A CASE HISTORY of GROUND TREATMENT with JET GROUTING AGAINST LIQUEFACTION, FOR A CIGARETTE FACTORY in TURKEY

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Abstract

This case study reports the application of jet grouting as the ground treatment method for the construction of a cigarette factory in Tire Organized Industrial Zone located at the west of Turkey. Total treatment area covers approximately 20000 m² and designed to house a factory building, a two-storey administration building and a utilities building. The project is carried out according to international standards (mainly British) following quality control and quality assurance schemes.

The site situated within the Kucuk Menderes alluvial plain, 70 km south-east of the Aegean coastal city of Izmir and classified as being within the 1st Degree Earthquake Zone (greatest risk category). Stratigraphy of the site was shown to comprise uncontrolled fill overlying alluvial deposits, predominantly micaceous silt with interbedded sandy gravels and clays, overlying colluvial deposits, comprising stiff sandy clays, draped over the steeply dipping bedrock. Alluvial deposit thickness reaches a maximum of 12 m and the groundwater lies at a depth of 4.7 m, below the base of the fill.

The maximum design loading for individual factory columns was too large for shallow foundations and hence deep bored pile foundations are implemented for the factory building. However, the slab-on-grades of the factory building and some auxiliary buildings are supported only on jet grout columns. The liquefaction risk beneath all buildings is eliminated by systematic jet grouting design based on specific area ratio reaching down to colluvium layer. The jet grout columns are

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mainly constructed by double fluid method since single fluid method was insufficient in silt deposits to obtain the design diameter of 80 cm. The soils were improved by approximately 32000 m of jet grouting, to reduce liquefaction potential considering the high seismic activity of the region and to increase the bearing support for the slabs-on-grade for the main factory and for the shallow foundations.

An extensive testing programme consisting of coring, exhumation, piston-sampling for compression testing and full-scale load tests was performed for the quality control of jet grout column construction. A site specific detailed calibration survey of the jet grouting technique with various parameters was implemented at the beginning of the works. This paper describes the design, construction and performance of jet grouting application focusing on the results of quality control tests performed during the improvement works.

**Introduction**

A new cigarette factory is planned to be constructed in southwest of Turkey close to the coastal city of Izmir. Mott MacDonald Limited have been appointed to provide geotechnical consultancy, structural design and supervisory during construction.

The soils were improved with jet grouting method to increase the bearing support for shallow foundations and reduce liquefaction potential considering the high seismic activity of the region. Total soil improvement area covers an area of about 20000 m² and designed to include a main factory building, an administration office, and a utilities building to house water and oil tanks etc. A total quality control programme was performed during the soil improvement works. This case study describes the design, construction and performance of jet grouting works. Within the scope of this paper, first geotechnical modeling set by ground investigations and foundation engineering evaluations will be explained and then, the details and results of quality control/quality assurance tests performed during the treatment works are to be given for a better understanding of the improved ground characteristics.

**Site Description**

*Location and morphology.* The total factory site covers an area of approximately 120,000 m² situated within the Kucuk Menderes alluvial plain near Tire which is a small town 70 km southeast of Izmir (see Figure 1). The region is within the East-West trending Kucuk Menderes Basin, an extensional horst and graben system. Original site topography dipped gently towards the north-east, with small hills situated to the south-east and north of the site. A small river runs parallel to the site to the immediate east. Earthworks have taken place to allow a flat site elevation.

*Regional geology.* The geology of the area comprises alluvial deposits overlying interbedded metamorphosed bedrock. Localized geology specific to the site comprises steeply dipping interbedded Paleozoic metamorphic bedrock overlain by either Tertiary or Quaternary colluvial deposits and Quaternary alluvial deposits.
The alluvial deposits were formed by material transported and deposited by the Kucuk Menderes river and associated tributaries, and typically comprise silt with subordinate sand and clay. Alluvial cone thicknesses of up to 180 m have been recorded within the vicinity of Tire. Bedrock, in general, comprises interbedded gneiss, chloritic, mica and quartzite-schists and marble.

**Seismicity.** The Kucuk Menderes horst and graben system and associated extensional faults trend east to west. Secondary faulting is recorded trending north-east to south-west. The site is located within the 1st degree earthquake zone as classified by the Turkish Ministry of Public Works and Housing (MPH) and is situated within the greatest risk category classified in accordance with the Mercalli Scale. Total of 329 earthquakes ranging in magnitude between 4.2 and 7.0 on Richter scale were recorded within Izmir region and its vicinity between the years 1881 and 1986. Details of these earthquakes are presented with epicenters plotted in Figure 2. It is estimated that for a 50 year design life, there is a 10% chance of a magnitude 7.5 earthquake. The peak ground acceleration (PGA) in the horizontal direction is 0.4 g and vertical ground acceleration should be assumed to be 50% of horizontal ground acceleration.

