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A Review of the Settlement of Stone Columns in Compressible Soils

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ABSTRACT: The behaviour of Vibro Replacement stone columns has yet to be captured fully by analytical or numerical means, and predicting stone column performance in soft cohesive soils brings specific challenges. In this paper, a new database of settlement improvement factors is developed, drawn from both published and unpublished data. The database illustrates that the improvement is generally predicted quite well by Priebe's (1995) basic improvement factor. Moreover, the extent of improvement reflects the construction method, with the preferred dry bottom feed system performing consistently better than other column construction systems.

INTRODUCTION

Vibro Replacement (VR) has emerged as one of the world's most widely used forms of ground improvement in cohesive soils, as solutions may be tailored to meet specific bearing capacity, settlement magnitude and rate requirements. Mounting pressure nowadays to develop 'marginal' sites has focussed attention on the potential of VR to offer technically and economically viable solutions in these deposits. There are many challenges specific to VR in fine soils. Stress changes and ground movement caused by both the formation of cavities by the poker and the subsequent construction of compacted columns are poorly understood (Egan *et al.*, 2008). The effect of clay sensitivity on stone column performance has not been widely researched, and to date there is no consensus on the extent to which stone columns arrest creep.

The most popular analytical settlement prediction method in European ground improvement practice (Priebe 1995) contains many simplifying assumptions and some empiricism in its formulation. Significant advances have been made in developing constitutive models for soft natural soils for use in conjunction with finite element software to incorporate characteristics such as creep, anisotropy, destructuration and bonding (i.e. Karstunen *et al.*, 2005, Leoni *et al.*, 2008). However, industry practitioners in ground improvement design do not routinely use these models and, in general, finite element approaches are currently limited by their inability to capture installation effects satisfactorily, especially the 3-D formulations.

In light of these uncertainties, it was beneficial to carry out a detailed review of stone column field settlement performance records. A new database of settlement improvement factors for soft cohesive deposits is presented and interpreted herein. The discussion considers the operational friction angle of the stone and the effect of the column construction method, and provides a useful reference for practitioners designing ground improvement schemes in compressible deposits.

STONE COLUMN CONSTRUCTION METHODS

A brief explanation of the main VR systems is given below, where the terms top-feed or bottom-feed describe the stone supply method, and wet or dry relates to the jetting medium. The appropriate choice of construction method and proper on-site implementation is paramount to the successful improvement of soft and very soft soils.

(i) *Dry top feed* is predominantly used for shallow to medium treatment depths of coarse and more competent cohesive deposits. The hole formed by the first penetration of the poker remains stable as the column is constructed. Controlled air flush is often used to aid construction and while commonly used for lightly-loaded to heavily-loaded developments, it is rarely suitable for use in soft cohesive soils.
(ii) *Wet top feed* is used for medium to deep treatment below the water table and treatment of softer cohesive deposits. In cohesive soils, water flush helps remove arisings from the void formed by the poker and maintain its stability. While wet top feed has been used with success in soft cohesive soils (i.e. Munfakh *et al.,* 1983), it is used less frequently nowadays due to difficulty in disposal of the flush arisings, so it is often reserved for larger-scale moderately-loaded to highly-loaded developments.
(iii) *Dry bottom feed* has now largely replaced the wet top feed method since its inception in the late 1970s and is principally used for treatment of water-bearing and soft cohesive deposits. Controlled air flush is used to aid construction and maintain stability of the void formed by the vibrating poker. Now the preferred construction technique in soft soils, there is compelling evidence (i.e. Wehr, 2006) that the dry bottom feed method can successfully treat ground having c_u values well below the 15-20 kPa frequently quoted as the lower practical limit of the system's applicability.
(iv) Alternative construction methods have been used; De Cock and d'Hoore (1994) describe *bottom rammed* columns, which have evolved from the classic Franki pile. A tube is bottom-driven to the required depth. As it is withdrawn, successive charges of stone are introduced and progressively forced into the surrounding soil by intensive ramming. This method is neither practical nor economical for soft soils.

SETTLEMENT IMPROVEMENT DATABASE

Absolute and differential settlement criteria normally govern the design of stone columns in compressible soils. The authors have compiled a new database with settlement information from over 20 case histories in cohesive or predominantly cohesive soils. While the majority of these cases relate to loading of areas that are wide in relation to the stone column length (subsequently referred to as widespread loading), three of the cases relate to footings supported by small column groups.

