannot be achieved using the traditional compaction techniques and the utilisation of more effective vibrating techniques offers much greater degree of compaction. Among the various vibration techniques, the poker vibrator has been identified as a better option that can be used under saturated conditions, to achieve a greater degree of compaction in quarry dust. The poker vibrator can operate efficiently below groundwater, thus compacting soils normally inaccessible without drainage (Griffith, 1991). It is also a cost-effective technique, as it minimizes power consumption and the manpower required. However, there are no current valid guidelines or procedures on the use of poker vibrators to compact quarry dust, as few studies have been performed on this to date (Aziz et al., 2009). Therefore, the concept was initiated to conduct experiments on the use of this material and technique, to improve the bearing capacity of shallow footings on weak soil.

In field projects, this poker vibration technique is performed based on the experience of skill workers such as the officer in-charge at the site. However, this cannot guarantee optimum compaction and may not achieve the required degree of compaction in all cases. This is mainly due to the lack of knowledge and experience and the resultant inadequate guidance/practice. These issues can only be overcome by conducting comprehensive research on the topic and applying the knowledge obtained to introduce professional and precise guidelines.

According to Aziz et al., (2009), the quarry dust filling method is more applicable for shallow foundations with circular, rectangular or square individual footings, and the largest dimension should be less than 1.5 m. This led to the conduct of experiments using containers with diameters and widths of around 1 m. Further, the existing experimental studies have been performed under fully saturated conditions, because of the difficulties in controlling the moisture content. This is reliable, as in most practical situations, this technique is widely used when the water table is high. The saturated condition under shallow foundations is the most critical state, since the bearing strength of soil reduces greatly due to saturation. In other words, in the submerged case, soil foundation systems exhibit reduced bearing capacity (Pande et al., 2014). Agarwal and Rana (1987) conducted tests to assess settlement on square footings of three different sizes. Their results revealed that settlement approximately doubles when the soil is submerged. Murtaza et al. (1995) and Morgan et al. (2010) made similar conclusions regarding settlement. Therefore, it was proposed to conduct the experiments under saturated conditions.

As stated by Glover (1982), in the mid 1930's, Russian émigré, Stevermann and Degen had an idea for compacting cohesion-less soils, both above and below the water table. Both of them agreed the method would achieve effective compaction only if the vibrator was placed in the soil at the location where the compaction was required. The vibratory equipment would have to be in direct contact with the soil while emitting its' vibratory forces. These issues/concepts were taken into consideration when carrying out experiments to create ideal experimental conditions as close to practical situations as possible.

However, to date, few comprehensive experimental studies have been reported on the use of quarry dust in ground improvement, incorporating the effect of by various factors. It is therefore essential to study the optimum applications of poker vibrator for compacting quarry dust by carrying out laboratory experiments and then, eliminate inappropriate practice. Thus, the present study experimentally evaluates the optimum methods of using the poker vibrator to compact quarry dust by changing various parameters, including layer thickness, application time, different patterns, and the shape of the container. The conduct of this parametric study will assist in identifying the most advisable applications of poker vibrators to achieve optimum compaction in quarry dust and make possible more effective guidance to optimize current construction practices.

2 Methodology

The main objective of this study was to propose new guidelines and methods to optimize the current construction practices in the application of poker vibrators for the compaction of quarry dust, based on the results of a series of experiments. In order to achieve this objective, the degree of compaction in quarry dust under various conditions was examined by changing different parameters, such as the shape of the container, layer thickness, time of application of poker vibrator and the pattern of use.

2.1 Idealization and special considerations

Typically, excavations for shallow foundations are circular or square. Therefore, similar shaped containers were used in the experiments, as illustrated in Fig. 1 and the diameter and width of the containers were approximately 1 m. Since the containers were made of rigid material (fibre and concrete), they can be considered as similar to the boundaries in footing excavations in the ground, where the excavated surface is relatively rigid compared with the filling material.

Quarry dust was first placed on the containers in the loose state, and no effort was made initially to compact the dust, prior to the compaction provided by the poker vibrator. All the experiments were conducted under saturated conditions, because quarry dust is used as a filling material at sites where the water table is close to ground level.

As shown in Fig. 1, a common poker vibrator used in many construction sites was then used to apply the required vibration and the vibrator was applied in a manner similar to that used in most practical situations.

