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The undrained cohesion of the soil as a criterion for column installation with a depth vibrator

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ABSTRACT: Piles, vibro concrete columns and rigid inclusions cannot be installed in liquid media like water with $c_u = 0$ kPa, because a cone shaped slope will form instead of a cylindrical body. In international standards a limit of $c_u = 15$ kPa is currently used as a lower boundary. Additionally the minimum center to center distance between fresh concrete displacement piles without permanent casing is specified in EN 12699 between 6–10 times the diameter depending on the c_u-value. These limits should be applied to all kinds of displacement piles like rigid inclusions in order to avoid damaging neighbouring columns during installation.
However, recent world-wide site experiences reveal that these limits are not valid for granular columns like vibro stone columns. The limit of the undrained cohesion should be reduced to $c_u \approx 5$ kPa.

1 INTRODUCTION

It is common knowledge that vibro stone columns and vibro concrete columns cannot be installed in liquid media like water with $c_u = 0$ kPa, because a cone shaped slope will form instead of a column. In the German recommendation (FGFS 1979) for soil improvement with depth vibrators, dated 1979, limits of $c_u = 15$–25 kPa are given. Since that time the lower limit value has been, and still is, used in all kinds of German and international standards. However, more than 10 years of site experiences of the Keller company around the world reveal that this limit value is far too conservative and should be reduced to $c_u = 5$ kPa.

The aim of this publication is to find out the limit value of the undrained cohesion where a column installation is no longer possible. Site experiences of Keller have been compiled and summarized and furthermore systematic model tests are presented varying the c_u-value.

2 PREVIOUS SITE EXPERIENCES

The c_u-values of Keller sites have been compiled, where an installation of vibro stone columns (VSC) or vibro concrete columns (VCC) with a depth vibrator was possible in soils with $c_u < 15$ kPa. Details may be found in the following references.

Austria:

- Klagenfurt, VSC, metro-market, $c_u = 5$–10 kPa (Marte et al., 2005)

Germany:

- Lübeck-Herrenwyk, VSC, metal factory, $c_u = 11$–26 kPa (Völzke, 2001)
- Mering, VCC, railroad embankment, $c_u = 5$–20 kPa (Borchert et al. 2004)
- Rethen, VSC, sugar plant, $c_u = 12$–18 kPa
- Zossen, VCC, dam for ring road, $c_u = 4$–8 kPa (Zimmermann, 2003)

Malaysia:

- Shah Alam Expressway, VSC, (Raju/Hoffmann 1996, Raju 1997)
  - Kinrara Interchange, VSC, $c_u = 6$–40 kPa
  - Sri Petaling Interchange, VSC, $c_u = 8$–50 kPa
  - Shah Alam West, VSC, $c_u = 5$–15 kPa
- Putrajaya Boulevard, VSC, $c_u = 5$–20 kPa (Raju, 2002)

Poland:

- VSC, highway embankment, $c_u = 5$ kPa (Marte et al., 2005)

In summary, the experience of all the above previous sites show that the installation of vibro stone columns and vibro concrete columns is possible well below the old limit value of $c_u = 15$–25 kPa, and that the actual limit value should be approximately $c_u = 4$–5 kPa.

3 MODEL TESTS AT KAISERSLAUTERN UNIVERSITY

The aim of these model tests is to find a new c_u limit value for dynamic excitation using a liquefiable very well defined silt. Here the results of a Diploma thesis are presented (Gundacker 2004).

3.1 *Test materials*

All tests were executed in silt with different water contents. For each water content the corresponding undrained cohesion was determined with laboratory shear vane tests, see Table 1.

Perlea (2000) describes the liquefaction of silt under dynamic excitation with impressive case histories, i.e. earthquakes, and emphasizes that not only sand can liquefy.

He gives the following conditions for liquefaction of silts:

- Clay content < 20%
- Plasticity index $I_p \leq 13$
- Liquid limit $w_L < 33.5\%$ and water content $w > 30\%$ or $w > 0.87\ w_L$ and $w < 30\%$
- Sensitivity $S > 4$

A mixture of 97.5% crushed stone powder and 2.5% caolinite fulfills all these criteria, except for the sensitivity of 1.6 being below the recommended value of 4. This mixture is used for all further tests.

In order to model the stone material a uniform coarse sand is used with $d_{50} = 0.77$ mm, $e_{max} = 0.875$ and $e_{min} = 0.434$.

3.2 *Test layout*

The model scale is 1:10 and results mainly from the size of the PVC-tube modeling the depth vibrator.

A PVC container with an inner diameter of 29 cm and a height of 60 cm was filled with silt up to a height of 50 cm, see Figure 1.

