Introduction of Vibro Dynamic Replacement – Case Study

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GeoCalgary 2022 October 2-5
Reflection on Resources

ABSTRACT
Soil improvement by dynamic replacement (DR) consists of creating compacted granular pillars of diameters ranging from 1.5 to 2.5 m typically within non-compactable soils (high fines content) following a grid (uniform treatment) or localized treatment. However, maximum depth of DR is around 4 to 6 m depending on the ground condition. For deeper ground improvement other techniques should be employed. This paper introduces a new technique named “Vibro Dynamic Replacement” (VDR) in which sand columns are executed and compacted to depths beyond the reach of conventional DR. In the next phase, the DR technique is applied to create compacted granular columns in the top layers and to transmit the energy to the deeper soils via sand columns executed in the first phase and improve the full treatment depth. VDR is very efficient in grounds with problematic layers (e.g., soft clays) deeper than 5 to 6 m. In this method compacted sand columns are executed within the problematic soil using a bottom feed vibro replacement rig. A VDR project recently conducted and thoroughly investigated is also presented and discussed as a case study.

RÉSUMÉ
L’amélioration de sol par remplacement dynamique consiste à créer des colonnes de matériel compacté, d’un diamètre de 1.5 a 2.5 m, généralement dans des sols non compactables (pourcentage de fines élevé), arrangées en grille ou suivant un traitement localisé. Cependant, le traitement maximum pour le remplacement dynamique est de l’ordre de 4 a 6 m selon les conditions de sol. Pour des traitements plus profonds, d’autres technique devraient être utilisées. Cet article introduit une nouvelle technique, nommée «Vibro Remplacement Dynamique» dans laquelle une colonne de sable est exécutée a des profondeurs non atteignables par les techniques de remplacement dynamique traditionnelle. Lors de l’étape suivante, la technique de remplacement dynamique est utilisée pour créer une colonne dans les couches supérieures de sol et pour transmettre l’énergie dans les couches inferieures par le biais des colonnes de sable exécutées lors de la première phase. La technique de Vibro Remplacement Dynamique est très efficace dans les sols ayant des couches problématiques (argiles) à des profondeurs supérieures à 5 a 6 m. Pour cette méthode, les colonnes de sables sont exécutées dans les sols problématiques avec un vibreur par voie sèche. Un projet récemment exécuté est discuté dans le cadre d’une étude de cas.

1 INTRODUCTION

Vibro sand column and dynamic replacement are two of most widely employer ground improvement techniques which do not need concrete, steel or aggregates, hence considered as environmentally friendly and cost efficient methods.

Regarding the limitations of these methods, in order to extend their applicability to a wider range of problems (e.g., deep soft layers), a new ground improvement product is introduced which is a combination of sand column and dynamic replacement. This method was executed and tested in this research.

2 CONVENTIONAL METHODS

2.1 Vibro Sand Columns

Vibro sand columns (or simply sand columns) are vertical and -usually- cylindrical elements installed in the ground using bottom feed vibro replacement technique (Kirsch and Bell 2019) to the maximum depth 18-20 m (depending on the available equipment and ground condition). Sand columns are denoted in this paper by SaC. Execution and hydro-mechanical function of SaC are very similar to those of stone columns (SC). The difference is mainly in the external material inserted in the natural ground, which is clean gravel for SC and compactable sand (e.g., fines content <15%) for SaC. Needless to say, level of improvement SC can bring about is considerably higher than that of SaC.

To execute the SaCs of this research, a depth vibrator was used equipped with a channel through which sand could flow and reach the tip of the vibrator by pressurized air. When the vibrator was penetrated down to the design depth, sand was fed into a funnel and transported through the channel (Figure 1). During the withdrawal steps, sand flowed from the vibrator tip into the created annular space and then compacted and pressed into the surrounding soil during the following re-penetration step.

SC and SaC are typically designed as per homogenization or unit cell approach, considering equivalent parameters for the improved ground instead of considering them as individual elements (Hassen et al. 2010, Maheshwari and Khatri 2012, Babu at al. 2013, Ng and Tan 2015, Killeen and McCabe 2014, and Nayak et al. 2019, among others). The most famous calculation method based on the unit cell approach was proposed by Priebe

(1976) and later updated and modified by Priebe (1987, 1988, 1995, and 2003).

