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Ground improvement by vibroreplacement
Renforcement du sous-sol par vibro-substitution

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ABSTRACT

This article describes the design, construction, quality control and performance of vibroreplacement stone columns conducted for an off-shore platform construction yard project in Baku, Azerbaijan. The project consists of modernization and strengthening of quayside works, where the petroleum platforms are constructed on land near seaside of Caspian Sea. The subsoil conditions consist of 8 m thick loose to medium dense fine sand with gravel underlain by 7 m thick sandy clay. Below this layer a stiff to hard clay layer extends down to 40 m depth. The groundwater table was located at 1.5 m depth. Due to significant pressure transmitted and loose subsoil conditions, a ground improvement by vibroreplacement technique is implemented to increase the bearing capacity and liquefaction mitigation. The geotechnical design consisted of 800 mm nominal diameter and 8 m long stone columns. A comprehensive quality control program was pursued in the project. The plate load tests (preliminary and post improvement test) in accordance with ASTM D 1194 were conducted, and results were presented and discussed.

RÉSUMÉ

Le texte décrit la conception, la construction, le contrôle de qualité et la performance des colonnes ballastées mises en œuvre par vibro-substitution pour le renforcement du sous-sol d’un chantier de construction pour la plate forme en mer à Baku en Azerbaïdjan. Le projet consistait en la modernisation et le renforcement du quai au bord de la Mer Caspienne où les pièces de la plate forme en mer sont construites et assemblées. Le sous sol consiste de sable fin avec du gravier d’une épaisseur de 1 m, et de compacité variant de lâche à moyenne. En dessous de cette couche se trouve de l’argile limoneuse d’une épaisseur de 8 m. Le substratum consiste de l’argile de consistance raide à très dure jusqu’à une profondeur de 40 m. La nappe phréatique se trouve à 1,5 m de profondeur. Les propriétés des sols ont été améliorées pour accroître leur portance et diminuer le risque de liquéfaction par des colonnes ballastées mise en œuvre par vibro-substitution. Le réseau consiste de colonnes ballastées de 800 mm de diamètre et de 8 m de longueur mise en place. Un programme complet a été adopté pour la vérification de la qualité du projet. Des essais de chargement statique à la plaque et des essais de pénétration statique ont été effectués. Les résultats de ces essais sont présentés et discutés.

1 INTRODUCTION

This paper describes recently completed ground improvement works at ATA Yard (a consortium of AMEC-Tekfen-Azfen) in Baku, Azerbaijan, which is part of the most challenging project of the 21st Century at the Caspian Sea; namely Azeri Project, which is a part of the pipeline construction between Caspian Sea to Mediterranean Sea.

ATA Yard, which has been under operation since 2004, an upgrade project consists of modernization and strengthening of quayside works, where the C&WP (compression and water injection) platform was constructed on land near seaside of Caspian Sea. Construction of platforms was performed on concrete skid-ways, which were strengthening by driven tubular pipe piles. Under the load-out frame area, the platforms were transported onto skid-ways by heavy duty cranes after construction was completed. During this process extremely high loads were to be applied by the heavy cranes to an area outside skid-ways. Therefore ground improvement by stone column method was implemented to increase the bearing capacity and liquefaction mitigation under the load out frame area. A total of 122,000 m stone columns with a length of 8 m were installed by using vibroreplacement technique (Fig. 1).

2 SUBSOIL CONDITIONS AND SEISMICITY

Detailed soil investigations were carried out at the proposed site, in two different campaigns, the first one in 2000 and the second in 2001. Subsoil investigation included advancing 12 boreholes to depths of 40 m
and conducting standard penetration tests and sampling. 6 Cone penetration tests were also carried out to a maximum depth of 15 m at locations adjacent to boreholes.

