Vibratory Ground Improvement to Increase Slope Stability

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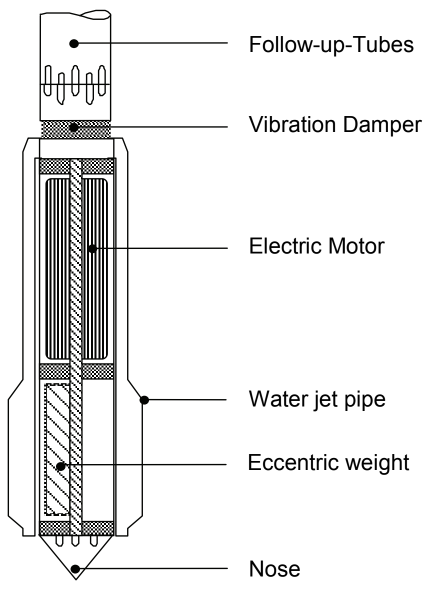
Keywords: vibro compaction, vibroprobe, vibroflot

ABSTRACT: Since its invention by W. L. Degen and S. Steuerman during the mid 1930ies in Germany, Vibro Compaction was used to compact clean sands to reduce load settlements. With the advent of Wet Top Feed Stone Columns in the mid 1950ies and Dry Bottom Feed Stone Columns in the early 1970ies, applications today range from settlement reduction, over increase in shear strength to the prevention of soil liquefaction due to earthquakes. The soils that can be successfully treated vary from clean sands and gravels to soft silts and clays. This paper describes the methods Vibro Compaction, Top Feed Stone Columns and Bottom Feed Stone Columns with special emphasis on their application for slope stability.

1 INTRODUCTION

The key tool for the installation of either Stone Columns or Vibro Compaction is the Vibroprobe (also called 'vibroflot'). Figure.1 shows a general purpose machine, that can install both, stone columns and vibro compaction.

In Figure.2 technical characteristics for some typical machines are listed.



a) Cross section through a Vibroprobe.

b) Vibroprobe at West Kowloon Reclamation.

Figure 1: Vibroprobe.

In order to achieve their design purpose, vibroprobes must generate large vibration amplitudes, for which heavy rotating weights and a strong motor are required. Contradicting this is the need to make the machines as slender as possible to assure they can penetrate to the required depth. Between these two conflicting goals lies the art of finding the best design for depth vibrators.

Table 1: Typical Vibroprobes and their range of use (courtesy Betterground Ltd.).

Machine Name	B15	B27	B44
Purpose	Stone Col.	StCol & VC	Vibro Comp.
Length [mm]	3430	3480	4250
Diameter [mm]	310	354	418
Weight [kg]	1920	2200	3960
Motor [kW]	105	140	250
Frequency [Hz]	50	30	30
Amplitude [mm]	12	24	42
Dyn.Force [kN]	190	270	520

2 SOIL TYPES AND THEIR SUITABLITY FOR VIBROFLOTATION METHODS

Soils with a fines content (<0.06mm or < #200 sieve) of more than 12 % and/or a clay content of more than 2 % (soils to the left of zone B) cannot be compacted by Vibro Compaction, since water cannot be expelled from this type of soil by vibration alone.

However, if a soil in Zone C (liquefiable silty sand with 12 % to 20 % fines content) is treated with Stone Columns, a marked densification can be often measured.

Top Feed Stone Columns were not "invented" but rather evolved from the Vibro Compaction process, which, when used in silty sands could not achieve compaction unless gravel instead of sand was added in the process. Later it was found that the installed gravel columns could bear substantial loads (in silty sands up to 80 tons per column).

Zone D contains the silts and clays. These soils can be treated successfully with stone columns, which accelerate time settlements, increase shear strength and bear foundation loads (typically 15 to 60 tons per column) in soft cohesive soils.

