

# DESIGN OF COLUMN-REINFORCED FOUNDATIONS



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# AN INTRODUCTION TO COLUMN-REINFORCED FOUNDATIONS

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## ABSTRACT

Column-reinforced foundations are introduced as a set of in situ ground improvement techniques that consist of installed vertical inclusions to enhance the geotechnical properties of weak and highly compressible soils. Focus is given to the most-practiced worldwide techniques: sand compaction piles (SCP), stone columns, and the deep mixing method (DMM). This chapter introduces the mechanical modeling that will be considered throughout the following chapters, which are aimed at the design and analysis of column-reinforced foundations.

Methods of installation, the types of equipment used, expected performance, and the quality control methods of these techniques are described and reviewed.

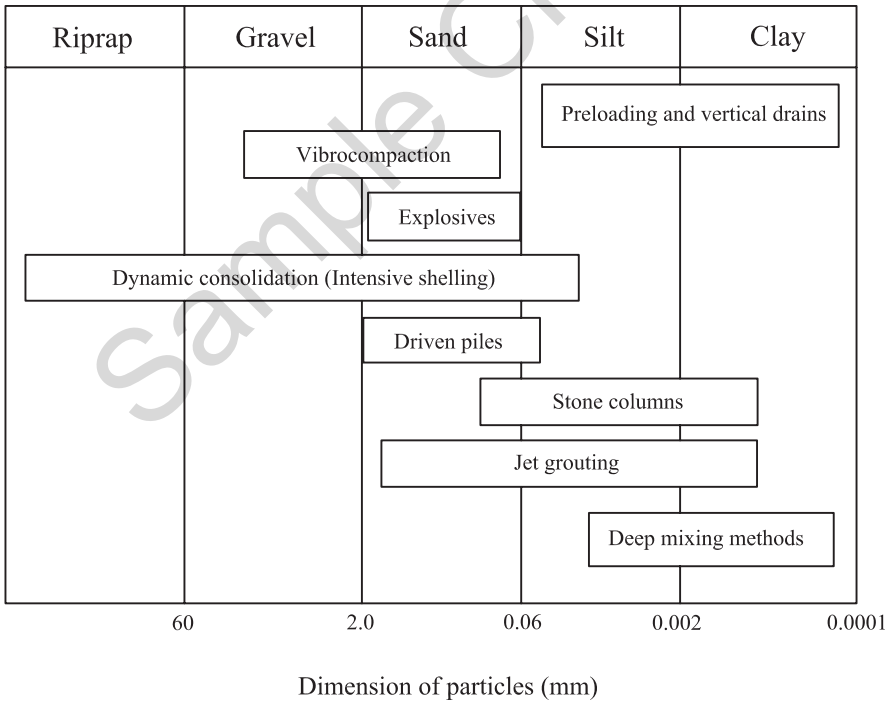
## 1.1 GROUND IMPROVEMENT TECHNIQUES

When facing the construction of structures on problematic soils such as soft clays, the possibility to practice an in situ ground improvement must be well analyzed in order to avoid the expensive conventional deep foundation solution. Soil improvement techniques are not usually time-consuming in terms of installation and they remain cost-effective in comparison to pile foundations.

Nevertheless, when a soil improvement technique is being decided on, it is necessary to check, in situ, both its feasibility and whether the targeted advantages of soil treatment are well-obtained. Accordingly, plot tests are often performed to quantify the improvement of initial soil by comparing its pre- and post-treatment behaviors on the basis of in situ testing results, which also serve for the assessment of adopted assumptions and geotechnical parameters in the design process.

*On which basis is a soil improvement technique decided?* The unimproved (or initial) soil is primarily identified by its gradation curve which remains a key parameter toward deciding which improvement technique is suitable for it (Dhouib and Blondeau, 2005). Depending on the type of soil (i.e., granular or fine) different improvement techniques can be adopted as sketched in Figure 1.1. Note that for soils having an intermediate grain size distribution, several improvement techniques might be adopted (Bouassida, 2011).

Reinforcement of in situ soil can be made by means of rigid inclusions, like micropiles, and flexible and semi-rigid inclusions, such as column reinforcement techniques, which is the focal theme of this book. Reinforcement



**Figure 1.1** In situ ground improvement techniques as a function of original soil grain size distribution (Bouassida, 2011) (with permission from editor A. Bouafia)

of man-made geotechnical structures by transported soil material that is reinforced by added inclusions (e.g., reinforced earth, geogrids, etc.) is not covered.

## 1.2 REINFORCEMENT BY COLUMNS

The reinforcement by column inclusions of weak and very compressible soils has been practiced worldwide since the 1970s. Among the well-known techniques of installation, we can cite SCP, stone columns, and cement- or lime-treated soil columns.

Column-reinforced foundations usually involve the incorporation of a non-negligible quantity of material in a proportion that varies from 10 to 70 percent of the initial soil volume. The quantity of added material depends on the adopted technique (i.e., stone columns, sand piles, treated soil with cement or lime), as well as the targeted performance.

Reinforcement by columns can be adopted for typically weak soils—hereafter called initial soil, such as highly compressible soft clays—with Young's modulus  $E < 3$  MPa and undrained cohesion  $c_u < 30$  kPa and loose sands with a friction angle  $\varphi < 30^\circ$  (i.e., SPT blow count  $< 10$ ).

Reinforcement of weak soils by columns aims to increase the bearing capacity, reduce settlement, accelerate consolidation by drained column material, and prevent liquefaction risk—especially in the case of saturated loose sands.