Figure 1. Vibro replacement rig (Vibrocat TR5)

2.2 Dynamic Replacement

Typical dynamic replacement technique (DR) is a modified version of dynamic compaction (DC) altered to extend the ground improvement to cohesive soils (i.e., silty or clayey soils) or loose granular soils with high fines content.

For execution of a DR column, first, a 0.5-to-1-m deep crater is made in the ground by releasing a 10-30-ton pounder multiple times from a height of 10-20 m. Next, the open crater is filled with a compactable material (as described below). The backfilled material is compacted and pushed down by pounding in same manner. This procedure is repeated further to create a so called DR column usually with depth of 3 to 6 m and diameter of 2 to 3 m.

The fill material are usually made of sand, natural gravel, quarried or recycled stone, etc. The specifications of the employed material should be:

- Granular material with up to 15% fines contents
- Clay content less than 2%
- Maximum particle size: 200 mm
- Non-plastic, non-collapsible and free from organic matters

The purpose of DR is to increase bearing capacity, reduce total and differential post-construction settlements and minimize liquefaction potential. The created granular columns act as drains increasing the dissipation rate of excess pore pressure, hence accelerating the consolidation rate.

Characteristics of DR improved grounds can be estimated using one of the homogenization methods similar to SC or SaC. However, since a DR column is relatively shorter and thicker compared to a SC or SaC, many of complexities involved in slender reinforcing elements can be ignored (e.g., bulging, depth effect, soil-column interface, etc.). Hence a simple homogenization would be enough for DR improvement. In practice and many research works (e.g., Hamidi et al. 2010, Ng and Tan 2015, Kanty et al. 2015) properties of the composite material (natural soil plus DR columns) is assumed to be weighted average of that parameter inside the column and in the natural soil with respect to the replacement ratio as presented in Equation 1 for modulus of elasticity.

$$E_{eq} = a \times E_c + (1 - a) \times E_s \qquad (1)$$

Where E_{eq}, E_c, E_s and a are moduli of elasticity of composite material, column, soil and the replacement ratio (the ratio of the DR column area to the area of the ground per DR column).

3 VIBRO DYNAMIC REPLACEMENT

As mentioned earlier the maximum depth DR columns can reach is around 6 m (subject to the soil condition). In order to improve (or replace) soft layers below this depth we may need to execute SaC, although SaC are typically softer than DR columns. In this research work these two techniques are combined to create deeper and at the same time denser columns.

In this technique, here named “Vibro Dynamic Replacement” (VDR), first, two or three sand columns are to be executed. In the trial column of this research three 0.7-m columns were executed 1.2 m apart as presented in Figure 2.

Next, by releasing a DR pounder several times on top of the SaCs a crater should be formed. In the case study of this work the depth of crater was 2.5 m per pass and 5 m cumulatively. In Figure 2 the dashed and solid circles represent the DR crater and the SaCs, respectively.

After each DR pass the open crater was backfilled with the same sand used in SaC. This imposed deformation not only pushes the SaCs downwards, but also causes large lateral bulging in them which densifies both the columns and the surrounding natural soil. The soil in between and around the SaCs receives different levels of densification depending on its initial condition, depth, water table, geometry, etc.

SaCs can even reach together and form a single column as demonstrated in Figure 3. In such cases the natural soil may be mixed with the inserted sand.

4 QUALITY CONTROL

Figure 3 schematically illustrates the VDR execution procedure. In this methos sand and DR columns are almost merged and form a “VDR column”. In order to map the extent of VDR column and to study its homogeneity more than one penetration tests (here CPT) is needed.

For the trial VDR column executed in this research twelve CPTs were carried out at different locations and steps to determine the size, depth and effectiveness of the applied VDR. In Figure 2 triangles show the CPT points.

