DENSIFICATION OF POND ASH BY BLASTING

By Shailesh R. Gandhi,1 Ashim K. Dey,2 and S. Selvam3

ABSTRACT: Fly ash from thermal power plants is disposed, in huge quantities in ash ponds, which occupy large land areas otherwise useful for agriculture, housing, or other development. For effective rehabilitation of ash ponds, densification of the slurry deposit is essential to increase the bearing capacity and to improve its resistance to liquefaction. Extensive field trials were carried out to evaluate the effectiveness of deep blasting for densification of deposited fly ash. Ninety explosions comprising 15 single blasts, each having 25 charges placed at various spacings, were carried out. The compaction achieved in terms of an increase in relative density was evaluated from surface settlement measurements. Extensive field monitoring was undertaken through pore-water pressure measurements, vibration measurements, penetration tests, and block vibration tests. For the average charge of 2–4 g of explosive per cubic meter of untreated deposit, the average relative density was found to improve from 50% to 56–58%. Analysis of the test results indicates that deep blasting may be an effective technique for modest compaction of loose fly ash deposits. The field testing program presented in this paper provides valuable information that can be used for planning blast densification of fly ash deposits.

INTRODUCTION

Disposal of large quantities of fly ash from thermal power plants is a major concern. In contrast to high utilization of fly ash in most of the advanced countries, the utilization in India is a mere 5%. Fly ash along with bottom ash is normally transported in the form of a slurry and deposited in an ash pond. After the ash particles settle, the clear decanted water from the top is discharged into a natural stream. Typically, an ash pond spreads over an area up to 10 km² for a 500-MW power plant and is filled with ash up to 10 m in height within a period of 5 years. Due to scarcity of land around a thermal power plant, the only option for increasing the capacity of an ash pond is by raising its height. In many places the total height of the deposit is > 30 m.

The ash deposit placed in slurry form has a very low density and leads to problems such as liquefaction during earthquake, poor bearing capacity, large settlement, etc. Considerable research has been conducted to improve the density of ash by different techniques such as vacuum dewatering, electroosmosis, vibrocompaction, stone columns, blasting, etc. (Gandhi et al. 1997). Among the various methods examined, blasting has been found to be simple, easy, and cost effective. Blasting does not require special construction machinery, and it may be effective for deep compaction of cohesionless deposits over a large area.

The technique was successfully used at the Franklin Falls Dam in New Hampshire as early as 1940 (Hall 1962). Since then, blasting has been applied in many cases to densify saturated loose cohesionless deposits. It is reported that in a saturated loose cohesionless deposit, deep blasting initiates a large release of energy to create compression waves that instantaneously build up pore-water pressure thereby reducing shear strength. Compression waves are followed by shear waves that are responsible for failure of the soil mass. Passage of these two waves ultimately results in the soil particles settling into a denser and more stable condition (Solymar and Mitchell 1986; and Jenkins et al. 1994). The technique has been used for densification of loose cohesionless deposits at Karnafully Dam in Bangladesh (Hall 1962), in foundation soils of three transmission towers in Pittsfield, Mass. (Wild 1961), in a 42-m-high, zoned rockfill dam at Jebba, Nigeria (Solymar 1984), and in the Lusitania mine region in Germany (Raju and Gudehus 1994). As a rule of thumb, 15–150 trinitrotoluene (TNT)- equivalent grams of explosive are required for treatment of 1-m³ of granular soil (Van Impe 1989), and the depth of the charge may be two-thirds the depth of the deposit to be treated (Prugh 1963). Raju and Gudehus (1994) observed nearly 100% liquefaction below the charge. Jenkins et al. (1994) presented a case study of blast densification of loose debris at a depth of 40 m. They demonstrated that the technique was effectively used to densify the debris and, therefore, to prevent liquefaction and to mitigate the probability of extreme ground settlement during an earthquake. Narin Van Court and Mitchell (1995) suggested a new methodology for predicting soil compaction resulting from blasting based on soil penetration resistance and powder factor. The results indicate a good correlation of penetration resistance with energy input, which is described as a function of the powder factor and overburden pressure. According to Van Impe (1989), the relationship between the weight of the charge W (in equivalent TNT, in kilograms) and the pore-water pressure developed, in kilopascals, at a distance R from the location of charge is expressed as a function of Hopkinson’s number W⁰/R, which is the reciprocal of the commonly used scaled distance R/W₀. The settlement at the ground surface is also expressed as a function of Hopkinson’s number, but both pore-water pressure and settlement functions are not well defined. According to Van Impe (1989), liquefaction is also related to Hopkinson’s number in the sense that liquefaction will not occur if Hopkinson’s number is limited to a value ≤0.15 (i.e., a scaled distance ≥6.67 m/kg⁰). However, until now, blast densification designs are by a rule of thumb, and no precise methodology has been developed. Ash densification by blasting is also a new concept and hence requires a systematic study for application.