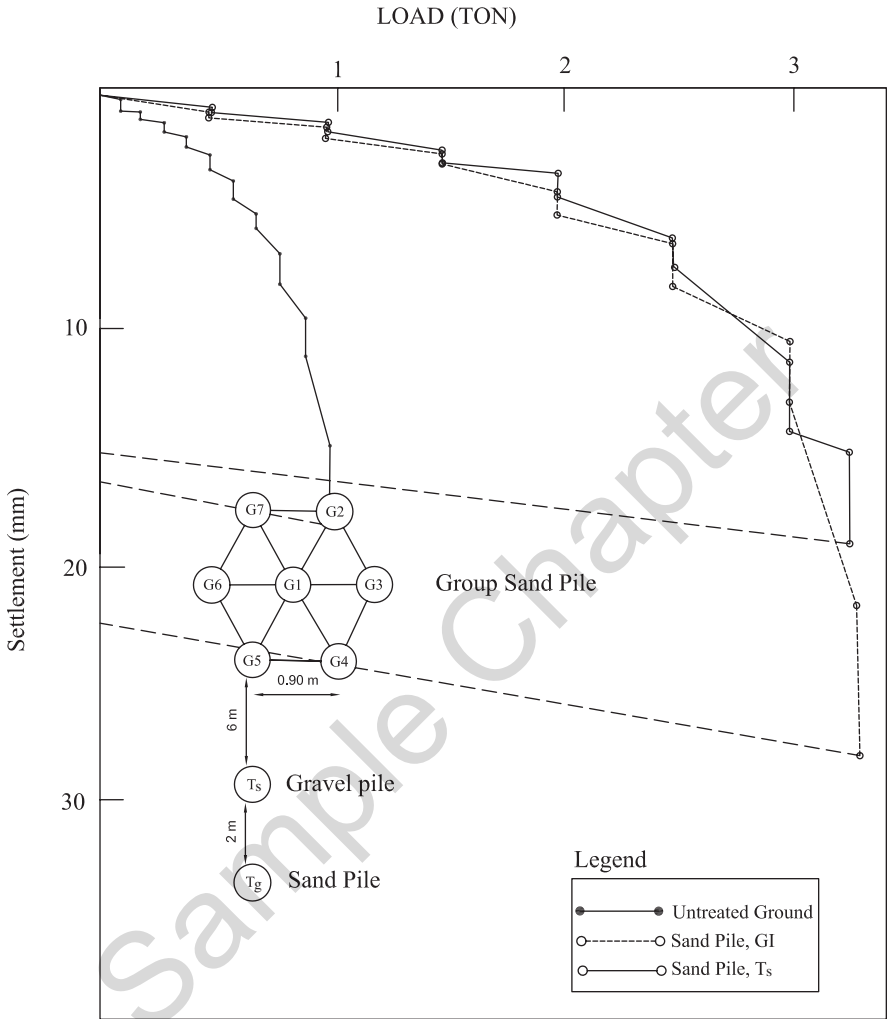
Figure 1.2 presents the load-settlement curves from full-scale field measurements obtained from loading tests of soft Bangkok clay reinforced by sand and gravel piles (Bergado et al., 1984). This figure well illustrates the advantages provided by the reinforcement, namely the increase in bearing capacity: the carrying load is multiplied by three for a settlement of 5 mm; and the very significant reduction in settlement—from 15 mm to approximately 3 mm under a carrying load of one ton.

The cost of a column-reinforced foundation is essentially controlled by the volume fraction of incorporated column material in reference to the improvement area ratio (IAR) that is defined by the total cross section of columns divided by the total area of the loaded foundation.

Table 1.1 summarizes the currently practiced values of IAR as a function of the column techniques and the associated diameters of columns, which are usually assumed to be a circular cross-section for the purpose of design.

Table 1.2 gives the range of enhanced column material rigidity and strength characteristics.

Column-reinforced foundations can be used especially for uniformly loaded structures inducing a surcharge of up to 150 kPa. For example, several types of storage tanks and embankments are built, preferably on reinforced soil, by



**Figure 1.2** Load-settlement relationship of granular piles from full-scale load tests (Bergado et al., 1984) (reprinted with permission from author D. Bergado)

**Table 1.1** Practiced IAR and diameters of columns

Columns installation method	Improvement Area Ratio (%)	Columns diameter (m)
Sand compaction piles	$5 < \eta < 10$	0.4 – 0.6
Stone columns & vibro-compaction	$10 < \eta < 33$	0.8 – 1.2
Lime-cement treated soil	$15 < \eta < 70$	0.3 – 0.7

**Table 1.2** Mechanical characteristics of column material

Column material	Friction angle	Cohesion, $C_c$ (kPa)	Young's modulus (kPa)
Sand	$35^\circ < \varphi_c < 38^\circ$	0	$5 E$ to $10 E$
Stone & gravel	$\varphi_c > 38^\circ$	5 – 15	$15 E$ to $50 E$
Lime-cement treated soil	$\varphi_c < 20^\circ$	20 C – 200 C	$50 E$ to $200 E$

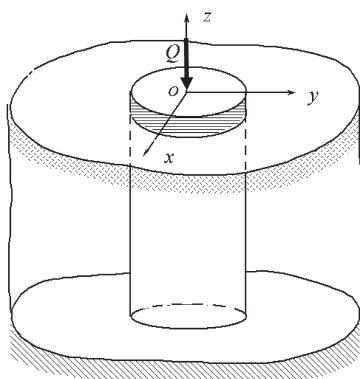
end-bearing (i.e., resting on rigid stratum) columns which induce quasi-uniform settlement within an allowable margin.

## 1.3 MODELING OF COLUMN-REINFORCED FOUNDATIONS

Contributions that are dedicated for the study of column-reinforced foundations have usually considered three mechanical behavior models which can be classified as: the isolated column and trench models, the unit cell (or composite) model, and the group of columns model. Each of the three models is introduced in the following sections.

### 1.3.1 Isolated Column and Trench Models

The isolated column model is composed of a single inclusion surrounded by an unlimited volume of initial soil. The column is assumed to be cylindrical and, therefore, the axisymmetric condition is suitable for the analysis (Figure 1.3).



**Figure 1.3** Isolated column model (axisymmetric condition) (reprinted from Bouassida, 1996b)

The isolated column is suitable for the assessment of the loading test performed in a trial field on a single column (Bergado and Lam, 1987).

The trench model consists of a wall of reinforcement; it is representative of the plane strain condition (Figure 1.4). The loading is applied on the column or trench cross section which implies that IAR is equal to one (Bouassida, 1996b).

### 1.3.2 Unit Cell Model

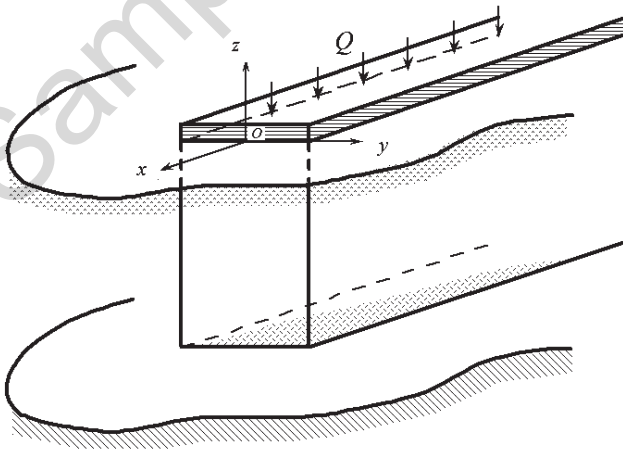
This model is considered from the distribution of a group of columns installed in a regular pattern. Geometrically, it is a reproducible volume which includes a single column with a circular cross section surrounded by a given volume of initial soil. For example, when columns are installed in square or triangular patterns, the periodic volumes of unit cell model correspond to the parallelepiped and hexagonal cylinders respectively, as shown in Figure 1.5.

