Improvement of soft soils with stone pillars built using dynamic replacement – A case history

Marc Lauzon, MScA, ing, P.Eng.
Géopac Tech inc., Boucherville, Québec, Canada

ABSTRACT
This paper describes the ground improvement works completed for the construction of 6 vegetable oil tanks that had to be built on loose fill materials underlain by a layer of soft organic clay. To ensure the stability and the proper behavior of the structures, a ground reinforcement system composed of mix of large stone columns, also called stone pillars, built using the dynamic replacement ground improvement technique and dynamic compaction, was designed and realized on a site near Trois-Rivières, QC.

RÉSUMÉ
Cet article traite de la construction de 6 réservoirs d'huile végétale devant être construits sur des sols de remblai déversés dans l'eau et reposant sur une couche d'argile organique de consistance molle. Afin d'assurer la stabilité et le bon comprotement des fondations des réservoirs, un sytème de renforcement de sols au moyen d'une combinaison de piliers de pierre, aussi appelés plots ballastés, construits à l'aide de la méthode de remplacement dynamique, et de compactage dynamique a été conçu et réalisé pour un terrain situé à proximité de Trois-Rivières, QC.

1 INTRODUCTION

Tank farms construction on poor soil conditions poses difficulties related to the typically large footprints of the structures, the high loads when high compressible soils are encountered. Many solutions can be regarded for this type of soil conditions including Controlled Modulus Columns (CMC) (Lauzon et al., 2009), stone columns and dynamic compaction. This paper describes a project where large stone columns, or stone pillars, were installed, using the dynamic replacement method, to reinforce the supporting soils of large steel tanks.

2 PROJECT DESCRIPTION

The project includes the construction of 6 steel tanks, 4 of them are 22.4 m diameter and the 2 others are 14.6 m and 11.6 metres in diameter. The project is located in the port of Bécancour, which is on the St-Lawrence River near Trois-Rivières in Québec (Figure 1). The site itself covers an area of 8100 square metres.

Tanks are built to store vegetable oils produced or used at a nearby vegetable oil refinery.

This part of the port facilities were built by backfilling into the St-Lawrence River. This operation left the site with an important layer of loose fill covering an organic silty clay layer which used to form the bed of the river.

3 SOIL CONDITIONS

The geotechnical investigation conducted on the site. included 8 boreholes with soil sampling and Standard Penetration Tests (SPT) drilled to a maximum depth of 10.0 metres. At the time the geotechnical study was conducted, the surface of the site was paved. The roadway foundation was composed of about 100 mm of asphalt, 300 mm of 20-0 mm crushed stone and 300 mm of sand with traces of silt. Under this road structure, approximately 3 metres of fill were identified in the boreholes.

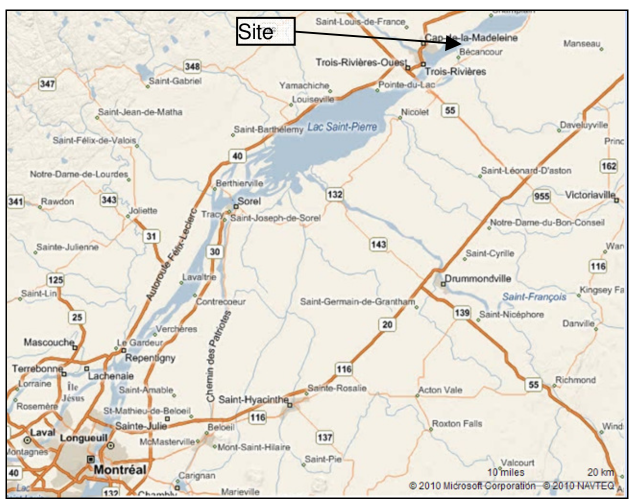

Figure 1. Site Location (Map from Bing Maps)

The fill materials are composed mostly of silty sand with some gravel and traces of clay. This material is compact down to a depth of 1.4 metres, but becomes very loose to loose between depths of 1.4 and 3.6 metres.

The fill materials overlay a 300 to 600 mm thick layer of organic silty clay. This material is very soft with SPT N values of 1 blow for 0.3 metre or less. The organic silty clay rests on a 3 metre thick layer of dense till overlaying bedrock found at a depth of about 7 metres.

The depth of the groundwater was established at about 2.0 metres below the original ground level.

4 THE DYNAMIC REPLACEMENT METHOD

The dynamic replacement method is used to build stone columns of about 2.4 metres in diameter. Due to their diameter significantly larger than what is built with vibro-replacement stone columns, this type of stone columns is usually identified as stone pillars. The process uses the same equipment used to perform dynamic compaction: a lifting crane and a large steel tamper.