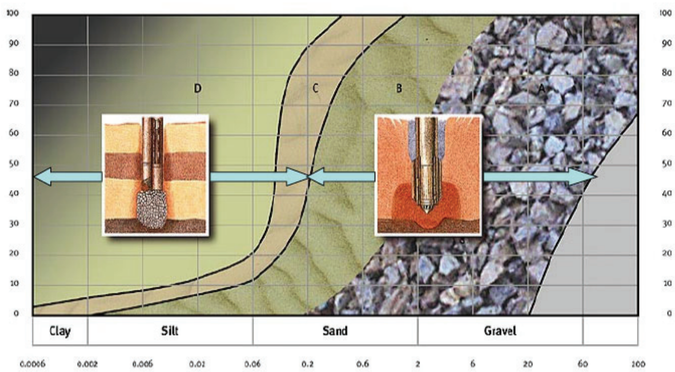


Figure 2: Range of soils for Stone Columns and Vibro Compaction.

3 VIBRO COMPACTION

The Vibro Compaction process has two phases. First the machine, with the assistance of water and/or air flushing from the tip of the Vibroprobe (Figure. 3, left) penetrates to the required depth. Then the water or air at the tip is switched off and the machine held at 0.5 m to 1.0 m depth intervals for 15 to 40 seconds. Within this time granular soil flows towards the vibroprobe (indicated by the red zone in Figure. 3, right) which has a dampening effect on the vibroprobe. This effect can be measured by the Ampere drawn by the motor of the Vibroprobe and is an important quality control parameter.

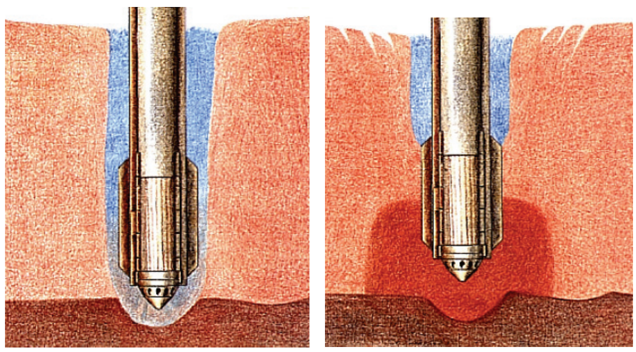


Figure 3: Vibro Compaction installation steps.

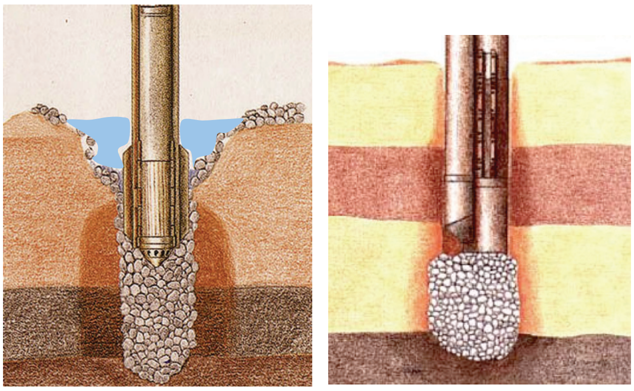
4 TOP FEED AND BOTTOM FEED STONE COLUMNS

Top Feed Stone Columns (Figure.4, left) are installed similar to Vibro Compaction. The difference is that typically the water at the tip of the vibroprobe stays activated at all times and by this water flushing an annular space is washed out around the vibroprobe. In this space gravel (5 to 50 mm) falls down to the tip of the vibroprobe and is there displaced laterally into the soil by up and down movements of the vibroprobe.

Bottom Feed Stone Columns (Figure. 4, right) are installed by a vibroprobe that has a tremie pipe under air pressure attached to one side. In the tremie pipe the gravel (8 to 32 mm max.) is fed to the tip of the vibroprobe and released into the soil by a specially designed nose cone.

As for the Top Feed method, the vibroprobe also drives several times up and down within previously released gravel batches to widen the Stone Column to its required diameter, which is in the range of 0.6 m to 1.5 m depending on soil conditions and design targets.

Top Feed is the faster and usually less costly system and in silty sands above groundwater it often achieves better compaction of the soil than a Bottom Feed system.



TOP FEED BOTTOM FEED

Figure 4 : Stone Column installation methods.