Then, in order to carry out the axisymmetric condition, an equivalent unit cell with circular cross section is adopted (Figure 1.6). The IAR is written:

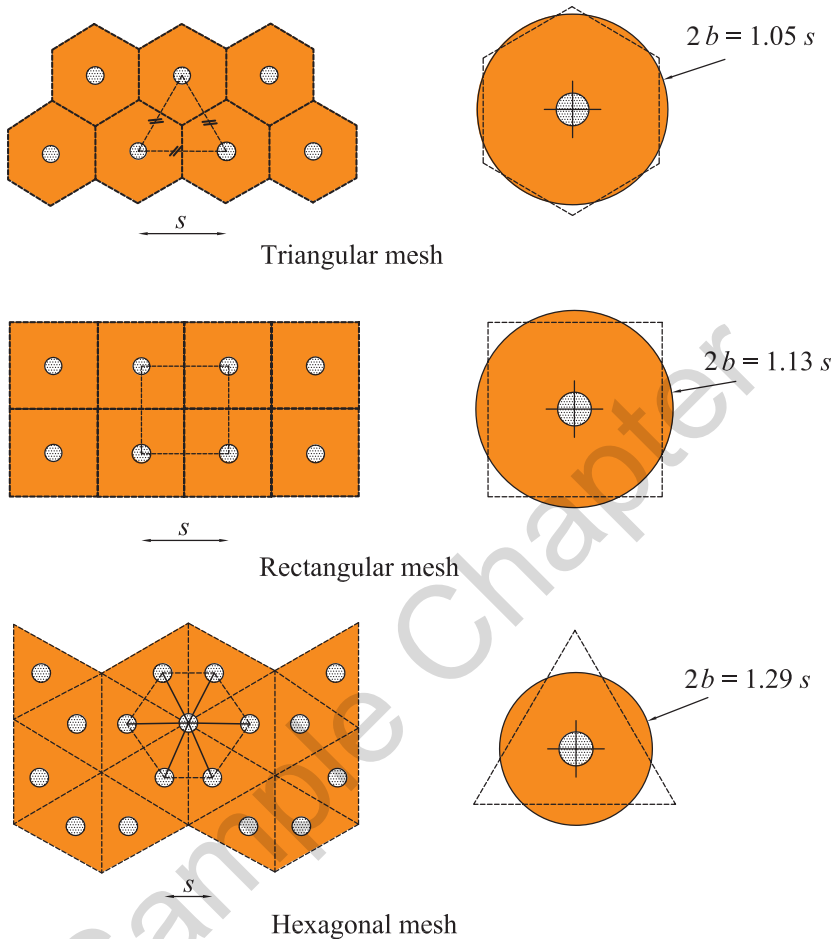
$$\eta = \frac{a^2}{b^2} \quad (1.1)$$

The radius of the unit cell model,  $b$ , is expressed as a function of the axis-to-axis spacing between columns,  $s$ ;  $a$  denotes the column's radius (Figure 1.5).

The unit cell model is mainly investigated when carrying out laboratory experimental studies in triaxial conditions (Bouassida, 1996a).



**Figure 1.4** Trench model (plane strain condition) (reprinted from Bouassida, 1996b)



**Figure 1.5** Unit cell models as a function of regular columns pattern

### 1.3.3 Group of Columns Model

The loading structure, whether rigid (rafts or footings) or flexible (embankment), has an arbitrary area (Figure 1.7). All columns having circular cross sections with different diameters are located under the foundation in an arbitrary arrangement. Reinforcement by floating columns represents the general configuration of modeling by assuming total adhesion along the soil-column interfaces. The geometry of columns is defined by their length  $H_c$  and total cross section  $A_c$ . A rigid stratum is encountered at depth  $H > H_c$ , (Figure 1.8). The total area of the foundation, denoted by  $A$ , is decomposed as:

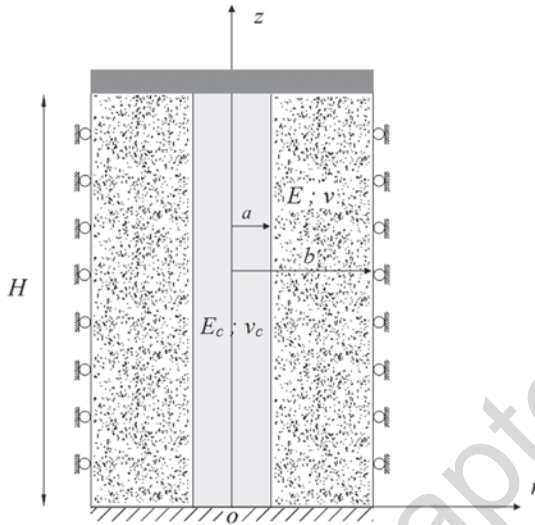


Figure 1.6 Equivalent unit cell model

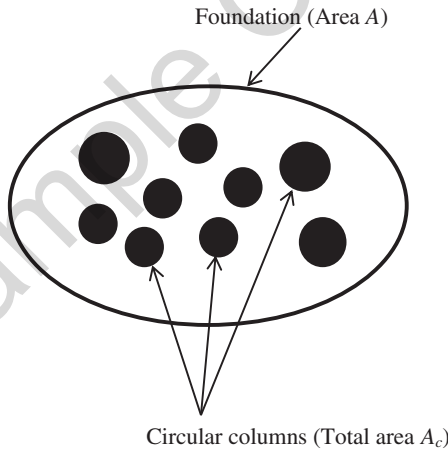
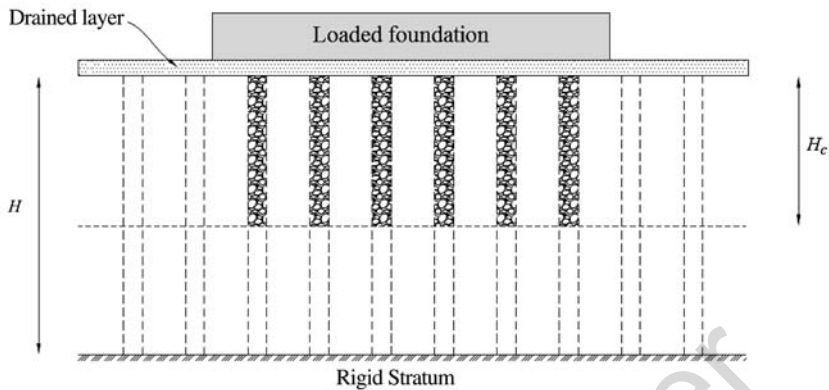


Figure 1.7 Foundation on reinforced soil by a group of columns

$$A = A_c + A_s = \eta A + (1 - \eta)A \tag{1.2}$$

The IAR being defined by:

$$\eta = \frac{A_c}{A} \tag{1.3}$$



**Figure 1.8** Modeling of reinforced soil by a group of floating columns

Geotechnical parameters of reinforced soil constituents  $E$ ;  $\nu$  and  $E_c$ ;  $\nu_c$  denote the Young's modulus and Poisson's ratio of the initial soil and column material, respectively, which are assumed linearly elastic media. The shear strength characteristics of reinforced soil:  $C$  ( $C_c$ ) and  $\varphi$  ( $\varphi_c$ ) denote the cohesion and the friction angle of the native soil and those of the column material, respectively.

