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The Role of Vibro-Stone Column for Enhancing the Soft Soil Properties

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Abstract**—**This study investigated the behavior of improved soft soils through the vibro replacement technique by considering their settlements and consolidation rates and the applicability of this technique in various types of soils and settlement and bearing capacity calculations.

Keywords**—**Bearing capacity, expansive clay, stone columns, vibro techniques.

I. Introduction

IN today's world, technology has offered solutions to a myriad of problems and by offering different methods and techniques which improve the quality, structure and capacity of soils. The ground improvement techniques have substituted the traditional pile foundation system [1]. Vibro-Flotation refers to the various forms of ground improvement through a vibrating poker inserted into the ground, and encompasses vibro-Compaction and vibro-replacement. Vibro-Replacement is also referred to as vibro- Stone Columns. In this paper, the vibro-Replacement process and the mechanism of stone column behavior under load will be discussed along with the related design mechanisms. Vibro-stone columns have been used to improve the quality of soils from loose sedimentary sands to soft sediment and expansive clays which possess undrained shear strength of 15 kPa or more. Vibro-stone columns have proved to be ineffective for soft cohesive soils whose undrained shear strengths is below10 kPa. However, these columns are a very effective technique which makes thick aggregate columns (stone columns) through a vibrator attached to a crane going into the ground. This technique improves all kinds of soils and thickens coarse soils. Vibro-stone columns can be constructed by two processes: the wet top feed process or the dry bottom feed process.

It was only in 1960s that vibro-compaction proved effective with German river-borne coarse soils and started to be used for business purposes since it was only then that it was used to improve the quality of cohesive soils. [2] Since then, this technique has been very popular due to its cost efficiency and program schedule. The primary aim of the system has been to improve loose coarse soils, however, with in the past 35 years, it has been used extensively to improve the quality of soft cohesive soils and mixed fills. [2]

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The paper also will present the specimen of the stone columns in marginal ground conditions along with the empirical results of recent research programs. Moreover, a number of works and references have been cited [2]. In the second process, the wet top feed process, a vibrator digs the ground with its water jet tip by the use of force and vibration. The crushed stone or recycled concrete is added on the ground to the space provided around the vibrator and they go down to the tip of the vibrator through the jet water and fill the void dug by the vibrator while being lift up. The vibrator then is lowered and lifted several times to densify and displace the stones in the lower layers. This process will not stop until the process reaches the surface.

II. Geotechnical

Through the use of the intense vibration, the soil particles located in the vibration area are densified and compacted. The density and structure of this process is determined by the type of the vibrator, the soil and the method used. Soil compaction can be reduced up to 15% depending on the soil conditions and the power of the compaction work [9].

III. Subsoil

The soil properties are usually included in the soil investigation checklist. Deep vibro techniques are a cost-effective ground improvement technique that can be used for the types of soils that cannot fulfil the requirements determined by the anticipated loading conditions. They can be used to almost any depth.

IV. Vibro- Replacement Stone Column

Vibro-replacement technique results from the vibro-compaction process. Vibro-compaction cannot treat certain soils such as clays, sands, pure silts, and clay or mixed deposits of silts because this technique cannot work properly with vibration [1]. The vibro-replacement technique uses aggregate grained materials to bear load and also crushed stone aggregate to fill the voids. The vibro-replacement technique makes use of two methods namely the wet and the dry method. Vibro-replacement stone columns can treat a range of soils by vibratory techniques. Improving the quality of soils with compacted grainy columns or stone column can be carried out through either a top-feed or a bottom-feed method. Vibration alone cannot densify cohesive, diverse and layered soils [1]. However, the vibr-replacement stone column technique is an answer to these types of soils. In these columns, the broken small stone can enhance the bearing capacity, decrease settlement, increase the potential for liquefaction and enhance shear resistance.

Fig. 1 Bottom-Feed method of stone column construction [5]

V. Vibro-Compaction and Vibro-Replacement

Three special techniques use the depth vibrator, but their soil enhancement and load transfer mechanism vary [9]. As a result, Keller group designs the techniques based on the geotechnical and structural engineers' consultation. In the Vibro Compaction technique, coarse soils are compacted with small materials by readjustment of the soil particles into a thicker state. The vibro Replacement technique constructs heavy weight bearing columns built from pebbles or crushed stones in cohesive soils and coarse soils with very small pieces. The third technique produces physical footing elements in the ground which can bear very heavy weight without even having lateral support for vibro Replacement columns [9]. A vibrating poker carries out the vibro-Flotation by piercing the soil up to the specified depth just by the force gained through vibration and the rig which is equipped with the pull-down winch facility. The produced vibrations go down mainly horizontally enhancing the relative density of soil with the coarse content of greater than 90% (Fig 2).