A settlement improvement factor (n) is used to quantity the degree of treatment, and is defined as:

$$n = \frac{s_{untreated}}{s_{treated}} \qquad [1]$$

where $s_{treated}$ and $s_{untreated}$ are the settlements with and without stone columns respectively for a particular loaded zone. The database necessarily comprises two categories of data, distinguished as follows:

(i) Cases where $s_{treated}$ and a reference value of $s_{untreated}$ have both been measured, so the value of n is entirely measurement-based (Table 1).

(ii) Cases where $s_{treated}$ values have been measured; however $s_{untreated}$ values have not been measured but instead predicted either analytically or from experience of measurements in local of similar ground conditions (Table 2). The values of $s_{untreated}$ used in this paper are those quoted/inferred in the original references.

Priebe (1995) uses the area replacement ratio r =A_c/A to capture the proportion of ground replaced by stone in an infinite array; A_c is the area of one column and A is the plan area of the 'unit cell' attributed to a single column. The value of r may be deduced from the column diameter (D) and spacing (s) according to:

$$r = \frac{A_c}{A} = k\left(\frac{D}{s}\right)^2 \qquad [2]$$

Table 1. Case histories in which $s_{untreated}$ and $s_{treated}$ were measured

Reference and Site Location	**Material Treated**	**Avg. Treatment Depth (m)**	**Treatment Configuration**	**Treatment Method**	**Loading Type**	**Area Replacement Ratio, r**	**Settlement Impr. Factor, n**
Watts *et al.* (2000) Lancashire, U.K.	clay, ash fill	3.50	L	DTF	test strip	0.209	1.47
Greenwood (1970) Bremerhaven, Germany	clay, peat	6.0	TR	WTF	emb.	0.260	1.63
Munfakh et al. (1983) New Orleans, U.S.A.	clay	≈20	TR	WTF	emb.	0.253	1.70
Cooper and Rose (1999) Bristol, U.K.	clay	4.35	TR	BF	emb.	0.075	1.85
		4.35	TR	BF	emb.	0.146	2.55

Legend: L=linear, TR = triangular, DTF = dry top feed, WTF= wet top feed, BF = bottom feed, emb. = embankment

Table 2. Case histories with measured $s_{treated}$ but predicted $s_{untreated}$

Reference and Site Location	Material Treated	Avg. Treatment Depth (m)	Treatment Configuration	Treatment Method	Loading Type	Area Replacement Ratio, r	Settlement Impr. Factor, n
Venmans (1998) Holendrecht-Abcoude, Netherlands	clay	5.2	TR	BF	emb.	0.170	1.67
Greenwood (1991) Canvey Island, U.K.	clay/ silt	10.0	TR	WTF	stg. tank	0.221	2.38
Raju *et al.* (2004) Kajang, Malaysia	silt, fill	13.5	SQ	WTF +BF	emb.	0.240	2.60
De Cock and D'hoore (1994) Antwerp, Belgium	peaty clay	8.5	TR	BR	stg. tank	0.287	3.0
Oreye, Belgium	silt	11.0	TR	BR	stg. tank	0.227	1.83
Baumann and Bauer (1974) Konstanz, Germany	silt	5.5	TR	WTF	raft	0.472	4.03
Watt *et al.* (1974) Teesport 104, U.K.	silt	6.1	TR	WTF	stg. tank	0.296	2.80
Teesport 165, U.K.	silt	6.1	TR	WTF	stg. tank	0.296	3.43
Hedon, U.K.	clay	6.7	TR	WTF	stg. tank	0.269	2.77
Greenwood (1974) Stanlow, U.K.				WTF	stg. tank	0.309	5.47
Raju (1997) Kinrara, Malaysia	silt, fill	17.0	SQ	BF	emb.	0.350	4.0
Kebun, Malaysia	clay	15.0	SQ	BF	emb.	0.196	2.5
Bell (1993) Stockton, U.K.	clay	4.4	TR	WTF	emb.	0.086	1.38
						0.055	1.24
						0.038	1.15
Kirsch (1979) Essen, Germany	silt	5.0	STQ	WTF	stg. tank	0.345	2.35
Kirsch (unpublished) Berlin-B'burg B, Germany	clay/ silt	7.1	SQ	BF	pad	0.070	1.94
Berlin-B'burg C, Germany	clay/ silt	6.8	SQ	BF	pad	0.130	2.1
Keller Foundations (unpubl.) Contract 'B', Scotland	clay	5.5	L	BF	test strip	0.226	1.2
Goughnour and Bayuk (1979) Hampton, U.S.A.	silt, clay	6.4	TR	WTF	emb.	0.339	2.4

Legend: TR = triangular, SQ=square, STQ = staggered square, L=linear, WTF= wet top feed, BF = bottom feed, BR = bottom rammed, emb. = embankment, stg. tank = storage tank.