- On the virgin ground
- After execution of SaCs on points 1 to 4

- After execution of DR on points 1 to 7

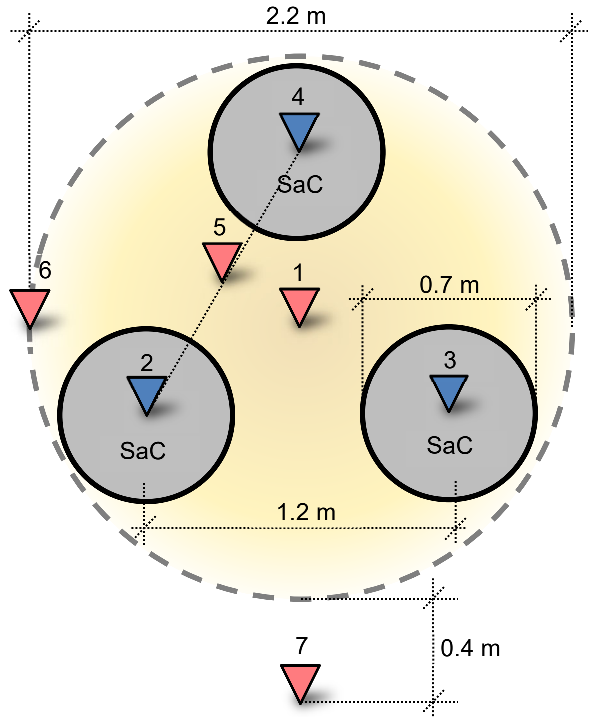

Figure 2. Geometry of the VDR trial and the CPTs

Same concept of homogenization as explained in section 2.2 can also be employed to estimate the behaviour of VDR treated ground by taking weighted average of CPT results using Equation (2).

$$q_{c,eq} = a \times q_{c,c} + (1-a) \times q_{c,s} \tag{2}$$

$q_{c,c}$ and $q_{c,s}$ are CPT cone resistance in the column and soil, respectively, and $q_{c,eq}$ is the equivalent cone resistance of the treated ground. In this work $q_{c,c}$ itself was weighted average of CPT results at different locations of the column with respect to the area they represent.

To evaluate the VDR performance, other types of quality control assessments can also be carried out such as SPT, shear vane, pressure-meter, static loading (in small or large scales) or field density tests.

5 RESULTS AND DISCUSSIONS

In this section CPT results conducted during and after installation of the trial VDR column are presented and the efficiency of the VDR is discussed.

The natural subsoil profile of the ground consisted of roughly 4 m dense to very dense sand followed by around 2.5 m very soft clayey soil. The bedrock appeared at depth of ~8 m. Figure 4 shows the q_c values of the natural ground. The problematic layer which necessitates ground improvement is around depths of 4 to 7 m. in this paper CPT results of the untreated ground are denoted by PR.

To execute the trial VDR column, as mentioned earlier, first three SaCs were installed. Prior to the DR phase, four CPTs were conducted; one at the centroid of the columns and three at the center of the SaCs. These CPTs are denoted by PO-SaC-1 to -4.