As part of a research project, a series of 90 blasts was carried out in an ash pond to study the densification. Detailed measurements were made on settlement before and after each blast. Also, penetration resistance was measured in a few locations. Piezometers were used to measure the pore-water pressure in the deposit. The relative density increase due to a blast was evaluated with respect to quantity and depth of the charge.
DETAILS OF TEST SITE

All field tests were carried out in an ash pond at the Mettur Thermal Power Plant, which is located about 40 km northwest of Salem City in the state of Tamil Nadu in South India. Fig. 1 shows the layout of the ash pond and test locations. Two sides of the ash pond were bounded by hillocks and the other two sides by earth and rockfill embankments. The bottom of the pond consists of bedrock. The fly ash and bottom ash were mixed with water and discharged into the pond in slurry form. The discharge points and decanting wells are shown in Fig. 1. At the time of testing, the pond was filled with a 12-m ash deposit, and the ground-water table was 0.8–4 m below the surface.

Properties of Ash

Due to successive deposition of ash particles, variations are noticed in particle size, density, etc. in both horizontal and vertical directions. To get the average property of the deposit, 15 disturbed representative samples were collected. The samples were obtained using the standard penetration test (SPT) spoon sampler from four boreholes (shown in Fig. 1) at different locations with varying elevations. The samples were mixed thoroughly to prepare a single representative sample of the deposit. The average properties are \( \gamma_{\text{max}} = 12.62 \text{ kN/m}^3 \), \( \gamma_{\text{min}} = 9.27 \text{ kN/m}^3 \), \( e_{\text{min}} = 0.54 \), \( e_{\text{max}} = 1.10 \), \( G_s = 1.983 \), \( c = 7.5 \text{ kPa} \), and \( \phi = 20^\circ \) (based on consolidated undrained triaxial tests, for relative density of 50%). The low specific gravity of fly ash is due to its hollow spherical grains known as cenospheres. A typical particle size distribution curve is shown in Fig. 2.

To measure the field density, two pits, 600 mm wide, 600 mm long, and 500 mm deep, were made. The average in situ properties were determined as \( \gamma_d = 10.69 \text{ kN/m}^3 \) and \( e = 0.82 \).

EXPLOSIVE

Of the many commercially explosives available, a slurry-type explosive encapsulated in cartridges was chosen. The main constituents of the explosive are a mixture of ammonium nitrate and sodium nitrate with aluminum powder and a sensitizing agent. Some merits of this type of explosive are excellent water resistivity, low density, low detonation velocity,
accidental blasting due to fire or friction, low postblast fumes, no smell, and no irritation to eyes, etc. (Kate and Vinod 1997). Each cartridge was 83 mm in diameter and 500 m in length and weighed 2.78 kg.