Figure 2 summarizes the main steps used to build the stone pillars. The first step is to excavate a part of the soil in place and replace it with coarse granular material, like a crushed stone or gravel. During the second step, the freshly placed crushed stone is pounded repeatedly with the steel tamper. This operation literally pushes the crushed stone into the soil. The step 2 is repeated until the volume of stone pushed into the soil reached the design volume. Sometimes, the soils are not excavated at step 1 and the crushed stone is put into the crater produced by the pounding of the soil with the tamper.

Depending on the weight of the tamper and the number of drops, it is possible to push the crushed stone to depths in the range of 4 to 6 metres. Considering the tampers are typically 1.2 to 2.1 metres in diameter, the stone pillars built with this process are about 1.5 to 2.5 metres in diameter.

This technique was successfully used for the densification of the foundations soils for the cement silo of Lafarge in Exshaw, Alberta (Dumas et al 1993). The Dynamic Compaction method is described in Ménard (1974), Ménard and Broise (1975) and the Canadian Foundation Engineering Manual (2006).

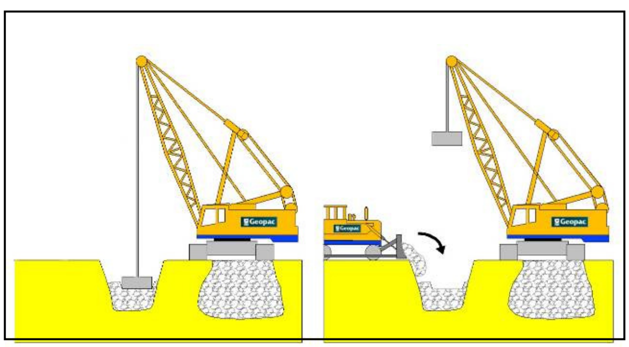

Figure 2. Main steps to build stone pillars using dynamic replacement method.

5 DESIGN PROCESS

The tanks are going to impose a load of about 150 kPa on the ground surface. Considering the diameter of the tank and the relative shallow depth of the compressible layers, stresses in the ground is about the same value. The loose backfill could be improved with dynamic compaction, but not the organic clay, which is too soft to be compacted and could not be left in place untreated.

Consequently ground improvement with inclusions was considered the best approach to reinforce the foundation soils and reduce potential settlements in this case. The possibility to use Vibro stone columns or Controlled modulus columns (CMC) was studied. CMC were used for oil tanks in the port of Québec City, where it was found to be the most economical approach (Lauzon et al, 2009). In these particular soil conditions, CMC were found to be more costly than the Dynamic Replacement approach. Vibro replacement stone columns could have been an option but significant ground improvement of the loose fill would not be possible with this method due to the high silt content of the fill material in place. On this perspective, Dynamic Replacement was considered the most efficient approach since this process permits to put in place a stone column in the organic clay layer and at the same time compact the loose fill layer found above it.

Considering the organic clay had SPT N values in the range of about 1 blow per 0.3 metre, it was estimated that its shear strength would be in the range of 10 kPa. With such low shear strength values, the organic clay was considered normally consolidated. A settlement analysis using a deformation modulus of 0.7 MPa indicated that settlement in the range of about 150 mm could be foreseen in that layer alone. To estimate de replacement ratio required to reduce the settlement, equation 1 (Mitchell, 1981), which is based on the unit cell model, was used.

$$\beta = 1/(1+(n-1)*a_s)) \quad [1]$$

where β is the settlement reduction factor, n is the ratio between the deformation modulus of the stone column and the surrounding soil. a_s is the replacement ratio, i.e. the ratio of the area of the stone column to the area of the unit cell.

Based on these analyses, it was estimated that a replacement ratio of 17% or more could reduce the settlement under the tank load in the 15 to 25 mm range.

The safety factor against failure was also checked. Pressure on the stone pillars was estimated using the unit cell approach. For the case of an elastic material, equation 2 (Mitchell, 1981) is used to compute the stress on the pillar.

$$\mu = n/(1+(n-1)*a_s)) \quad [2]$$

where μ is the stress amplification factor. The stress on the column is the average stress at this level multiplied by μ. With the design parameters, the stress on the pillar under a ground pressure of 150 kPa was estimated to 825 kPa.

The maximum load that a stone column can support without failure can be estimated with the pressuremeter limit pressure using equation 3 (Briaud, 1992)

$$\sigma_v = K_p*(p_L-u) \quad [3]$$

where K_p is the coefficient of passive earth pressure, p_L is the pressuremeter limit pressure and u is the pore pressure.