Figure 1. Application of poker vibrator in both circular and square containers, under saturated condition

After compaction, the free surface was carefully scraped to make it approximately horizontal. A steel rod was used to measure the average depth of the quarry dust. Depths from several locations were measured to obtain the average value.

2.2 Determination of field dry density in each trial

The total wet weight *(W_{wet})* of the quarry dust was measured before placing it into the container and the dry weight *(W_{dry})* of the quarry dust was obtained by measuring the average moisture content *(M_0)* of the sample*;*

$$W_{dry} = \frac{W_{wet}}{1+M_o} \qquad [1]$$

Since both the circular and square containers were rigid, the sectional areas were considered to be constants, so that the volume of compacted quarry dust could be determined by measuring the average depth *(d_{avg})* of quarry dust after compaction *(V_{avg})*.

Volume of the sample in circular container:

$$V_{avg} = \frac{1}{4}.\pi.D^2{}_{avg}.d_{avg} \qquad [2]$$

Volume of the sample in square container:

$$V_{avg} = l_{avg}{}^2.d_{avg} \qquad [3]$$

Where, V_{avg} is the volume of the compacted quarry dust sample remaining in the container, d_{avg} is the average depth of the quarry dust sample after compaction, D_{avg} is the average diameter of the circular container and l_{avg} is the average length of an edge of the square container.

Field dry density *($\gamma_{dry,field}$)* can be obtained by knowing the dry weight of the quarry dust and the average volume of the sample after compaction:

$$\gamma_{dry,\,field} = \frac{W_{dry}}{V_{avg}} \qquad [4]$$

Finally, after calculating the field dry density in each trial and the maximum dry density from the standard Proctor compaction test, the degree of compaction (DOC) can be determined in each trial:

$$DOC = \frac{\gamma_{dry,field}}{\gamma_{dry,\max}} \times 100\% \qquad [5]$$

2.3 Variation of parameters

The parameters to be varied were selected following a comprehensive literature review, and the highest priorities were given to those with maximum effect on the degree of compaction. Four main parameters were considered, which are, time of application of poker vibrator, shape of the container, distance between two points of application of poker vibrator (pattern) and layer thickness of quarry dust.

Each parameter was carefully varied while keeping other three parameters constant. The corresponding degree of compaction was determined and all the results were plotted (i.e. relevant parameter vs. degree of compaction) to find the optimum combinations.

2.3.1 Time of poker vibrator application

Currently, there is no pre-defined time period for the application of the poker vibrator to compact quarry dust to achieve higher DOCs. Therefore, in most cases, the vibrator is applied according to the instructions given by a skilled labourer. This often creates a low degree of compaction due to the use of insufficient or excessive times of application.

Therefore, the first phase of the experiments focussed on the evaluation of the optimum time for poker vibrator application to achieve the desired DOC. In order to do this, while keeping the other three parameters constant, the time of poker vibrator application was gradually increased by 5 s increments.

2.3.2 Shape of containers used

Since, variously shaped excavations have to be filled with quarry dust in practical situations, it was necessary to conduct experiments with different shapes of containers and assess the variation of DOC with varying shape. The experiments were therefore conducted in circular and square containers, and the dimensions of the containers were approximately equal and similar to excavations under shallow footings. The two containers used are: 1) circular container with 1075 mm diameter, and 2) square container with 1100 mm edges.

2.3.3 Distance between two poker vibrator application points (Pattern)

Several shapes of individual footings, including rectangular, square and circular, have to be constructed according to the design of the sub-structure. The application patterns of the poker vibrator may play a critical role in each of these compaction processes and they may vary due to the shape of the footing. This was studied by changing the vibrator application pattern in containers of different shapes, and the plan views of several patterns adopted in the experiments are illustrated in Fig. 2 and Fig. 3.