Total unit weights of initial soil and column material are denoted by  $\gamma$  and  $\gamma_c$ , respectively.

## 1.4 INSTALLATION OF COLUMNS

A brief description is given in the following sections about methods of installation, types of equipment used, and illustrations of performances provided by SCP, stone columns, and lime and/or cement treated soils.

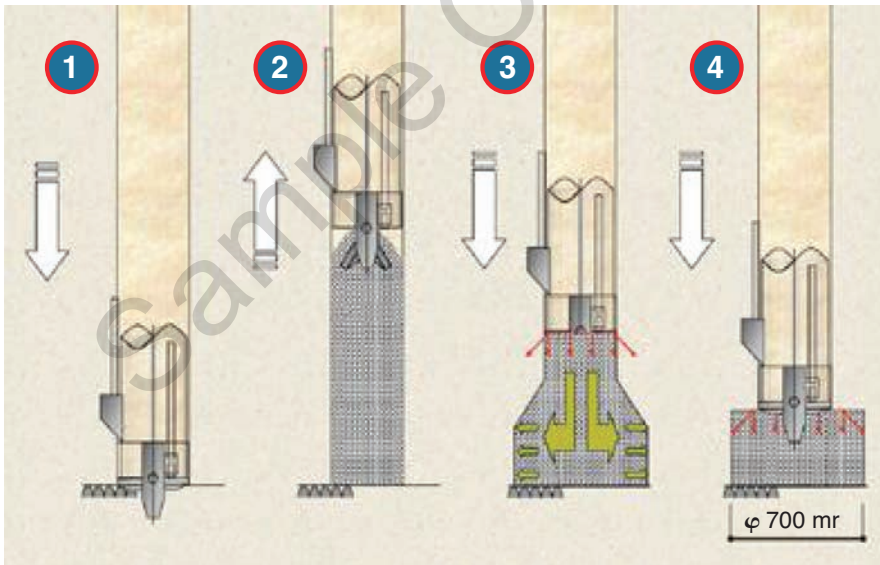
### 1.4.1 Sand Compaction Piles

The SCP method is commonly used to reinforce soft clays and sandy soils especially in coastal areas. Even though it is installed with a low IAR (Table 1.1), the bearing capacity of the composite ground can be increased and its compressibility reduced. The SCP material is granular and has good permeability which makes it behave like a vertical drain by accelerating the consolidation settlement and minimizing the post construction settlements.

Tried in many countries during the last three decades, the SCP method has found very extensive and effective applications, especially in Japan and Korea, for both on-land and marine applications. It consists of well-compacted sand

piles that are installed in soft ground by using a vibrating casing pipe (Figure 1.9). Through this process, compacted sand piles are placed by vibration, dynamic impact, or static pressure in the soft or loose ground in a grid pattern over the prescribed area. Installation is done by driving a casing pipe into the soft ground by using a vibratory hammer. The driven casing is then repeatedly filled and compacted with sand. The casing is gradually withdrawn during the filling and compacting, thus creating a dense sand pile.

Among so many contributions, Aboshi et al. (1979) and Kimura (1983) have deeply investigated the mechanical behavior of reinforced ground using the SCP method. These authors discussed the concentration of vertical stress on the surface of composite ground when it is subjected to a loaded rigid raft. Since the settlement in such a case is almost uniform at the surface of the reinforced ground, a vertical stress concentration on the sand columns occurs due to the difference in rigidities of the weak soil and the sand material. The stress concentration factor, defined as the ratio between the vertical stresses induced on the sand piles and soft soil, depends on the IAR. From experimental projects of SCP, the stress concentration factor varied: from 2 to 5 as reported by Vautrain



(1): Driving casing pipe into soft ground

(2): Withdrawing casing pipe and bottom-feeding sand pile

(3): Compacting sand pile to increase pile diameter

(4): Completing first cycle of sand pile installation and repeating steps 2 through 4

**Figure 1.9** Installation of sand compaction piles

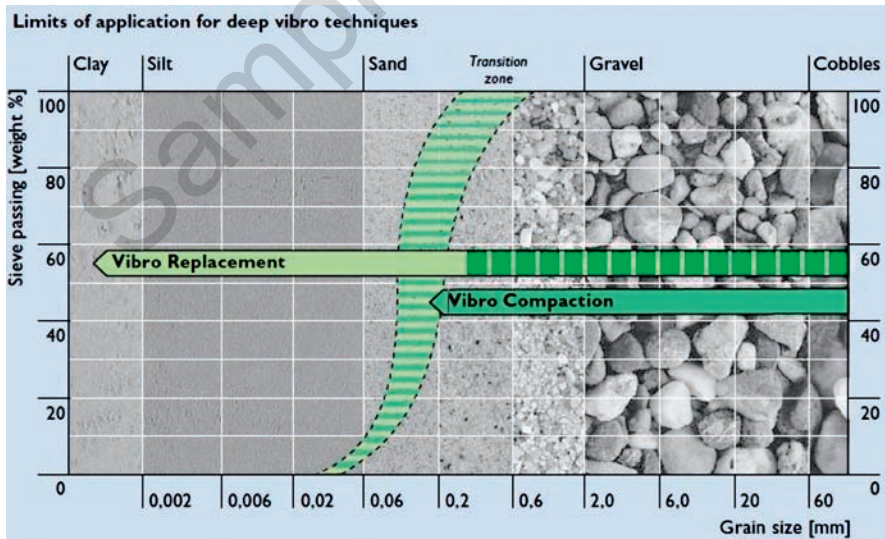
(1980) and Goughnour (1983), up to 9 as reported by Aboshi et al. (1979) and Bergado et al. (1987).