The Bottom Feed method reduces the effort for sludge handling on sites with clayey soils. It is ideal for foundations on contaminated soil, where the contaminants shall remain at depth but would be washed to the surface with the Top Feed system.

5 STONE COLUMNS INCREASE SLOPE STABILITY OF ROAD EMBANKMENTS

One of the premier applications of stone columns is a bridge approach fill on soft soils. Stone Columns have in this case three positive effects:

1) Accelerated settlements, since stone columns act as vertical drains
2) Reduction of total settlements and creep settlements, since stone columns reduce settlements due to the fact that they are 2 to 5 times stiffer than the surrounding soil.
3) Instant increase in shear strength due to the displacement of 10 % to 30% of the soft soil by crushed rock with a friction angle of over 40 degrees. Thus allowing for a fill of the embankment in one step without a need for interim fill stages due to stability concerns.

Item 3 can be calculated using classical laminar slope stability calculations. The width of the laminar elements containing stone columns is calculated by distributing the cross sectional area of the columns into fictive “wall elements”. Since the stone columns are 2 to 5 times stiffer than the surroundings soil, they attract vertical stresses over proportionally. This is beneficial for the overall stability, since larger vertical stresses in the columns allow for proportionally larger shear resistance stresses in these columns (see right sketch in figure.5).

It is often overlooked that only the portion of the normal effective stress that results from loads applied after stone column installation can be considered to concentrate over-proportionally in the stone columns as this is indicated with σ_s in the right part of figure.5 The stresses that were already in equilibrium before column installation will not concentrate into the columns. This is very often forgotten and lies then very much on the unsafe side.

As the embankment over soft soil reaches a greater height, the stone column grids have to be tighter to provide slope stability. In this design principle is demonstrated.

6 SLOPE STABILIZATION BY VIBRO COMPACTION

In the Lusatia north of Dresden, the LAUBAG company was operating large lignite mining pits. A total of over 150 km of shoreline along the lakes of former open pit excavations was closed to the public because of possible sudden shear failure of the reclaimed fill. Single slides of several million cubic meters have been observed, causing Tsunami size waves.

The magnitude of the slides can be attributed to the very loose state of the reclaimed sands, combined with a very unusual grain roundness and very smooth grain surface. This makes it possible for kilometer long landslides of reclaimed fill to develop on a tertiary base sediment, although this firm sediment is only inclined by some 2 to 4 degrees.

Local research has found out, that sands and gravels up to a fines content of about 25 % are susceptible to the phenomenon of "Setzungsfliessen" [engl. translation: a sudden collapse, causing flowing terrain (fliessen) and settlements (Setzung)].

The shaded area in Figure.8 shows the soil range susceptible to "Setzungsfliessen".

In a large number of pits the dewatering wells have been switched off. With the rising ground water the stability along the shorelines is further reduced, since the stabilizing effect of capillary cohesion in the unsaturated zone of the slope disappears with the rising ground water level.

6.1 *Compaction blasting and Vibro Compaction*

If compaction blasting is carried out near the shoreline, the energy induced by the explosives is transferred into the soil within seconds. In the past, compaction blasting has triggered several catastrophic landslides in the area, until this method was abandoned.

For the energy of one blasting event, a vibroprobe needs one or more days. Consequently the risk of initiating a slope failure by transfer of compaction energy is very low with Vibro Compaction. This made it the method of choice for over 500 km of shoreline protection compaction in the Lusatia area of Germany.

6.2 *The "hidden dam"*

At the "Restloch Sedlitz" the company BUL-Brandenburg compacted a total of two million cubic meters of "hidden dam". The purpose of the hidden dam is to ensure that shear failures on the shoreline remain local and do not propagate into the hinterland.

The vibroprobe penetrates to the required compaction depth normally in under three minutes. One compaction point of 56 m is then completed in approximately one hour. The area per compaction point varies from 11 m^2 to 18 m^2, which gives an hourly production of around 800 m^3 of compacted fill.

Figure 10 shows the compaction requirement that has been stipulated on the basis of long experience with the phenomenon of "Setzungsfliessen" in the Lusatia area.

