# Application of Ground Improvement: Jet Grouting

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Application of Ground Improvement: Jet Grouting

1 Introduction

Ground improvement is becoming an increasingly common technique for solving a number of temporary and permanent problems in the field of civil engineering.

The aim of this document is to provide a basic understanding to the engineer such that:

i) There is a recognition when and how ground improvement can be applied*

ii) There is equally a knowledge of the limits and risks involved

The success of ground improvement is due to good design, appropriate techniques and most importantly experience and skill on site.

2 Application of Ground Improvement

The successful application of ground improvement requires both a correct design concept and also correct execution. It can therefore be regarded as a design and construct method. The use of the systems described below is intended to be taken as a guide, so it is important to recognise that some ground conditions may be complex leading to difficult solutions. Consultation with engineers experienced in the design and execution of jetgrouting is always recommended.

2.1 Jet Grouting

Jet grouting differs from permeation grouting in that the intent with the latter is not to disturb the fabric/structure of the soil whereas with the former this has to be the case for successful application.

Typical Uses

Because the product of jet grouting tends to be more structural in nature, it has a great range of application.

When installed beneath buildings it can extend foundations through poor ground or support them while excavations, often unsupported, are carried out next to them.

It can provide support underground where openings are necessary such as for TBM break out or break in or cross passages or equally to support tunnel faces. Because it does not rely on passage through the ground its product usually is more predictable and significantly less dependent on ground strength or composition.

It can provide ground water control at the base of excavation and prop retaining walls at the same time. It can truly be a multi-application tool dealing with support, groundwater control and increasing efficiency of site usage simultaneously.
Technique

Jet grouting consists of drilling down with a small diameter rod system, typically 90-130mm in diameter and then injecting a high pressure fluid while rotating and withdrawing the rod.

There are three basic systems available:-
(a) Single System
(b) Double system
(c) Triple System

The single system as the name implies, is the injection of grout only at high pressure. This was the first system to be used and gives limited column diameter and the borehole has a tendency to become blocked often resulting in ground heave. Column sizes are small usually up to 1m in diameter.

The double system is effectively the single system with the addition of an air shroud to the nozzle. The addition of the air shroud increases jetting efficiency dramatically giving typically 30% or more increase in diameter for the same jetting energy. This system is very common currently and a number of specialists operate similar systems of variable power. Typically column diameters being designed and used with the double system are now approaching 3m due to the advent of more powerful high pressure pumps.

There are other company specific systems. These are very versatile and powerful systems with column diameter capability of up to 4-5m in most soils.

The triple system differs from the single and double systems in that the erosion of the ground is carried out by a high pressure water jet shrouded with air with an additional low pressure grout line. The column diameters achieved with this system are greater than those of the single system but the energy is relatively low compared to the double systems. Columns are usually only up to 1.7m to 2m (in exceptional ground) in diameter. Some companies have recently increased the power of the triple system to match that of the double system giving diameter capabilities of 2-3m.

The Xjet system is unique in that it consists of a pair of intersecting air-shrouded water jets with separate grout jets and is designed to cut a nominal 2m diameter column in any ground. The figure below shows the concept.
It is most applicable in variable weak ground such as soft clays and peat where overcutting of the design diameter can be a problem.

The ranges of applications for the systems are similar and the selection is a site specific requirement. The single system is rarely used unless there are concerns about the air usage and loss of strength so the choice normally rests between the use of the double or triple system.

Generally the triple system can produce more spoil but is it usually less viscous and hence offers less risk for blockage and potential structural or ground movement.

Risk

Jet grouting historically has been considered as a risky ground improvement process due to the high pressures involved and the spoil generation. With good experience, site operatives, site control and proper design the system can be no risky than other processes.

