UTILIZATION OF HIGH MODULUS COLUMNS IN FOUNDATION ENGINEERING UNDER SEISMIC LOADINGS

H. Turan. Durgunoglu [1]

ABSTRACT

In this paper, definition of various foundation systems are provided. Among these systems, utilization of jet grouting as high controlled modulus columns for various foundation engineering purposes are evaluated together with construction parameters, quality control and verification of design criteria. The method of calculation of factor of safety against liquefaction under seismic loading is given together with the utilization of jet grout columns as high modulus columns against liquefaction. Proposed design methodology is evaluated and verified, based on three case studies where jet grouting was implemented before August 17, 1999 Kocaeli/Turkey Earthquake observing the performance of subsoil and foundations during the earthquake.

Introduction

In the selection of various foundation systems loading conditions together with hazard identification are considered. In seismically active areas such as Turkey often the design of the foundation is controlled by the parameters of the selected design earthquakes. Liquefaction of subsoil, under earthquakes is one of the primary hazard that has to be considered during the design and construction. The factor of safety against liquefaction could easily be determined based on the detailed soil modeling at a given site for a design earthquake. There are various mitigation procedures against liquefaction based on the following principles.

- Utilization of prefabricated special high permeability drains or stone columns to facilitate the immediate drainage of excess pore water pressure developed during shaking.
- Utilization of subsoil compaction by means of vibroflotation, vibroreplacment, compaction piles, and dynamic compaction to increase CRR
- Utilization of high modulus columns by means of deep mixing and/or jet grouting within the subsoil to decrease CSR taken by the subsoil.

This paper will describe only the last procedure. The construction and design parameters of such columns will be defined. A simplified design algorithm for the utilization of these

[1] Professor of Geotechnical Engineering Emeritus, Bogazici University, and
Chairman of Zetas Earth Technolgy Corp., Istanbul, Turkey

columns against liquefaction and their effects towards the factor of safety will be provided. The result of three case studies related to positive performance of such improved foundations during 17 August 1999 Kocaeli/Turkey Earthquake is also provided.

Definition of High Modulus Columns

Structural members-columns having different stiffnesses are designed and constructed for various purposes within the soil as part of the foundation systems in different civil engineering structures. These columns having higher modulus than the original foundation subsoil could be classified in three groups as follows:

Rigid Foundation Systems - RFS

The reinforced concrete piles constructed using various techniques could be included in this group. Driven piles, driven cast-in-situ piles, cast-in-situ piles and micropiles are some examples of rigid foundation systems. In this system the rigidity of the structural member, i.e. pile is much larger than the surrounding soil, and therefore the vertical loads from the upperstructure is carried only by these members by means of skin friction and/or tip resistance. For the lateral loads, pile caps supported by the foundation subsoil or structural slab-on-grade slab and special steel reinforcement close to the top of the pile are often utilized. For such rigid structural reinforced concrete column the deformation modulus could be taken as E_{cl}= 25,000 MPa and the modulus ratio (modulus of column/modulus of subsoil) could vary E_{cl}/E_s ~ 1000-6000 depending on the nature and stiffness of the subsoil.

High Modulus Foundation System - HMFS

These systems also named as high (controlled) modulus columns, are constructed within the soil by mixing with cement slurry with the in-situ subsoil. In the deep-mix procedure the soil mixed with the cement slurry using mechanical equipment and units. High modulus columns could also be constructed by means of jet grouting technique. In this technique the soil is mixed with the cement slurry under a very high pressure using special pumps and monitor by jetting the slurry while rotating and retrieving the monitor attached to the cylindrical rods.

In both cases the in-situ soil is mixed with controlled cement slurry resulting into a partially controlled material called soilcrete. The mechanical properties of soilcrete column are determined and controlled by means of various factors, such as construction procedure, quality of cement slurry and the nature of in-situ soil. For various soils the modulus of these columns constructed using both technique could vary in the range of E_{jg}= 500-1200 MPa, (Durgunoglu 2004). Therefore, this will yield to a modulus ratio of E_{jg}/E_s ~ 10-150$^+$.

