Influence of tamper weight shape on dynamic compaction

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This paper presents the effect of tamper weight shape on the dynamic compaction method in granular soils. Although the dynamic compaction method appears to be very simple, it requires careful design of the compaction process. The aim of this study is to improve the efficiency and decrease the cost of deep compaction by using cylinder-shaped tamper weights. The influence of the shape of the bottom of the tamper weight on dynamic compaction efficiency was evaluated experimentally on sandy soils. Sands of three different densities were used to evaluate the compaction efficiency. Conical-bottom tamper weights were studied with the conic angle approximately the same values as the internal friction angles of the three different densities of soil. Also, in order to compare results, a flat-bottom tamper was used with the same weight. The results indicated significant increases of the amount of ground improvement by using a conical rather than a flat-bottom load.

Keywords: conic angle; density; dynamic compaction; tamper weight shape;

Cet article traite de l'effet de la forme du poids de dameuse sur la méthode de compactage dynamique sur les sols granulaires. Bien que cette méthode apparaisse très simple, elle demande une conception soignée du processus de compactage. Cette étude a pour objectif d'améliorer l'efficacité et de réduire le coût du compactage profond en utilisant des poids de dameuse de forme cylindrique. Elle évalue expérimentalement l'influence de la forme de la base du poids de dameuse sur l'efficacité du compactage dynamique pour des sols sablonneux. Des sables de trois densités différentes ont été utilisés pour déterminer l'efficacité du compactage. L'étude porte sur des poids de dameuse de forme conique avec un angle conique correspondant approximativement aux mêmes valeurs que les angles de frottement interne des trois différentes densités de sable. Une dameuse de base plate, de même poids, a également été utilisée en vue d'établir une comparaison. Les résultats indiquent une augmentation significative de l'amélioration du sol lorsque l'on utilise une charge à base conique plutôt que plate.

Introduction

Soil densification by dynamic compaction is a well-known compaction method. The densification effect is strongly influenced by the dynamic response characteristics of the soil to be compacted, but also by the falling weights (or tampers). Square or circular weights made of steel or concrete are usually used as tampers. The imparted energy is transmitted from the ground surface to the deeper soil layers by the propagation of shear and compression waves, which force the soil particles into a denser state.

Dynamic compaction has evolved as an accepted method of site improvement for treating poor soil in situ. As Mayne *et al.* (1984) showed, the method is an economically attractive alternative to conventional solutions for utilising shallow foundations and preparing subgrades for construction.

Dynamic compaction requires a controlled application of dynamic stresses to the ground surface. The stresses are created by the impact of heavy steel or concrete tampers falling from heights of up to 25 m on a predetermined grid pattern. A crater is formed at the impact point, and may be up to 2·5 m deep. The craters are backfilled by end-dumping fill into the craters. Several phases or passes of tamping may be required across the site, depending upon the level of improvement required. Following completion of the 'high-energy' tamping, a low-energy or 'ironing' phase is performed to compact the material in the craters and in the upper 1·5 m of the formation. The ironing phase consists of dropping the weight from a height of 3–6 m on the refilled craters.

According to Lukas (1984), the maximum depth of improvement (D_{max}) can be calculated from

$$D_{max} = n\sqrt{WH} \tag{1}$$

where W is the mass of the tamper, H is the fall height, and n is an empirical constant. Lukas (1995) showed that the variation of n is attributed to the total amount of applied energy, the type of soil, the presence of soil layers, and the efficiency of the drop mechanism. Some published values for n are: 0·5 for clayey soils and 0·65 for silty soils (Van Impe, 1989); 0·3–0·8 (Mayne, 1984); and 0·65–0·8 (Lukas, 1984).

Scott and Pearce (1976) modelled an unconfined mass of soil that had been struck by a falling weight. They investigated the effect on both unsaturated and saturated soils, monitoring the elastic properties, surface deflection and stress concentrations in order to model the stress and movement at the impact surface. However, as Chow *et al.* (1994) showed, the design of dynamic compaction work is still essentially empirical in nature, relying heavily on the

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designer's experience as well as on a substantial amount of costly and time-consuming field trials.