**Planned facilities.** The main factory building is designed as wide span steel framed structure having dimensions of 70 mx200 m, with the emphasis being on open internal workspace. Other planned Phase 1 buildings include a two-storey administration office, a utilities building to house generators, water and oil tanks etc, and a reception gatehouse. Future phases of development are planned for
expansion of the main factory. Unfactored column loadings for the factory range between 400 kN to 1500 kN in the vertical direction, and 60 kN to 110 kN in the horizontal direction.

Subsoil Investigations and Soil Conditions

Ground investigation works were carried out in October 2000, comprising seven boreholes and 19 trial pits. Boreholes are carried out using wash-boring and rotary coring techniques to a maximum depth of 25 m. In-situ and laboratory based geotechnical testing has been undertaken and analyzed. All ground investigation fieldwork was carried out in accordance with BS5930 which is the British code of practice for site investigations.

Stratigraphy of the site was shown to comprise uncontrolled fill consisting of cobbles and boulders in a very sandy silt matrix overlying alluvial deposits, predominantly slightly cemented micaceous silt with interbedded sandy gravels and clays, overlying colluvial deposits/residual soil, comprising stiff sandy clays, draped over steeply dipping bedrock of weak micaceous schists and moderately strong crystalline schists. Alluvial deposits thickness increases towards the north-east reaching a maximum of approximately 12 m. Groundwater, measured at the end of the dry season, was shown to lie at a depth of 4.7 m below the base of the uncontrolled fill. However it was anticipated to rise during the winter period. Beneath the main buildings the profile can be summarized as shown in Table 1.

Based on particle size analysis, the alluvial silts are assumed to have more than 35% silt and clay, alluvial sands about 25% silt and clay and alluvial clays, more than 50% silt and clay. Plasticity index varies between 10% and 20%, and undrained strength is assumed to be 50 kN/m². Layout of soil investigation points...
also showing the contours of depth of colluvial deposits below ground level is given in Figure 3.

Table 1. Soil profile summary of the site

<table>
<thead>
<tr>
<th>Strata</th>
<th>Thickness (m)</th>
<th>Depth to base of layer</th>
<th>Main Soil Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled fill</td>
<td>0 to 1.5 m</td>
<td>0 to 1.5 m</td>
<td>Medium dense sandy SILT with cobbles and boulders</td>
</tr>
<tr>
<td>Alluvium</td>
<td>3 to 8 m</td>
<td>3 to 10 m</td>
<td>Loose sandy SILT interbedded with loose silty SAND and soft CLAY (micaceous)</td>
</tr>
<tr>
<td>Colluvium (residual soil)</td>
<td>2 to 5 m</td>
<td>7 to 14 m</td>
<td>Firm to stiff CLAY</td>
</tr>
<tr>
<td>Bedrock</td>
<td>N/A</td>
<td></td>
<td>Very weak fractured micaschist</td>
</tr>
</tbody>
</table>

Geotechnical Engineering Considerations

Shallow and deep foundations. Considering the construction layout, the founding strata for shallow foundations are uncontrolled fill and alluvial deposits of heterogeneous nature. Therefore allowable bearing pressures are controlled by total (<20 mm) and differential settlements and for pad or strip footings. An allowable bearing pressure of 100 kN/m² is adopted in the absence of any earthquake design considerations for the lower-bound proposed loadings.

For the upper-bound loadings for the main factory, and also for the utilities buildings, deep foundations socketed within competent rockhead (unconfined compressive strength >1 MPa) are suggested. Preliminary calculations based on SPT data and rock laboratory testing showed that for the maximum unfactored loading of 1500 kN, a single 90 cm diameter bored pile is capable of restricting vertical settlement to 20-25 mm.

Liquefaction. It is shown that during a design earthquake, the alluvial soils are likely to liquefy with a factor of safety of only 0.4 and the factor of safety value is expected to drop below 1.0 for an earthquake accelerations of about 0.17 g, based on the methodology outlined in the 1996 NCEER workshop proceedings. Below the north-east corner of the factory, post-liquefaction settlement of the order of 300 mm is anticipated, with horizontal displacements in excess of 500 mm.

Therefore soil improvement is proposed to minimize stiffness degradation within the alluvial deposits and to transfer loads to the underlying stiffer colluvial deposits during the design earthquake event considering both the shallow and deep foundations.