Deformable Foundation Systems - DFS

In these systems the rigidity of the structural column within the soil is the least among the three different categories. Therefore, these systems are named as deformable foundation systems which are utilized using crushed stones. Dry and wet systems together top and bottom feeding mechanisms using vibroreplacement technique have been adopted in various stone-column construction procedures. In Turkey stone columns are usually constructed by closed end steel pipe driven into the soil, and latter crushed stone is placed within the casing while vibrating and extracting the casing. (Durgunoglu 1995). The modulus of stone column could be taken as E_{sc}= 40-80 MPa, yielding to modulus ratio of E_{sc}/E_s ~ 4-10. The foundations supplied by stone column may experience excessive vertical displacement especially when utilized in soft clays due to the limited confinement of the subsoil.

In this paper, only the utilization of high modulus columns in various foundation applications with special emphasis on soil liquefaction mitigation under seismic loading will be presented.

High Modulus Columns By Means of Jet Grouting

Jet Grout System Construction Parameters

In the jet grouting system controlled quantities of cement is injected through small diameter nozzles into the subsoil to create certain diameter soilcrete columns. The construction parameters of the system could be stated as follows:

- Fluid system (namely, single Jet-1, double Jet-2 and triple Jet-3 fluid systems, using grout alone, grout + air, grout + water + air)
- The injection pressure (Bar)
- Number and diameter of nozzles (mm)
- The rotation speed of the monitor (rpm)
- The retrieval speed of the monitor (cm/min)
- Water/cement ratio
- The pump capacity (lt/min)

The typical parameters and their range of values are summarized in Table 1, (Lunardi 1997).

Table 1. Jetgrout Parameters, (Lunardi 1977).

System	Fluid Type	Pressure (bar)	No of nozzles and dia (no, mm)	Lifting speed (cm/min)	Rotation speed (rpm)	w/c ratio	Pump capacity (lt/min)
JET1	Cement	400 - 550	1-2 x 2-5	15-100	5-15	1.0-1.5	70-600
JET2	Cement	400 - 550	1-2 x 2-5	10-30	4-8	1.0-1.5	70-600
	Air	10 - 12	-	10-30	-	-	4,000 – 10,000

JET3	Cement	50 - 100	1-2 x 4-5	6-15	4-8	1.2-1.5	80-200
	Air	10 - 12	-	6-15	-	-	4,000 – 10,000
	Water			6-15	-	-	40-100

Jet Grout Columns Design Specifications

In the design of high modulus column with a jet grouting system, various design parameters are specified. The most common design parameters of the columns are listed below.

- Diameter of Column

It is known that in jet grouting system the diameter is controlled by the system construction parameters and as well as the nature of the subsoil. Therefore, the obtained diameters of the columns have to be checked within the quality control programme.

- The Length of Column

The length of the columns are specified in design and checked by means of pile integrity testing within the quality control programme.

- Compression Strength and Modulus of Soilcrete, f_{jg}'-E_{jg} (MPa)

The compressive strength of the soilcrete is determined in the laboratory by means of compression test on cylindrical core samples taken from the soilcrete columns. The small diameter core result is converted to cylindrical compressive strength using conversion factor of 1.25. The core samples could also be obtained from the soilcrete just immediately after the jetting using piston sampler prior to curing, (Durgunoglu 2003). The measurement of deformation modulus during compression tests is also a standard procedure, (Saglamer 2002).

- Shear Strength of Soilcrete, τ_{jg} (MPa)

In the utilization of high modulus column against liquefaction, the shear strength of the soilcrete obtained has the primary significance. Either shear strength is determined by means of special shear tests or using empirical relationship of

$$\tau_{jg}(MPa) = 0.3\sqrt{f_{jg}'}(MPa) \quad (1)$$

and the shear force capacity of a single column could be determined by

$$V_{jg} = \tau_{hg} * A_{jg} \quad (2)$$

where A_{jg} is cross sectional area of the column.

- Compressive and/or Tensile Capacity of Column

The high modulus columns could be used for various purposes in foundation engineering applications as listed later with or without liquefaction mitigation against liquefaction. Therefore, the compressive and/or tensile capacity of certain number of the constructed columns should be measured for the capacity assessment within the quality control programme similar to pile foundation applications, (Durgunoglu 2003).