Installation and Firing Method

A borehole was made by jetting compressed air through a sonic drill and driving a 100-mm-diameter plastic pipe through the borehole. The pipe was closed with a conical metal cone at the bottom as shown in Fig. 3. The depth was adjusted such that the center of the charge was at the required depth. The end of the cordex was connected to the charge and the other end to an electric delay detonator. The cartridges were lowered one over the other with the cordex connected at the bottom. Stemming material consisted of coarse sand below the water table and locally available reddish clayey sand above the water table that was poured in layers and adequately compacted. The detonators were connected, and the necessary current was supplied from a dynamo to initiate the blast.

FIELD MONITORING

To evaluate the degree of compaction, the test field was monitored both before and after each blast. The following procedures were taken at selected points:

1. Settlement of ground surface using surveying instruments
2. Pore-water pressure and its variation with time using vibrating wire-type piezometers
3. Ground vibration levels at a fixed distance of 30 m from the blast point using a vibration meter
4. Penetration resistance of SPT and cone penetration test (CPT)
5. Dynamic properties by block vibration test

The vibrating wire-type piezometers were calibrated in the laboratory using a standard pressure gauge, and the response was found to be linear. A 50-mm-diameter × 300-mm-long galvanized iron pipe was used to install the piezometers as shown in Fig. 4. One end of the pipe was closed with a metallic shoe. A nonwoven geotextile that satisfies the filtration criteria of ash was placed inside the pipe. After the piezometer was placed in position, coarse-grained sand was poured and compacted. The entire assembly was lowered to a depth of 9 m. The electric wire from the piezometer was connected to a readout unit. This arrangement was made so that the piezometer could be retrieved after each use.

The vibration meter used for monitoring vibration levels is a piezoelectric vibration pickup capable of measuring mechanical vibration and shock in terms of either acceleration or velocity in the frequency range of 0.3 Hz to 15 kHz. The meter is fully portable and battery operated. It is directly calibrated in metric units to read the peak particle velocity. Typically, larger ground accelerations are measured in the vertical direction than in the longitudinal direction as a result of blasting (e.g., Charlie et al. (1992)). The pickup was therefore placed with its axis in the vertical direction on a thick metal plate over the ground surface. A detailed description of the instrumentation and field monitoring is given by Sharma (1998).

For single point blasts, a vibrating wire-type piezometer was installed at a distance of 5 m from blast hole B7. The vibration meter was placed at a distance of 30 m from each blast hole. The positions of the different monitoring instruments used and the blast holes are shown in Fig. 1 for single point blasts and in Fig. 5 for a group blast.

TEST RESULTS AND ANALYSIS

Single Point Blasts

A total of 15 single point blasts was carried out. The objective was to find the optimum depth of the charge, optimum quantity of explosive per borehole, and the radius of influence R. The radius of influence is defined as the average distance from the center of the blast hole to a distance where settlement is essentially zero. The following parameters were varied for this purpose:

- Number of cartridges per borehole = 2–6.
- Depth of center of charge = D/2, 2D/3, and 3D/4, where D = average depth of ash deposit.

In addition, to study the effect of a higher quantity of charge, a test was conducted with 10 cartridges placed at 3D/4.

Observations Immediately after Blast

Immediately after a blast, minute radial cracks near the blast hole and circumferential cracks away from the blast hole were...
observed. With passage of time, the width and the extent of cracks increased. The maximum radius of the circular cracks was 24 m. The maximum width was 5 mm. The surface ash heaved up initially and gradually became a saucer-shaped depression. In locations where the water table was close to the surface, there was immediate gushing out of water and formation of a pool. In blast hole B6, the fly deposit was thrown into the air along with the stemming material due to poor compaction.