The main risks associated with the process are the use of high pressures and the potential generation of movement. When jet grouting is carried out beneath buildings care must be taken to ensure that heave of the walls or floors is maintained within agreed limits. It is absolutely critical that the construction of the floors and walls can withstand the potential effect of jet grouting. Where floor construction is poor and non sealed then it is advisable to maintain a visual inspection and potentially monitoring during jet grouting. Wall movement during jet grouting can be controlled in the long term by precise levelling and in the short term by the use of rotating laser targets fixed to the wall.

Sequence is extremely important during underpinning operations as there is the possibility of loss of support if too large an area is jetted at the same time. Where structural foundation condition is poor i.e. poorly cemented masonry or brick then a pregrouting exercise using lancing or end of casing can be considered with the intent to reinforce the available bonding and reduce the risk of partial wall collapse into a freshly completed column. For underpinning work it is usual to restrict the jetting of adjacent columns to intervals of at least 12 hours. For isolated foundations, the sequence must be designed to prevent loss of support and in extreme cases temporary load transfer should be provided during the jet grouting operation.

There is usually excellent bonding between the foundation and the jet grout columns as subsequent adjacent columns always treat this zone and ensure perfect contact.

Careful attention to the location of any service or underground structure is needed as grout can end up in services, especially old sewers where the lining is not competent. It is essential to identify such services prior to grouting and consider the effects of the scheme on the service. In particular for sensitive services (i.e. gas or chemical pipelines) additional monitoring and control will be required. For grouting adjacent to tunnels, due consideration to the effects of the injection pressure needs to be taken especially in the case of segmental construction.
When jet grouting, care must be taken to control the spoil return as any blockages are detrimental and can cause ground movements if uncontrolled.

Health and Safety Issues

Apart from the H&S issues arising out of adopting this solution in situations where failure could impact on safety, the technique requires grout to be pumped at high pressure. Potential failure of grout hoses in this situation needs to be addressed as escaping grout can impact on a wide area and cause serious injuries through the high pressure fluid or whiplash of hoses.

Grouting close to underground structures needs careful consideration and any grouting carried out within 3-5m of any underground structure will require a specific risk assessment. Wherever possible, consultation with the original designer is advisable to understand the specifics of the ground improvement.

The use of jet grouting for remedial ground improvement for dams or other water retaining structures needs careful consideration due to the additional risk of spoil blockage and subsequent ground fracture creating leakage paths which could ultimately cause serious problems with the safety of the structure.

Design Considerations

Because of the ability of jet grouting to bond soil particles and create relatively strong bodies (UCS range 2-10Mpa), the design process is similar to the design of brick or masonry.

Strength of treated ground is usually assessed on the basis of unconfined compressive strength tests of samples obtained by in situ wet sampling or coring. The histograms shown in the Figure below demonstrate experimental unconfined compressive strengths in sandy and cohesive soils. The Japan Jet Grouting Association has adopted these distribution charts, defining the unconfined compressive strength used for design to be the minimum safe values which range between 1 to 5 percent from the least values in the whole group.

This definition gives the standard unconfined compressive strengths as follows (where the Water/Cement ratio of the grout is typically 1)
Table 1. Standard strengths in designing

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Qu: Unconfined Compressive strength (MN/m²)</th>
<th>C : Cohesive strength (MN/m²)</th>
<th>f : Bond strength (MN/m²)</th>
<th>σ : Bending tensile strength (MN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesive</td>
<td>1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Granular</td>
<td>1-3</td>
<td>0.2-0.5*</td>
<td>1/3C</td>
<td>2/3C</td>
</tr>
</tbody>
</table>

* depending on grout type according to the JGA

Strength is usually only an issue for base slabs and shaft break out or in. In these cases the strength can influence the design as the jet grouting is required to span across openings and hence has to be designed with a minimum structural integrity.

Jet grout column layout is designed based upon the two factors:-

(a) Hole Deviation
(b) Column Diameter

When drilling holes for most operations, hole verticality tolerance is unlikely to be better than 1 in 100 and is typically specified at 1 in 75. For shallow holes this does not create an issue but as depth increases it becomes a more important influence on the design of the jet grout layout.