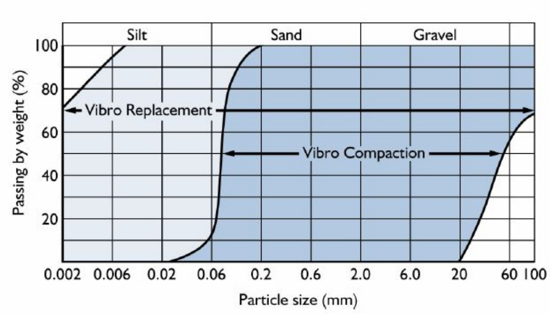


Fig. 2 Particle size distribution showing applicability of vibro-Compaction and vibro-replacement [2]

This process is also called vibro-Compaction and has been applied to densify incohesive sands to depths of 30m. However, the effect of vibrations on cohesive soils such as clays and silts is negligible. Therefore, poker constructs stone columns in these and mixed soils. The movement of the ground by the vibrating poker brings about high friction angle in the construction of coarse columns; as a result, the compacted soil body gains a greater average strength and compaction than the untreated ground.

VI. Advantage

The deep vibro techniques are very effective techniques that can be used for a range of ground conditions and foundation requirements. The method they use is very fast especially in case of the improvement of large amount of soil and when structural works are quickly needed after improvement [9]. Enhancing the quality of soil is very cost effective for contractors because they do not have to use deep footings. Another upside of the deep vibro techniques is its environmental friendliness because in these techniques natural and environmental materials are utilized. Moreover, a little amount of soil is wasted during the work. They are also cost effective and cheaper than piling and trench filling.

VII. The Vibro Compaction Process in Granular Soils

A. Equipment and Implementation

Densifying coarse soils can be carried out with vibro-fluctuation at relatively low frequency to attain the best densification of the soil particles. The vibrator is attached to a crane. The water flushing jets determine the penetration depth as well as the compaction process [9]. The vibrator string is composed of two important parts namely pressure pipes and jets. The densification of soil is done gradually from the bottom up to the top. The compaction created depends on the soil properties as well as the vibration.

VIII. Vibro -Replacement in Granular Soils with High Fines Content and in Cohesive Soils

A. Equipment and Execution

Vibro replacement columns are constructed through the tip of the vibrator by starting from the bottom where coarse granular materials are arranged and mixed through pressurized air. For better efficiency and performance optimization of the process, Keller has added a vibrocast base unit which moves the vibrator on its leader and exerts an extra pull-down pressure during penetration and compaction. The Vibro Replacement process is carried out through different steps. In the retraction step, pebbles are transferred from the vibrator tip into the cyclic space created which is then densified and mixed with the neighboring soil during the subsequent re-penetration step. Therefore, stone columns are constructed from the bottom to the top by compacting and mixing with the surrounding soil under load [9].

IX. Behaviour and Design of Stone Columns

The majority of improvement made on a certain area of the ground is usually carried out with the intention of working with the current ground, while adding materials such as rigid piles are intended to move the ground to a certain degree.

Stone columns mostly transfer the load to the sides moving the soil around it, although some load is also transmitted along the column interface and base. For many geotechnical problems, Cylindrical Cavity Expansion Theory (CCET) is applied to interpret the pressure meter test assessing the surface load or stresses in the ground [1]. This test can also be used to show the lateral load exerted by granular columns and predict load capacity and settlement performance as well as to model the lateral movement of the granular columns. The modeling can also predict the bearing capacity and settlement performance of the granular columns.

X. Bearing Capacity

Two eminent scientists, Hughes and Withers [3] carried out the earlier studies on sand columns in a cylindrical chamber of clay in laboratory situations. Through the use of radiography, they recorded the behavior of column both inside and outside of the cylinder. The CCET test was proved to be quite effective in showing the column behavior. The two scientists obtained the ultimate vertical stress in a stone column as:

$$q= \frac{1+\sin\Phi}{1-\sin\Phi}(\sigma'_{ro} + 4C_n) \quad (1)$$

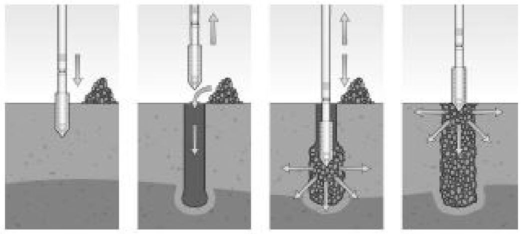
φ' represents the friction angle of the stone infill, σ'_{ro} is the free-field side effective stress and cu represents the undrained shear strength.