The results of soil investigation indicated that the subsurface lithology at the site is capped by 1.50 m thick made ground consisting of sand with gravel and crushed stone. The fill is underlain by a stratum of loose to medium dense sand that extends down to 8 m depth. Below a soft sandy clay layer extend to a depth of 15 m, and beneath this layer a hard clay layer extends for the remainder of the depth investigated. Groundwater table is encountered at a depth of 1.50 m below ground level. Typical soil profile and average corrected SPT N values performed as a part of design soil investigation are given in Fig. 2.

Based on the results of 145 no’s of sieve analysis tests performed on soil samples taken from various depths, soil particle size distribution vs. depth correlation is studied and presented in Fig. 3.

The project area is located in high seismic hazard zone with a peak ground acceleration of $a_{\text{max}} = 0.50$ g with 10% probability of expedience in 50 years. Liquefaction potential of loose to medium dense sand is a significant issue. Liquefaction analysis, based on SPT N-values indicates that sand is highly liquefiable.

3 GEOTECHNICAL DESIGN

There are two types of crawler cranes to be operated at site. At the “Load out frame area” a special type Demag CC 400 crawler crane will be operated. Operating weight of Demag CC 400 crawler crane is 15,000 kN and the maximum stress to be imposed to the ground is specified as 600 KPa.

At the “General Assembly & Storage Site” a 1,000 kN capacity crawler crane will be operated and the maximum stress to be imposed to the ground is specified as 200 KPa. As a result of bearing capacity, settlement and liquefaction analysis performed for each loading condition, it was concluded that two different types of soil improvement scheme to be implemented depending on the stress applied to the ground in order to improve soil characteristics and to eliminate the risk of liquefaction.

The use of 2 layers of geogrids produced from high strength drawn polyester with a tensile strength of 80 KN/m was recommended at the “General Assembly Area” where the transmitted loads are comparatively low. (Güler 2002) For other areas soil improvement with stone column is considered an economical and reliable solution so as to increase soil bearing capacity.
Table 1. Engineering Properties of Soil Layers

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>0-8</th>
<th>8-15</th>
<th>15-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of internal friction ((\phi))</td>
<td>32</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Cohesion (c) kPa</td>
<td>5</td>
<td>20</td>
<td>250</td>
</tr>
<tr>
<td>Bulk density ((\gamma_b)) kN/m(^3)</td>
<td>18.5</td>
<td>19.5</td>
<td>20</td>
</tr>
<tr>
<td>Mod. of Compressibility (E) MPa</td>
<td>12.5</td>
<td>6</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 2. Predicted Settlements pre and post improvement

<table>
<thead>
<tr>
<th>Calculation Method</th>
<th>Pre Improvement</th>
<th>Post Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaxis</td>
<td>111 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>Priebe</td>
<td>45.4 mm</td>
<td>25.8 mm</td>
</tr>
</tbody>
</table>

and to control settlement at the area of crawler crane track. The serviceability criteria of the equipment and structures for both normal and earthquake conditions are considered. The following soil parameters were adopted in the geotechnical design.

The design of ground improvement was based on finite element softwares; Plaxis 8.2. and Priebe (1995). Predicted settlements before and after stone column installation are summarized in Table 2. After analysis with different column lengths and grids, the application parameters of stone column works are decided.

4 STONE COLUMN INSTALLATION

The construction works on site was commenced in March 2003 and the ground improvement works were completed in 90 days. The total soil improvement work consists of 122,000 m of 800-1000 mm diameter stone columns with a length of 8 m. During the installations, four no. of vibroflotation sets consisting of 100 kW vibroflot having a maximum frequency of 3000 rpm (50 Hz) with a corresponding maximum centrifugal force of 400 kN were used. The top feed wet method was applied.

5 PRELIMINARY TESTS

Prior to the commencement of the improvement works, a trial test area of 25 m \(\times\) 25 m was prepared on the north side of the site as shown in Fig. 1. Five Cone Penetration Tests (CPT) were carried out prior to the commencement of works. The trial test area was improved by stone columns with vibroreplacement method. After the improvement, five additional CPT’s were carried out four days upon completion of stone columns. The modified cone resistance, \(q_c\) calculated by a relationship proposed by Seed et al. (1983) and \(D_R\) curves calculated by a relationship proposed by Jamiolkowski (1985) along the depth are shown in Fig. 4.