Soil improvement. Ground improvement options including dynamic compaction, preloading, vibro-stone columns, jet grout columns, deep soil mixing, excavation-replacement are evaluated and compared in terms of applicability, effectiveness considering the ground conditions and; cost and local availability of the related experience. Alluvium contains certain amount of mica making the sandy silt soil more compressible. Consequently ground improvement with jet grout columns is proposed for the subject site as the most appropriate soil improvement scheme.
Figure 3. Layout plan for the site showing contours of depth of colluvial deposits below ground level
leading to construction of more rigid columns. It is anticipated that the calculated displacements are to be less than 50% of the values when no improvement is done. In addition, jet grout improvement would result in a stiffer ground, increasing the natural frequency of the ground and therefore avoiding amplification effects for long period structures.

**Soil Improvement Application with Jet grouting**

The jet grouting is found to be the most feasible solution for mitigating the anticipated liquefaction hazard and for an improved bearing support for shallow foundations considering the locally available technologies and encountered ground conditions. The proposed ground treatment scheme involved reinforcement of alluvial soils by jet grout jet grout columns; together with a load transfer platform of well-graded compacted granular material and multiple layers of geogrid. The preliminary design assumed 80 cm column diameter and spacing at 2.1 m centers to assure an area replacement ratio of $A_r = 0.23$. In addition, it was required in the technical specification that the average unconfined compressive strength has to exceed 1 MPa (10 kg/cm$^2$) based on six separate tests and each single value has to be higher than 0.6 MPa (6 kg/cm$^2$) from any selected jet grout column. However, the design and technical specifications permitted calibration and verification of the jet grouting scheme prior to commencement, based on the preliminary trial testing.

**Preliminary trial testing.** Trial tests are realized in two different stages on non-working jet grout columns performed within a trial area. In the first stage, jet grouts are constructed using different jetting parameters and then exhumed to check the size and shape for determination of the final jetting parameters. In the second stage, the jet grouts are constructed with the chosen set of parameters and the quality is assured with additional testing. The trial tests are comprised of five loads tests to verify the ultimate capacity of the jet grout columns, exhumation of the columns down to 3 to 6 m below existing ground level for inspection of the diameter and, rotary coring (minimum 100 mm in diameter) of the columns for strength testing. Various socket lengths into the colluvium layer are adopted for the load tests while the “standard length column” is defined as the column penetrating at 0.5 m below the top of the colluvial layer. Therefore boreholes are also drilled to identify the alluvial-colluvial interface and to check the subsoil properties. Length of the jet grout columns chosen for load tests, varied according to the alluvium-colluvium interface depth and socket length within the colluvium layer. In addition, a grid of settlement/heave monitoring points is established over the trial area to monitor the relative movements.

Total of ten standard length jet grout columns are constructed using ten different jetting parameters i.e. three with Jet-1 (mono fluid) and seven with Jet-2 (double fluid) systems within the scope of trial testing. The parameters of the last four columns (namely C’, I’, O, P) are adjusted in order to refine the quality after inspecting the results for the first six columns (C to I). The variables for the jetting parameters include pressure, nozzle size, retrieval and rotation speed and cement dosage. First eight jet grout columns are exhumed (excavation and exposure of the column) down to 3.0 m depth and the remaining two (namely C’ and P) columns
which are believed to be the best representatives of Jet-1 and Jet-2 methods, are exhumed down to 6.0 m depth for the purpose of full inspection. At this stage, core samples of 93 mm diameter are taken using electrical hand coring machine from various levels of the exhumed columns. In addition full-length coring by conventional rotary rig using various core barrel types is realized. Table 2 lists the jetting parameters for each jet grout set.