According to Lukas (1986), the potential energy of the drops applied per unit area is calculated by

$$E = \frac{NWHg}{A} \quad (2)$$

where E is the applied energy (kJ/m^2), W is the mass of the tamper, H is the fall height, N is the number of drops, A is the compacted area on each tamping point, and g is the acceleration due to gravity (9·81 m/s^2).

In the contest of the study, the efficiency of a conical-bottom tamper weight was compared with conventional flat-bottom tamper weights. The internal friction angle, depending on the density of the granular materials, was the main parameter in deciding the conical shape. These tampers were falling from a constant height onto the sandy soil. Crater depths and widths were measured after each fall to calculate the amount of modification.

Soil properties and experimental study

The soil for the tests was brought from the bed of the Sakarya river, Turkey. It consisted of sandy gravel, with an average moisture content of 7%. The grain size distribution, unit weight and water content of the granular materials are given in Fig. 1 and Table 1. The soil is classified as well graded sand (SW) according to the ASTM D 2488 (1995) classification system. The unit weight of the in situ soil was 13·9 kN/m^3. The minimum and maximum dry unit weights of the soil are 12·9 kN/m^3 and 16·2 kN/m^3 respectively.

The samples were prepared at three different densities, defined in this paper as: loose (LS), with a unit weight of 13·0 kN/m^3; medium dense (MDS), with a unit weight of 13·8 kN/m^3; and dense (DS) with a unit weight of 14·7 kN/m^3. The samples were pluviated into the chamber using a pluviation apparatus. The sand was levelled and the final height of the sample was measured so that the density (or void ratio) of the soil could be calculated. For the loose sample the chosen pluviation height was 50 cm, for the medium dense sample it was 100 cm, and for the dense sample it was 150 cm.

A series of large-scale direct shear box tests were conducted to evaluate the shear strength properties of the granular materials. The dimensions of the shear box were 300 mm × 300 mm × 100 mm height (Fig. 2). The direct shear tests were conducted under vertical stress of 50 kPa, 100 kPa and 200 kPa by applying air pressure.

After the internal friction angles had been determined, the bottom shapes of the tamper weights were prepared according to the internal friction angles of the granular soils. Conical angles of 30°, 35° and 40° were in direct relationship with the internal soil friction angle of the loose, medium dense and dense sands respectively. The cross-sections of the flat-bottom and conical-bottom tamper weights are shown in Figs 3–5.

The sample was placed in a rigid steel chamber by using the pluviation method. The internal dimensions of the chamber were 1120 mm × 760 mm × 400 mm. The tamper weights were about 67 kN and were made of steel. The tampers fell from a constant height of 2·40 m onto the 400 mm deep layer of sandy gravel. The test set-up is shown

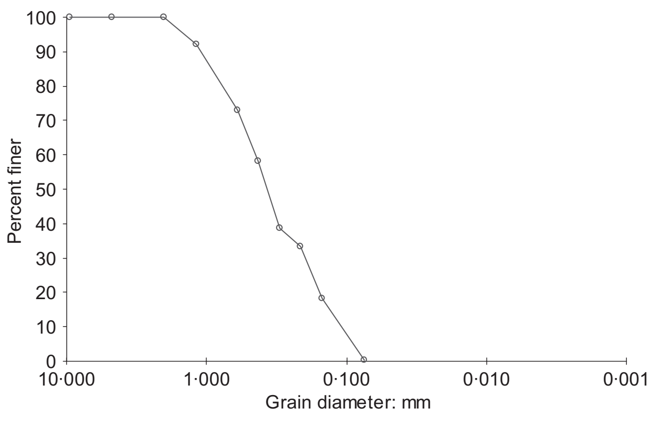

Fig. 1. Particle size distribution of granular soils

Table 1. Properties of the granular soils

	Loose sand	Medium dense sand	Dense sand
Internal friction angle, ϕ : degrees	29·7	34	39
Water content: %	7	7	7
Unit weight: kN/m^3	13·0	13·8	14·7