**Settlement of Ground**

Ground settlement in the vicinity of a point blast was measured 24–48 h after each blast. Maximum ground surface settlements caused by all 15 single blasts are summarized in Table 1. A typical section of the depression that formed after the blast at location B7 is shown in Fig. 6. In general, in locations where the water table was near the ground surface, the volume of the depression was observed to be relatively large (e.g., B5 and B7). Typical sections of the ground depression for different quantities of explosive placed at 2D/3 are shown in Fig. 7. It can be seen that the volume of the depression in the case of B5 as well as B7 is the highest of all the values. Fig. 8 shows the depression for blasts with four cartridges at three different depths. As can be seen in Figs. 7 and 8, at some blast locations R, is beyond 20 m, but for the purposes of calculation the maximum R, was considered to be 20 m. The results indicate that compared with a charge placed at D/2 or 2D/3, the densification is more effective for a blast where the charge is placed at 3D/4. This is clearly reflected by the volume of the depression. Among the results of blasts with charges at 3D/4, it is observed that the volume of the depression increases with the increase of the number of cartridges up to 6 cartridges. Although the results of the blast at B2 (10 cartridges) indicate that beyond 6 cartridges no compaction benefit is achieved, no definite conclusion can be drawn based on only one test. Thus, the optimum depth and quantity of charge were adopted as 3D/4 and 6 cartridges, respectively. The same depth and quantity were used for the group blasts.

The variation of scaled settlement with scaled distance for a single blast having a charge at 3D/4 is shown in Fig. 9. As can be seen, the trend is comparable with Ivanov’s observations, which is probably due to the presence of more fines and apparent cohesion in fly ash. The best-fit equation is obtained as follows:

\[ S/W^{1/3} = 0.1893 - 0.0438(R/W^{1/3}) + 0.0024(R/W^{1/3})^2 \quad (1) \]

where \( S \) = settlement (m) at a radial distance \( R \) (m) from a charge; and \( W \) = weight of the charge (kg).

**Relative Density**

The preblast \( \gamma_0 \) value was measured by excavating the pits. After the blast, the density is expected to vary in radial as well as in vertical directions. The average relative density (RD) after the blast was obtained as follows:
### Table 1. Results of Single Point Blast

