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COMBINATION OF BORED PILES AND STONE COLUMNS FOR THE EARTHQUAKE RESISTANT DESIGN

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ABSTRACT

A Gas Turbine (CCGT) Power Plant has been currently under erection in the South of Turkey. A design driving factor for the layout of the foundations is the influence of the design earthquake event. Thus an increased effort for the foundation solution became necessary. To minimize the technical and economical effort a combined solution for the foundation of heavy buildings has been developed. The main idea has been to avoid liquefaction in case of an earthquake in the liquefiable soil around the bored piles by installing highly compacted and permeable stone columns. Also many other, lighter structures have been founded on soil improvement executing stone columns. In the given paper a detailed description of the design by taking into account the positive effects of stone columns are presented. For the bored piles a standard design – after having ensured non-liquefaction by stone column application - has been applied and is therefore not described below.

PROJECT AND GEOLOGY

This site is located in the district of the Hatay province, at the north-east shore of the Bay of Iskenderun, in the south east of Turkey (figure 1). This region has suffered from severe earthquakes in the past (figure 2).

The project consists of a Combined Cycle Gas Turbine (CCGT) power station with a nominal generation capacity of 910 MW net output, for the supply of electricity to the Turkey Grid network (figure 3). The Power Plant comprises of 38 piled and non-piled buildings / structures. In order to prevent the area from flooding from the near coastline, the whole area has been filled with a compacted granular material of up to 3m height (figure 4). In the case of liquefaction the foundation piles would be loaded by lateral spread of the soil for which they are not designed for. Also severe settlements and loss of stability is expected for both piled and non-piled areas, thus a countermeasure was seeked and found with the implementation of stone columns.

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Figure 1: Location of the site.

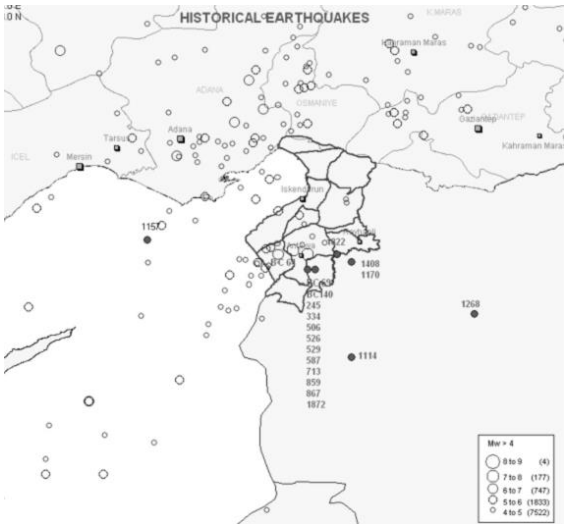

Figure 2: Historical earthquakes with magnitude - from Bogazici Univ. 2009.

Figure 3: Erzin Combined Cycle Gas Turbine Power Plant.

The ground conditions can be summarized as follows: below a 2-4m thick dense gravel layer loose to medium dense sand silt mixture follows (0-20m). Soft to very soft clay is located in depth between 20m and 30m, below which the bedrock consisting of basalt is following. Especially the sand silt mixture has a high risk of liquefaction. Ground water table is close to ground surface. In other words the natural ground consists of a layer of sand (liquefiable), underlain by a layer of silty sand (liquefiable), which in turn is underlain by a layer of clay resting on Basalt bedrock (figure 5).

For the foundation of the heavy structural parts such as the gas turbines, the turbine hall or the steam turbine bored piles of a diameter of 80cm to 120cm were installed. In order to ensure a low settlement the piles penetrate the basalt by 2,5*D (2m and 3m respectively). In between the bored piles dry bottom feed stone columns with a diameter of 80cm for the liquefaction prevention became necessary. Otherwise the liquefied soil in an earthquake event would put additional load from the lateral spread to the piles, which would lead to a dramatic increase in the number of piles to be installed.

In order to ensure the necessary stone column diameter pre-boring until depth of 14m to 18m was necessary to loosen the soil. Following the design and to minimize the effect of negative skin friction the stone columns were installed before the pile installation.