So far none of the hidden dams has failed after being compacted by Vibro Compaction. When "Setzungsfliessen" occurred locally, it always was contained abruptly when reaching the hidden dam.

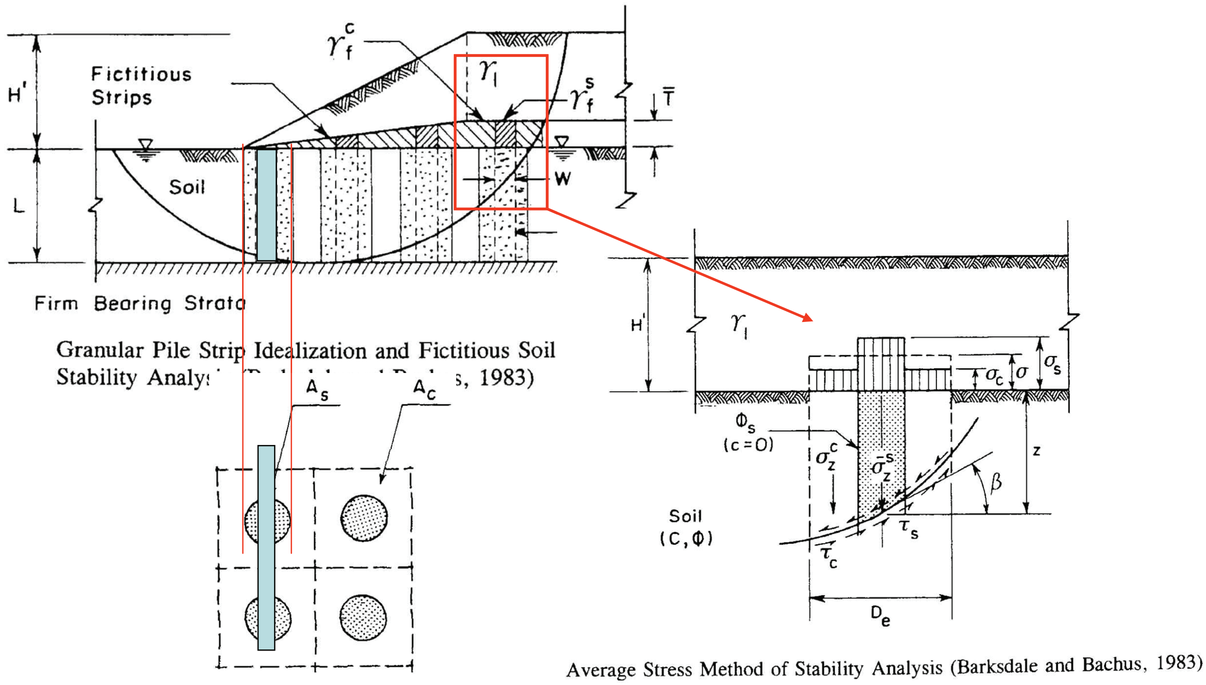


Figure 5: Slip circle analysis using the laminar method with equivalent strips of gravel.