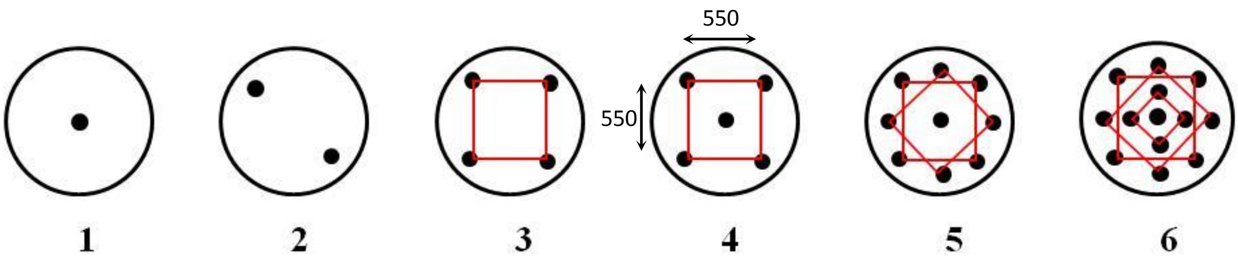

Figure 2. Patterns used in circular container (all dimensions are in millimetres).

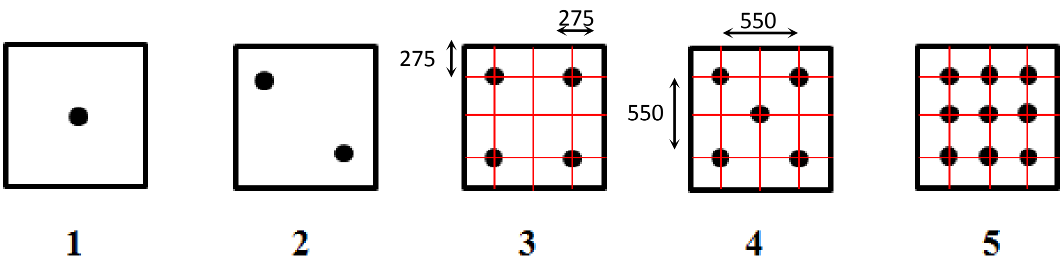

Figure 3. Patterns used in square container (all dimensions are in millimetres).

2.3.4 Layer thickness of the quarry dust

In most practical situations, quarry dust has to be placed in several layers according to the excavation depth, level of ground water table, required bearing capacity, etc. Therefore, the layer thickness used in such situations is believed to play a major role in compaction. This was the subject of the next stage of the study. Three layer thicknesses, 300 mm, 450 mm and 600 mm were used, and for each layer thickness, the poker vibrator was applied in several patterns. The DOCs were plotted in graphs to illustrate the variation.

3 Results and discussion

3.1 Standard Proctor compaction test

The maximum dry density of the selected quarry dust sample was first determined using the standard Proctor compaction test to calculate the degree of compaction in each trial. The test was carried out in the geotechnical laboratory at the University of Moratuwa, according to the ASTM D698 standard specifications. The results are shown in Fig. 4. According to the Proctor compaction test, the maximum dry density of the quarry dust sample was around 19.4 kN/m^3 and the optimum moisture content was around 8.32%.