When creating a jet grout base slab, the design is normally based on a triangular grid.

This figure shows the effect when a single column deviates from the design position. The solution is to reduce the column spacing. This has a significant influence on cost as column diameter and spacing determine the quantity of columns.

Validation

Validation is as described above. Because jet grouting generally is structurally more sound, coring can be more successful if care is taken. In addition the process lends itself to trial exposure whereby a number of initial columns are jetted on site and then exposed after 24-48 hours to determine size and uniformity. With jet grouting, the column diameter tends to be the more important parameter for validation as this is
fundamental in the construction of gravity or underpinning blocks. In granular soils, strength is not usually an issue.

New techniques being used by a number of jetgrouting specialists include the use of microphones installed in boreholes close to the columns to assess whether the diameter is achieved by detecting the noise as the grout/water jet strikes the microphone tube. Also in-column calliper systems have been used to measure diameter directly by extending calliper arms till they touch the sides of the columns.

Interpretation of the results can be problematic but it shows promise in providing a usable system to demonstrate the column diameter.

**REFERENCES**

1. Xanthakos, Abramson and Bruce, Ground Control and Improvement, Chapter 8, 1994, published by Wiley (An excellent guide to jet grouting covering both design and execution)
2. RD Essler, Shibazaki, Jet grouting Chapter, Ground Improvement 2nd Edition 2005 published Taylor & Francis (Covers design and case histories)
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Application of Ground Improvement: Deep Mixing

1 Introduction

Ground improvement is becoming an increasingly common technique for solving a number of temporary and permanent problems in the field of civil engineering. The success of ground improvement is due to good design, appropriate techniques and most importantly experience and skill on site.

Deep mixing is an in-situ soil stabilization technique using cement and/or lime as a stabilizing agent, was developed in Japan and in the Scandinavian countries independently in 1970s. The Various methods in the Deep Mixing Methods are classified in Fig. 1.1.

![Deep Mixing Methods Classification Diagram](image_url)

Figure 1.1. Classification of Deep Mixing Method.

2 Typical uses

Deep mixing has been frequently applied to many structures: foundation of structures, retaining wall, embankments, slopes, excavations, soil tank and shield tunnel. The purpose of these applications is varied, including reducing settlement, increasing bearing capacity of the ground, increasing stability and ground liquefaction strength, reducing active earth pressure, cutting off ground water, and increasing pile’s bearing capacity against lateral forces, etc. The Deep Mixing Method (DMM) has usually
been applied to the improvement of soft clays and organic soils for various purposes and in various ground conditions. Depending on the purposes and ground conditions, several configurations have been conceived as shown in Fig. 2.1: a) block-type improvement, wall-type improvement, lattice-type improvement (grid-type) and group column-type improvement.

Table 2.1 shows a comparison of the characteristics of the above mentioned improvements. It is concluded that the block-type improvement achieves the most stable improvement, but it is expensive. The wall-type improvement and the lattice-type improvement also achieve stable improvement, and are more economical, but both require high quality continuous overlapping work.

Figure 2.1. Typical improvement patterns of treated soil mass.
### Table 2.1. Characteristics of improvement types.

