Compaction of Loose Sand Deposits by Underground Explosion

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ABSTRACT: This paper reports the experimental study of underground explosion in modelled loose sand deposits based on the assumption that the vibration would destroy any cavities and holes thereby increasing the density. The modelled sand layer was prepared into two conditions: dry and saturated. The levels of vibration during explosion were monitored and recorded by accelerometers and a data acquisition system. A cone penetrometer was specifically developed to measure the cone resistance just before and after the explosion for 1, 7, and 15 days. It was observed that the vibration generated in the saturated sand is much higher. This was in accordance with the density measurement as the after-explosion density for the saturated sand is much greater. The findings suggest that underground explosion could be used to increase the density of loose sand deposits.

1 INTRODUCTION

A sink hole is land subsidence that results in the forming of a hole. Even though regarded as natural phenomenon, the causes may be from both natural and human activities, including load transmission from structures into the ground, construction on loose sand, flow of groundwater, and geological conditions comprising calcareous rock. It should be noted that the occurrence of a sink hole has been reported around the world. Most of them, however, occur in remote areas. If they do occur in residential areas, damage is then inevitable.

As the population is growing rapidly, it is thus necessary to find new spaces to accommodate the demand. It has been customary to conduct a subsurface investigation before a new construction project begins. If the stratum conditions suggest a sink hole is likely to occur, an engineer ought to further analyses in details in order to prepare countermeasures. For example, the following methods may be employed: dynamic compaction by means of dropping a weight from a certain height and vibro-compaction with or without water jet.

This paper investigated a technique for getting rid of the voids and cavities in loose sand deposits of which are one of the causes that triggers the occurrence of a sink hole. It was achieved by placing explosive charges at specified depths in modelled loose sand layer. Then, they were ignited in order to generate the vibration that would cause the rearrangement of soil particles. This would result in the reduction of the voids thereby increasing the density. Notice that this technique has been regarded as one of soil stabilisation methods.

2 METHODOLOGY

The first task was to obtain a method that could produce modelled loose sand deposits of which the density is about 1300 to 1500 kg/m^3 (Carter, 1983). After several techniques were experimented, it was found that depositing by a funnel having virtually zero-dropping height is most suitable. Pleased be noted that this technique has been regarded as air-pluviation method. Then, two explosive charges were installed in the centre of modelled sand layer at specified depths. A steel chamber having the diameter and height of 120 and 90 cm was also fabricated to house the sand because the material could withstand the explosion. After these preparations the charges were ignited to create an underground vibration. This initiated the transmission of stress waves to the surrounding soil resulting in the rearrangement of soil particles thereby reducing the voids and subsequently increasing the density. This can be observed visually as the surface subsides. The test arrangements are shown in Fig. 1.

To monitor the vibration levels, three accelerometers were installed at the radii of 5, 25, and 50 cm at the surface. All of them were connected to a data acquisition system and a computer for monitoring and recording the signals. However, the most important parameter was the density of the loose sand layer before and after the explosion. Therefore, a cone penetrometer, shown in Fig. 2, was developed to measure the cone tip resistances just before the ignition and after the explosion for 1, 7, and 15 days. Consequently, the measured values were compared to evaluate the efficiency of the method in terms of increased density.

It should be noted that the densification of loose sand deposits by means of underground explosion has long been studied. The results indicate that the technique, compared with other methods, is highly efficient. For example, Prugh (1963) and Ivanov (1967) reported the development of density due to underground explosion; while Lyman (1941), Hall (1962), and Solymar (1984) summarised the results of foundation-soil improvement obtained from dam construction projects (Dowding and Hryciw, 1986). In addition, Gohl et al. (2000) reported that just after explosion the surface heave slightly. After a while, however, the land began to subside; and, it continued to do so for hours.

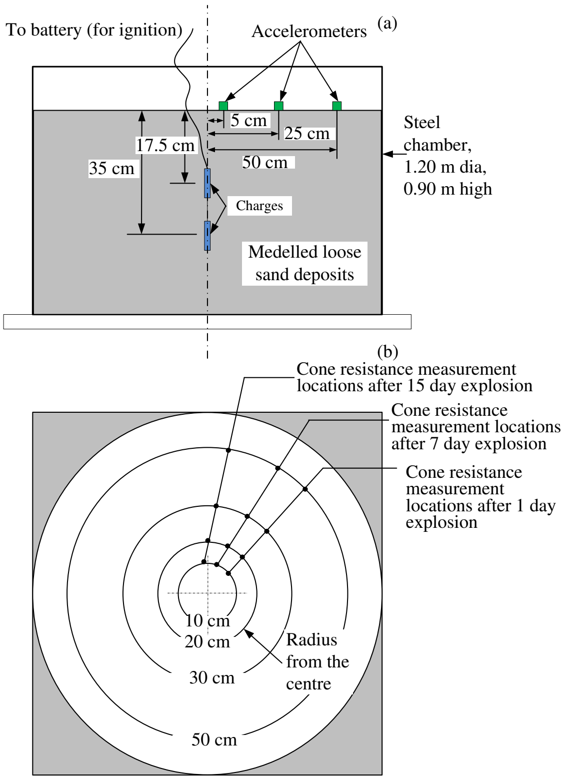

Fig. 1 Installation of explosive charges and accelerometers (a) locations of cone resistance measurement (b)