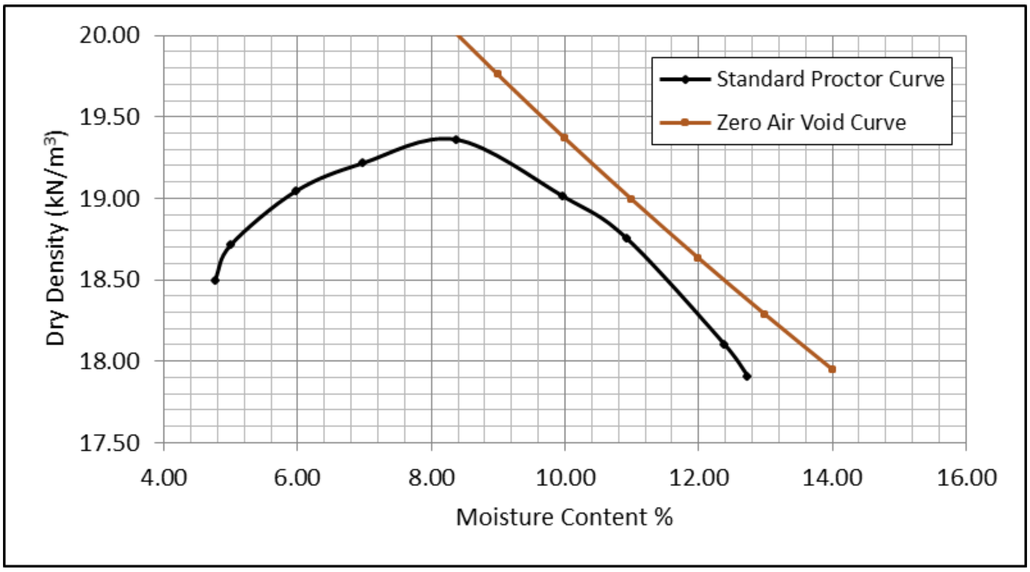

Figure 4. Standard Proctor curve of quarry dust

3.2 Variation of degree of compaction with application time of poker vibrator

In order to examine the effect of poker vibration application time on compaction, a series of experiments was conducted in a circular container with an initial layer thickness of 300 mm. The observed variation of DOC with application time is shown in Fig. 5 below.

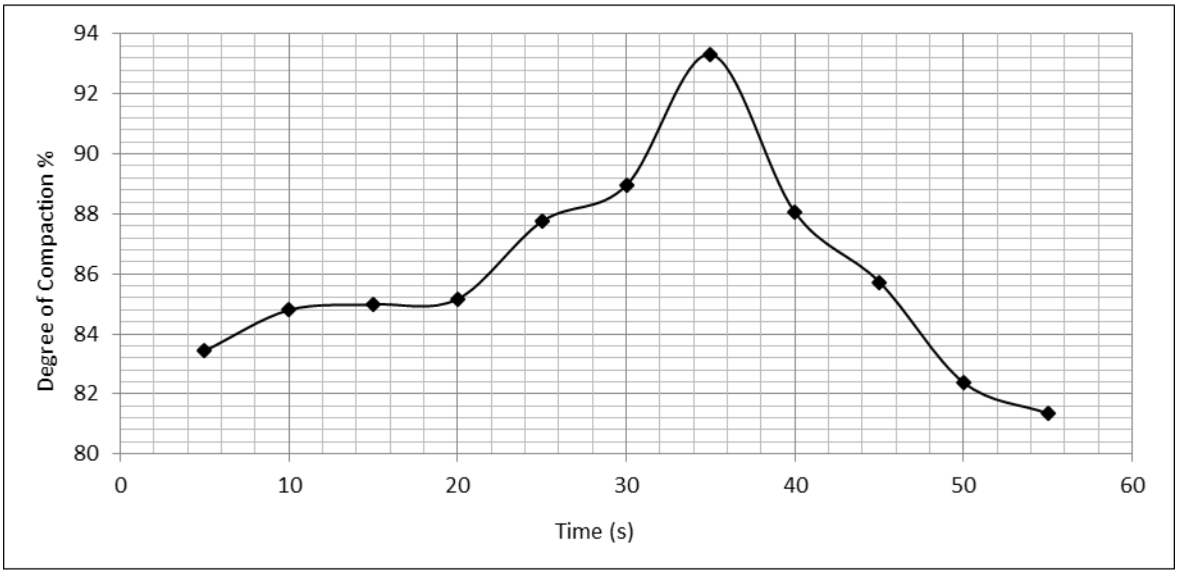

Figure 5. Variation of DOC with vibrator application time

According to Fig.5, the DOC first increases with increasing time (up to 35 s) and then start to reduce with time (after reaching a peak value). This can be explained technically, as the application of poker vibration for a longer time period may loosen the soil again, due to excessive vibration, and it may diminish the degree of compaction. Therefore, it is considered that the optimum compaction occurred after around 35 s of vibration and that particular time was chosen as the optimum time of application of the poker vibrator per point. All the remaining experiments were conducted with this application time of 35 s/point.

3.3 Variation of degree of compaction with application pattern of poker vibrator

The variation of DOC with application pattern was assessed for several layer thicknesses by conducting a series of experiments in both circular and square containers. All the experiments were conducted with an application time of 35 s per application point, which was considered to be an optimum application time according to the above results (see Fig.5).

3.3.1 Variation of DOC with application pattern for different layer thicknesses in circular container

Fig. 6 shows the effect of vibrator application pattern on quarry dust compaction, observed in a circular container for various layer thicknesses.