In order to install the sand columns, a PVC-tube with an outer diameter of 5.0 cm and an inner diameter of 4.6 cm was used. This PVC-tube replaces the vibrator and follower tubes which have a diameter of approximately 40 cm in reality. The PVC-tube is necessary to keep the hole open during sand filling, because no water or pressurized air is used as in reality.

Table 1. Undrained cohesion depending on the water content of the silt.

Water content in%	29.9	30.5	32.0	35.5
Undrained cohesion in kPa	5.5	4.0	3.5	2.0

Figure 1. PVC container.

To model the vibrations of a real vibrator, a small vibrator was fixed to the lower end of a second PVC-tube ("vibrator tube") with an outer diameter of 4.5 cm. The vibrator tube fits exactly into the first tube. Horizontal vibrations were applied. Details are given in Table 2.

Being able to observe the shape of the model columns after the tests, the sand was mixed with cement in the ratio of 4:1. This changes the behavior of the sand column only in a negligible way. The cement is able to harden by sucking water out of the surrounding silt.

3.3 *Column installation and definition of failure*

Although static penetration has been included in the test program, in the following sections only dynamic penetration will be reported. In this way the reality is modelled best. Applying a static weight of 40 N on both tubes this assembly creates a hole in the soil. In reality static pull down forces of up to 200 kN are used.

After reaching the desired depth the vibrator tube is removed. Subsequently sand with a height of 3 cm is filled into the outer tube and then the tube is pulled upwards resulting in a 2 cm high sand column only supported by the soil. As a next step the vibrator tube is reintroduced with the static weight on top. The vibrations are stopped,

Table 2. Comparison of vibrators.

	Reality	Model
Frequency	40–60 hertz	50 hertz
Diameter	30–45 cm	4.5 cm
Double amplitude	3–15 mm	1–2 mm

if the settlement of the column does not change anymore. Empirically this procedure ends after a maximum time of 2 minutes. However, if the sand settles more than 1 cm, the vibrations are stopped, a new layer of sand is added and finally the vibrator is reintroduced and started again. Before the start of the tests it has been calculated how much sand is necessary to double the diameter of the sand column. Such an increase is regarded as failure during the installation of a column. If it is possible to introduce even more sand, only a negligible resistance of the soil can be expected. In this case the test is ended.

3.4 *Test results*

Test no. 1: $c_u = 5.0$ kN/m^2 – w = 29.0%

In the literature there are several examples where the undrained cohesion of 4 to 5 kN/m^2 was sufficient to install vibro stone columns, see section 2. For this reason the first test was executed with a $c_u = 5$ kN/m^2. The aim of this test was to prove that this undrained cohesion of a soil which is liquefiable according to Perlea (2000) is sufficient to support a vibro column. No failure was observed during installation.

Test no. 2: $c_u = 4.0$ kN/m^2 – w = 30.5%

In the following tests the water content is subsequently increased by 1.5%. With a water content of 30.5% an undrained cohesion of 4.0 kN/m^2 is reached. Here as well there was no failure during column installation.

Test no. 3: $c_u = 3.5$ kN/m^2 – w = 32.0%

In this test the water content was again raised by 1.5%. Here failure was observed with an enlargement of the diameter by 100%, see Figure 2. The closer the installation comes to the surface the smaller are the stresses acting as soil resistance and the faster failure is reached.

Test no. 4: $c_u = 4.0$ kN/m^2 – w = 30.5%

In this test the same c_u-value as in test no. 2 was chosen, but the static weight was doubled from 40 N to 80 N. Under this higher load more sand was vibrated into the surrounding soil, but no failure was observed.

Figure 2. Column with $c_u = 3.5$ kN/m^2, where failure has occurred.

4 CONCLUSION

Site experiences and systematic model tests demonstrate that the installation of vibro stone columns and vibro concrete columns is possible with a depth vibrator, even in a very soft soil with an undrained cohesion of $c_u \geq 4$ kPa. The old limit value of $c_u = 15$ kPa is no longer valid.

However, vibro columns in such soils should only be installed by specialist contractors with intense monitoring (depth, amperage of motor, stone/concrete consumption, vibration frequency), preferably online. This is absolutely necessary, because the above criterion can only serve as an indicator of the soil before the ground improvement starts, but does not cover aspects of the dynamic behavior of the system, i.e. centrifugal force of the vibrator, tendency for soil liquefaction, etc.

In the case of vibro concrete columns it may be necessary to install a vibro gravel drain first in order to improve the existing soil. Then the vibro concrete column is protected by a ring of gravel. The drain and the column can be installed with the same bottom feed vibrator unit.

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