Considering the ratio between the length of the column in the soft soil and its diameter, the stone pillar can support a maximum load of about 3000 kPa. A safety factor of 3 is used to be sure the service load does not exceed the ultimate load, which limits the allowable load to 1000 kPa.

To obtain a replacement ratio of 17%, it is possible to install 2.4 metre diameter columns on a triangular spacing of 5.5 metres. Considering the circular shape of the tank, a triangular grid is more appropriate than a square grid as it fits better inside a circle. The typical disposition of the stone pillars under a tank is shown on figure 3.

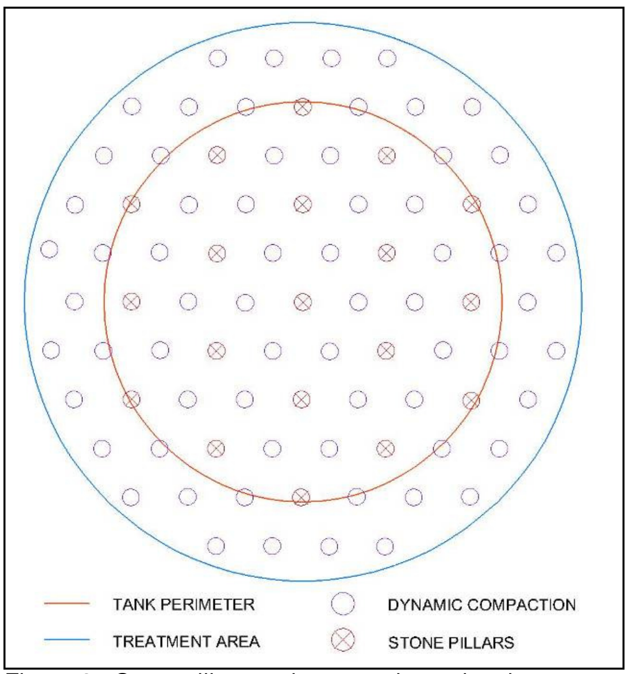

Figure 3. Stone pillars and compaction points layout.

6 GROUND IMPROVEMENT WORK

Ground improvement work started with the excavation and disposal of the asphalt layer. The first layer of crushed stone below the asphalt layer was excavated from the site and stockpiled for its use for the construction of the stone pillars. The sand layer found under the crushed stone was left in place to be used as a working platform.

At the location of each stone pillar, the sand layer was set aside and the remaining soils were excavated to a depth ranging from 2.1 to 2.7 metres. These soils were hauled off site. The excavation dimensions were about by 2.5 x 2.5 metres (figure 4).

Figure 4. Excavating for a pillar.

Once the excavation was completed, the cavity was filled with the previously stock piled crushed stone.

Each pillars location was then pounded with a 14 tonnes steel tamper using a specially adapted dynamic compaction crane capable of lifting and dropping the weight to a height of 18 metres (figure 5).

Once the stone pillars were put in place, the area between them was compacted using the same equipment with the technique of dynamic compaction. The compaction area extended the area of each tank by 3 metres to ensure a confinement effect for the soils underneath the tank. A crater spacing of 3.2 metres was used and the number of drops per points varied between 2 and 7. Finally, the complete surface of the site was compacted with an ironing square plate measuring 2.43 metres in width. This plate weighs 10 tonnes and is dropped from a height of 10 metres. This compaction pass ensures that the loose soils used to backfill the craters and the soils between the craters are compacted.

Figure 5. Pounding a stone pillar

7 QUALITY CONTROL RESULTS

To prevent any reclamation from neighbours, the vibrations produced by the compaction operations were monitored during the work. Results indicated that the peek particle velocity at nearby structures were below safety standards. The closest structure was a concrete support for transportation ducts located at a distance of about 40 metres from the closest compaction area. Vibrations of 3.2 mm/s were measured at this structure, well below the usual 50 mm/s safety level used for structures (Wiss, 1981). Peak particles velocities measured as a function of the distance from the impact point are shown on figure 6.

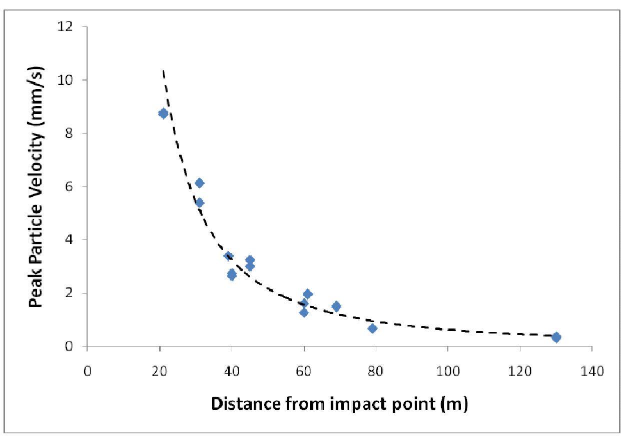

Figure 6. Vibration monitoring results

A survey of the surface elevation, before and after the soil treatment was used to estimate the degree of densification obtained. Since a part of the soils in place was excavated and disposed off site, and crushed stone was added in the excavations, this evaluation also accounted for the net volume of soil extracted from the site. Once taken into account, the survey indicated that the surface had settled about 210 mm, indicating a soil densification of about 6%.