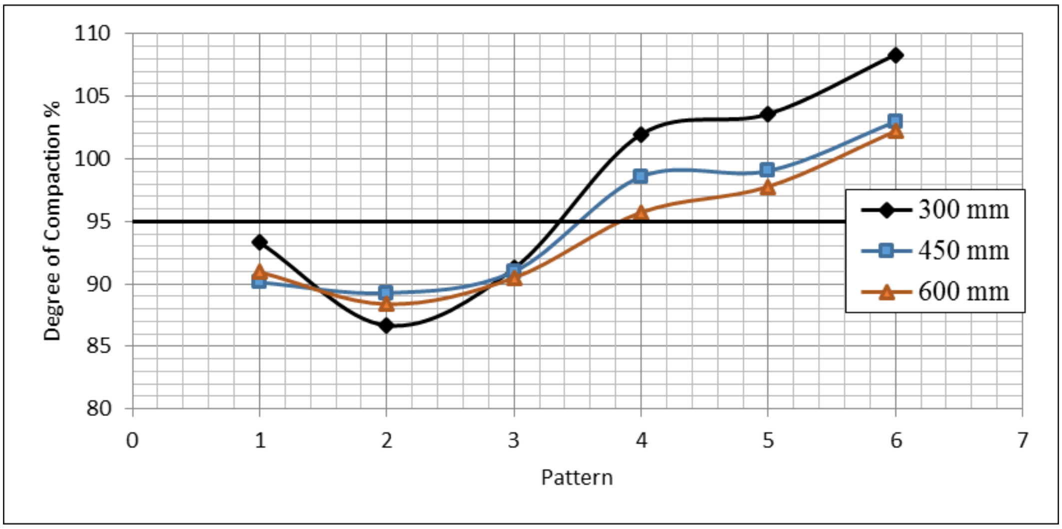

Figure 6. Variation of DOC with patterns for different layer thicknesses in circular container

According to Fig.6, the variation of DOC with vibrator application patterns exhibits a similar pattern for each layer thickness, and the DOC generally increases with increasing pattern number (see Fig.2). This was expected, because the higher the pattern number, the greater the number of vibration points, which enhances the compaction process. However, a careful examination of Fig.6 shows that the DOC in the first pattern (application of vibrator only at the centre) is relatively higher than that in patterns 2 and 3 (application near the circumference). This may be because the rigid boundary may hinder the vibration effect provided by the poker vibrator. However, the DOC commonly increases with increasing pattern number, and the variation of DOC from pattern 3 to 4 shows the highest gradient for all layer thicknesses. This shows that changing the pattern number from 3 to 4 causes a large enhancement in quarry dust DOC. If patterns 3 and 4 in Fig.2 are examined, it can be seen in pattern 4 that vibration compaction occurred at the centre and corners and in pattern 3, vibration compaction occurred only at the corners. This was also the case for the first observation, as in pattern 1 vibration compaction occurred in the centre and in patterns 2 and 3 compaction occurred in the corners. This implies that the application of the vibrator at the centre of the footing offers a greater degree of compaction compared to its application at corners. This was expected, as vibration of the middle area affects a greater area of the quarry fill compared to vibration at a corner. This is further confirmed by the slightly reduced DOC exhibited in patterns 4 to 5, followed by the greater enhancement in DOC when the pattern increases from 5 to 6. Here, it should be noted that only pattern 6 gives an additional vibration point in the middle portion of the quarry fill and pattern 5 provides additional vibration points in the corners, which appear to be less effective than the additional vibration point in the middle in pattern 6.

3.3.2 Variation of DOC with application pattern for different layer thicknesses in square container

In the next stage of the study, the container geometry was changed to square and the pattern effect (see Fig.3) was examined for two layer thicknesses (300 and 600 mm). According to Fig. 7, similar to the circular filling area, the DOC generally increases with pattern number or increasing vibration points, with a reduction of DOC when the pattern number increases from 1 to 2 due to the reduced centre compaction points. In most cases, patterns 4 and 5 give DOC s greater than 95% and in some cases (e.g. pattern 5 with 300 mm layer thickness) it is more than 100%. It is important to note that pattern 3 offers greater DOC to the quarry dust filling than pattern 1, and pattern 3 has 4 corner vibration points and pattern 1 has 1 centre vibration point. This is contrasts with the observation for the circular container, in which the centre vibration point always has the maximum influence, regardless of the number of vibration points at the corners. It is possible that, in the circular container, the placement of the vibrator at the corners is closer to the edges than in the square container. This implies that vibration should take place away from the edges as far as possible, to enable the vibration compaction process to proceed effectively. However, in the case of square or rectangular footings, it is recommended to also apply the poker vibrator at the corners, in order to achieve full and uniform compaction throughout the filling, including at the edges.