Table 2. Summary of jet grouting parameters for column diameter of 80 cm

<table>
<thead>
<tr>
<th>Set / jg no</th>
<th>Jetting method</th>
<th>w/c (by weight)</th>
<th>cement dosage kg/m^3</th>
<th>pressure bar</th>
<th>retrieval speed cm/min</th>
<th>rotation speed rpm</th>
<th>nozzle diameter mm</th>
<th>pre-flush</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/C</td>
<td>Jet-2</td>
<td>1.0</td>
<td>300</td>
<td>400</td>
<td>67</td>
<td>20</td>
<td>2x2.5</td>
<td>No</td>
</tr>
<tr>
<td>2/E</td>
<td>Jet-2</td>
<td>1.2</td>
<td>300</td>
<td>450</td>
<td>91</td>
<td>20</td>
<td>2x3.0</td>
<td>No</td>
</tr>
<tr>
<td>3/F</td>
<td>Jet-1</td>
<td>1.0</td>
<td>300</td>
<td>500</td>
<td>48</td>
<td>20</td>
<td>2x2.0</td>
<td>No</td>
</tr>
<tr>
<td>4/G</td>
<td>Jet-1</td>
<td>1.0</td>
<td>350</td>
<td>500</td>
<td>50</td>
<td>20</td>
<td>2x2.2</td>
<td>No</td>
</tr>
<tr>
<td>5/H</td>
<td>Jet-2</td>
<td>1.0</td>
<td>325</td>
<td>400</td>
<td>63</td>
<td>20</td>
<td>2x2.5</td>
<td>No</td>
</tr>
<tr>
<td>6/I</td>
<td>Jet-2</td>
<td>1.0</td>
<td>350</td>
<td>400</td>
<td>56</td>
<td>20</td>
<td>2x2.5</td>
<td>Yes</td>
</tr>
<tr>
<td>1'/C'</td>
<td>Jet-2</td>
<td>1.0</td>
<td>300</td>
<td>400</td>
<td>67</td>
<td>50</td>
<td>2x2.5</td>
<td>Yes</td>
</tr>
<tr>
<td>6'/I'</td>
<td>Jet-2</td>
<td>1.0</td>
<td>350</td>
<td>400</td>
<td>56</td>
<td>50</td>
<td>2x2.2</td>
<td>Yes</td>
</tr>
<tr>
<td>7/O</td>
<td>Jet-2</td>
<td>1.5</td>
<td>300</td>
<td>350</td>
<td>45</td>
<td>50</td>
<td>2x2.5</td>
<td>Yes</td>
</tr>
<tr>
<td>8/P</td>
<td>Jet-1</td>
<td>1.5</td>
<td>250</td>
<td>550</td>
<td>43</td>
<td>50</td>
<td>2x2.0</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Results of the trial testing prior to commencement of ground improvement. Upon completion of the first six trial zone jet grouting, columns are exhumed for visual inspection. It is observed that columns formed by double fluid (Jet-2) method exhibited a more heterogeneous nature without the uniform mixing of soil and grout material where no such problem is encountered in the columns formed by single fluid (Jet-1) method. On the other hand, the jet grouts columns constructed using method Jet-2 are determined to have diameters generally greater than the design requirement of 80 cm, reaching up to 110 cm throughout the exhumation depth of 3.0 m whereas the ones constructed with Jet-1 method are noted to have much smaller diameters being in the order of 55-60 cm. Poor core recovery during rotary drilling and low compressive strength values obtained by laboratory testing also verified the nonhomogenous nature of the Jet-2 jet grout columns. The last four columns namely, C’, I’, O and P are constructed using more refined parameters by an increased rotational speed (i.e. 50 rpm instead of 20 rpm), applying preflushing before jetting and by a reduced air delivery rate of 6 m^3/hour (almost half of the original value) for the purpose of obtaining more uniform column material and reducing the diameter of Jet-2 jet grouts. In addition, column P is constructed with an increased pressure of 550 bars, to check if preflushing and increase in pressure could provide larger diameter columns of 80 cm with method Jet-1. Effects of different parameters on the observed column diameter and compressive strength values are shown in Figure 4. The photographs from the exhumed jet grout columns (C’ by Jet-2 and P by Jet 1) are shown in Figure 5.

Refinement of the jetting parameters for the last four columns is observed to improve the quality of the jet grout columns yielding a perfect uniformity and much less air voids. Visual inspection of column P indicated the diameter is in the order
of 65-76 cm down to 6.0 m depth from the ground level. On the other hand columns of C’ and I’ formed with Jet-2 method are still noted to have larger diameters then 80 cm and exhibiting variability in diameter with depth. It is important to note that increased diameter due to ground conditions leads to a decrease in the cement dosage therefore resulting also in a reduced compressive strength values.

The results of two full-scale load tests realized in the preliminary trial zone are also given in Figure 6. It could be seen from this figure that, although the load carrying capacities are similar for the columns formed by Jet-1 and Jet-2 techniques, the observed deformation is almost twice as much in the Jet-2 method.