Fig. 2 Cone penetrometer for cone tip resistance measurement before and after explosion

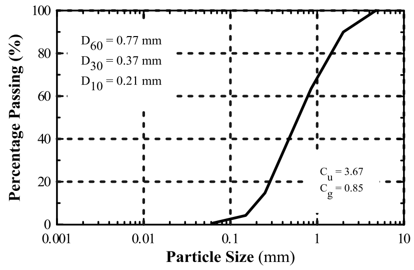

Fig. 3 Grain size distribution of tested sand

Fig. 4 Examples of explosive charge

3 MATERIALS

3.1 *Sand*

The river sand located in Suratthani province, Southern Thailand, was chosen to be used as loose sand deposits. It had a specific gravity of 2.65 in which is in a range of typical values for this type of soil in Thailand. The physical characteristics of the sand were obtained by conducting a particle size analysis. This resulted in the size distribution curve, as shown in Fig. 3. In addition, it was found that the coefficient of uniformity, Cu is 3.66 and the coefficient of gradation, Cg is 0.84. According to the unified soil classification system, the soil was classified as SP.

3.2 *Explosive charge*

A total of two types of charge were used in this experiment: (1) immediate ignition, and (2) delayed ignition. The latter can be delayed for 0, 50, and 100 ms. The amount of explosive powder for both types was about 0.8 g. Fig. 4 shows the examples of charge used in this study.

4 TEST PROGRAMMES AND PROCEDURES

4.1 *Test programmes*

The main objective of this study was to find a solution for proactive countermeasures to the occurrence of a sink hole. Nonetheless, the study was also concerned with densifying loose sand deposits. The method chosen for this project was to use the underground explosion. To cover all possible field conditions, the underground explosion was carried out under two conditions: (1) dry state (dry series), and (2) saturated state (saturated series). A total of six tests were conducted, as shown in Table 1.

Table 1. List of underground explosion tests

Series	Test no.	Levels of detonation (cm)*	Delay times (ms)**	Label
Dry	1	35, 17.5	0, 0	D00
	2	35, 17.5	0, 50	D050
	3	35, 17.5	0, 100	D0100
Saturated	4	35, 17.5	0, 0	W00
	5	35, 17.5	0, 50	W050
	6	35, 17.5	0, 100	W0100

* Measured from the surface
** Corresponding to the detonation levels (column 3)

4.2 *Procedures*

This study comprised three main procedures: (1) preparing loose sand deposits and installing explosive charges, (2) installing sensors and data acquisition system, and (3) performing cone penetration resistance measurements before and after explosion. It should be noted that the method chosen for loose sand layer preparation was very time consuming and laborious. For the dry series, the experiment was conducted as follows:

(a) Prepared loose sand deposits; in the meantime, installed two explosive charges at the depths of 35 and 17.5 cm, from the surface.
(b) Conducted penetration tests at the radii of 10, 20, 30, and 50 cm just before explosion.
(c) Installed three accelerometers at the radii of 5, 25, and 50 cm, respectively.
(d) Ignited the explosion; recorded the signals.
(e) Conducted the cone penetration test at the radii of 10, 20, 30, and 50 cm; and, measured the surface settlement at the radii of 0, 10, 20, 30, 50, and 60 cm after the explosion for 1, 7, and 15 days.

Notice that for the saturated series a pressure transducer was also installed during loose sand layer preparation to measure the pore water pressure.

The explosion under the ground would generate two forms of energy: (1) shock waves, including mostly compressive and shear waves, and (2) energy due to the high-pressure gas caused by the expansion of explosive charge. These would create temporary cavities around the location of installed explosive charge. Afterwards, the cavities collapses because of the overburden stress thereby increasing the density. Even though the explosion occurs underground, one might concern that the vibration would damage structures situated nearby. In such a case, the Hopkinson's Number (*HN*) may be employed to assess the risk (Gohl et al., 2000).

$$HN = \frac{w^{0.33}}{r} \qquad (1)$$

Where w is mass of explosive charge and r is the distance from explosion to an interested location.

5 RESULTS AND DISCUSSION

Even though the main purpose was to destroy cavities and increase the density of loose sand deposits, it does not mean any amounts of explosive powder can be employed. In the other words, explosive charge should be just enough for the task but does not damage nearby structures.

Table 2 displays the maximum accelerations for all tests. Overall, it was found that the acceleration for the saturated series is much higher than those of the dry series. This may be because the energy is prevented by the pore water to dissipate thereby increasing the compression waves. The maximum accelerations for the dry and saturated series were obtained from test numbers 1 and 4, respectively. This indicates that if maximum vibration is a target, all charges installed should be ignited at the same time.