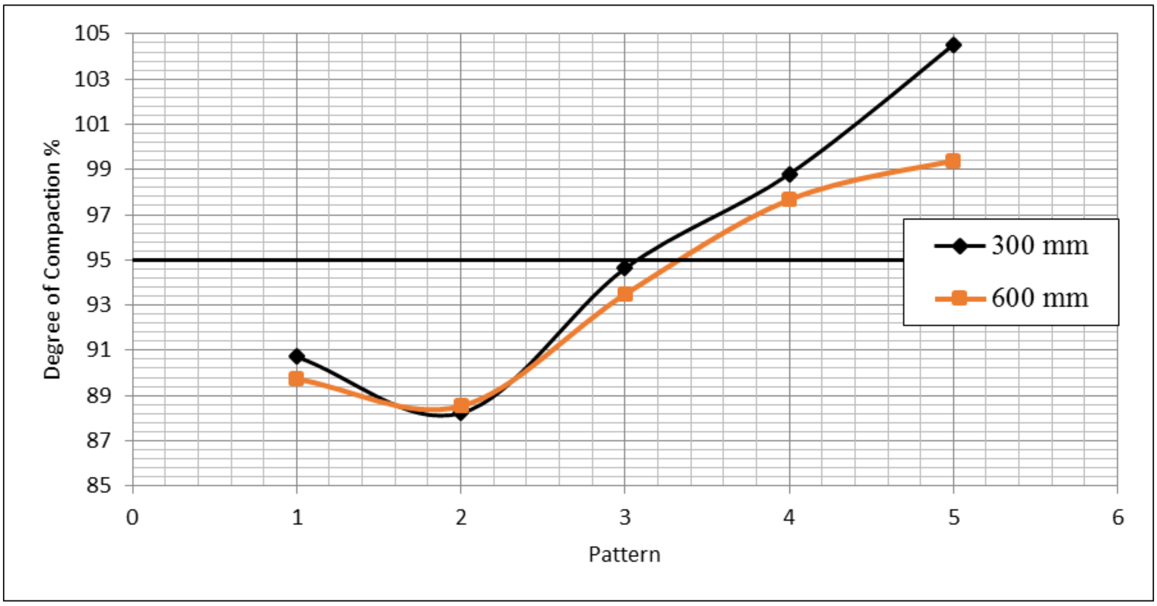

Figure 7. Variation of DOC with patterns for different layer thicknesses in square container

3.4 Variation of degree of compaction with layer thicknesses

The variation between initial layer thickness and DOC was then assessed, maintaining the application time at 35 s per point.

3.4.1 Variation of DOC with initial thickness for different patterns in circular container

Fig.8 shows the variation DOC of quarry dust with layer thickness in a circular container. According to Fig.8, DOC decreases with increasing initial layer thickness, regardless of pattern. For example, increasing the layer thickness from 300 mm to 600 mm causes the DOC in pattern 6 to be reduced from around 108 to 103 %. This is because reducing the layer thickness causes the vibration applying dust thickness to be reduced, causing more vibration of the dust in the entire layer. If the layer thickness is too deep, the vibrating power may be not sufficient to achieve adequate compaction, so that only the top dust is subject to full vibration and the dust at the bottom of the layer is subject to a poor vibration. As a result, the effect of vibration on the entire dust thickness is less. Another interesting observation is that, this layer thickness effect is more significant for greater layer patterns (4, 5 and 6). For example, increasing the layer thickness from 300 mm to 600 mm causes the DOC in patterns 1 and 6 to be reduced from around 93% to 91% and 108% to 103%, respectively. This is probably due to the fact, that the greater the number of vibration point, the greater the influence of thickness. However, for all the cases, the DOCs are greater than 95% for patterns 4, 5 and 6.