XI. Construction Methods

A number of terminologies have been used to describe vibro-stone column techniques such as vibro-compaction, vibro-flotation, vibro-replacement and vibro-displacement, but, Building Research Establishment (BRE) Document BR 391 (2000) has addressed this by describing vibro stone columns. In this document, terms are defined with reference to the top or bottom-feed, the method of stone aggregate supply or delivery, the jetting medium (wet or dry) [4]. This document has come up with a number of terms as follows:

- dry bottom-feed
- dry top-feed
- wet top-feed

The three vibro stone column techniques described previously are hydraulic and work with electricity, that is, they make use of the same kinds of vibro-flots. The front end excavator with a lateral facility constructs the stone aggregate which varies with regard to the ground and environmental conditions, and digging stability. One of the techniques which can be used in a variety of soil types is the dry top-feed technique (Figs. 3 (a), (b)); however, this technique can be used when certain requirements are met such as the bore stability, and the absence of groundwater within the treatment depth range [5]. The vibro-flot bores the soil by moving the surrounding soil. The jets in the nose cone of the vibrator handles the suction forces through the air flush. When the vibro-flot reaches the required depth, it is withdrawn from the bore and the granular backfill materials are added. Then, the aggregate is tipped and compacted through the vibro-flot in the bore by moving the materials downward and laterally.



(a)

(b)

Fig. 3 Dry top-feed stone column installation sequence (a) [6]. Dry top-feed stone column installation in the field (b) [2]

This procedure continues until the stone column is constructed up to the ground surface. Typically, stone columns with diameters of about 500-600 mm are constructed which vary with regard to soil and vibro-flot equipment properties [5], [6]. In the case of fine-grained soils, the technique is usually used for clays with undrained shear strengths which range between 30-60 kN/m2. The dry bottom-feed technique is recommended for weak finegrained soil with a high water table where dry top-feed method cannot guarantee bore stability of the stone column construction.

The dry bottom-feed technique is usually adopted in case of the soils with undrained shear strengths of 15-30 kN/m^2 [4]. The way the vibro-flot works in this technique is like that of the dry top-feed technique, however, in the dry bottom-feed technique, the vibro-flot is equipped with a pipe which feeds stones and aggregates to the tip of the vibro-flot without being withdrawn from the bore. Therefore, this added facility does not allow any instability in the bore. The air lock system discharges the aggregates with compressed air.

The vibro-flot unit is fixed on leaders which are then attached to other machines which help the vibro-flot to be penetrated into the ground. When the penetration starts by the vibro-flot, the stone pipe is filled with the aggregates; upon reaching the desired depth, the vibro-flot is lifted to a certain extent from the depth and stone aggregates are discharged with the air pressure from the tip of the vibro-flot. Then the materials are compressed and compacted through the lifting and penetration of the vibro-flot. This procedure is repeated in approximately 0.5 m lifts until the stone column construction reaches the ground surface. However, in this technique, due to the weak soil properties, more stone aggregate is used and the column diameters of about 600-800 mm are yielded which are larger than that of the dry top-feed technique [4].

XII. Main Applications of Vibro Stone Columns

Vibro stone columns are mostly used in two cases:

A. Structural Foundations

The stone columns provide the low foundations for residential housing, industrial warehouses, big markets etc. [4]. They are not usually recommended for peaty or organic soils; however, vibro-stone column technique might be used in the context of thin, superficial organic or peaty soils where the ratio of layer thickness to column diameter is less than two. Some guidance has been offered by Slocombe [11] with regard to stone column bearing pressure of 50-100 kN/m2 and settlement of 15 to 75 (see Table I).

TABLE I
Typical Improvements Achievable in Terms of Load Bearing Capacity and Settlement after Vibratory Stabilization (after Slocombe

Soil type	Bearing pressure (kN/m2)	Settlement range after treatment (mm)
Made Ground: (cohesive and mixed Granular and cohesive)	100-165	5-25
Made Ground (granular)	100-215	5-20
Natural Sands or Sands and Gravels	165-500	5-25
Soft Alluvial Clays	50-100	15-75

B. Embankment Maintenance and Stability

Vibro stone columns can also be used to enhance the property of soft soil beneath highway and railway embankments where the shear strength of columns is of great importance. The stone columns not only strengthen the base of the embankment, they also do not allow rotational and linear type stability failures [4]. Settlements produced as a result of stone column reinforced soft soils beneath embankments are very higher than those of the structural foundations. However, the settlements must take place during or soon after the construction of embankments (usually between three to six months) due to the considerably shorter drainage paths created by the stone columns for effective pore-water pressure spread during staged load use. Therefore, the rest of the initial densification settlements of the surface of the roads or rail tracks are expected to be in the range of 50 mm [7].