Calibration of the Design Specifications

As it is shown that, the design specifications will include the dimensions (diameter, length) of these columns and the mechanical properties of the soilcrete (i.e. compressive strength, modulus, shear strength). Since these end products are influenced and controlled by the system construction parameters given previously (i.e. jetting system, injection pressure, size and number of nozzles, rotation and retrieval speed of the monitor and the capacity of the injection pump), they must be interlinked and calibrated at the site prior to any permanent construction. Consequently, optimization of the construction time and cost of specific end product could be obtained. Such procedure is summarized in Fig. 1.

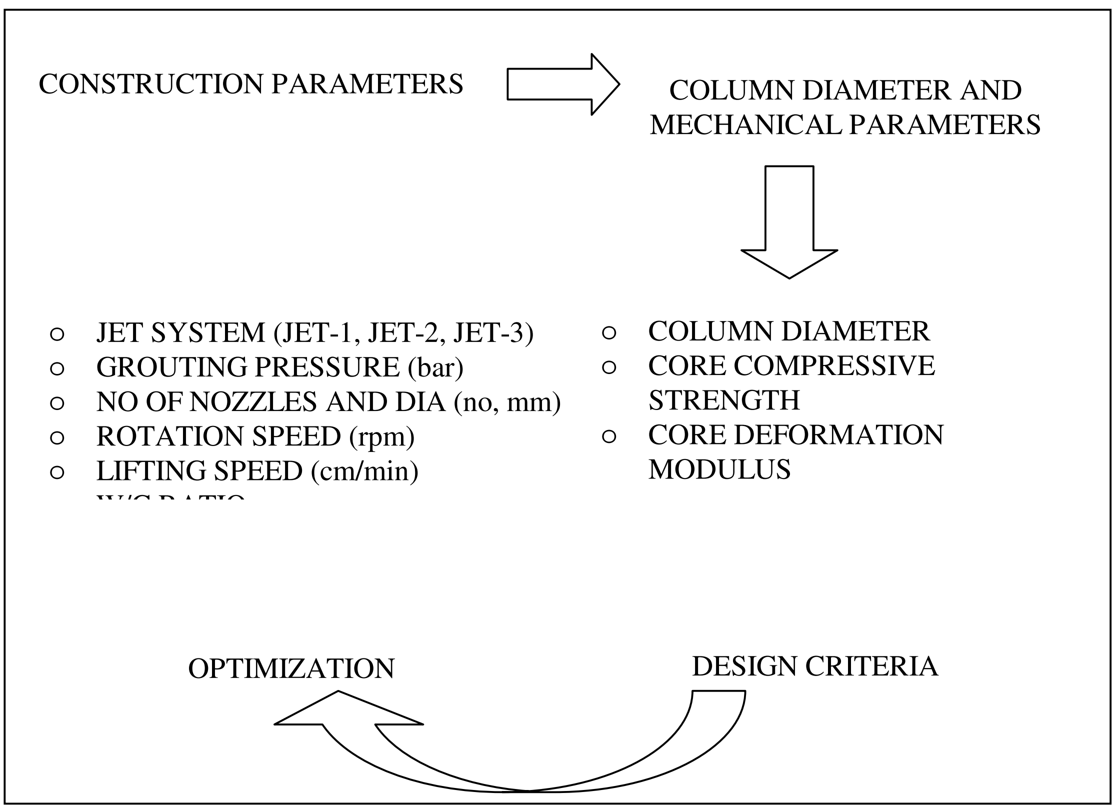

Figure 1. In-situ calibration, control and optimization of design criteria.

An example of such an optimization and calibration procedure is reported by

(Durgunoglu 2003).

The Utilization of High Modulus Columns in Foundation Engineering

The high modulus columns constructed by means of jet grouting has been utilized in various foundation engineering applications for various purposes in the past, (Durgunoglu 2004). These could be summarized as:

- Utilize as compression members, under foundations to increase bearing capacity and to reduce settlement
- Utilize as compression members, below slab on grade under high surcharge loads to increase bearing capacity and to reduce settlement
- Utilize as compression members under fills and embankments to increase bearing capacity and to reduce settlement
- Utilize as compression members below approach embankments in bridges to prevent negative skin friction on abutment piles, to decrease lateral loads due to embankment on abutment piles.
- Utilize as tension member against uplift complementing with reinforcement in water reservoirs and structures located below ground water table.
- Utilize in series of rows as gravity type retaining structures in excavations
- Utilize as vertical bending member complemented with steel reinforcement within a retaining structure in excavation
- Utilize as special anchor complemented with steel reinforcement in tieback excavation.
- Utilize as a member of diaphragm wall between structural piles, instead of intersecting piles.
- Utilize as bottom strut in a deep excavation in soft clays constructed from the top prior to excavation.
- Utilize as cut-off member at the base of the excavation against seepage towards the cut.
- Utilize as soil improvement system above the tunnels prior to excavation and mucking of the tunnel.
- Utilize as structural umbrella in front and above the tunnel face excavation in soft ground tunneling.