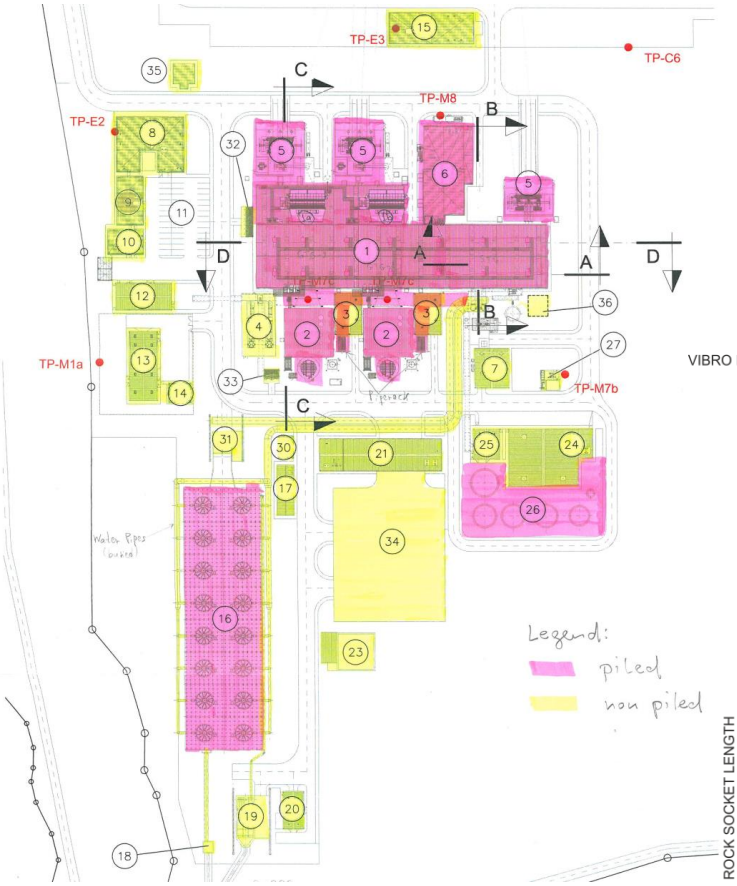

Figure 4: Plan view with piled (light) and non-piled (dark) areas.

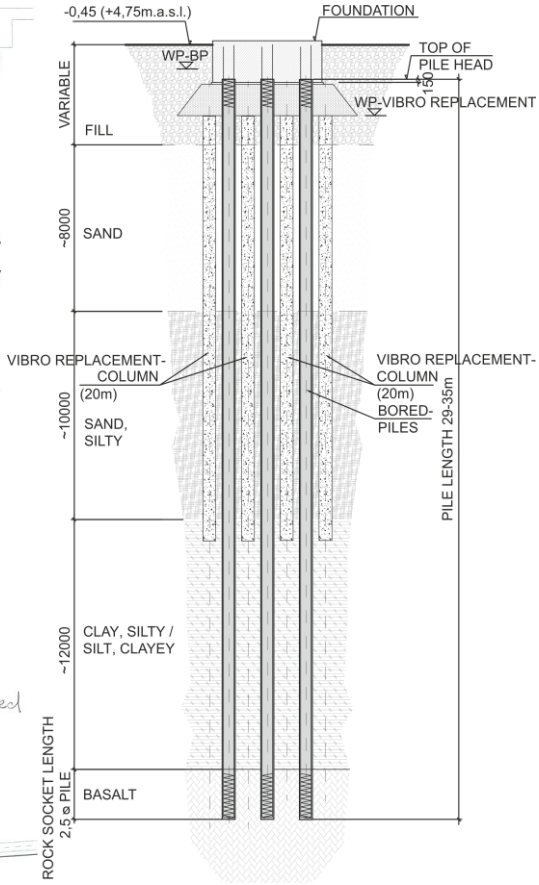

Figure 5: Typical soil profile and foundation for heavy structures.

In all other areas which undergo considerable less loading from the structures shallow foundations together with stone columns as a ground improvement measure to reduce settlement and prevent liquefaction were installed up to depth of 20m.

A very detailed quality assurance program was implemented for bored piles and stone column works in order to ensure that the as built situation follows the design assumptions with a continuous high quality. Apart from numerous pile load tests and material testing especially for the stone columns high requirements had to be met, due to the necessity of guaranteeing a continuous drainage effect of the stone columns.

The design of the stone columns for the reduction of the liquefaction potential and thus for the earthquake resistant pile foundation was made under the specific design earthquake event with a peak ground acceleration of 0,5g. With the design the stiffening effect of the stone material is incorporated as well as the reduction of drain path due to the implementation of the columns.