<table>
<thead>
<tr>
<th>Type</th>
<th>Stability</th>
<th>Cost</th>
<th>Installation</th>
<th>Design Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Block Type</strong></td>
<td>Large solid block resists external forces.</td>
<td>Volume of improvement is greater than other types. High cost.</td>
<td>Takes longer time because all columns are overlapped.</td>
<td>Design of size of block is in the same way as the gravity structures.</td>
</tr>
<tr>
<td></td>
<td>Highly stable.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wall Type</strong></td>
<td>Where all improved walls are linked firmly, high stability is obtained.</td>
<td>Volume of improvement is smaller than block type. Lower cost.</td>
<td>Requires precise operation of overlapping of long and short units.</td>
<td>Requires consideration of unimproved soil between walls. Improvement size affected by internal stability.</td>
</tr>
<tr>
<td><strong>Lattice Type</strong></td>
<td>Highly stable next to Block Type.</td>
<td>Cost range is between Block type and Wall type.</td>
<td>Installation sequences are complicated because lattice shape must be formed.</td>
<td>Requires design on three-dimensional internal forces.</td>
</tr>
<tr>
<td>(Grid Type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Group Column Type</strong></td>
<td>Where lateral forces are small, high stability is obtained.</td>
<td>Installation requires short period, and volume of improvement is small. Low cost.</td>
<td>Overlapping operation is not required.</td>
<td>Requires design on overall stability and on internal force of piles.</td>
</tr>
</tbody>
</table>
3 Execution

(1) DRY MIXING
Dry mixing is normally carried out in accordance with some general principles, summarised in Fig. 3.1. As can be seen in the flow chart, the binder is fed into the soil in dry form with the aid of compressed air. Two major techniques for dry mixing exist at present: the Nordic and the Japanese techniques.

![Flow chart for the execution of dry mixing](image)

Figure 3.1. Flow chart for the execution of dry mixing

![Installation procedure](image)

Figure 3.2. The installation is carried out according to the following procedure, from left to right:

1) mixing tool is correctly positioned;
2) mixing shaft penetrates to the desired depth of treatment with simultaneous disaggregation of the soil by the mixing tool;
3) after reaching the desired depth, the shaft is withdrawn and at the same time, the binder in granular or powder form is injected into the soil;
4) mixing tool rotates in the horizontal plane and mixes the soil and the binder;
5) completion of the treated column.
**Nordic technique**

Equipments used in the Nordic countries are able to install columns to a depth of 25 m with a column diameter of normally 0.6 m to 1.0 m. The columns can be inclined up to about 70° in relation to the vertical. The machines have one mixing shaft with the injection outlet positioned at the mixing tool. Mixing energy and amount of binder are monitored and in some cases automatically controlled to achieve sufficiently uniform treated soil.

The mixing tool is drilled down to the final depth and a predetermined amount of binder is added through an inner tube with an opening at the mixing tool (during the retrieval phase). During the retrieval phase, the soil and binder are mixed by continued turning of the mixing tool, eventually changing the direction several times (homogenisation phase). Both phases can be repeated for the same location, if required.

The rotation speed of the mixing tool and the speed with which it is withdrawn is adjusted to produce uniform mixing, sufficient for the purpose. The amount of mixing work involved in producing a dry-mixed column depends on the type of binder, quantity of binder and type of soil. When using cement as binder compared to lime only, a higher amount of mixing energy is required. Bellows equipment has been developed to contain air and dust.

**Japanese technique**

There are several variations of execution machines, which have either one or two mixing shafts. Each mixing shaft of these machines have several blades with 0.8 m to 1.3 m diameter and are able to install columns to a depth of 33 m. The binder, usually cement powder, is brought to the mixing machine by compressed air. A bellows covering the mixing shaft has the function to avoid scatter of the air that comes up from the ground. The mixing tool is composed of several stacks of mixing blades to achieve uniformity of the treated column. The injection outlets are positioned above and below the mixing blades at the mixing shaft. A steel bar fixes the distance between two mixing shafts. The bar, and sometimes additional freely rotating (undriven or counteracting) mixing blades, also function to prevent rotation of soil adhering to the driven mixing blades and shaft. Air pressure and amount of binder are automatically controlled to achieve homogeneity of the treated column. The binder is injected during the penetration stage or both during the penetration and retrieval stages.
(2) WET MIXING

Wet mixing is carried out in accordance with some general principles, which can be summarised as shown in Figure 3.3.

![Flow chart for the execution of wet mixing](image)

Figure 3.3. Flow chart for the execution of wet mixing

In wet mixing the binder is usually cement slurry. Filler (sand and additives) may be added to the slurry when necessary. The specific quantity of slurry added can vary with depth. For machines with the outlet below the mixing tool the slurry must not be added during the retrieval phase.