Fig. 2. Large-scale direct shear box

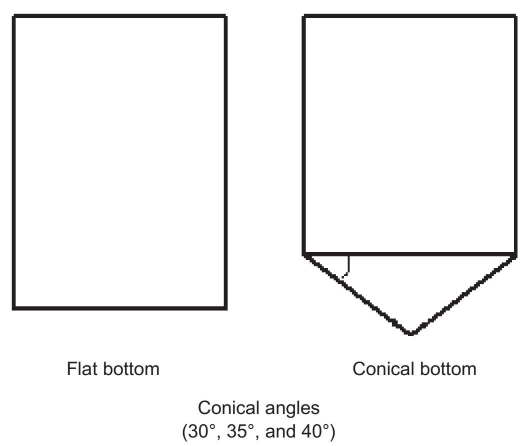

Fig. 3. Shapes of tamper weight

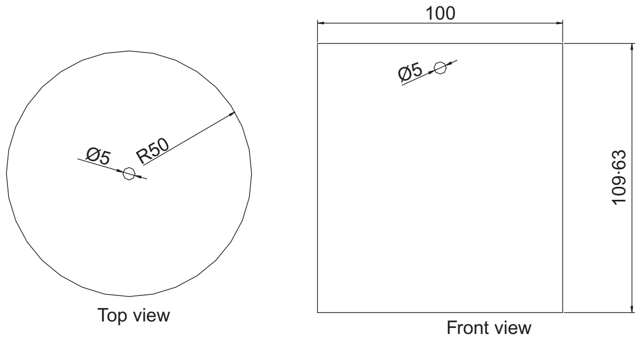

Fig. 4. Flat-bottom tamper weight dimensions (units are mm)

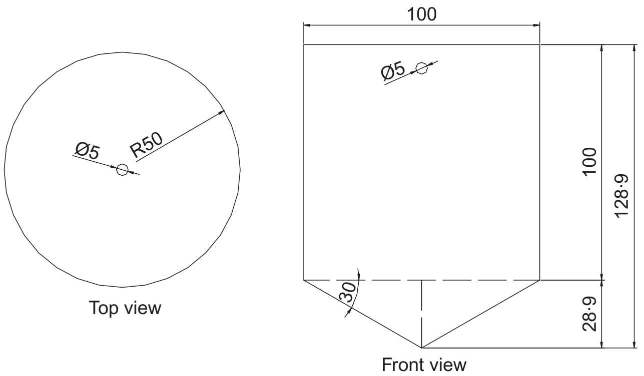

Fig. 5. Conical-bottom tamper weight dimensions (units are mm)