LIQUEFACTION MITIGATION IN AN EARTHQUAKE EVENT

The site was subdivided into several design soil profiles each of which was analyzed with respect to the liquefaction potential using software SHAKE 2000. It became obvious that both sand and silty sand layers will undergo substantial loss of strength due to liquefaction in an earthquake event.

To mitigate the liquefaction potential, ground improvement was considered necessary extending from the ground surface (being the top of the fill) down to the silty sand / clay interface. The ground

improvement in both piled and non-piled areas was performed by constructing stone columns formed by vibro-replacement (dry bottom-feed method) using imported crushed stone or gravel (Kirsch & Kirsch 2010). Vibro-replacement is a stone column installation method in which a vibroflot (down-hole vibratory probe) compacts aggregate into a column and wherever possible densifies the surrounding soils to increase bearing capacity and reduce settlement of a structure (figure 6). Vibro-replacement stone columns can also serve to increase shear resistance, particularly when a load is placed above them.

According to the design, the stone columns had a diameter of 80cm and were placed on a square / triangular grid at different spacings (figure 7). The depth of the stone column installation varied across the site from 18m to 22m below natural ground level, whereas the depth of installation from the working platform kept constant with 20m. Because of their higher permeability, stone columns function as drains for the de-confinement of pore pressure and the reduction of the required consolidation time.

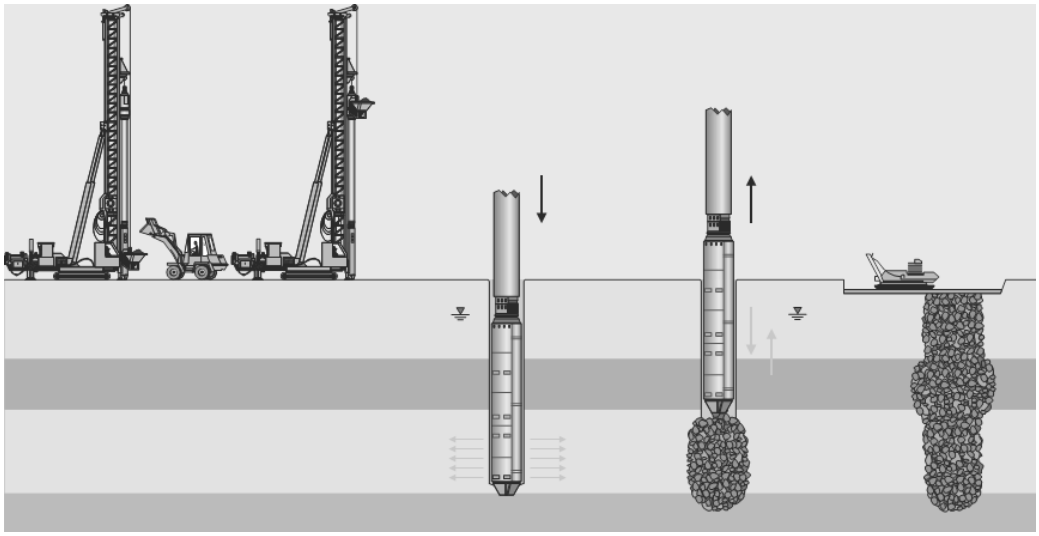

Figure 6: Stone columns: Dry bottom feed method.

This is the main effect for the use of stone columns to mitigate liquefaction. In cases of loose sand or silty sand, the method of stone columns is indicated for the reduction of liquefaction hazard of these soil materials. The use of stone columns helps the increase of the relative density of the loose soil material, resulting in an increase of the shear strength of these materials in dynamic loads and in an obstruction of the appearance of liquefaction phenomena. On the other hand, using stone columns in soft, cohesive materials offers increase of the bearing capacity, reduction of settlements and reduction of the required time for the completion of settlements.

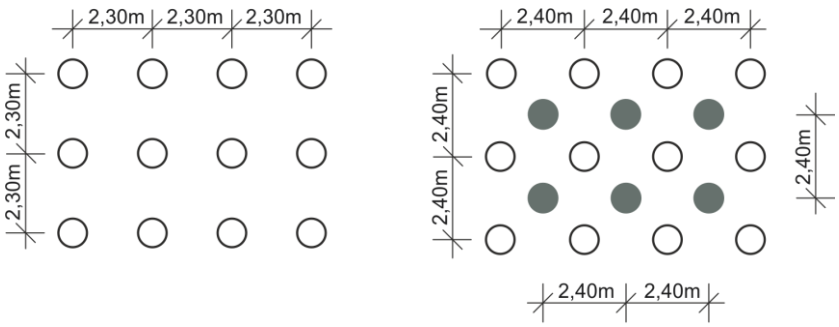

Figure 7: Left - Pure stone columns for lighter structures; Right - Combination of stone columns & bored piles