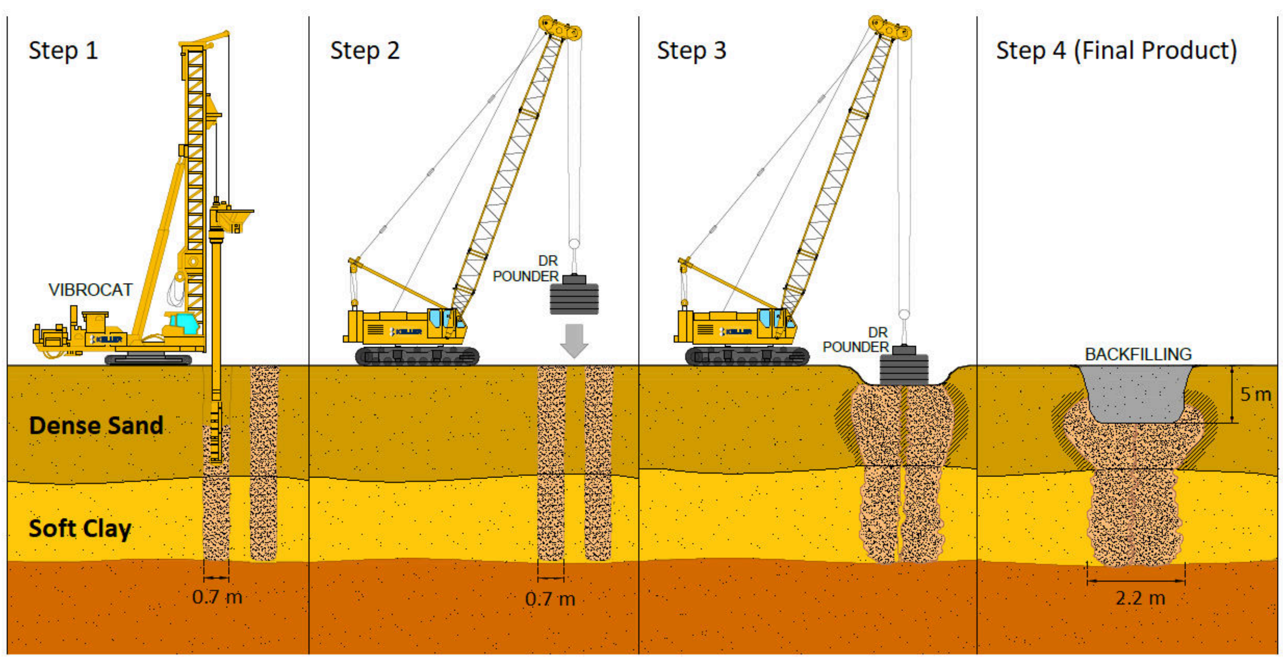

Figure 3. Schematic sequence of VDR execution (not to scale). Only two SaCs are shown in the cross-sectional view. Step 1: SaC installation, steps 2 and 3 : stagewise execution of DR column and backfilling, step 4: final product

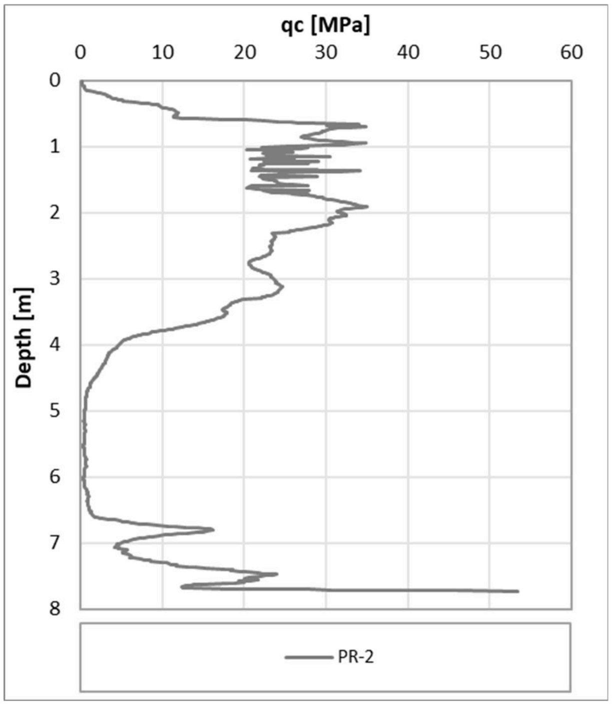

Figure 4. q_c values of natural ground (PR-2)

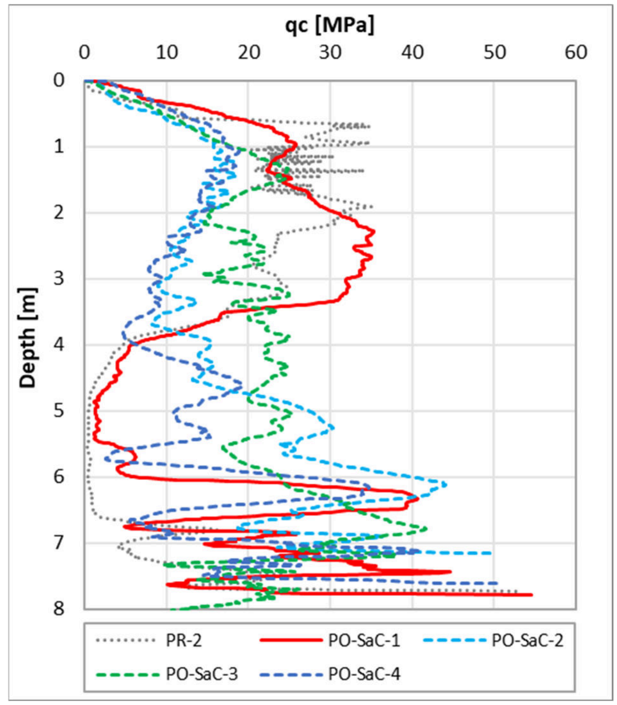

Figure 5. q_c values of natural ground and after SaC but before DR (PO-SaC)