To evaluate the success of the stone pillars installation, pressuremeter tests were performed in 8 boreholes. Two of those boreholes were performed at the center of a stone pillar and the remaining 6 were performed at the center of the compaction grid. The boreholes were put down to a depth varying between 4.5 and 6.0 metres, with pressuremeter tests performed at an interval of 1.5 metres.

Testing was performed with a Menard pressuremeter, model G-Am, and an A-size probe installed inside a slotted tube driven to the test level. Test data were compiled to obtain the pressuremeter modulus and the limit pressure for each test. Average pressuremeter modulus for tests performed on the pillar and in between the dynamic compaction points are presented on the chart of figure 7.

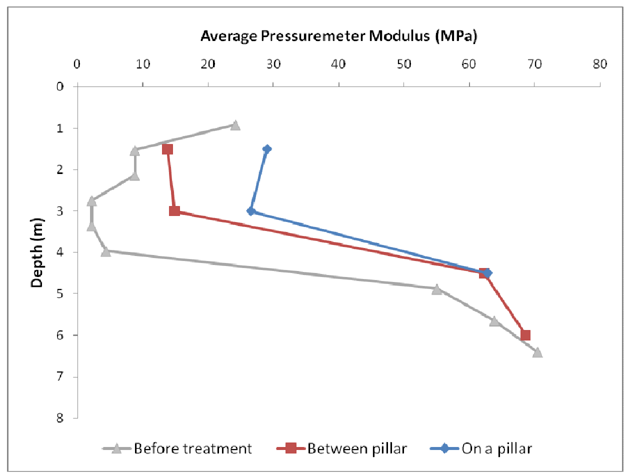

Figure 7. Comparison of average pressuremeter modulus

Figure 8 shows the average results for the limit pressures measured at those same locations. For comparison, estimated values of the pressuremeter modulus and the limit pressure are also indicated on those 2 charts. These values are based on correlations between SPT N values and pressuremeter parameters (Briaud, 1992).

The pressuremeter test results were used to estimate the settlement under the service load and the allowable bearing capacity. To perform those calculations and take into account the presence of the stone pillars, the properties of the composite soils were established using equation 4 (Mitchell, 1981)

$$E_{eq} = E_{col} * a_s + E_{soil} * (1 - a_s) \qquad [4]$$

where E_{eq} is the modulus of the composite soil, E_{col} is the modulus of the stone column, E_{soil} is the modulus of the soil and a_s is the replacement ratio.

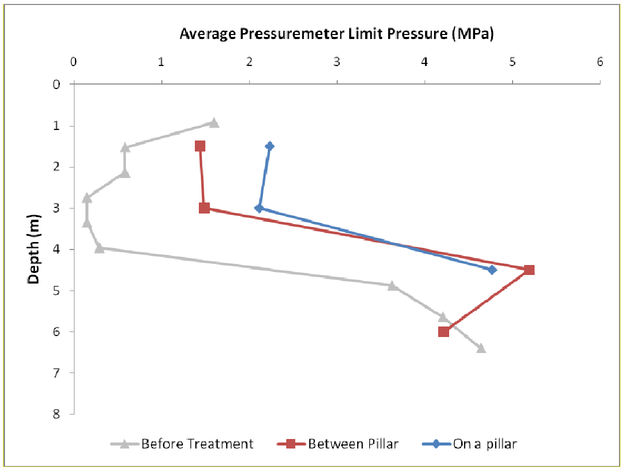

Figure 8. Comparison of average limit pressures

Bearing capacity and expected settlement were computed using pressuremeter modulus and limit pressures of the composite soil with the pressuremeter method (Menard, 1965). The results indicated a bearing capacity of 450 kPa could be used and expected settlement under a load of 150 kPa was about 10 mm.

8 CONCLUSIONS

For this project, the installation of stone pillars was found to be an efficient ground improvement method, permitting to limit settlement to acceptable values and reinforcing the ground to support the loads imposed by the vegetable oil tank.

Pressuremeter testing in the pillars and between them indicated significant ground improvement in the loose fill and also in terms of composite material.

ACKNOWLEDGEMENTS

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