### 1.4.2 Stone Columns and Vibro-compaction

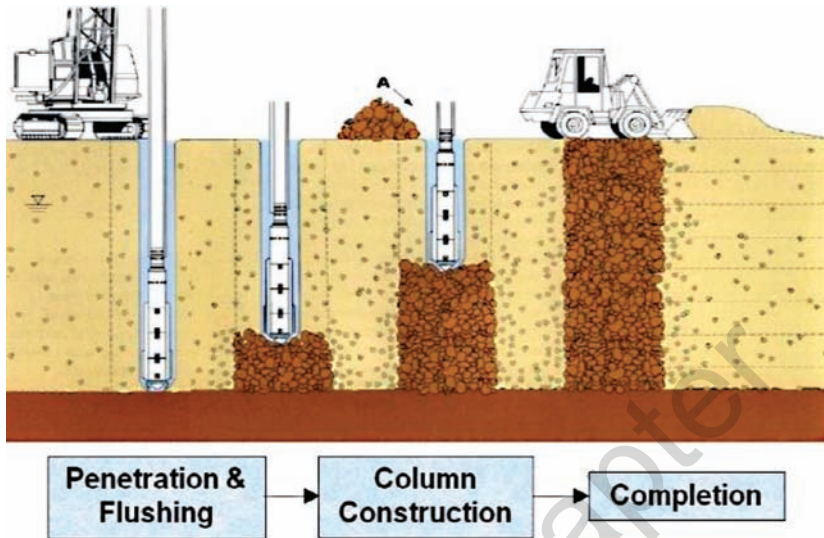
Stone columns are basically installed using either vibro-replacement or vibro-displacement techniques. More detailed descriptions of the equipment and the procedures used can be found in Moseley and Priebe (1993), Van Impe et al. (1997), Kirsch and Sondermann (2003), etc.

Figure 1.10 shows the possibilities of installing stone columns and vibro-compaction methods for different gradation curves of the original soil. The latter can belong to categories of soils like organic and alluvial clays or gravel and coarse rubble fills (Greenwood, 1970).

Stone columns are often installed in two ways: either by the dry method, which uses (pressurized) compressed air or by the wet method, which uses compressed water. The stages of installation of a stone column using the vibro-displacement technique by the wet method are depicted in Figure 1.11, at a given point of treatment. A vibro-probe (with an extension of tube elements) is gently descended at a prefixed depth under the combined effects of gravity and water pressure. The initial soil is then saturated by induced vibrations to create a tentative localized liquefied zone.



**Figure 1.10** Possibilities of installation of stone and vibro-compacted columns as a function of grain size distribution of initial soil (courtesy Keller GmbH)



**Figure 1.11** Installation of vibro-compacted stone columns, wet method (source from [www.keller.com](http://www.keller.com))

Characteristics of the vibro-probe and installation method rely on the type of initial soil and its saturation, as well as on the characteristics of added material and the targeted degree of improvement. The type and grain size of added material should meet standard specifications for homogenous natural stones, either rolled or crushed.

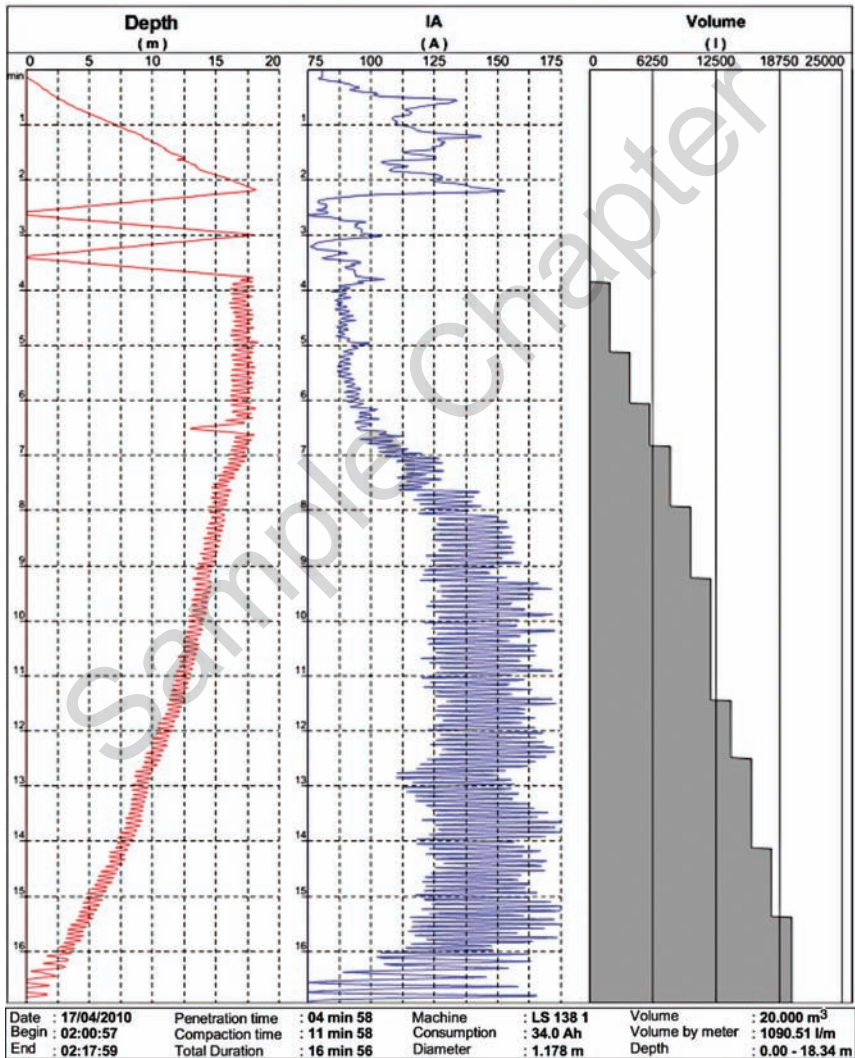
During installation of the columns, the penetration of compacted formations or obstacles might be overcome by a pre-boring, with or without the extraction of initial soil. In such a case, whenever necessary, any excavated volume of initial soil must be filled and compacted by added material. The latter is incorporated until the tip of the vibro-probe is within the created boring, while water is being supplied continuously to evacuate fine particles. The added material is then expanded horizontally, with induced vibrations against the initial soil to form the stone column by successive passes of about 0.5 m in depth.