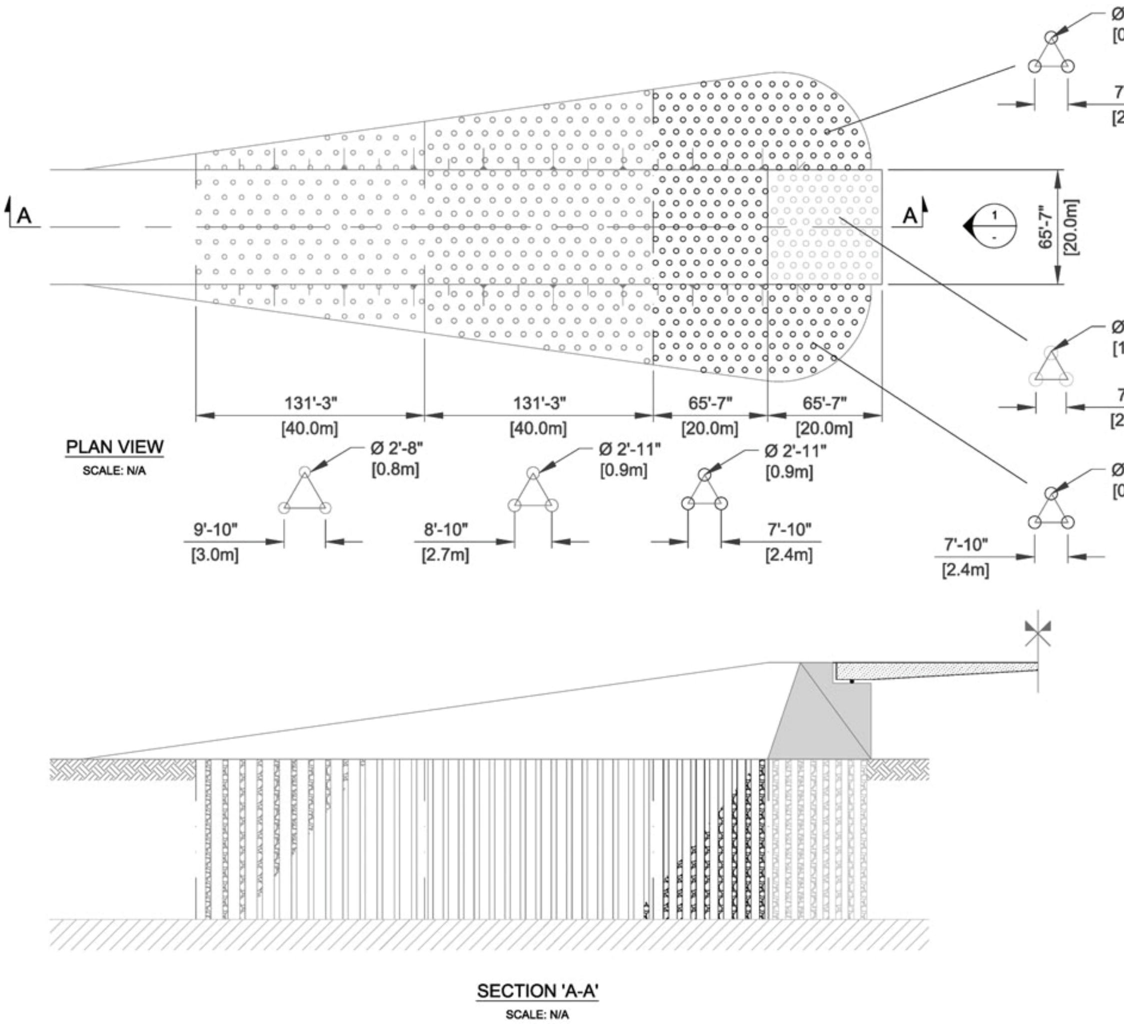


Figure 6 : Treatment intensity as a function of embankment height.

Figure 7: Typical landslide in the Lusatian mining area (Location: Restloch Sedlitz), from Degen (1997).

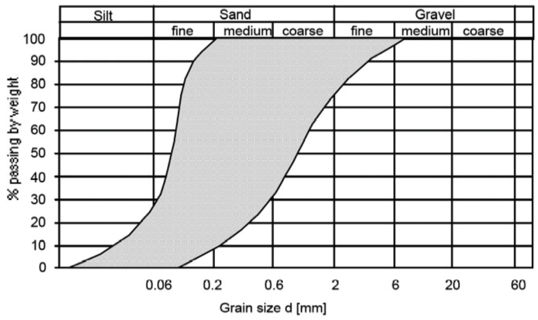


Figure 8 : Soils susceptible to "Setzungsfliessen", from Laubag.