<table>
<thead>
<tr>
<th>Blast number</th>
<th>Number of cartridges</th>
<th>Total weight (kg)</th>
<th>Depth of charge [m]</th>
<th>Radius of influence [m]</th>
<th>Maximum settlement [m]</th>
<th>Volume of depression [m$^3$]</th>
<th>Approximate location of GWT [m]</th>
<th>Scaled distance [mm/s$^{0.5}$]</th>
<th>Peak particle velocity [m/s]</th>
<th>Acceleration [m/s$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>6</td>
<td>16.68</td>
<td>11/2</td>
<td>18</td>
<td>0.3</td>
<td>74.4</td>
<td>4.00</td>
<td>11.741</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>B2</td>
<td>10</td>
<td>27.8</td>
<td>3D/4</td>
<td>20</td>
<td>0.4</td>
<td>95.0</td>
<td>4.00</td>
<td>9.903</td>
<td>12</td>
<td>2.4</td>
</tr>
<tr>
<td>B3</td>
<td>4</td>
<td>11.12</td>
<td>D/2</td>
<td>20</td>
<td>0.33</td>
<td>83.4</td>
<td>1.85</td>
<td>14.793</td>
<td>8.6</td>
<td>1.5</td>
</tr>
<tr>
<td>B4</td>
<td>3</td>
<td>8.34</td>
<td>D/2</td>
<td>20</td>
<td>0.5</td>
<td>139.0</td>
<td>1.00</td>
<td>16.934</td>
<td>2.2</td>
<td>0.3</td>
</tr>
<tr>
<td>B5</td>
<td>2</td>
<td>5.56</td>
<td>D/2</td>
<td>20</td>
<td>0.5</td>
<td>66.4</td>
<td>0.80</td>
<td>11.741</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>B6</td>
<td>6</td>
<td>16.68</td>
<td>2D/3</td>
<td>15.5</td>
<td>0.48</td>
<td>138.4</td>
<td>0.80</td>
<td>12.477</td>
<td>7</td>
<td>0.9</td>
</tr>
<tr>
<td>B7</td>
<td>5</td>
<td>13.9</td>
<td>2D/3</td>
<td>20</td>
<td>0.35</td>
<td>56.3</td>
<td>1.50</td>
<td>13.440</td>
<td>10</td>
<td>1.3</td>
</tr>
<tr>
<td>B8</td>
<td>4</td>
<td>11.12</td>
<td>2D/3</td>
<td>20</td>
<td>0.46</td>
<td>64.1</td>
<td>1.50</td>
<td>14.793</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>B9</td>
<td>3</td>
<td>8.34</td>
<td>2D/3</td>
<td>18</td>
<td>0.28</td>
<td>59.6</td>
<td>3.50</td>
<td>16.934</td>
<td>12</td>
<td>1.5</td>
</tr>
<tr>
<td>B10</td>
<td>2</td>
<td>5.56</td>
<td>2D/3</td>
<td>19.2</td>
<td>0.5</td>
<td>108.4</td>
<td>4.00</td>
<td>11.741</td>
<td>12</td>
<td>1.5</td>
</tr>
<tr>
<td>B11</td>
<td>6</td>
<td>16.68</td>
<td>3D/4</td>
<td>20</td>
<td>0.43</td>
<td>107.4</td>
<td>4.00</td>
<td>12.477</td>
<td>8.5</td>
<td>1.5</td>
</tr>
<tr>
<td>B12</td>
<td>5</td>
<td>13.9</td>
<td>3D/4</td>
<td>20</td>
<td>0.45</td>
<td>99.1</td>
<td>4.00</td>
<td>13.440</td>
<td>8.5</td>
<td>1.5</td>
</tr>
<tr>
<td>B13</td>
<td>4</td>
<td>11.12</td>
<td>3D/4</td>
<td>20</td>
<td>0.54</td>
<td>82.7</td>
<td>3.85</td>
<td>14.793</td>
<td>7.4</td>
<td>0.95</td>
</tr>
<tr>
<td>B14</td>
<td>3</td>
<td>8.34</td>
<td>3D/4</td>
<td>10</td>
<td>0.29</td>
<td>23.7</td>
<td>3.85</td>
<td>16.934</td>
<td>5.5</td>
<td>0.7</td>
</tr>
<tr>
<td>B15</td>
<td>2</td>
<td>5.56</td>
<td>3D/4</td>
<td>10</td>
<td>0.29</td>
<td>23.7</td>
<td>3.85</td>
<td>16.934</td>
<td>5.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

$\text{GWT} = \text{ground-water level.}$

$\text{Above each slurry cartridge one ammonium nitrate cartridge was placed to observe the effect.}$

$\text{Extrapolated from acceleration measurement.}$

$\text{Extrapolated from velocity measurement.}$

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**Figure 6.** Typical Section of Depression for Single Blast

**Figure 7.** Typical Sections of Depression for Different Quantities of Charge at 2D/3 (GWT = Ground-Water Level)

Average RD = \[
\varepsilon_{\text{max}} - \left[ \frac{e - S_{\text{max}}}{D} (1 + e) \right]
\]  \hspace{1cm} (2)

Maximum RD = \[
\varepsilon_{\text{max}} - \frac{e - S_{\text{max}}}{D} (1 + e)
\]  \hspace{1cm} (3)

where $S_{\text{max}} = \text{maximum settlement at the blast point.}$ Fig. 10 shows the average relative density variation for different powder factors. Powder factor is defined as quantity of charge in grams divided by the volume of deposit influenced by the blast.
The variation of maximum relative density is also indicated in Fig. 10. It is seen that the relative density increases with the increase in powder factor. For a powder factor of 2 g/m³ the improved average and the maximum relative densities are 52.5 and 63%, respectively. The results from B2 and B15 were not considered because the former had 10 cartridges and the latter had 2 ammonium nitrate cartridges.