Virtually, the presence of the stone columns creates a complex soil material of higher strength and lower compressibility. The lateral restriction that contributes to the increase of stiffness of the stone columns and to the reduction of compressibility comes from the increase of lateral pressure of the inappropriate soil material. With the installation of the material the soft soil is displaced and thus the stone column, due to its more significant stiffness, bears higher loads. With the re-distribution of stresses in the area of the stone column, higher bearing capacities and lower settlements are achieved.

DESIGN OF STONE COLUMNS FOR LIQUIFACTION MITIGATION

In general, the main effects of the stone columns are:

1. the shortening of the drainage path,
2. the increase of the average soil stiffness,
3. the increase of the density of the soil caused by the vibrations during their installation.

The first two of these effects were considered directly by the design methodology of the stone columns at the Erzin CCGT Power Plant project described below. The third effect was not included in the design, but rather considered as additional safety. The steps of this design methodology are presented in the following paragraphs.

Step 1: Geotechnical design profile

For the design of the stone columns a design soil profile for each analyzed structure / building is defined. The information that needs to be included for each soil layer is:

- SPT values (N)
- shear wave velocities (V_s) or dynamic shear modulus (G_{dyn})
- unit weights (γ)
- horizontal permeability (k_h)
- coefficient of compressibility (m_v)
- design water tables
- strength parameters (φ, c)
- relative density (D_r)

Step 2: Earthquake input values

- Firstly the relevant acceleration time history is identified from the seismological report (figure 8)
- Then the number of equivalent stress cycles (N_{eq}) according to the method of Seed et al. (1975) is determined.
- The duration of the relevant shaking time t_d is also determined.

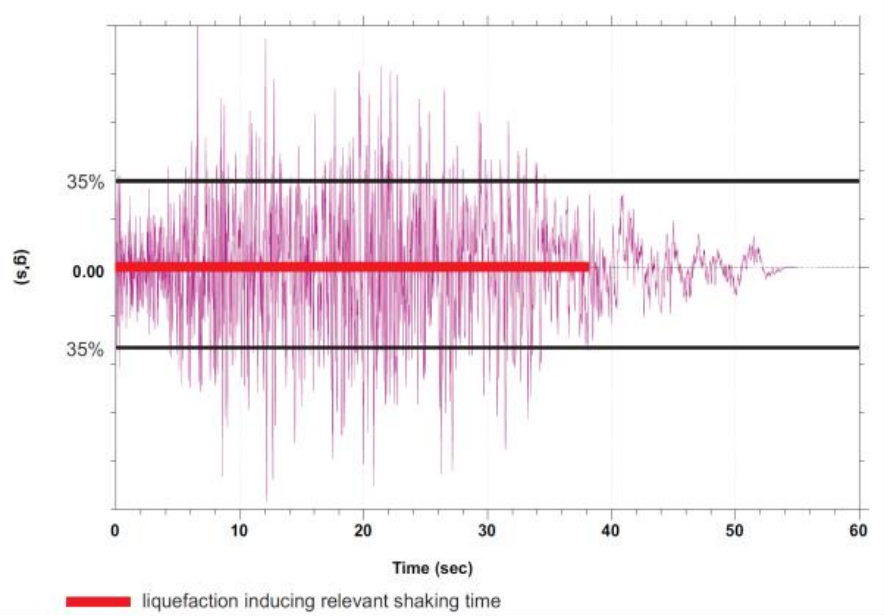

Figure 8: Charakteristic design earthquake - from Bogacici Univ. (2009)

Step 3: Improvement factor for a given area ratio

The design method for Vibro-Replacement Stone Columns by Priebe (1995) is used in order to assess the overall improvement of the stiffness of the soil-column-system. The input parameters to determine the basic improvement factor n_0 are:

A = area of improvement,
A_S = stone column area,
μ_B = Poisson's ratio of the soil,
φ_S = angle of friction of the stone column material.