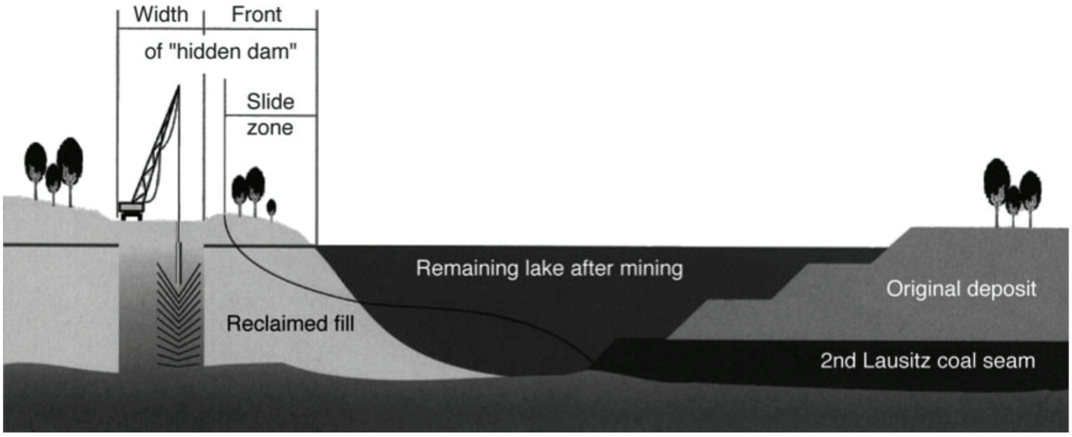


Figure 9: Open pit shoreline, with 56 m deep “hidden dam” for landslide stabilization.

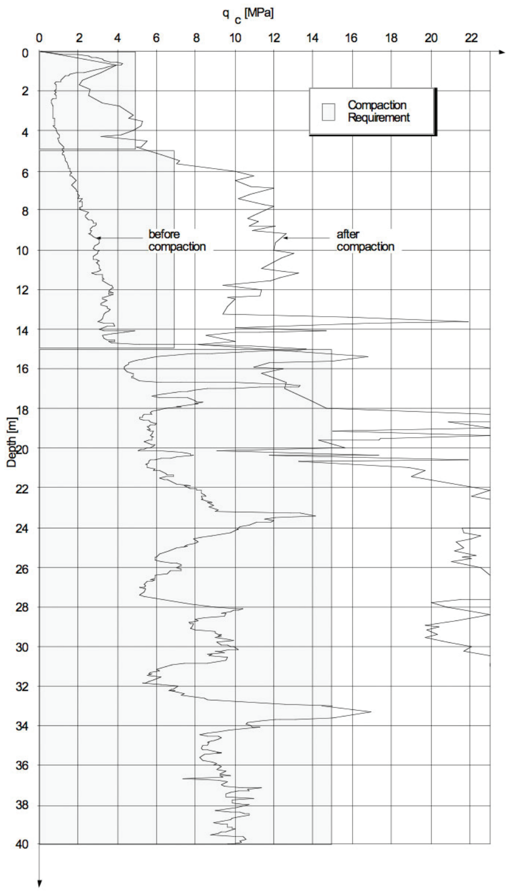


Figure 10: CPT resistance before and after compaction, compaction criteria, from Degen (1997).

7 QUALITY CONTROL FOR STONE COLUMNS

7.1 *During installation*

Most quality issues with stone columns can be avoided by diligent workmanship during column installation. Digital data recorders that log all relevant process data are nowadays state-of-practice. Installation records of a stone column can be plotted either over time or over depth.

The diameter and ampere over depth profiles allow insight into the local soil conditions for each stone column location. In this way the installation records can complement the information gained in the original soil exploration boreholes, CPT and SPT.

7.2 *Load Testing*

If stone columns are installed in lieu of piles, some of the stone column might be tested in a full-scale load test. For stone columns it is beneficial to load at least two or three columns under the same loading plate, since stone columns, other than piles, are known to bear more load per column if loaded in a group. This can be easily explained by the fact that most of the column deformations stem from a bulging of the column in the top 2 to 3 diameters of its length. If there are other stone columns nearby that also bulge out under the same load, they prevent each other from this deformation and thereby reduce for each column the settlement.