### ***Control of Installed Columns***

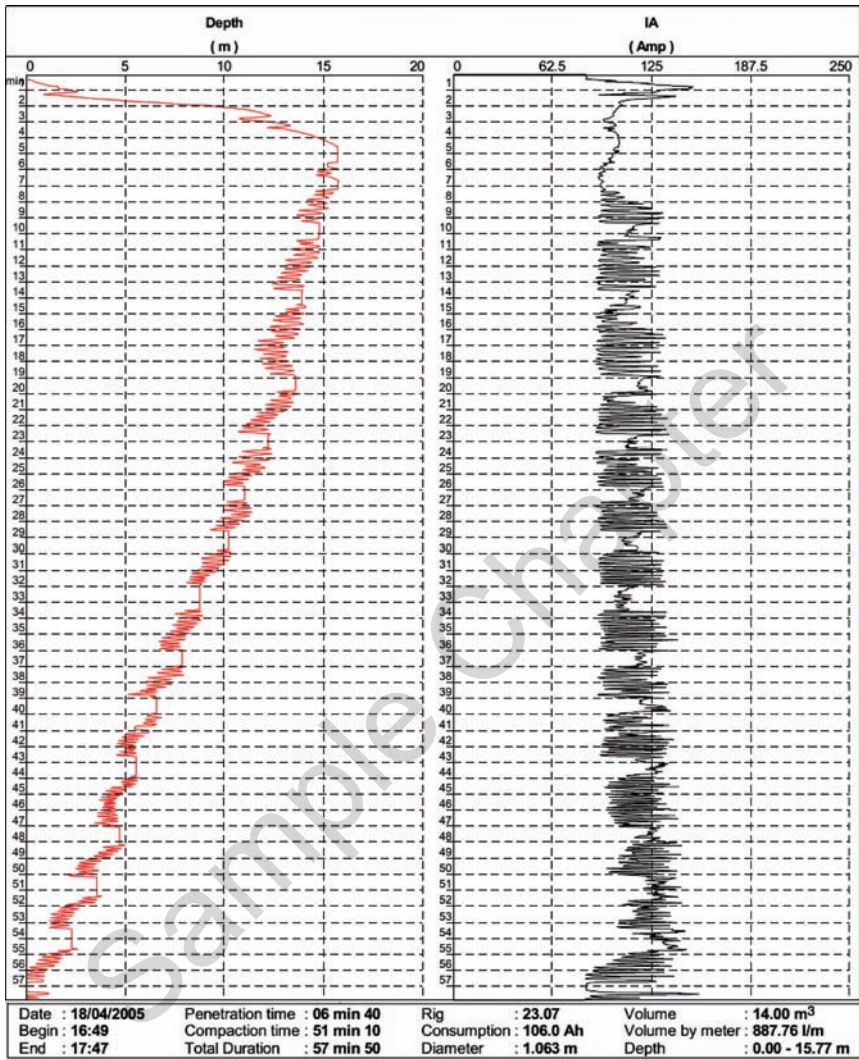
Soil reinforcement is conducted with a procedure of quality assurance/quality control to ensure that the targeted performance of each installed stone column is satisfactory.

Monitoring of the installation of a stone column is performed by the use of an automated computerized recorder device. This instrument yields a computer record of the installation process in a continuous graphical mode, plotting

depth versus time and compaction effort versus time. The provided information comprises a stone column reference number, date of installation, the required period for installation, and the maximum depth and compaction effort during the penetration and compaction process. These printouts represent the main quality control information of the installation process. Typical stone column monitoring printouts are shown in Figures 1.12 and 1.13 (Debats and Degen, 2001).



**Figure 1.12** Printouts of stone column records for the wet method of installation (courtesy Vibro services; Germany)



**Figure 1.13** Printouts of stone column records for the dry method of installation (courtesy Vibro services; Germany)

Adding to the above-mentioned performances, which result from the installed stone columns, the improvement of initial soil characteristics due to the horizontal expansion of added material is another factor to be considered for the design (Debats et al., 2003).

### 1.4.3 Deep Mixing Method for Lime-Cement Columns

This technique was primarily tested regarding the reinforcement of soft clays existing around the foundations of harbor facilities and, later on, was extended for embankment and excavation projects.

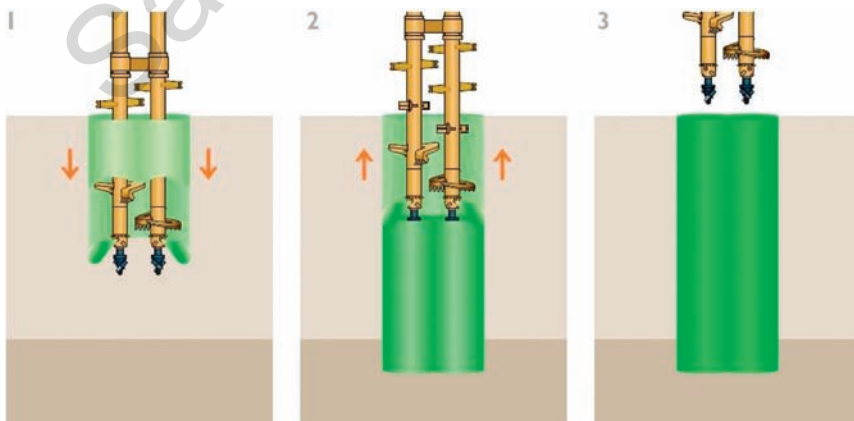
Field applications of soil-cemented columns had been reported by Bergado et al. (1996) and Porbaha (2000), when they presented, in detail, the practiced process for the treatment of soft soils and performances of the well-known DMM.

Soft clays are usually stabilized by adding a low percentage by weight (8 to 12%) of lime, cement, or lime-cement as a result of pouzzolanic reactions described primarily by Broms and Boman (1977). Since the seventies, the DMM has been extensively practiced in Sweden, Japan, and then worldwide for a wide variety of civil engineering structures.

Steps of installation utilizing the deep mixing technique are shown in Figure 1.14. This technique offers the possibility of installing contiguous columns. It follows that the values of IAR for the reinforcement by the DMM projects are higher than those adopted for the SCP and stone columns applications (Table 1.1).

The choice of binder, such as lime, cement, or lime-cement, depends on several factors: the cost of material, the climate where the treatment is intended, and the targeted gain in shear strength. For example, in the Southern Asiatic environment, Broms (1982) reported that the use of cement is mostly recommended due to the following facts:

- Lime, compared to cement, is not cost-effective;
- Hot-humid climate does not favor the storage of slaked lime; and
- Cement treatment provides higher shear strength.