Assuming a Poisson's ratio of the soil of 1/3, the relationship between the improvement factor n, the reciprocal area ratio A/A_S and the angle of friction of the material of the stone columns φ_S is shown on figure 9. The basic improvement factor is further corrected taking into account the column compressibility and the effective vertical stress state in the surrounding soil. The input values needed for the determination of the corrections are:

E_S = Young's modulus of the stone column material,
E_B = Young's modulus of the natural soil.

As a result, an adapted improvement factor n_1 and finally n_2 can be determined.

Step 4: Design calculations using SHAKE 2000

- Calculation models in computer program Shake2000 are created according to the geotechnical profiles.
- The unscaled acceleration time history at rock level is introduced and the τ/σ'_0 ratio (CSR) for each soil layer is calculated.
- The acceleration time history is than scaled to get peak ground acceleration (PGA) of 0,5g for buildings and foundations acc. to design basis.

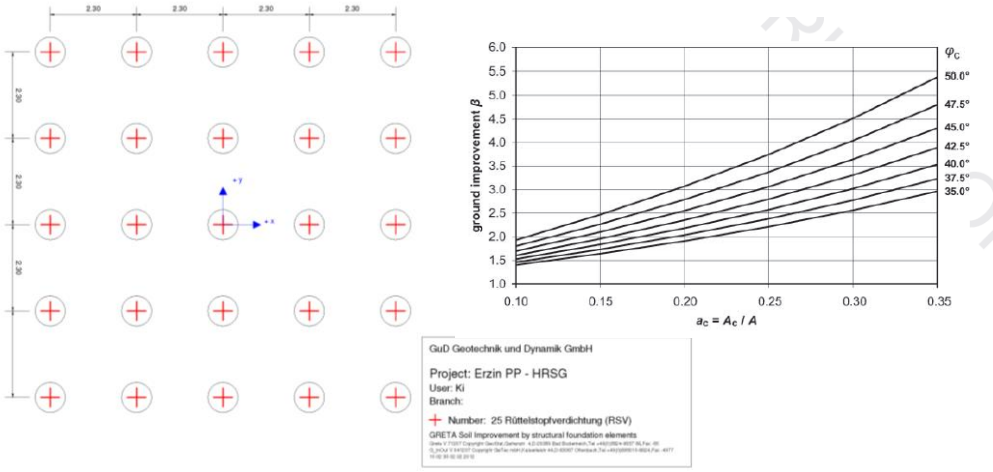

Figure 9: Stiffness increase due to stone columns – Acc. to Priebe

Step 5: Stress ratio reduction

- Application of the improvement factor n_2 on the overall shear modulus of the improved ground in the same manner as on the vertical modulus. The τ/σ'_0 values (stress ratio computed for the unimproved soil) are reduced by the n_2 factor derived from the Priebe analysis.

It is assumed that the overall stiffness improvement due to the installation of the stone columns leads to a corresponding reduction of the shear strain in the soil-column-system during an earthquake event. This reduced shear strain leads to an evenly reduced cyclic stress ratio (CSR) in the liquefiable soil.

Step 6: Number of cycles to liquefaction

The number of cycles necessary to initiate liquefaction N_{liq} is determined in the laboratory or as a presumed value is estimated according to FINN et al. (1971) using the calculated reduced τ/σ'_0 values and the relative density of the soil.

Step 7: Reduction of Liquefaction Potential

In order to provide effective drainage, the spacing between the stone columns must be designed in such manner, that excess pore pressures get dissipated almost as fast as they are generated. The design method suggested by Seed and Booker (1977) is used for this analysis. Under the assumption of purely radial flow, the pore pressure ratio throughout the natural soil and drain system can be expressed as a function of the dimensionless parameters:

1. $a / b = d / d_e$
2. N_{eq} / N_{liq}
3. $T_{ad} = \frac{k_h}{\gamma_w} \cdot \frac{t_d}{m_{v3} \cdot d_e^{\,2}}$

The respective design charts for the relationship between pore pressure ratio generated during the earthquake, the properties of the soil-column-system and the earthquake are given by from Seed and Booker (1977) and shown on the figure below (figure 11).