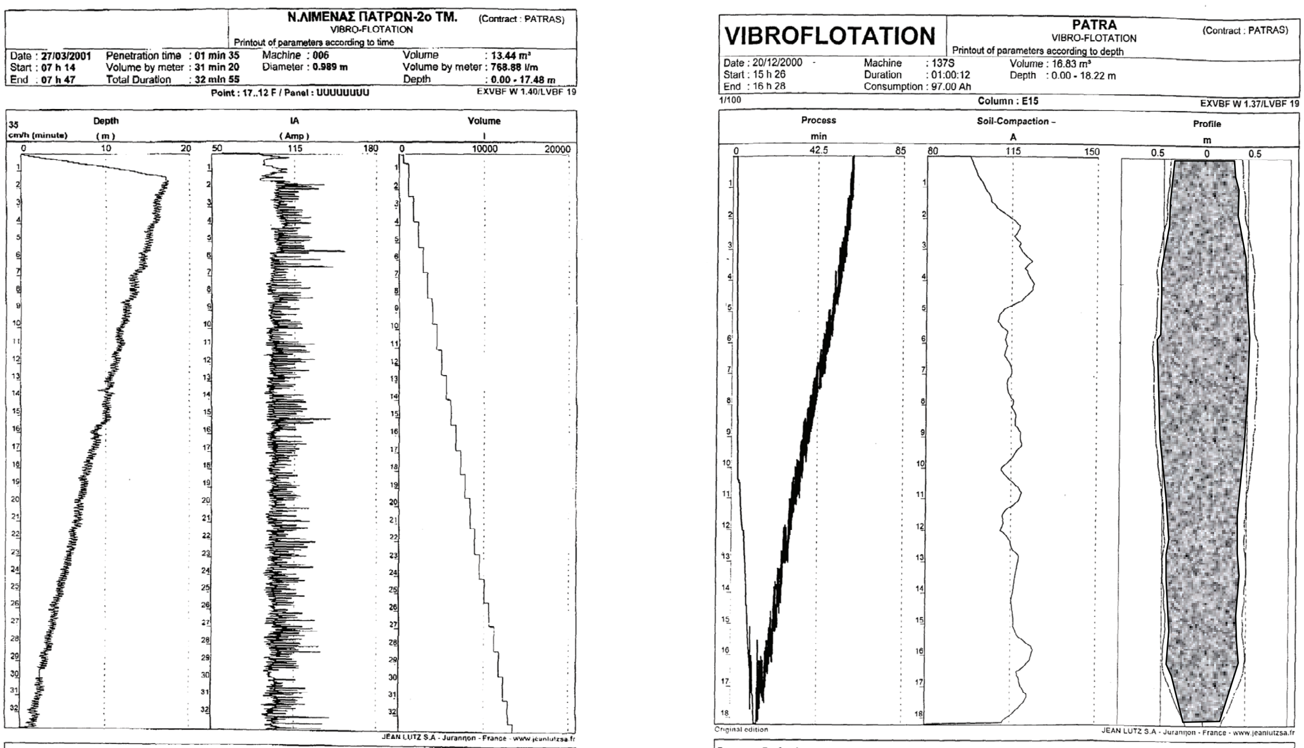


Figure 11: Digital data acquisition of amperage and added gravel over time (left) and depth (right).

8 SUMMARY AND CONCLUSIONS

Vibro Compaction and Stone Columns are technologies that are used throughout the world since 75 years and 55 years respectively. In recent years improvement in the equipment but also in the quality control measures and design tools have matured these products to a degree that they can now be used confidently and competitively on all types of projects. What has not changed over the years is that the quality of the product, like for all special foundation technologies, still depends on the experience of the specialized firm and its qualified installation personnel.

Present trends in land reclamation and earthquake engineering make these methods more popular than in their entire history. Consequently, equipment will be further automatized and even more process parameters will be recorded. The trend to ever-stronger machines also seems to continue.

A recent trend is also the combination of Stone Columns with Prefabricated Vertical Drains (PVDs) to very economically further enhance the drainage capability of the soil.

In the near future a major leap for the technology is expected in earthquake prone areas, because engineers begin to realize that ground treated against soil liquefaction by Stone Columns or Vibro Compaction often does not need additional expensive piling schemes for load bearing. The stone columns or Vibro Compaction treatment is often capable to provide three benefits in one product: Liquefaction prevention, load settlement reduction, and instant increase in slope stability.

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