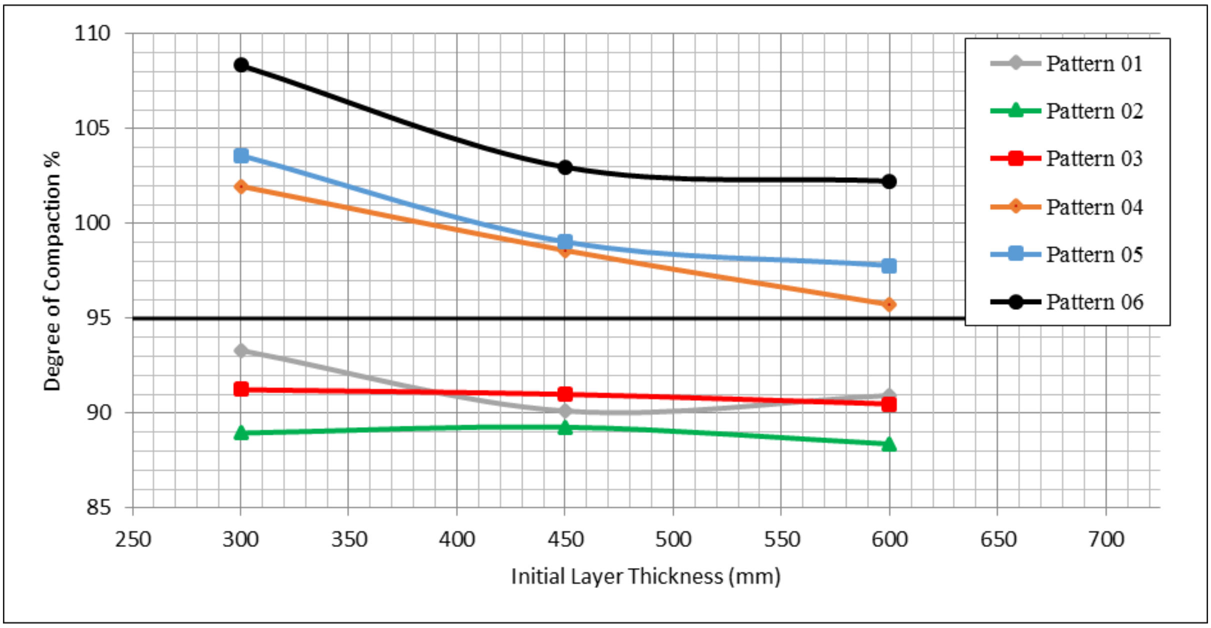

Figure 8. Variation of DOC with layer thickness for different patterns in circular container

3.4.2 Variation of DOC with initial thickness for different patterns in square container

Next, the effect of layer thickness on the DOC of quarry dust in a square container was examined and the results are shown in Fig. 9. According to the figure, all DOCs in the square container follow the same variation as the circular container, such that DOC decreases with layer thickness for all patterns and the influence of layer thickness increases with increasing pattern number. However, with the exception of pattern 05, the layer thickness effect seems to be much less. For example, in pattern 4, increasing the layer thickness from 300 mm to 600 mm causes only 99% to 98 % reduction in DOC.