In Figure 5 PO-SaC CPTs are plotted and compared with the PR-2 results. As it can be seen, q_c values of PO-SaC-1 are very similar to those of PR-2 which implies that SaCs have not met at the centroid point; whereas, the CPTs carried out inside the SaCs (i.e., PO-SaC-2 to -3) were in the same range over the full depth of the columns.

After completion of the SaC and DR phases, seven CPTs were performed, one at the centroid, three inside the columns and three at different locations but outside SaCs (as shown in Figure 2) denoted by PO-DR-1 to -7.

Figure 6 shows the CPT results at the centroid point and inside the SaCs (PO-DR-1 to -4). After the DR phase SaCs are compacted and demonstrated significantly higher resistance against CPT penetration. The noteworthy outcome of this graph is the growth observed in the q_c values of PO-DR-1 (centroid) compared to that in Figure 5. This confirms that the SaCs have bulged and densified the natural soil in between or even have collided at the mid point between three columns.

Figure 7 also presents PO-DR results, but for CPTs executed outside original locations of SaCs (PO-DR-5 to -7). This graph confirms that PO-DR-1, -5 and -6 are reasonably similar, hence we can conclude that the SaC bulging and/or densification of the natural ground has reached to those locations.

Although due to the DC effect of DR some improvement was observed in the sandy layers of PO-DR-7, no meaningful improvement was occurred in the clayey layer; thus, point 6 should be considered as boundary of the VDR column. That means the diameter of VDR column for the studied case was 2.2 m.

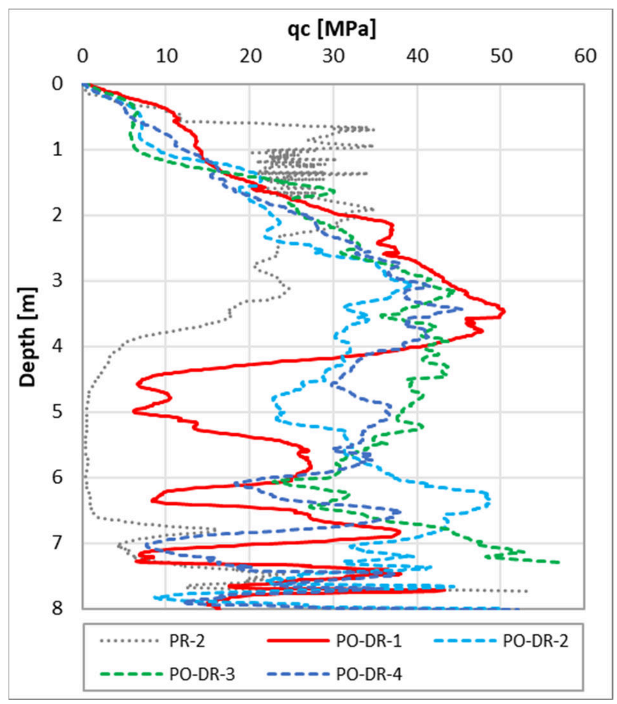

Figure 6. q_c values of natural ground and after completion of DR (PO-DR) – part 1