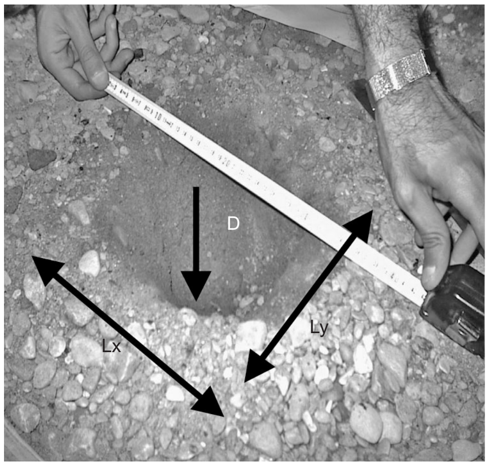

Fig. 7. Measurements of crater depth and width

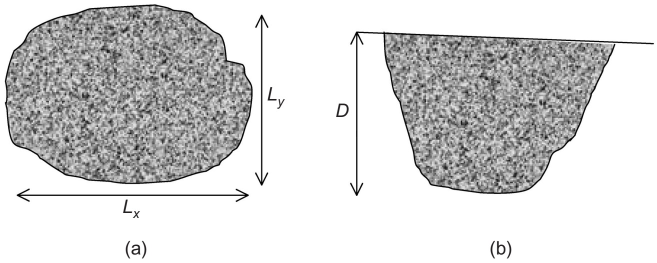

Fig. 8. (a) Crater area; (b) crater depth

in Fig. 6. The number of drops was chosen as 10 because no increase of crater depth was observed for more than this number of drops during the preliminary tests. The crater area S and crater depth D were measured after each drop, as shown in Figs 7 and 8. In order to compare results, first flat-bottom tampers were dropped from a constant height onto the sample, and then the conical-bottom tampers were dropped onto another sample with the same unit weight.

Results and discussion

The main parameters for the laboratory study are the number of drops at the same location point, N, the crater depth D and the approximate crater area S. The data were registered for each condition of the soil and for each tamper weight bottom shape. The approximate crater area was determined by taking the average of the crater dimensions L_x, L_y as the diameter of a circle, because the shape of the area was found to be nearly a circle. All dimensions are in cm and cm^2. Because the total degree of improvement is dependent on the total applied energy, the energy applied to the ground was also calculated by using equation (2).

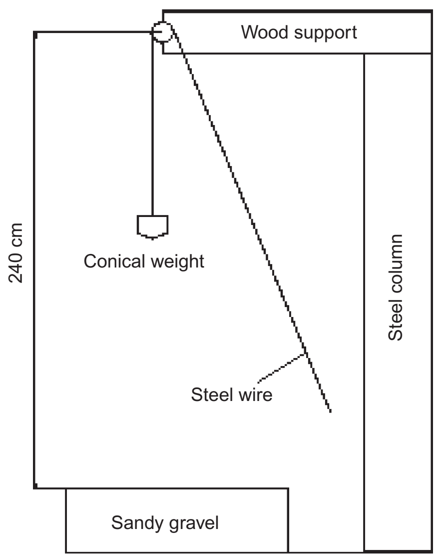

Fig. 6. Test set-up

The three different densities of sand were tested by using both flat-bottom and conical-bottom tamper weights. The results of the tests can be seen in Table 2 and Figs 9–17.

The relationships between crater depth and crater area, and the effect of tamper weight shape on these parameters are shown in Figs 11, 14 and 17 for the different densities.

The simplest approach to evaluating the improvement would be to determine the relationships between energy and crater depth, between energy and crater area, and between crater area and crater depth. The crater depth and crater area are greatly influenced by the shape of the tamper bottom. As shown in Fig. 9, the maximum crater depth for loose sand using the flat-bottom tamper is 11·36 cm after the tenth drop. As can be seen from Fig. 10, when using the conical-bottom tamper weight the crater depth is about the same value after the third drop. The amount of consumed energy after the tenth drop is 2·5 times greater than that after the fourth drop.

Figure 10 shows that there is no significant difference for the approximate crater area between the conical-bottom and flat-bottom tamper weights. The increment of the crater depth is about 15% and the increment of the crater area is only about 4% for loose sand. However, if the depth and area are compared through the data from Fig. 11, it can be seen that the compacted crater volume is about 20% higher for the conical-bottom tamper weight than for the flat-bottom tamper after the tenth drop:

Table 2. Crater sizes after tenth drop

Soil	Flat-bottom tamper weight			Conical-bottom tamper weight		
	LS	MDS	DS	LS	MDS	DS
Crater depth: cm	11·36	7·50	7·0	13·02	10·34	9·26
Crater area: cm^2	406·29	254·34	346·19	424·34	329·90	326·90