In addition to these applications, high modulus columns could also be utilized against seismic loads due to the earthquakes in seismically active areas. Such practice in the past could be stated as:

- To reduce the vertical and horizontal displacements of foundations under seismic loadings, utilize as restraining structure around and below the foundation.
- To reduce the lateral loads to be transferred to pile foundations under seismic loading, by utilizing together with piles under the foundation mats

and finally,

- To utilize with certain spacing and diameter below the foundations, to mitigate the liquefaction hazard under earthquake loading.

High Modulus Columns Under Seismic Loading

In fact, this last specific application towards liquefaction mitigation has been applied in various civil engineering structures during the past ten years in Turkey. Considerable, experience has been gained by examining their behavior during 17 August 1999 Kocaeli Earthquake. The design procedure for the utilization of high modulus columns against liquefaction developed earlier (Ozsoy and Durgunoglu 2003) is summarized.Various case studies related to the performance of this procedure is provided below.

Design Procedure

The first Simplified Method of (Seed and Idriss 1971) based on the performance of ground during Alaska and Niagata 1964 earthquakes, were modified and further refined over the years, such as (Seed and Idriss 1982)-EERI, (NCR 1985) , (Youd 2001)-ASCE. All of the methods give the factor of safety against liquefaction as the ratio of:

$$FS_l = {CRR}/{CSR} \qquad (3)$$

where CRR=Cyclic Resistance Ratio and CSR=Cyclic Stress Ratio.

Based on the depth and the magnitude of the design earthquake, the variation of CRR with depth could be determined using the above references. Similarly, utilizing soil resistance data in the form of SPT blow counts, or/and CPT unit tip and skin resistances or/and, shear wave velocities and their variation with depth, the variation of CSR with depth could also be estimated. Therefore, the change of FS against liquefaction with depth could be determined. The cyclic resistance ratios in the above references are obtained based on the site observations with a specific earthquake magnitude of M=7.5. Therefore, these values are modified using MSF=magnitude scaling factors (Youd 2001) as:

$$FS_l = \frac{(CRR)_{7.5}}{CSR} * MSF \qquad (4)$$

Reduction Factor, S_G

The utilization of high modulus columns against liquefaction and the related design procedure was studied earlier, and was reported in (Ozsoy and Durgunoglu 2003) although the early applications of the method goes back to 1995 in Turkey. Unit cell approach , has been used as an approximation in order to separate the shear forces taken by the column and the surrounding in-situ soil within the unit cell. Using the strain compatibility between the soil and the high modulus column the following relationship has been developed for the reduction factor, S_G

$$S_G = \frac{1}{G_r} * \frac{1}{\left[a_r + \frac{1}{G_r}(1 - a_r) \right]} \quad (5)$$

where G_r is the modulus ratio, defined as G_{jg}/G_s, G_{jg} is shear modulus of jetgrouted column, G_s shear modulus of in-situ soil, a_r is the area replacement ratio defined as A_{jg}/A, where $A=S_H*S_v$. A_{jg} is cross sectional area of the jet grouted column, A is area of unit cell, product of horizontal spacings in two perpendicular directions.

In this case, the design value of CSR could be determined from:

$$CSR_{design} = S_R * CSR \quad (6)$$

giving the resulting factor of safety against liquefaction:

$$FS_l = \frac{(CRR)_{7.5}}{S_R * CSR} * MSF \quad (7)$$

The variation of reduction factor $S_G= f(a_r,G_r)$ of Eq. 5. is given in Fig. 2. The G_r range of 10-150 values are utilized in the Fig. 2. It could be seen that area replacement ratio of a_r= 7-10% will be effective to obtain reduction factor of nearly S_G(%) 10-60. Since, the factor of safety is inversely proportional with S_G, a great increase in factor of safety could be obtained based on the specific values of modulus, and area replacement ratios.