Whereas a continuous flight auger may be sufficient for predominantly granular soils, increasing fineness and stiffness requires more complicated mixing tools provided with mixing and cutting blades of different shapes and arrangements. The rotary drives, turning the shaft, must have enough power to destroy the matrix of the soil for intimate mixture with the slurry.

Depending on the type of soil and slurry, a mortar-like mixture is created which hardens during the hydration process. Strength and permeability depend strongly on the composition and characteristics of the soil (fines content, organic content, type of clay, shape of the grains, grain size distribution, grain hardness), the amount and type of binder and the mixing procedure.

Wet mixing is common in Central and Southern Europe, North America and Japan.

A column of treated soil is usually manufactured by the procedure as shown in Fig. 2.5. During the penetration of the mixing shaft to the desired depth of improvement, mixing blades at the bottom end of the mixing shafts cut and disturb the soft soil to reduce the strength of the original soil. At the same time, the stabilizing agent is forced into the soft soil at a constant flow rate. In the withdrawal stage of the machine, the mixing blades rotating reversibly in the horizontal plane mix the soft soil and the stabilizer again.
European technique
In Europe the installation of wet-mixed columns is either carried out by means of flight auger(s) (continuous or sectional, single or multiple) or by means of blades, depending on ground conditions and applications. In reinforced soil wall structures, steel bars, steel cages or steel beams can be installed into the fresh mixed-in-place columns or elements. The aid of a vibrator may be required for the installation process.

Japanese technique
In Japan, the wet mixing technique has been used frequently for both on-land constructions and marine constructions (CDIT, 2002). In on-land construction, machines with one, two or four mixing shafts have been used (Figs. 3.5, 3.6). The mixing tool is composed of several stacks of mixing blades to achieve uniformity of the treated column. The mixing blade has a diameter of about 1 m, which can make a column with a cross-sectional area ranging from 0.8 m$^2$ to 1.5 m$^2$. The maximum depth of treatment reaches down to 40 m. The two shaft-type mixing machine usually has a bracing plate to keep the distance of the two mixing shafts (see Fig. 3.6). The plate is also expected to function to increase the mixing degree by preventing the "entrained rotation phenomenon", a condition in which disturbed soft soil adheres to and rotates with the mixing blade without efficient mixing of the cement slurry and soil. For the single blade type mixing head, a "free blade", an extra blade about 10 cm longer than the mixing blades (see Fig. 3.6), is usually installed close to the mixing blades to prevent the "entrained rotation phenomenon".
In marine constructions, large execution vessels are usually used for rapid treatment of considerable soil volumes, Fig. 3.7. On the vessel, a mixing machine, a batching plant, storage tanks and a control room are installed. The machines for marine works usually have more than two mixing shafts. The deep-mixing machines currently available in Japan are capable of constructing columns with a cross-sectional area of 1.5 m² to 6.9 m² to a maximum depth from the sea water level of up to 70 m.
4 Quality control and quality assurance

The design, construction and quality control procedure for the Deep Mixing method (DMM) is shown in Fig. 4.1. To ensure the sufficient quality of the stabilized column, quality control and quality assurance is required before, during and after construction. For this purpose, quality control for the Deep Mixing Method mainly consists of i) laboratory mixing tests, ii) quality control during construction and iii) post construction quality verification through check boring and column head inspection.