**Penetration Tests**

The results of CPT around B11 are shown in Fig. 11, which shows improvement in the cone resistance after the blast. All penetration tests were carried out after a minimum period of 28 days. Improvement at a radial distance of 5 m is less compared with the results beyond 5 m. This may be due to the high disturbance during cavity expansions or gas pressure. Beyond 20 m, there was no significant improvement.

**Pore-Water Pressure**

The change in pore-water pressure with time for four blasts is shown in Fig. 12. The pore pressure is found to increase with successive blasts. It is observed that the peak pore-water pressure increases as the scaled distance of the blast point from the piezometer location decreases, as shown in Fig. 13. This relationship is consistent with those obtained by Lyakhov (1961) and Charlie et al. (1992) for soils, as shown in Fig. 13.
FIG. 12. Variation of Pore Pressure

FIG. 13. Peak Pore Pressure against Distance from Blast

**Peak Particle Velocity**

The peak particle velocity measured at a distance of 30 m from each blast is presented in Table 1. For two locations only, B1 and B6, the acceleration was measured in place of the peak particle velocity. In both of these cases, the peak particle velocity is arrived at from the tripartite plot for harmonic motion (Kramer 1996). At locations where the velocity was measured, the acceleration is arrived at from the same plot considering the natural frequency of 20 Hz (based on the results of the block vibration test described later) and is also shown in Table 1. The best-fit equation for peak particle velocity is found to be

\[ V_{\text{peak}} = 14.054(R/W^{1/3})^{-2.8296} \]  

where \( V_{\text{peak}} \) = peak particle velocity (mm/s); \( R \) = radial distance from charge (m); and \( W \) = weight of charge (kg).

This is compared with the values given by Charlie et al. (1992), Hryciw (1986), and Drake and Little (1983) as presented in Fig. 14. It can be seen that the observed values are below those obtained by others. The above expression can be used to find the safe distance of a charge hole from an existing structure/plant for a particular vibration level. For example, for a vibration level of 25 mm/s the safe distance for 16.68 kg of charge is approximately 24 m.

**FIG. 14. Variation of Peak Particle Velocity with Scaled Distance**

**Group Blasts**

A total of 75 blasts was carried out in three groups each of 25 blasts. Every blast had six cartridges placed at 3D/4 and an approximate radius of influence \( R \), of 20 m. The objective was to find the group effect and the relationship between the powder factor and the relative density. A layout adopted for the group blasts is shown in Fig. 5. The layout was used for the three groups with varying spacing \( z = 0.9R, 1.1R, \) and \( 1.3R \).

Successive detonations were carried out in parallel waves of equilateral triangles. The charges \( i, i - 1, i - 2 \), shown in Fig. 5, were first detonated with a time interval of 25 ms. The remaining 10 charges \( j \) and \( j - 1 \) were detonated after 24 h in the second phase with the same time interval. Although guidelines to arrive at the interval between the two phases are not available, a period of 24 h was considered to be sufficient for release of gases possibly trapped below the surface.

**Ground Settlement**

A typical ground profile after 2 days of blasting for the three different groups is shown in Fig. 15. With the decrease in spacing, there is more overlapping of cones of depression and the ground settles more uniformly. The average depression versus spacing is shown in Fig. 16. It can be seen that the average depression increases from 0.24 to 0.29 m when spacing is reduced from 26 to 18 m. The settlements from the group blasts are summarized in Table 2. As can be seen in Table 2, there is a consistent increase in the average depression with an increase in powder factor as well as duration after the blast. Only in the case of group blast II between 7 and 30 days, as well as in the case of group blast III between 2 and 7 days, was a marginal decrease in the average depression noticed. During the above period, there was rain, which is believed to be the reason for migration of fly ash particles from the surrounding area into the depression.

The settlement records show that from the time of the blast, up to a period of 7 days, there has been an increase in the ground settlement. Beyond this period, up to 30 days, there is no significant increase in settlement. Raju and Gudehus (1994) also reported stabilization of the ground within 5 days after the blast.

