Densification of deep soil deposits is achieved by the following techniques:

a. Precompression
b. Explosion
c. Heavy tamping
d. Vibration
e. Compaction grouting
a. Precompression

A site is loaded by means of a surcharge or by lowering the groundwater level, causing the ground to consolidate.

Usually reserved for cohesive soils.

Consolidation of these soils is a long-term process, unless the existing longest drainage paths are shortened by the installation of:

- Sand columns
- Paper wicks or
- Geocomposite drains.
Scheme of Sand Drain Method

- **Airport Island**
- **Sand Drainage**
- **Holocene clay layer**
- **Sand Pleistocene**

**With No Improvement**
- Considerable distance to point where clay water can be drained

**With Improvement by Sand Drainage**
- Little distance to point where clay water can be drained

**vertical drain**
Typical vertical drain installation
b. Explosion

Explosives are detonated (exploded) on the surface, or more likely, in an array of boreholes,

causing a loose soil structure to collapse which leads to a denser arrangement of the particles.

The final density may not be achieved immediately, as the dissipation of excess pore pressures generated may take some time.

Square Grid
Explosives can be employed to modify:

- Sands
- Loose rock and
- Special soils such as loess which is characterized by relatively high porosity.

In saturated soils temporary high pore pressures are set up, causing liquifaction.

These excess semidynamic pore pressures are essential for effective densification resulting from subsequent consolidation.

Installation of vertical drains may assist the explosion-induced consolidation process.
Care must be taken that structures adjacent to the blasting site are not affected.

Excess pore pressure and settlement due to explosion are related to the ratio:

$$N_h = W^{1/3}/R$$

Where

$N_h$: Hopkinson’s number

$W$: weight of explosives, equivalent kg of TNT (trinitroglycerol)

$R$: radial distance from point of explosion, m
If $N_h <$ the range of 0.09 to 0.15
little or no liquifaction occurs.

This can be used to estimate a safe distance from the explosion.

Experience with sandy soils in Netherlands suggested the following relationships obtained from a statistical analysis of field results:

$$\Delta u/\sigma' = 1.65 + 0.65\ln(N_h)$$
$$\Delta h/h = 2.73 + 0.9\ln(N_h)$$

where:
$\Delta u$: excess pore pressure
$\sigma'$: effective overburden pressure
$\Delta h$: surface settlement
$h$: the height of the soil layer.
Barendsen and Kok stated that for optimum densification

\[ \frac{\Delta u}{\sigma'} > 0.8 \] is required.

For lower ratios, only partial liquefaction may occur, resulting in lower compaction efficiency.

Field studies on the effect of explosions within saturated fine to medium grained cohesionless soils led to the conclusion that

the depth of placement, \( h \) (meters)

of a

charge of mass \( c \) (kg)

is related empirically by the expression:

\[ c = 0.055h^3 \]

and depth of compaction \( h_c \) of loose sandy soil is,

\[ h_c = 1.5 \ h \]
$h_c$ decreases to 1.2h-1.3h (avr. 1.25h) for sands of medium initial density.

The max. lateral extent of the compaction $R_c$ (meters) is:

$$R_c = k_3 \cdot 3\sqrt{c}$$

$k_3$: empirical constant

The charges are placed on a square grid spaced at

$$D = k_4 \cdot 3\sqrt{c}$$

Values of factors $k_3$ and $k_4$ for a TNT charge within sand:

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Packing</th>
<th>$k_3$</th>
<th>$k_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose</td>
<td>25-15</td>
<td>10-8</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>9-8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Dense</td>
<td>&lt; 7</td>
<td>&lt; 5</td>
<td></td>
</tr>
</tbody>
</table>

| Medium sand        |         |        |        |
| Medium             | 8-7     | 6-5    |
| Dense              | < 6     | < 5    |
Relative Density, RD

Relative Density, RD : \(\frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}}\)

- \(e_{\text{max}}\): max. void ratio for the loosest possible state
- \(e_{\text{min}}\): min. void ratio for the densest possible state
- \(e\): void ratio of the soil for which relative density is defined.

<table>
<thead>
<tr>
<th>Relative Density</th>
<th>Packing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>Very loose</td>
</tr>
<tr>
<td>15-35</td>
<td>Loose</td>
</tr>
<tr>
<td>35-65</td>
<td>Medium</td>
</tr>
<tr>
<td>65-85</td>
<td>Dense</td>
</tr>
<tr>
<td>85-100</td>
<td>Very dense</td>
</tr>
</tbody>
</table>
EXAMPLE

• These calculations provide a first estimate.

• It is usually necessary to conduct in-situ tests to establish the effectiveness of the empirical relationships and the degree of compaction achieved by a single or series of charges.

• If a liquified state is achieved in a particular region, there is no advantage in increasing the size of charge.
• **Further compaction** is achieved by exploding a series of charges.

It was shown that the **first charge** causes 50-60% of the total compaction (or settlement),

**the second 20-30% more** and remaining charges have progressively reduced effect.

• One of the **disadvantages of the blasting technique** is the effect on **adjacent structures** and people.

• **Soil closest to the surface** will be poorly compacted and may need compaction by another method or removal.

• **Empirical data** are available which give the quantity of explosives that can be used without causing unwanted damage.

• **Blasting** has the particular **advantage over the other methods** that **no major items of capital equipment** are required, except conventional drilling or jetting machines.

• Small areas can be economically treated.

• **Layer thickness up to 20m can be compacted** to a relative of 70-80%. 