Figure 4.1. Example of a Flow chart for quality control and quality assurance for wet method.
5  Design Considerations

(1) GROUP COLUMN-TYPE IMPROVEMENT
Group column-type DMM-improved ground has frequently been applied to embankments or retaining walls in order to prevent sliding failure, to reduce deformation and, to increase bearing capacity. In the current design in Japan, group column-type improved ground is considered to be a sort of composite ground with an average strength of DMM columns and surrounding untreated soil. The slip circle analysis is carried out to determine the width of the improved ground. In the examination, the composite ground consisting of treated and untreated soils is assumed to have the average strength of the improved ground. The sliding failure of the improved ground is then examined, in which the improved ground is assumed to behave as a whole. In the examination, the stability is calculated based on the unbalanced earth pressure acting on both sides of the improved ground. The amount of consolidation settlement of improved ground overlying a stiff layer can be obtained by taking into account the stress concentration effect.

(2) BLOCK-TYPE IMPROVEMENT
As the treated soil strength is much higher than the surrounding soft soil strength, the block type treated soil is not considered to be a part of the ground, but rather to be a rigid structural member buried in the ground to transfer the external loads to a reliable stratum. The Japanese current design procedure was established by the Ministry of Transport, in which the design concept is, for the sake of simplicity, derived by analogy with the design procedure for a gravity-type structure such as a concrete retaining structure. In the design procedure, the external and internal stabilities are evaluated. In the external stability analysis, three failure modes are examined for the assumed cross section of the treated soil mass: sliding, overturning and bearing capacity failures. The sliding and overturning stabilities are calculated by the equilibrium of horizontal and moment forces. In the bearing capacity analysis, the induced pressure distribution on the bottom of the improved ground is calculated based on the simple force and moment equilibrium of external forces, and is confirmed to be lower than the allowable bearing capacity. In the internal stability analysis, the induced stresses in the improved ground are calculated based on elastic theory. The shape and size of the improved ground are determined so that the induced stresses become lower than the allowable strengths of the treated soil.

6  References and literature on deep mixing techniques


Yonekura, R., Terashi, M. and Shibazaki, M. edit. Proc. 2nd Int. Conf. on Ground Improvement Geosystems, Tokyo, 1996.

APPLICATION OF GROUND IMPROVEMENT: VIBRO REPLACEMENT

1. Introduction

Ground improvement techniques are widely adopted in many European countries and are increasingly being used in North America and world-wide for a vast variety of projects. As with all systems there is the requirement for a basic understanding of the geotechnical problem that requires to be solved. The comments provided below should be considered as an introductory guide. Discussions on the design requirements and practical issues are strongly recommended with Consultants and Specialist Contractors who are experienced in their performance.

2. Vibro Replacement

Vibro Replacement is the construction of vibrated stone columns where the added granular material is compacted using depth vibrators. These relatively rigid columns of stone then form a composite structure with the surrounding soils to achieve increased strength and reduced settlements under applied load.

The columns are constructed and compacted using depth vibrators that contain oscillating weights which cause horizontal vibration. The in-situ densification of loose granular soils using similar equipment but without the addition of stone is named Deep Vibratory Compaction and is described in BS EN 14731:2005. Methods which use impact, top vibratory driven casing or ramming techniques are not included in this Standard.

This note refers only to the Vibro Replacement technique, sometimes named Vibro Stone Columns, and is applicable to a wide range of soils.

Typical Uses

The technique is widely used to support new housing, industrial and commercial developments on poor ground. It has also been used beneath road/rail embankments, bridges, projects requiring protection against potential liquefaction caused by earthquakes, slope stability and coastal reclamation works.

Stone columns can be made stiffer by either the addition of cement to the granular backfill, by the use of concrete or other binder, or in combination of concrete through particularly soft layers with stone within more firm layers. Such approach is however relatively rare in comparison to the numbers of projects that simply utilise stone backfill material.
**Technique**

Vibro Replacement consists of large depth vibrators, typically about 300 to 600mm in diameter, that penetrate the ground to suitable depth and then constructing continuous stone columns up to the ground surface.

There are three basic systems available: -

a) Dry top-feed system  
b) Wet top-feed system  
c) Dry bottom-feed system

All three systems may be performed using similar types of depth vibrator, normally electrically or hydraulically driven. The eccentric weight assembly is housed in the base of a heavy tubular steel casing with tapered nose to assist penetration and vertical fines to prevent rotation as shown in the figure below. Steel follower tubes are then added to extend the length of the vibrator. The vibrators are either suspended from crawler cranes or attached to custom-designed Vibro rig units.