**Relative Density**

The average relative density after a group blast is calculated in the same way as that for a single blast. The total volume
of the treated deposit was considered as the area represented by the group that is $5s \times 5.25s$ (Fig. 5) times the depth of the deposit. Fig. 17 shows the variation of the average relative density with the powder factor. The powder factor in a group blast is considered as the weight of a charge in grams divided by the equivalent volume represented by a blast hole. It is seen that the relative density improved from 50 to 56.3%, 57%, and 58% for powder factors of 1.9, 2.8, and 4 g/m$^3$, respectively. The powder factor was kept low in consideration of the low specific gravity of pond ash so that throwing of ash in air could be minimized. Compared with the powder factor adopted by others [e.g., Solymar (1984) used a powder factor of 25–35 g/m$^3$], the present value is very small. A higher powder factor achieved by reducing the spacing could produce still higher relative density. Compared with a single blast, the improvement in the average relative density for a group blast, for the same powder factor, is found to be higher as shown in Fig. 17.

**Penetration Tests**

There is an improvement of cone resistance after a group blast. Fig. 18 shows a typical result for the group blast III. It can be seen that there is little or negligible improvement in cone resistance near the ground surface. In view of the smaller compaction near the surface compared with that at a larger depth, secondary compaction may have to be adopted. Hall (1962) also reported little compaction in the upper 0.9 m of sand.
In one of the corners of the group blast II, the quantity of the charge was distributed at three elevations to observe the effect of distribution of the charge. The charge was placed with one cartridge at a depth of 3.25 m, two cartridges at a depth of 6 m, and three cartridges at a depth of 9 m. Fig. 19 shows the preblast and the postblast CPT values at a distance of 7.5 m from this blast hole. There is good improvement in the CPT values below every charge. This shows that a distribution of cartridges at various elevations is more effective for uniform compaction compared with the concentration of all cartridges at one location.

Fig. 20 shows a comparison of the SPT N-values before and after a blast. It can be seen that the results are not consistent with the CPT. Possible reasons may be the increase in pore pressure in the ash immediately below the sampler tip or due to the disturbance caused by boring operations.

**Pore Pressure**

The excess pore-water pressure measurements for group blast III could not be taken because of the charging problem at the readout unit at the time of the blast. For the other two groups, measurements were taken immediately after blasting at 10-s intervals up to 1 min, 15-min intervals up to 1 h, and then at hourly intervals up to 24 h. A typical plot of the pore pressure variation with time is shown in Fig. 21. It is seen that immediately after a blast, the pore-water pressure shoots up. Dissipation of excess pore-water pressure starts after about 30 s, and almost full dissipation occurs within 24 h. The peak excess pore-water pressures for the different group blasts are shown in Table 3.

**Peak Particle Velocity**

Due to nonavailability of the vibration meter, the peak particle velocities for group blast I and group blast II could not be measured. The peak particle velocity for group blast III at a distance of 30 m from the outer blast point was measured as 16 mm/s during the first phase blast and 15 mm/s during

<table>
<thead>
<tr>
<th>Table 3. Peak Pore-Water Pressure</th>
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<tbody>
<tr>
<td>Group blast number</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>I at 26 m spacing:</td>
</tr>
<tr>
<td>After first phase</td>
</tr>
<tr>
<td>After second phase</td>
</tr>
<tr>
<td>II at 22 m spacing:</td>
</tr>
<tr>
<td>After first phase</td>
</tr>
<tr>
<td>After second phase</td>
</tr>
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</table>
FIG. 22. Typical Response Curve for Fly Ash Deposit

TABLE 4. Results of Block Vibration Test

<table>
<thead>
<tr>
<th>Ash parameter (1)</th>
<th>Virgin deposit (2)</th>
<th>Within group blast I (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic shear modulus (MPa)</td>
<td>15.11–18.46</td>
<td>14.32–20.26</td>
</tr>
<tr>
<td>Shear-wave velocity (m/s)</td>
<td>123–136</td>
<td>120–143</td>
</tr>
<tr>
<td>Damping constant</td>
<td>0.04–0.15</td>
<td>0.14–0.19</td>
</tr>
</tbody>
</table>

the second phase blast. Compared with the vibration level under a single blast (12 mm/s for six cartridges at 3D/4), there is only a marginal increase even with 15 explosions.