**Design recommendations/revisions.** In the light of trial zone testing, for the jet grouts columns to be constructed by Jet-2 method, parameter set 1’ (column C’) is proven to be the best combination to attain the required design criteria. The observed jet grout column diameter range is in between 0.80-1.20 m and compressive strength of the columns is obtained as varying from 3 to 35 kg/cm$^2$, greater than 10 kg/cm$^2$ for the columns having diameters up to 0.90 m. On the other hand parameter set 8 (column P) is considered to be the best combination to attain the required design criteria for the jet grout columns to be constructed by Jet-1 method. In this case,
Figure 6. Results of full-scale load tests

the observed jet grout column diameter range is in between 0.60-0.70 m and compressive strength values of the columns are obtained as being greater than 20 kg/cm$^2$ (2 MPa).

As a result, two different jet grout schemes are proposed to be implemented depending on the utilization of either Jet-1 or Jet-2 methods as shown in Figure 7 to satisfy the same area replacement ratio imposed by the preliminary design. Among the alternative jet grouting schemes, it was finally decided to adopt standard length columns to be formed by Jet-2 method with a triangular spacing of 2.1 m, in which larger diameter columns could be obtained considering that the ground improvement is realized mainly against liquefaction hazard (except utilities block where jet grout columns serve also as load carrying members). Therefore design criteria are upgraded to accept and cover the case of larger diameter columns with less compressive strength.

**Quality Control and Quality Assurance during the treatment works**

Following the trial testing, final jetting parameters are determined and working jet grouts are constructed. Nine (9) different improvement zones namely A to G, are defined according to toe and top elevations of the columns. The lengths of the columns are variable between 3.4 m and 8.4 m depending on the colluvium top level. Total of 3596 jet grout columns are constructed for the ground treatment of the project site.

Within the scope of quality control program, jet grout column samples including wet grab and core samples are obtained for unconfined compressive strength testing in laboratory. Wet sampling is a useful alternative to coring or in situ testing, which has been used to good effect in the USA and more recently in the UK. In this application, a piston sampler is employed to retrieve a wet sample from any desired depth immediately after construction (Bell et al. 1994). Test cylinders are cast from these wet samples and tested after an appropriate period of curing. This method represents a good alternative to coring of low strength jet grout material.
The frequency of the wet grab jet grout columns is adopted for the project, as once per every 100 installed jet grout columns and samples are retrieved within 60 minutes of the withdrawal of the mixing equipment at specific location. The device used to retrieve the wet grab soil samples is needed to be capable of obtaining a discrete fluid sample at a pre-determined depth and is capable of accepting particles not thoroughly mixed that are up to 100 mm in dimension. The compressive testing results of piston samples taken mostly from the jet grout portions with largest sectional diameter (120-150 cm) and therefore representing the lowest cement dosage, are shown in Figure 8 also showing the variation with time. In the literature, little data is available on the development of strength of the jet grout column with time. However available field and laboratory observation data indicate that setting commences rapidly after jetting and does not exhibit a noticeable variation in time in this case. Figure 8 illustrates that the compressive strength values vary between 0.3 and 1.0 MPa for most of the tested samples which is in accordance with the design approach of relaxed compressive strength requirement, for larger jet grout column sections, accepted based on the results of preliminary trials.

Quality control monitoring scheme also included systematic grout index tests and monitoring of jet grouting parameters. The grout mix is checked by measuring the specific gravity using a mud balance. In addition, the specific gravity and viscosity of the effluent are checked using a mud balance and Marsh cone. For the exhumation of jet grout columns, the photographs are taken from four orthogonal directions and jet grout column diameter is measured at 0.5 m intervals, throughout the exhumed column length and documented.

In the course of treatment works, vertical load tests are also realized on working jet grout columns (total of 11 tests) to verify the chosen capacity and to check the deformation behavior of the jet grout column. Measured column
settlements are between 1.7 mm and 8.6 mm under the load of 330 kN, therefore considered as within the allowable project limits.

![Figure 8. Variation of compressive strength values with time](image)

**Concluding remarks**

During the ground treatment using jet grouting technique for the cigarette factory site, it is proved that a comprehensive preliminary trial zone testing is essential for the calibration and verification of the concept design towards the final design, prior to commencement of treatment. In the course of the trial zone testing, jet grout columns constructed with mono fluid method exhibited higher compressive strength and less settlement under similar loads in full-scale load tests, compared to columns constructed with double fluid technique. However considering that the treatment is mainly done to reduce liquefaction hazard and therefore, load carrying capacity and deformation behavior under static loading are of secondary concern, double fluid (Jet-2) method is chosen having the required area replacement ratio as the most feasible solution for this site. The detailed and careful selection of the jetting parameters and a thorough quality control/quality assurance testing led to a successful ground treatment application for the subject cigarette factory site.

**References**