![Cross-sections through (a) normal and (b) bottom-feed vibrators](image)
The typical depth of treatment is within the range of 3 to 10m, although this has been extended to depths of up to 56m. Stone columns can also be constructed from barges below sea and river beds. The custom-designed Vibro rig units provide detailed computer-generated records of the construction of each stone column.

The dry top-feed system is generally used where the bore is formed using air-flush assisted penetration of the vibrator and would remain stable after withdrawal of the vibrator. A charge of suitable granular material is then fed from the ground surface into the base of the bore. The vibrator is re-inserted into the bore to compact the stone and again withdrawn. This sequence is then repeated to compact the column in stages up to the surface to form a continuous column of stone that interlocks tightly with the surrounding soils.

The dry top-feed system is normally used when improving soils above the water table of greater than about $Cu = 30$kPa soil strength. Typical gradings of the granular material are normally about 40 to 75mm. Stone column diameters of about 400 to 700mm will depend upon the strength of the soils and size/power of the vibrator.

The wet top-feed system is the original construction method which has been largely replaced by the first and third systems. However, the wet top-feed system can be used for the improvement of soft soils below the water table where larger column diameters are required. The penetration of the vibrator is assisted by water flushing. On attaining the required depth the vibrator can be partially withdrawn to then surge and flush out to further increase the column diameter. Following formation of the open hole the water pressure is reduced and vibrator kept in the ground.

Clean inert granular material is then placed around the top of the bore at ground level. This then falls under gravity against the slight upward flow of water in the annulus between sides of vibrator and soil down to the base of the bore. The vibrator is then slightly withdrawn and pushed back into the stone at the base of the bore to construct the stone columns in a series of lifts in similar manner to the top-feed system. It is however important that the water flow be maintained to ensure stability of the soils and to avoid potential contamination of the stone column.

Typical grading of the granular material is about 20 to 75mm with stone column diameters of about 600 to 1200mm being constructed.

The wet construction system requires consideration of provision of water supply, drainage ditches, settlement lagoons, disposal of effluent and contamination of the site surface.

The dry bottom-feed system combines the benefit of improving unstable soils below the water table with dry air-flush construction technique. The bottom-feed vibrator has a permanent heavy duty supply tube attached to the vibrator to form an integral vibrator/granular material supply to the base of the vibrator. Granular material is fed into the delivery tube via a chamber on the top of the
vibrator by a hopper system that is either suspended from a crawler crane, attached to special rig unit or by water pumping.

The construction sequence is the same as for the wet top-feed system, but without the ability to surge for larger column diameter, with vibrator remaining in the ground to maintain the stability of the bore.

Typical material grading is about 10 to 50mm for stone column diameters of about 500 to 1000mm.

The first and third systems can also be preceded by pre-boring using piling rigs to ensure that the vibrator can penetrate more competent upper layers to attain the required treatment depth.

**Risk**

Vibro Replacement is considered a safe ground improvement technique but, as with all geotechnical works, depends on experience, good site operatives, suitable controls and design for successful completion.

The main risks are using the stone column systems in unsuitable soils and where there is wide variation in soil beneath the structure, for example a building that straddles a backfilled quarry edge. The stone columns develop their capacity from the confining action of the soils in which the columns are constructed. Where the soils provide little lateral support, for example layers of very soft possibly organic soil of greater thickness than the column diameter, the stone columns would potentially bulge or even shear under load to not provide the desired settlement performance.

Many UK ground improvement projects involve the treatment of man-made fills. These carry the risk of variable constituents, density and strength. The main risk is however the possible localised presence of matter liable to long-term decay that would progressively reduce the column confinement with time. Some soils and fills are also susceptible to self-weight, collapse, and inundation settlements.