Block Vibration Tests

Two block vibration tests were carried out, one on virgin deposit and the other within group blast I, 30 days after the blasting operation, to find the dynamic properties of the deposit. In both cases, a mechanical oscillator was mounted on a reinforced concrete block of size $1.5 \times 1 \times 1$ m deep cast in a test pit of size $2 \times 2 \times 1.5$ m deep. The oscillator was connected through a flexible shaft with a direct current motor and a speed control unit. Purely vertical sinusoidal vibrations were created and were sensed by two acceleration pickups. Output signals from pickups were monitored and recorded using carrier frequency amplifiers and a digital storage oscilloscope. Choosing a suitable value of dynamic force, the oscillator was made to run at a constant frequency, and a steady-state response was recorded. The tests were carried out for four different dynamic forces. Typical response curves are shown in Fig. 22, and dynamic properties are given in Table 4.

The block vibration test carried out at a depth of 1.5 m after compaction reflects properties of the deposit to a limited depth only and not exactly the improved deposit at a deeper level. However, the test was carried out to evaluate the effect of blast compaction on shear modulus, shear-wave velocity, and damping constant. As can be seen in Table 4, although the effect of blasting on the shear modulus is marginal, the effect on the damping constant is significant. With an increased damping constant, the behavior of the machine foundation can improve.

SUMMARY AND CONCLUSIONS

This paper reports the results of 90 deep blasts carried out to densify a 12-m-thick fly ash deposit in an ash pond at Mettur Thermal Power Station, Tamil Nadu, India. The results show that the technique of densification by deep blasting has resulted in modest compaction even with a low powder factor and may be more effective with a higher powder factor. The densification is found to be very fast. The following conclusions have been drawn based on the field measurements and analyses of the data:

1. In a group blast, even for low powder factors of 1.9, 2.8, and 4 g/m$^3$, the average relative density is found to improve from 50 to 56.3%, 57%, and 58%, respectively. Compared with a single blast, a group blast is found to be more effective.

2. The increase in relative density depends on the depth of the water table. In locations where the water table is close to the surface, the improvement is higher.

3. Compared with the compaction achieved by placing the charge at one depth, the compaction is better when the charge is distributed at different elevations.

4. The results of CPTs show that there is no significant improvement near the surface. The surface may require secondary compaction.

5. The pore-water pressure increases immediately after each blast, continues to dissipate for 24 h, and becomes negligible after that.

6. The block vibration tests show that the amplitude of vibration is reduced after blasting. Though there is a negligible change in natural frequency, the damping constant is found to increase after the blast, which can improve the behavior of a machine foundation.

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APPENDIX I. REFERENCES


APPENDIX II. NOTATION

The following symbols are used in this paper:

- $c$ = cohesion;
- $D$ = average depth of fly ash deposit;
- $e$ = in situ void ratio;
- $e_{max}$ = maximum void ratio;
- $e_{min}$ = minimum void ratio;
- $G_s$ = specific gravity;
- $N$ = number of blows per foot in SPT;
- $R$ = radial distance from charge;
- $R_i$ = radius of influence;
- $S$ = settlement;
- $S_m$ = average settlement;
- $S_{max}$ = maximum settlement;
- $s$ = spacing;
- $V_{pmax}$ = peak particle velocity;
- $W$ = weight of charge;
- $\gamma_s$ = field dry density;
- $\gamma_{max}$ = maximum dry density;
- $\gamma_{min}$ = minimum dry density; and
- $\phi$ = angle of shearing resistance.