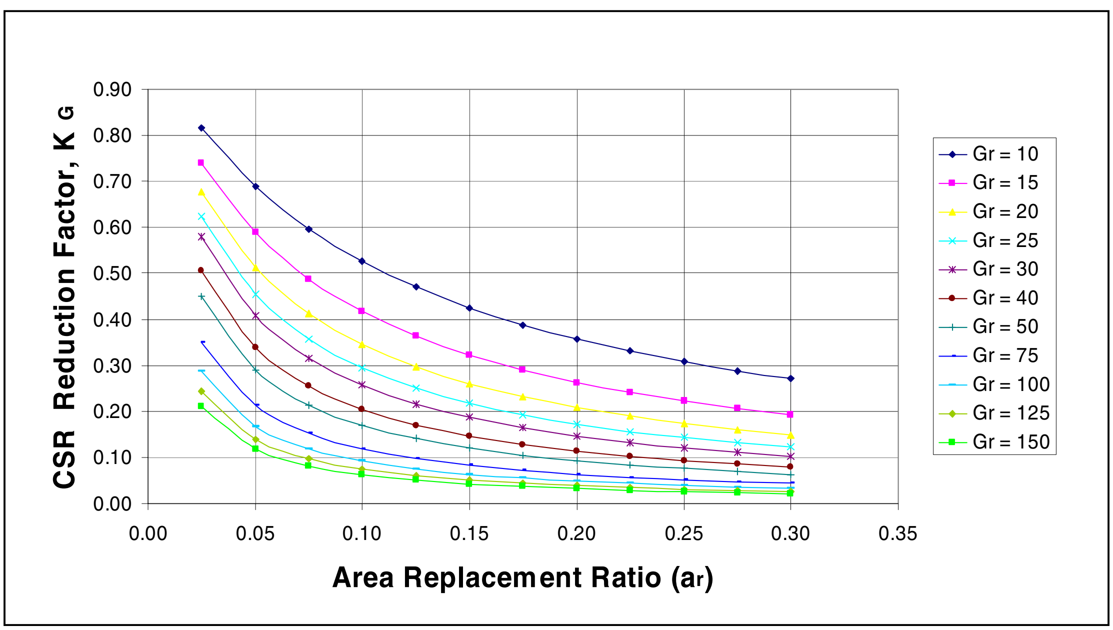

Figure 2. Variation of area replacement ratio with CSR (Ozsoy and Durgunoglu 2003).

Performance of High Modulus Columns During Earthquake

The design procedure and the implication of high modulus columns in foundation subsoils to mitigate liquefaction hazard in seismically active areas were applied in Turkey since 1995. The 17 August 1999 Kocaeli Earthquake gave the unique opportunity to evaluate the performance of improved sites by the described procedure and compare their performances with respect to unimproved nearby sites. Three important case studies related to foreign investments as joint-venture companies with Turkish partners were studied in detail and summarized in Table 2.

The details of the case studies could be obtained from these references.

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Table 2. Performance of high modulus columns against liquefaction during, 17 August 1999 Kocaeli Earthquake (M=7.4)

Structure	**Location**	**Reference**
Carrefour Shopping Mall	Izmıt	(Durgunoglu 2003), (Martin 2004)
Ipekagit Paper Tissue Factory	Karamursel	(Martin 2003), (Durgunoglu 2004)
Ford Otosan Car Factory	Golcuk	(Martin 2001), (Saglamer 2002), (Ozsoy and Durgunoglu 2003)

In summary, it was shown that the adopted usage of high modulus columns were very effective in mitigation of liquefaction and liquefaction induced hazards if any, especially with a combined benefit against other foundation hazards, such as low bearing capacity, excessive settlement and others, would even make them more desired due to cost optimization in foundation design and construction.

Conclusion

The high modulus columns designed and constructed according to the recommended procedure were shown to be one of the effective procedures towards the mitigation of liquefaction at seismically active areas. Their very positive performances during the past 1999 Kocaeli / Turkey Earthquake together with potential usage against other foundation hazards makes them very attractive and in some cases cost effective.

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