The main risks during construction are the transmission of vibration. The proximity of operations to sensitive utilities/services, retaining walls and structures will depend upon the power characteristics of the vibrator and condition of the adjacent feature. Vibrations can be reduced but not wholly overcome by the use of cut-off trenches and pre-boring the columns.

There is an increasing trend for the use of reclaimed materials as granular backfill. These are often not as hard as natural gravel or rock with lower angle of friction for design. The British Standard Ten per cent Fines Value, BS 812: Part 111:1990 is a useful measure of suitability of stone for use whilst the ASTM C131-89 Los Angeles test resistance should be less than 40 to avoid excessive particle breakdown during construction of the stone columns.

**Health and Safety Issues**
The height of equipment and proximity to adjacent roads, overhead power wires and railway lines will require specific risk assessment as will performing treatment on sloping sites and near to retaining walls.

**Design Considerations**

The basic design approach is that Vibro Replacement stone columns are relatively rigid springs, the rigidity of which depends on the confining action of the soil. When the soils are of a clean granular nature, they will be densified by the horizontal vibrations to provide even greater column rigidity.

The applied loads are then supported by an array of generally stronger stone column springs surrounded by weaker springs representing the soil. The density of column construction grid centres to residual volume of soil will then dictate the degree of improvement that can be achieved.

The main bearing capacity design procedures in use are:

a) DIN 4017 (adapted by Priebe)
b) Hughes and Withers (1974)
c) Brauns (1978)

Reduced settlements are then assessed by application of the Priebe (1995) formulae and design charts to standard classical methods of settlement prediction for the untreated soils.

Further design can then be applied using the stone columns’ ability to act as drains, to effectively accelerate the rate at which the reduced settlements occur, using with care vertical drain theory.

Similarly, stone columns are inclusions of material with high angle of friction that can be used to enhance the stability of slopes, particularly for road embankments. The basic approach is to simply modify soil parameters pro-rata to the Area Ratio for both total and effective stress analyses. Arching theory can also be applied with care for higher loading on the columns to further increase their shear resistance.

The majority of Vibro Replacement schemes are carried out on the basis of treating the full depth of the weak soils, terminating after a short penetration of better strata, with columns specifically located beneath foundation layouts. The numbers of columns and grid centres depend upon the soils profile, imposed loadings and required settlement tolerances.

However, there is increasing trend to provide treatment to such depth that would ensure the majority of the stresses from the imposed loads would be accommodated within the treatment zone where stresses on the untreated soils beneath would be of a low order and unlikely to contribute significantly to total and differential settlement. Clearly, if this design approach is adopted it is
important that sufficient site investigation be performed to be able to properly assess such settlements. The age and manner of placement of deep fills are important factors in this assessment.

**Validation**

The majority of Vibro Replacement projects involve the support of structures and hence validation is normally by load test. These can range between:

a) Short-term plate load test  
b) Zone load test  
c) Embankment load test

The plate load tests are normally of less than two hours duration with plate diameter comparable to the design column diameter, normally standardised at either 600 or 900mm. Loading is quickly applied to the test column to at least twice the design pressure over the plate area using crane or Vibro rig as reaction. The main aim of these tests, which are inexpensive, is quality control.

The zone load tests are normally of similar size to the project bases and are performed over a group of columns by either direct loading or against a system of grillage and kentledge for a period of up to one week. These tests are far more meaningful than plate tests since they apply load to the composite structure of both stone columns and soil, but are far more expensive.

Embankment loading tests can impose loads over larger areas for longer period of time. These are particularly useful for road embankments on soft ground where time-dependent performance may be important. As with untreated soft soils, the rate of loading should be carefully controlled.

In-situ tests are not normally performed to Vibro Replacement projects unless the aim is also the in-situ densification of granular soils.

**References**


5. **US Department of Transportation (USDT)**: Design and construction of stone columns, 1983.