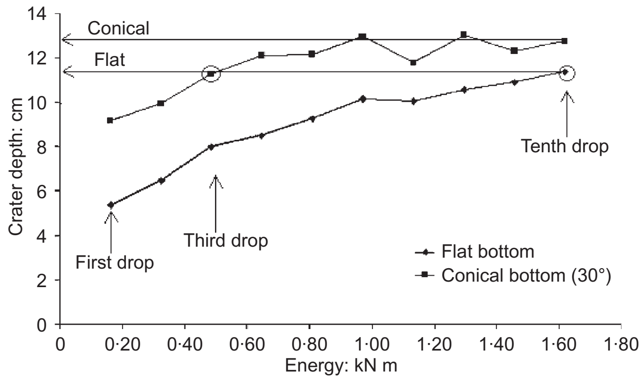

Fig. 9. Loose sand test results: energy and crater depth

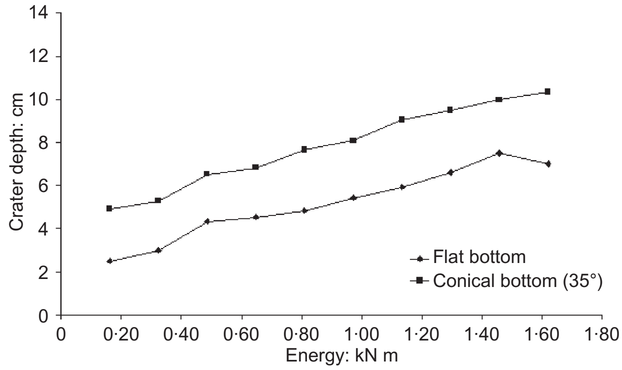

Fig. 12. Medium dense sand results: energy and crater depth

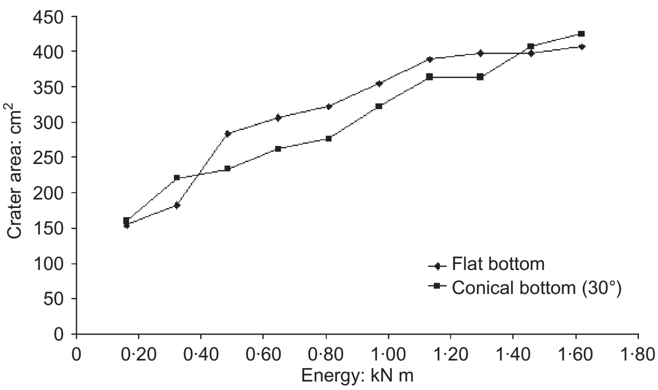

Fig. 10. Loose sand test results: energy and crater area

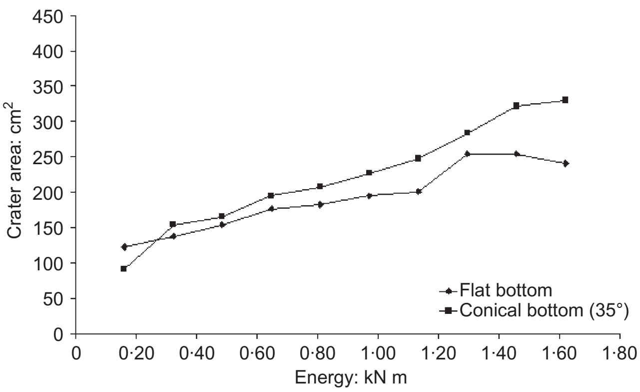

Fig. 13. Medium dense sand test results: energy and crater area

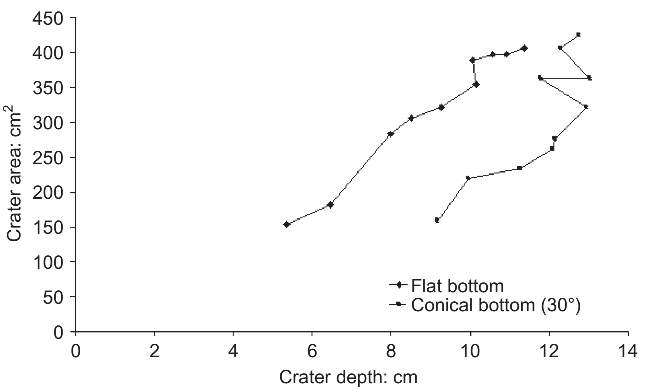

Fig. 11. Loose sand test results: crater depth and crater area

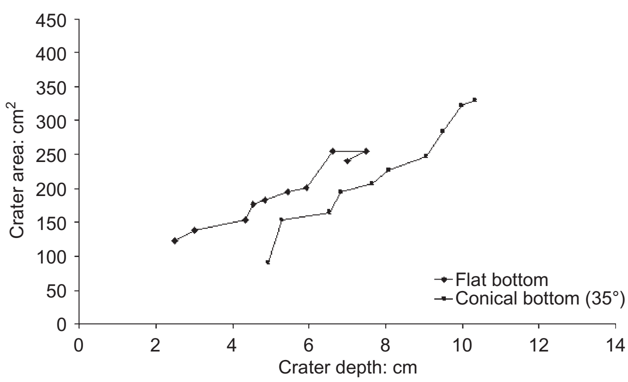

Fig. 14. Medium dense test results: crater depth and crater area

$$\frac{V_{\text{conical}} - V_{\text{flat}}}{V_{\text{flat}}} = \frac{424{\cdot}34 \times 13{\cdot}02 - 406{\cdot}29 \times 11{\cdot}36}{406{\cdot}29 \times 11{\cdot}36} = 19{\cdot}7\% \approx 20\% \tag{3}$$

The amount of improvement shows some differences for medium dense and dense sand. As shown in Fig. 12, the maximum crater depth for medium dense sand is 7·5 cm for the flat-bottom tamper weight; a similar value was measured after the fifth drop of the conical-bottom tamper. The use of the conical-bottom tamper with medium dense sand resulted in an increment of efficiency of about 38% for the maximum depth and 30% for the maximum area using conical-bottom tampers when compared with flat-bottom tampers.