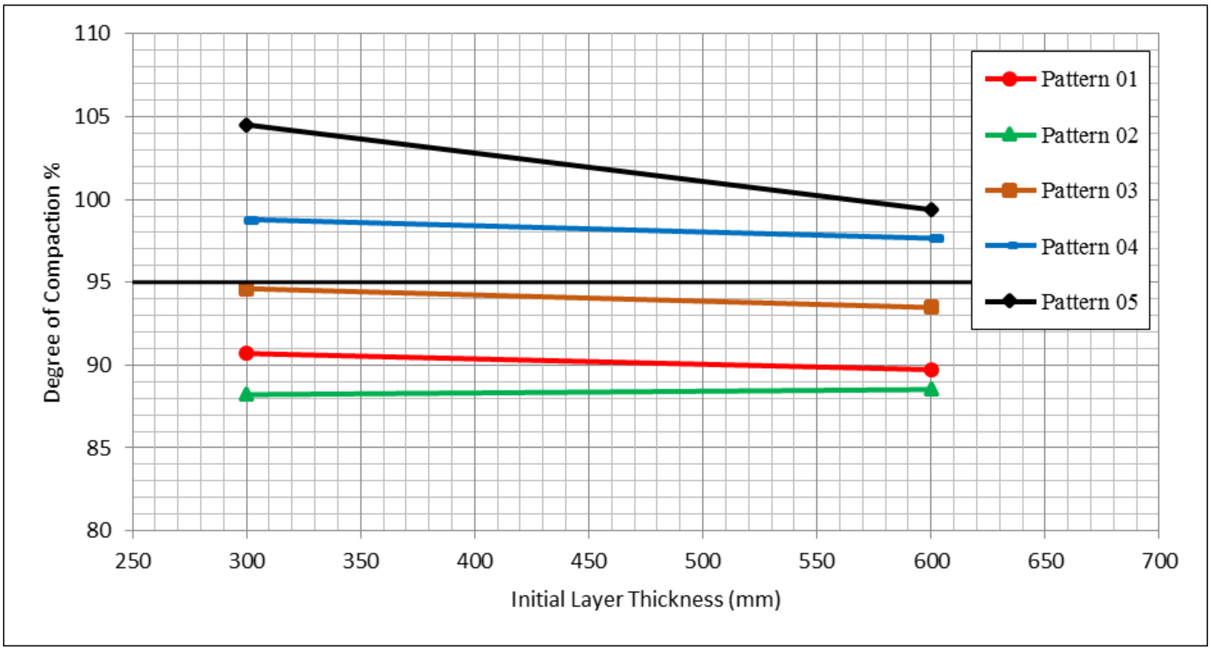

Figure 9. Variation of DOC with thickness for different patterns in square container

Based on all the results, although increasing the number of vibrator application points causes greater DOC in any shaped filling due to the higher compaction, the vibrator should be applied away from the rigid boundary to achieve effective compaction of quarry filling. In order to achieve a higher DOC, the poker vibrator should be applied at the middle as well as the corners, especially in the case of square or rectangular footings which have sharp edges/corners. Since the expected DOC reduces with the initial layer thickness, the layer thickness should be carefully designed to achieve the desired DOC. If the excavation is too deep, it can be filled with several layers by applying the poker vibrator to each layer separately, to effectively compact the soil.

4 Conclusions and recommendations

The study conducted a series of experiments to determine the optimum application scenarios for poker vibrators in compacting soil underneath shallow foundations. Based on the results, the following conclusions can be drawn:

- The most effective period of compaction for poker vibration is around 30 s after the compaction starts and lasts up to around 10 s. Application of poker vibration beyond this limit may loosen the soil due to excessive vibration and it may diminish the degree of compaction. Thus, an average application time of poker vibrator can be recommended as 35 s per point.
- Degree of Compaction (DOC) in both circular and square containers follow the same variation pattern with number of application points, and DOC generally increases with increasing application points. This observation can be justified according to Glover (1982), as he stated that, in order to have an effective compaction, the vibrator should be placed in the soil at the location where the compaction is required. Thus, it can be expected that, the higher the application locations, the greater the vibration effect, which enhances the compaction process.

- In every case, application of the vibrator at the middle gives a relatively higher DOC than application at the corners, because vibration of middle area affects a greater area in the quarry fill compared to vibrating at the corners. This may happen due to availability of rigid boundary at corners, which will hinder the vibration effect. Therefore, vibration should be applied away from the edges as much as possible, in order to achieve effective vibration compaction.
- However, in the case of square or rectangular footings, the poker vibrator should also be applied at the corners, to achieve full and uniform compaction throughout the filling, including all the edges.
- Regarding the layer thickness effect, DOC reduces with increasing initial layer thickness, regardless of number of application points, because reducing the layer thickness causes the vibration applying dust thickness to be reduced. This provides more vibration to the dust in the entire layer.
- Since the DOC reduces with the initial layer thickness, the layer thickness should be carefully designed to achieve the desired DOC. If the excavation is too deep, it can be filled with several layers by applying the poker vibrator to each layer separately, to effectively compact the soil.
- The layer thickness effect is more significant for greater number of application points, probably due to the fact, that the higher the number of vibration points, the greater the influence of thickness.

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