where *k* is π/4 and π/2√3 for square and triangular column grids respectively. Values of r are also given in Tables 1 and 2, with A_c either measured directly or deduced from stone consumption records. Values of n (Tables 1 and 2) are plotted against r in Figure 1 for the widespread loading cases. In order to provide a frame of reference for the data, Figure 1 also includes Priebe's (1995) basic improvement factor n_0 predictions (eqn 3; assuming Poisson's ratio of the soil ν_s=0.33 as is customary) adopting three different operational friction angles of $\phi'=35^0$, $\phi'=40^0$ and $\phi'=45^0$ for the stone.

$$n_0 = 1 + r\left[\frac{5-r}{4(1-r)\tan^2(45-\frac{\phi'}{2})} - 1\right] \qquad [3]$$

Case-specific values of ϕ' are generally not presented in the literature. Herle *et al.* (2008) advise that $\phi'\approx 40^0$ is conventionally adopted used in European design practice, and this would be especially true for soft soils. Additional parameters needed for predicting Priebe's (1995) n_1 and n_2 factors (amendments to n_0 to account for column compressibility and soil and column unit weights respectively) are not available.

Predicted values of n (n_{pred}) are plotted against measured (n_{meas}) values in Figure 2. Tests plotting below the $n_{pred} = n_{meas}$ line denote measurements which exceed predictions. Much of the data in Figure 2 is taken from Figure 1 (i.e. n_{pred} is n_0 based on $\phi'=40^0$). However, Figure 5 also incorporates data from two test strips (Watts *et al.*, 2001 and Keller Foundations Contract B, unpublished) and two pad footings (Kirsch, unpublished). The Priebe (1995) correction was applied to n_{pred} for the strips to allow for the reduced efficiency of small groups. No such correction was applied for the pads as the loaded columns underneath the footings were surrounded by 'buttressing' columns, so 'unit cell' conditions were assumed for the loaded columns. In Figure 2, Table 1 (true n measurements, filled symbols) and Table 2 data (open symbols) are differentiated, and the different systems used to construct the columns are highlighted.

DISCUSSION

Although some scatter is evident, eqn. [3] with $\phi'=40^0$ provides a good 'average' match to all the measured n-r data in Figure 1. This result is in spite of the fact that there is not enough resolution in the published data to take account of all of the factors that could have influenced the degree of settlement control. Although difficult to quantify, an experienced designer would need to account of the following:

(i) uncertainty in the 'as-constructed' column diameter and spacing

(ii) the time elapsed since loading at which n is measured is not consistent throughout all of the case studies. Due to the drainage effect of stone columns, primary settlement will occur at a faster rate for treated areas than for similarly loaded untreated areas. If the settlement of the untreated area is measured before primary settlement is complete, misleadingly low n values will be obtained.

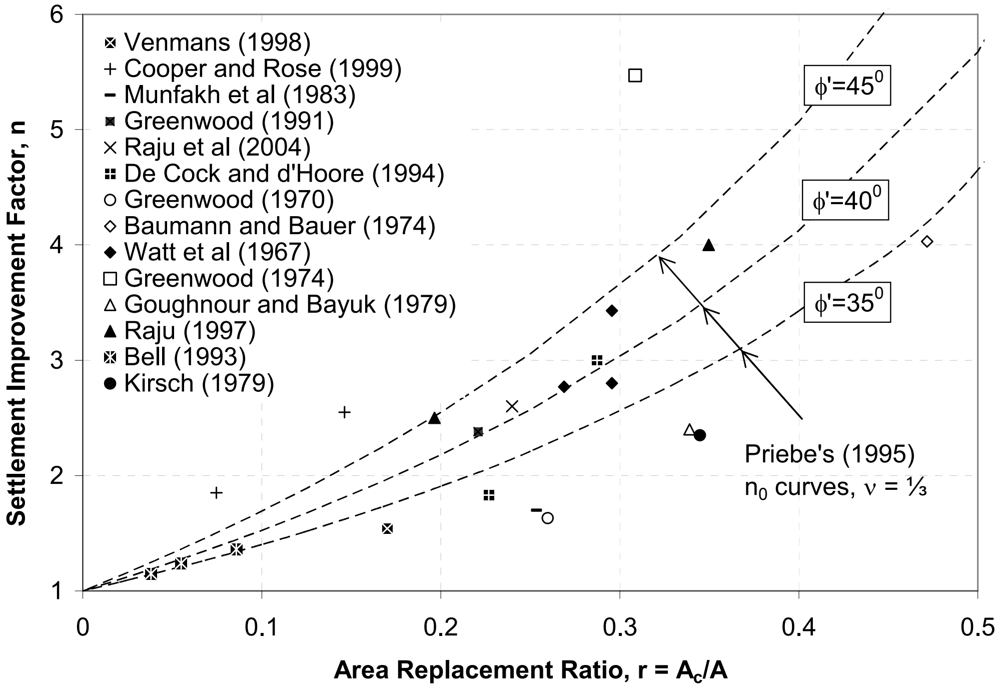

FIG. 1. Settlement improvement factor against area replacement ratio for sites with widespread loading