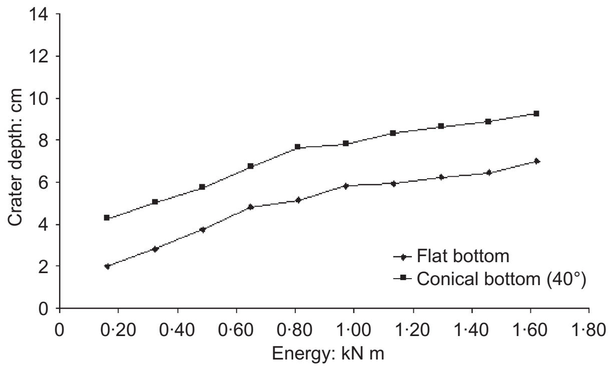

Fig. 15. Dense sand test results: energy and crater depth

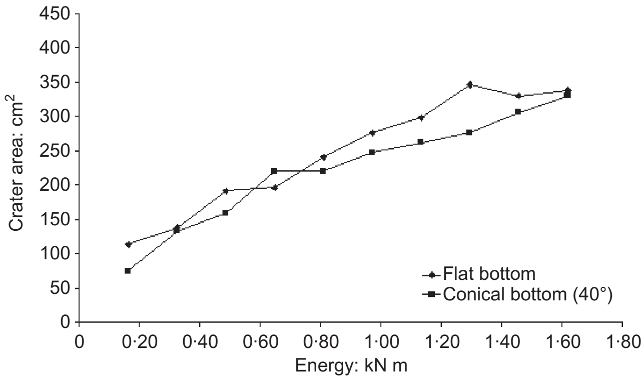

Fig. 16. Dense sand test results: energy and crater area

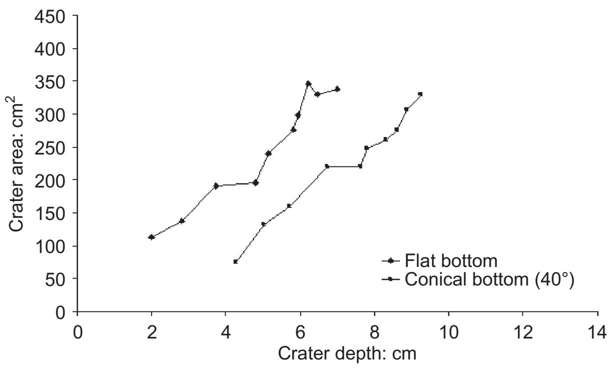

Fig. 17. Dense sand test results: crater depth and crater area

Figure 17 illustrates that, for dense sand, the maximum crater depth is 7·0 cm and the maximum crater area is about 346 cm^2 for the flat-bottom tamper, whereas the equivalent values for the conical-bottom tamper are 9·25 cm and 330 cm^2 respectively. This means that the crater depth increases by about 32%, whereas the crater area decreases by about 5%.

It is also easily seen that the efficiency of dynamic compaction is strongly related with the density of the soil. The method is more effective for loose and medium dense sands than for dense sands.

Densification is usually performed in multiple passes (or phases). Elias *et al.* (1999) defined a pass as the dropping of the weight at designated grid points for a predetermined number of times. Greater heights and larger masses are used for the first phase; such initial phases are intended to improve deeper layers. According to ASCE (1997), if the first phase is performed inappropriately, then the upper layer may be in a dense state, making it difficult to treat the loose material below. Thus reaching the deeper level in the first phase is an important step for dynamic compaction method. As shown above, the tamper reaches a deeper layer if a conical-bottom tamper is used rather than a flat bottom tamper.

It can be claimed that the improvement cannot be uniform if the tampers are not flat-bottomed. However, as is shown in equation (1) and explained in ASCE (1997), the aim of dynamic compaction is not modification of the surface layer. Dynamic compaction, and many other soil improvement techniques, are used for modification of deeper soil strata. Thus higher values of n values can be proposed for equation (1) if conical-bottom tampers are used.

As has been shown above, dynamic compaction of the soil mass is a promising method for ground modification. However, there is still a general lack of information in the field of dynamic compaction of soil. The factors that influence the densification and the efficiency of dynamic compaction should be evaluated, both experimentally and numerically, to make a further improvement to practical geotechnical problems.

Understanding of what happens to the soil during an impact blow is still in an early stage. The behaviour of granular soils under compaction should be monitored to make further contributions to dynamic compaction methods. In addition, the efficiency of dynamic compaction methods for different type of soils and the effects of tamper shape on the different type of soil should be investigated to improve the efficiency of the method.

Conclusions

An attempt has been made to evaluate the efficiency of dynamic compaction by using different shapes of tamper and different densities of sandy soil. In order to achieve a higher density, a significant amount of extra energy has to be transferred into the soil mass. Reducing this energy transfer or changing the way it is transferred has a marked effect on the final density that can be achieved. A new method for dynamic compaction method has been proposed in this study by using different shapes of tamper. Based on the results of dynamic compaction tests the following conclusions can be drawn:

(*a*) The shape of the tamper weight influences the efficiency of dynamic compaction. The crater depth and crater area are affected positively by conical-bottom tamper weights compared with flat-bottom tamper weights.

(*b*) The maximum crater depth and crater area reached at the end of the tenth drop of the flat-bottom tamper weights were reached after four to seven drops of the conical-bottom tamper weights. Thus the energy consumed to obtain a given amount of improvement with the conical-bottom tampers is less than half that with the flat-bottom tampers.

(*c*) The efficiency of dynamic compaction is related to the density of the soils.

(*d*) The effect of the shape of the tamper must also be tested in situ to see the scale effect on the efficiency of dynamic compaction. By using in situ tests after the dynamic compaction, such as SPT and CPT, the amount of modification can be evaluated.

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Discussion contributions on this paper should reach the editor by 1 October 2007