Table 3 shows average \(q_c\) and \(D_R\) before and after improvement works. The results show that the loose soil layers with an initial \(D_R\) of 20-65% were successfully improved to the specified minimum relative density of 75%.

In addition to CPT’s, three Plate Load Tests (PLT) were performed on a 840 mm diameter loading plate and to a maximum test load of 500 kN (applied pressure equals to 900 kPa) in accordance with ASTM D 1194 on an area improved by stone columns. The results show that maximum settlement values were in the range of 7.5-10.7 mm and residual settlement values were in the range of 4.7-6.9 mm under test load of 900 kPa.

Since results of CPT’s and PLT’s performed after the treatment were in good conformity with the design criteria, the trial column installation with an average compaction energy of \(~1100\) KJoule/m\(^3\) was selected as the operational parameter.

6 QUALITY CONTROL

During stone column installations, the following quality control tests were performed in accordance with strict quality control (QA) program pursued in the project. Among the most important quality control measures during the installation of stone columns was to monitor the recorded compaction pressure in bars
and to measure the amount of stone added to each column. A sophisticated computerized data collection & evaluation system consisting of a data collector and a number of special sensors, mounted on the vibroflotation equipment was used so as to control, monitor and optimize the stone column production continuously. The computerised system produces a diagrammatic print-out for each completed stone column.

The PLT’s were implemented as the primary quality control test method. Each plate load test was carried out for every 2,500 m² of improved area. A total of twenty plate load tests were carried out and the tests were evaluated with the following acceptance criteria:

- Settlement < 10 mm,
- $E_{v2}/E_{v1} < 2.2$
- $E_{v2} > 60$ MPa.

PLTs were carried out in two cycles. In the first cycle, design pressure of 600 kPa was applied and in the second cycle verification pressure of 900 kPa ($1.5 \times 600$ kPa) was applied in equal increments. Settlement values recorded under 600 kPa were lie within the range of 1.8-8.6 mm. Modulus of deformation values ($E_{v1}$) calculated for the first cycle were lie within the range of 88-468 MPa and average value of 250 MPa was obtained. Whereas settlement values recorded under 900 kPa were generally lie within the range of 4.5-10 mm. Modulus of deformation values ($E_{v2}$) calculated for second cycle were lie within range of 126-265 MPa and an average value of 175 MPa was obtained.

The average modulus of deformation ($E_v$) value was calculated by using the following empirical relationship for sandy soils:

$$E_v = 3 \times q_c$$  \hspace{1cm} (1)

where $q_c$ was obtained from CPT’s performed after the improvement. The results obtained for the top layers were generally in good conformity with the values calculated from PLT’s. Based on the results of PLT’s, it was concluded that the ground improvement was successfully implemented. The results were in good conformity with the values obtained in literature for similar soil conditions.

7 CONCLUSIONS

Ground improvement using vibroreplacement technique has been employed effectively to improve compressibility characteristics soil layers and to eliminate the risk of liquefaction. The design and installation of 122,000 m stone columns at ATA Yard were completed successfully both from technical and time schedule point of view.

From technical point of view, stone columns will safely provide required bearing capacity and control excessive settlements as verified by in situ tests. In addition to increased density and drainage characteristics of improved subsoil, stone columns will mitigate occurrence of liquefaction.

The data obtained from post construction quality control tests have clearly demonstrated the effectiveness of the employed improvement technique. Relative density (D_r) derived from CPT’s performed after the completion of stone columns varies within the range of 75-95%. The subgrade reaction modulus $k_s$ was calculated within the range of 150-500 MN/m³. Average of modulus of deformation, $E_v$ was calculated as 212 MPa. The calculated modulus values generally lie within the range specified in literature for similar soils.

REFERENCES