Table 3 shows the cone resistances measured just before and after the explosion for 1, 7, and 15 days. Overall, it was found that the resistance gradually increases with the increase of depth and measuring time. For both series, the resistance for 1 day after explosion was virtually no change. After that, however, it increased dramatically, especially after the explosion for 15 days. This may be because immediately after the explosion the soil heaved due to generated compression waves, resulting in the forming of small holes around the charges. This was visually observed as the surface lifted. After that the soil above and around the charges collapsed thereby increasing the density.

Comparing between the dry and saturated series, it can be seen that the after-explosion density for the latter is much greater. This may result from the pore water pressure generated by the explosion. For example, as the tested soil was sand, the pore water pressure would dissipate to the surface very quickly. This resulted in the occurrence of liquefaction thereby rearranging the sand particles and increasing the density. The cone tip resistance versus depth is plotted and shown in Fig. 5.

One of the evidences that support the increase of density due to underground explosion was the measurement of surface settlement. Fig. 6 (a) and (b) shows the surface settlement versus depth below surface for the dry series (D050) and saturated series (W050), respectively. It was observed that the final settlements at the centre for both series are very similar. However, for the dry series, the settlements at the radius of 20 cm and outwards were quite small. This was contrary to the saturated series as the settlements for the whole surface were very similar. The results suggest that, in terms of increased density, the underground explosion in saturated sand is much more efficient than in dry sand.

Table 2. Maximum acceleration results

Series	Label	Max. acc. (g) at the distances from the centre of			Max. pwp (kPa)
		5 cm	25 cm	50 cm	
Dry	D00	34.25	1.81	0.35	N/A
	D050	4.85	1.94	0.26	N/A
	D0100	10.42	3.92	2.15	N/A
Saturated	W00	51.32*	50.33*	13.53	75.75
	W050	50.33*	50.33*	8.27	63.13
	W0100	51.33*	50.32*	8.82	88.38

* Measured values exceed the capacity of sensors of 50 g

Table 3. Cone resistance results for D050 and W050 at the radius of 20 cm

Depth (cm)	D050				W050			
	Cone resistance (kPa) after the explosion of (days)							
	0*	1	7	15	0*	1	7	15
0	0	0	0	0	0	0	0	0
10	42	11	42	57	14	28	316	351
20	42	14	57	74	26	47	421	456
30	46	57	124	95	37	61	480	538
40	60	78	138	106	51	82	632	655
50	71	78	134	152	59	108	796	702

* Tests were conducted just before ignition

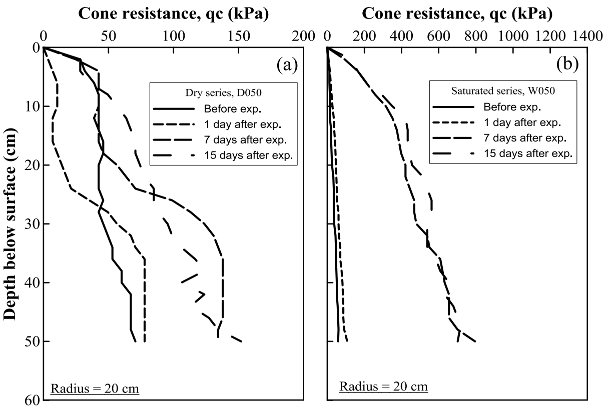

Fig. 5 qc vs. depth for D050 (a) and W050 (b)

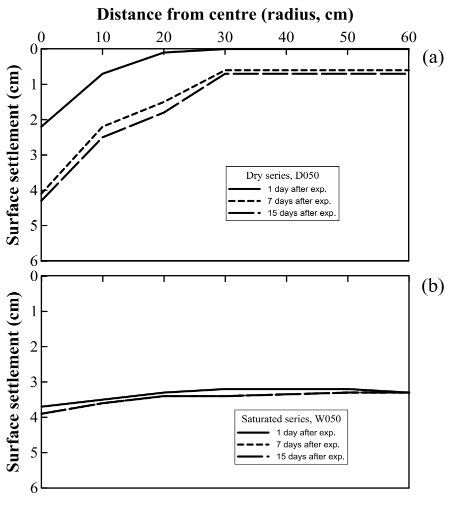

Fig. 6 Surface settlement after explosion for D050 (a) and W050 (b)

Even though a small-size chamber was used, no reflected waves were observed as evident from the acceleration monitored. However, it would be interesting to further experiment on sand having various degrees of saturation because the results would be very useful in terms of field application.

6 CONCLUSIONS

This study attempts to overcome the problems of loose sand deposits and sink holes by employing underground explosion. Based on the test results, the following conclusions have been drawn.

(a) The acceleration for the saturated sand is much higher than those for dry sand.

(b) If more than one explosive charge to be used, igniting them in the same time would generate the highest vibration.

(c) The before-explosion density for the saturated series is lower than that of the dry series; but, after the explosion it was much higher.

(d) The explosion under a saturated sand stratum would trigger the soil to liquefy thereby increasing the density afterwards.

(e) The saturated series settles uniformly across the surface; while the dry series creates a cone shape hole.

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