**Figure 1.14** Installation using the deep mixing technique (courtesy Keller GmbH)

Elsewhere, when lime treatment does not provide the due gain in strength, the use of a cement or lime-cement treatment can be decided. Notice that the optimum percentage of lime also depends on the type of initial soil and its grain size curve, more specifically the percentage of fines, i.e., with dimensions less than 2  $\mu\text{m}$  (Hilt and Davidson, 1960) as cited by Bergado et al. (1996).

The gain in shear strength is the main performance provided by cement and/or lime treatments. It is strongly dependent on the curing time during which the pouzzolanic reactions take place between the lime and the existing silicate aluminates in clay. Well-enhanced mechanical characteristics of lime-cement treated soil are usually obtained (Bruce, 2001). As a result, in terms of bearing capacity, full-scale loading tests conducted on isolated lime-treated columns have shown that, depending on the incorporated percentage of lime, the ultimate bearing capacity varies from 50 kN to 500 kN (Broms, 1982).

Several procedures of deep mixing installation have been patented. Among the very recent ones, Trenchmix has been successfully tested by Soletanche-Bachy (2009). Trenchmix is a soil improvement process that enables the installation of a network of trenches as a result of cut in situ soil that is then mixed with an added binder. A spread layer is then overlaid for load transfer to the reinforced soil by the network of trenches. The Trenchmix process is comprised of several steps which start with the placement (preparation) of binder, followed by the mix of ground to be treated by the prepared binder that can be completed by an added fluid. Figure 1.15 shows how the blade is put in a vertical position during the Trenchmix process.

The general procedure of implementation in the dry method, preceded by the provided binder in a pre-excavation, is illustrated in Figure 1.16, which shows a cross section of completely installed Trenchmix. The content of cement used for treatment varies as a function of the type of soil, type of cement, site conditions, and the prescribed unconfined compressive strength of Trenchmix.

Figure 1.17 was derived from records obtained by Soletanche-Bachy (2009) and shows orders of magnitude of cement content and the strength of the treated soil. With respect to performance, the Trenchmix process provides an IAR equaling three to six times that practiced by installed individual columns. However, the maximum spacing between trenches axis should not exceed 4 m, in the case that the thickness of the Trenchmix wall equals 0.4 m.

*Acceleration of consolidation—to what extent can the deep mixing technique provide a drained column material?* To date, this question remains a matter of discussion. Earlier, Broms and Boman (1977) reported that the hydraulic conductivity of lime- or cement-treated soil can reach as much as a hundred times that of soft clay—to the point that a DMM column can be equivalent to more than a geodrain to enhance the acceleration of consolidation. However, in further

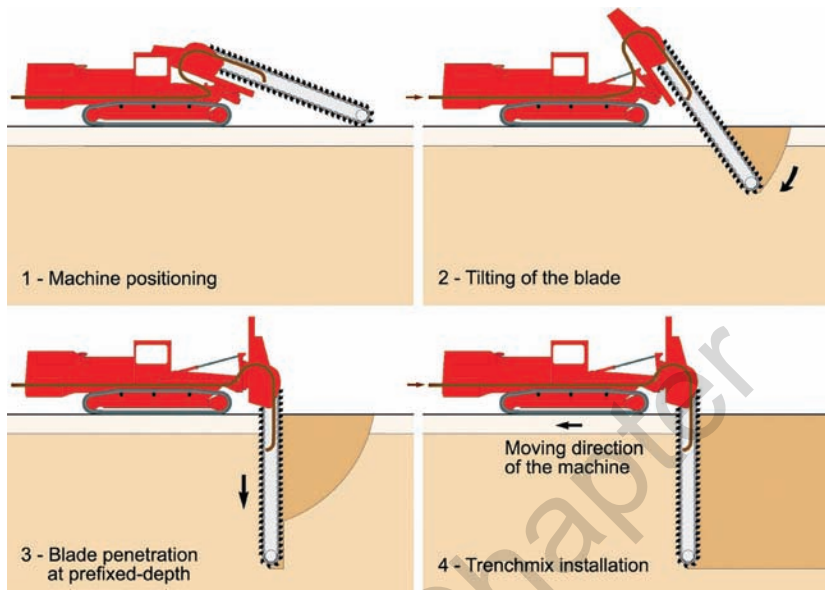


Figure 1.15 Trenchmix process installation (courtesy Soletanche-Bachy)

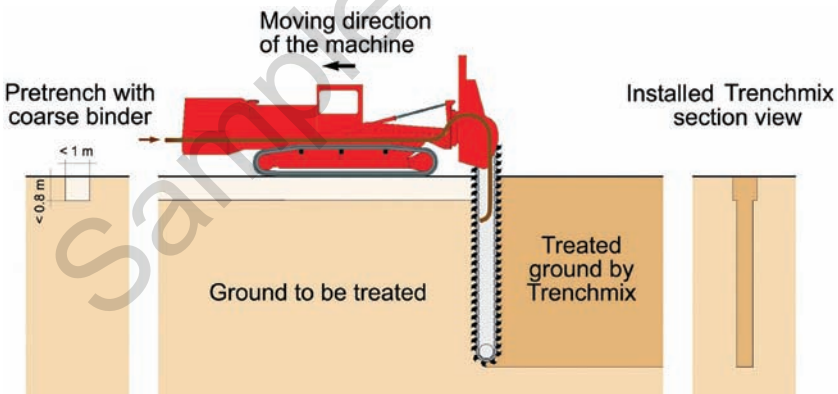
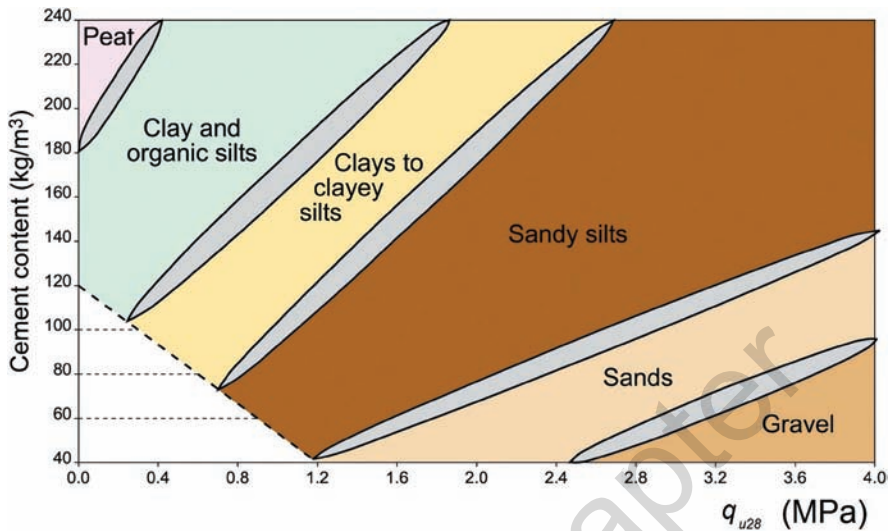