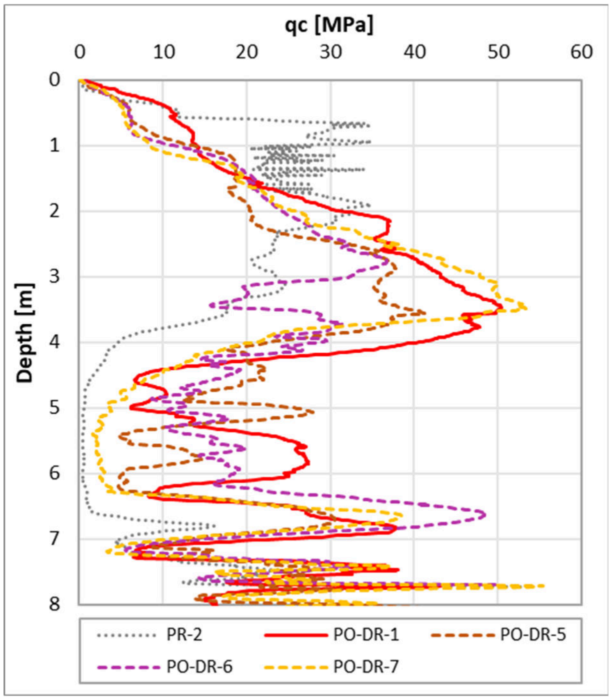

Figure 7. q_c values of natural ground and after completion of DR (PO-DR) – part 2

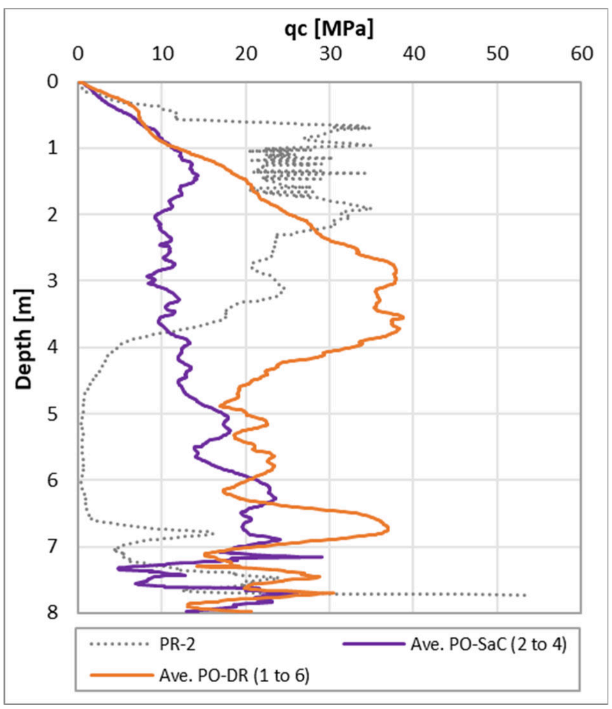

Figure 8. Average q_c values of PO-SaC and PO-DR conditions are compared with natural ground

Average q_c values of PO-SaC and PO-DR conditions are plotted in Figure 8 and compared with CPT result of unimproved ground (PR). The PO-SaC curve averages q_c results of points 2, 3 and 4 (inside SaCs only), whereas, PO-DR curve is the weighted average of PO-DR-1 to -6 (with respect to the covered area). As this graph demonstrates, average values of PO-SaC and PO-DR CPTs are in the same range over depths of 4.5 to 7 m where soft clay exists. This implies that the sand columns has bulged and created a single column (as schematically shown in Figure 3). The average PO-DR values can be used as the $q_{c,c}$ in Equation (2) to estimate the equivalent q_c of the VDR-treated ground ($q_{c,eq}$).

6 CONCLUSIONS AND RECOMMENDATIONS

In this paper conventional vibro sand column (SaC) and dynamic replacement (DR) techniques were briefly described. Neither SaC nor DR can improve deep soft layers, as DR influence depth is limited to 3-6 m and modulus of elasticity of SaC is not high enough for many applications. Hence, in this research by combining SaC and DR a new technique, named vibro dynamic replacement (VDR), is introduced and tested.

As confirmed by CPT tests, VDR columns can be executed in a same diameter and stiffness of DR columns, but to depths beyond reach of typical DR technique.

Regarding the heterogeneity of the VDR columns, to study their quality ($q_{c,c}$ in Equation (2)) at least two CPTs should be conducted inside the column: (1) in one of the SaCs and (2) at the centroid of SaCs. As shown in Figure 7, three CPTs carried out at different locations (within VDR footprint, but not inside SaCs) show reasonably similar results.

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