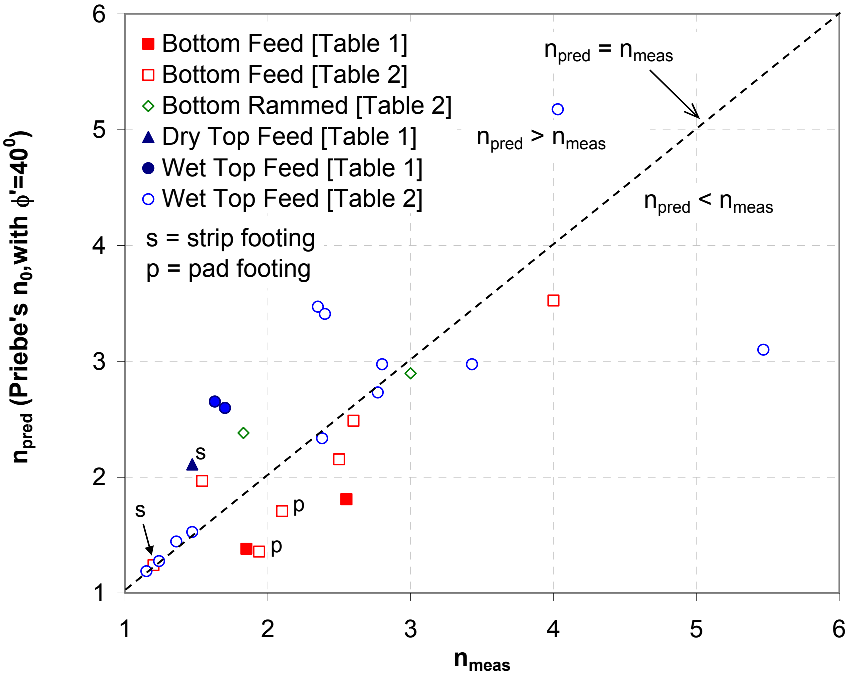

FIG. 2. Predicted versus measured settlement improvement factors (all sites: widespread loading and footings) distinguished by construction method

(iii) the relative contributions to surface settlement from compression over the depth of the treated zone and below the treated zone. It is rarely possible to separate the settlement solely arising from the treated zone in studies carried out on construction projects, hence in such situations the improvement attributed to the installation of the stone columns would probably be underestimated.
(iv) variations in the prediction methods used to determine the n values in Table 2.

Figure 2 implies that a design friction angle of $\phi'=40^0$ may not always give safe settlement predictions for the top feed system, but as already stated, there may be other possible variables besides the friction angle. For example, the deposits within the treatment zone at Bremerhaven (Greenwood, 1970) incorporated some peaty material.

Importantly, the higher n_{meas}/n_{pred} ratios in Figure 2 tend to relate to bottom feed projects, endorsing the use of this system for delivering consistent settlement improvement in soft ground conditions. In these cases, it appears appropriate to adopt a higher friction angle in the range $\phi'= 40\text{-}45^0$ in conjunction with Priebe (1995). Herle *et al.* (2008) advocate the use of higher ϕ' values (i.e. in excess of 50^0), but these are based on shear box tests carried out on stone at high relative density and not with soft soil in mind. Good design practice should consider the degree of stone compaction and the confining strength of the soil, best understood from rig instrumentation.

CONCLUSIONS

The Priebe (2005) design method with conventionally adopted friction angles of 40^0 provides a conservative estimate of the actual performance of the bottom feed system in practice. This method, which continues to be the favoured approach for leading stone column designers, is proved to be reliable even though it does not capture all of the fundamental soil and stress changes that take place during column construction and subsequent loading. More sophisticated approaches, such as finite element analysis, for example, provide another useful tool to geotechnical engineers, although they have not evolved to a stage of readiness for routine design.

The vast majority of published data pertains to large loaded areas and not to strip or pad footings. There remains a need for high quality instrumented field tests to improve our understanding of the factors controlling stone column settlement behaviour.

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