Figure 1.16 Trenchmix implementation procedure preceded by provided binder in a pre-trench (courtesy Soletanche-Bachy)

studies, authors did not fully agree with this observation and stated that the permeability of lime- or cement-treated soft clay can be less or equal to that of unimproved soil. The discussion reported by Chai et al. (2006) has given better insight into the observed acceleration of consolidation of lime-cement-treated



**Figure 1.17** Unconfined compressive strength of Trenchmix material versus soil type (courtesy Soletanche-Bachy)

soft soils. Regardless of the magnitude of its hydraulic conductivity, the compression index of treated soil, being proportional to the volumetric modulus (of volume change), is definitely much lower than that of soft clay. Therefore, the significant reduction of compressibility of treated column material will result in the increase of its coefficient of consolidation, which explains the acceleration of consolidation.

## 1.5 CONCLUSION

An introduction has been given to the techniques of reinforcement by columns which belong to a widespread set of ground improvement methods.

Advantages and methods of installation provided by the column reinforcement techniques have been illustrated. Modeling and specific geotechnical properties of the constituents of reinforced soils by columns were presented in order to carry out all steps of the design, which will be explained in detail in the following chapters.

## REFERENCES

- Aboshi, H., Ichimoto, E., Enoki, M. and Harada, K., The “Compozer”—a method to improve characteristics of soft clays by inclusion of large diameter sand columns. Proc. Int. Symp. On Soil Reinforcement, Paris, 1, 1979, 211–216.
- Bergado, D. T., Anderson, L. R., Miura, N. and Balasubramaniam, A. S., *Soft Ground Improvement in Lowland and Other Environments*. ASCE Press, New York, 1996.
- Bergado, D. T., Huat, S. H. and Kalvade, S., Improvement of soft Bangkok clay using granular piles in subsiding environment. Proc. 5th Int. Geotech. Sem. on case histories in soft clay. Singapore, 1987, 219–226.
- Bergado, D. T. and Lam, F. L., Full scale load test on granular piles with different densities and different proportions of gravel and sands on soft Bangkok clay. *Soils and Foundations*, 27 (1), 1987, 86–93.
- Bergado, D., Rantucci, G. and Widodo, S., (1984). Full-scale load tests of granular piles and sand drains in soft Bangkok clay. Proc. Int. Symp. “Soil reinforcement,” ENPC, Paris, 111–118.
- Bouassida, M., Etude expérimentale du renforcement de la vase de Tunis par colonnes de sable—Application pour la validation de la résistance en compression théorique d’une cellule composite confinée. *Revue Française de Géotechnique*, 75 (2), 1996a, 3–12.
- Bouassida, M., Determination of bearing capacity of rigid foundations resting on reinforced soil by columns (In French). Doctorate ès-Sciences. Nat. Eng. Sch. of Tunis, 1996b, 246.
- Bouassida, M., Amélioration des sols en place. *Introduction à la géotechnique*. Editions de l’Office des Publications Universitaires, Bouafia, A (Coordonnateur.) Algérie, Octobre 2011, Chapitre 6, tome 2, 139–163.
- Broms, B. B., Lime columns in theory and practice. Proc. Int. Conf. Soil Mech. Mexico, 1982, 149–165.
- Broms, B. B. and Boman, P., Lime columns, a new type of vertical drain. Proc. 9th Int. Conf. on Soil Mechanics and Found. Eng., 2, 1977, 41–75.
- Bruce, D. A., An introduction to deep mixing methods as used in geotechnical applications, III: The verification and properties of treated ground. U.S. Department of Transp. Fed. High. Adm. Rep. # FHWA RD, 2001, 99–167.
- Chai, J. C., Onitsuka, K. and Hayashi, S., Discussion paper on “Physical modeling of consolidation behavior of a composite foundation consisting of a cement-mixed soil column and untreated soft marine clay” by (Yin, J. H. and Fany, Z. *Géotechnique*, 56 (1), 63–68, 2006, *Géotechnique*, 56 (8), 2006, 579–582.

- Debats, J. M. and Degen, W. S., Colonne ballastées sous la mer—Extension du port de Patras (Grèce). Phase II. Proc. 15th Int. Conf. Soil Mech. and Geotech. Eng., (4), 2001, 2759–2763.
- Debats, J. M., Guetif, Z. and Bouassida, M., Soft soil improvement due to vibrocompacted columns installation. Proc. Int. Workshop on Geotechnics of soft soils. *Theory and practice*, Vermeer et al. Eds. September 17–19, Noordwijkerhout, Netherlands, 2003, 551–556.
- Dhouib, A. and Blondeau, F., *Colonne ballastées*. Techniques de mise en oeuvre, domaine d'application, comportement, justification, contrôle, axes de recherche et développement. Presses de l'école nationale des ponts et chaussées, 2005, Paris.
- Goughnour, R. R., Settlement of vertically loaded stone columns in soft ground. Proc. 8th Europ. Conf. on S.M.F.E., Helsinki, Finland, 1, 1983, 235–240.
- Greenwood, D. A., Mechanical improvement of soils below ground surface. Symp. on Ground Engineering, Institution of Civil Engineers, London, paper II, 1970, 11–22.
- Kimura, T., Centrifuge tests on sand compaction piles. Proc. 7th Asian Reg. Conf. S.M.F.E., 1, 1983, 73–122.
- Kirsch, K. and Sondermann, W., Ground improvement. Smoltczyk Eds, Geotechnical Engineering Handbook. (2), 1–56, Berlin, 2003, Ernst & Sohn.
- Moseley, M. P. and Priebe, H. J., Vibro-techniques Ground Improvement, Edited by M. P. Moseley, Blackie Academic & Professional 1993, 1–19.
- Porbaha, A., State of the art in deep mixing technology. Part III: Geomaterials characterization. *Ground Improvement* 4 (3), 2000, 91–110.
- Soletanche-Bachy, Trenchmix: Tranchées de sol traité au liant. Cahier des charges particulières. Paris, 2009.
- Van-Impe, W. F., De-Cock, F., Van-Der-Cruyssen, J. P. and Maertens, J., Soil improvement experiences in Belgium: part II vibro-compaction and stone columns. *Ground Improvement* J. 1, 1997, 157–168.
- Vautrain, J., Comportement et dimensionnement des colonnes ballastées. *Revue Française de Géotechnique*, 11 (2), 1980, 59–73.