C. Settlement

The length and spacing of columns usually follow certain standards. For example, Priebe [10] developed an effective method of predicting post-treatment settlement in Europe through the use of CCET [10]. This method has found to be effective in most of the applications despite its limited applications and empiricism in its development. Settlement improvement factor represented as n is obtained through:

$$n=\frac{settlement\ without\ treatment}{settlement\ with\ treatment} \quad (2)$$

This formula is a function of the friction angle of the stone φ', plus the soil's Poisson's ratio and an Area Replacement Ratio determined by the column voiding. The area replacement ratio is referred to as Ac/A, in which Ac represents the cross-sectional area of the column, and A refers to the entire cross-sectional area of the unit cell (Fig. 3). [2] Geometrically, Ac/A is related to the column radius (r) and column spacing (s) as in:

$$\frac{A_c}{A} = \mathrm{K}\left(\frac{r}{s}\right)^2 \quad (3)$$

k represents π and 2π/√3 for square and triangular column grids respectively. Calculating A_c directly as the entire foundation area divided by the number of supporting columns is enough in cases of footings and strips [2].

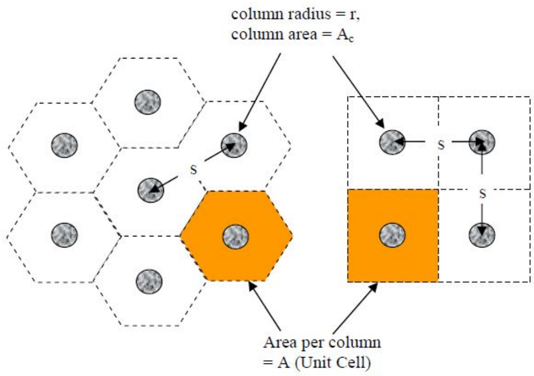


Fig. 4 Typical column arrangements, triangular grid (left) and square grid (right) [3]

XIII. Loose or Marginal Ground Conditions

Due to the considerable development of construction industry recently in Ireland and the increasing demand for marginal sites, stone columns have been widely used in the contexts of cohesive and organic soils. A checklist has been prepared for such applications which are described as follows:

A. Organic Soils

Organic soils have certain properties such as high moisture content, plasticity index and compressibility, therefore, constructing settlement in these soils are quite difficult. In majority of cases, organic silts and clays can be improved effectively. However, if a discrete layer with thickness of less than ≈0.6m is available, a stone column can be constructed in peat. However, when the layer thickness is larger or when there are many thin bands, the peat might not be able to hold the columns in place [8]. A dry plug of lean-mix concrete can be constructed to bind a compressible peat layer higher than 0.6m in thickness especially during the stone column construction process. In other cases where layers are weaker, Geogrids and geotextiles can be installed around the column's perimeter

B. Soil Recommended

Stone columns are recommended for the cases where the undrained strength of cu is 15kPa. It should not however be forgotten that there have been some cases where softer soils have been successfully treated [2]. The undisturbed strength of cohesive soil in its own right is not sufficient, because the sensitivity of the soil to disturbance should equally be calculated.

$$S_t = \frac{C_{u\ undistributedu}}{C_{u\ \text{remoulded}}} \quad (4)$$

C_u remolded represents the undrained strength of soil with its deformed structure. Consolidated clays typically possess higher sensitivity than the over consolidated ones with the S_t values ranging between 1 and 4. However, in the contexts of the common Scandanavian and Canadian quick clays, S_t may reach up to 150 [2].

C. Plasticity Index (PI)

It is referred to the potential for volume change; stone columns cannot handle .the soil swelling and shrinkage. Despite the recommendation of the UK National House Building Council (NHBC, 1988) on not using stone columns in cases where PI>40%, some studies have indicated that stone columns have treated high plasticity soils in some cases.

D. Clay Fill

The prediction of the self-load settlement of newly added or mixed clay fills (with high clay) may be difficult, especially in cases of low control. Although constructing stone columns using such fills may facilitate the settlement process, the volume of the settlement cannot be decreased. However, columns are not recommended for clay fill of less than 10 years old [2].

XIV. Conclusions

Vibro -Stone columns have been and are efficient and cost-effective techniques for the treatment of the load capacity and settlement attributes of geotechnical difficult and problematic soils. Vibro replacement as a deep vibratory compaction technique can be used in a variety of cases and for a range of soils. Despite its limited application in sand and gravel soils, vibro replacement technique can be applied in range of granular loose soils. Stone column can be installed even in cases of non-cohesive natural soils fit for vibro compaction, where coarse grained material is used as backfill.

However, stone column solutions have been proved to be more cost effective than trench fill where the depth exceeds 2m and where the ground conditions allow. Moreover, stone columns can save lots of contract programing over the other ground treatment methods such as preloading and vertical drains.

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