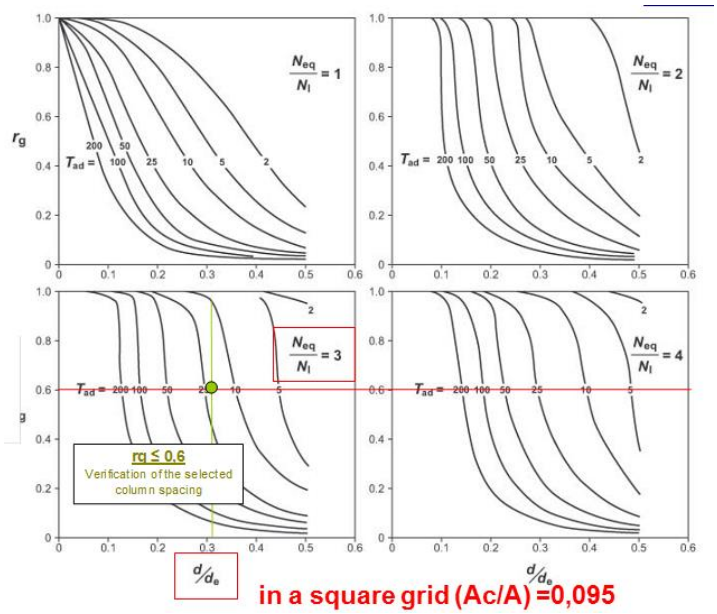

Figure 10: Design charts from Seed and Booker (1977).

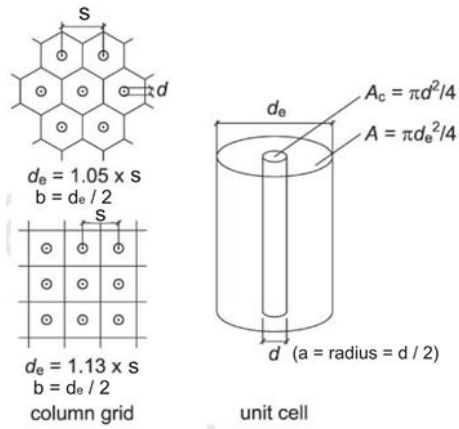

Figure 11: Stone column system for unit cell.

The factor T_{ad} relating the earthquake duration to the consolidation properties of the natural sand and silty sand is computed:

$$T_{ad} = (k_h / \gamma_w) \times [t_d / (m_v \times a^2)]$$

where:

k_h = horizontal permeability of the soil [m/sec]

γ_w = unit weight of water [kN/m³]

t_d = duration of the liquefaction inducing relevant shaking time [sec]

m_v = coefficient of volume compressibility of the natural soil [m²/kN]

a = stone column radius [m]

Also, the cycle's ratio is defined by the following relationship:

$$N_{eq} / N_{liq}$$

where N_{eq} is the equivalent number of cycles applied by the design earthquake and N_{liq} is the number of cycles needed to initiate liquefaction. The pore pressure ratio is given by the following relationship:

$$r_g = u / \sigma'_0$$

The allowable pore pressure ratio can be computed to an overall safety against liquefaction by the equation:

$$\eta = \frac{1}{r_g}$$

Due to the importance of the site, a design safety factor of $\eta = 1.67$ was considered, which corresponds to a pore pressure ratio of r_g = 0.6. It should be noted, that for values of $N_{eq} / N_{liq} > 4$,

linear extrapolation is used for the design chart of Figure 10 to obtain the corresponding r_g value. For values of $N_{eq} / N_{liq} < 1$ it is assumed that the soil will not liquefy.

Step 8: Stone column material with respect to filter criterion

In order to ensure a long-term drain effect, the column material needs to be adapted to the grain size distribution of the surrounding soil. The specification of the drainage material follows the design equation suggested by Saito et al. (1987):

$$20 \times d_{15} < D_{15} < 9 \times d_{85}$$

where:

D_{15} : refers to the particle size of the filter material for which 15% of the material, by weight, is smaller

d_{15} : refers to the particle size of the natural soil for which 15% of the soil, by weight, is smaller

d_{85} : refers to the particle size of the natural soil for which 85% of the soil, by weight, is smaller.

A ground improvement measure by the installation of stone columns in order to prevent liquefaction was designed according to the above description. The column installation took place in 2012 (figure 12). A total of approx. 9000 columns were installed successfully.

Figure 12: Stone column installation incl. predrilling for loosening

In figure 13 different phases for the execution of the bored piles are shown. The casing for the bored piles has been installed after finalization of the stone columns. Using typical bored pile rigs the drilling inside the casing was done as well as the reinforcement installation and concreting. After hardening of 28 days 7 pile load tests for vertical loads have been done successfully.

Figure 13: Construction and testing of bored piles

CONCLUSION

Utilizing the system of a bored pile foundation in combination with surrounding stone columns (highly compacted and dry bottom feed) a safe, technically and economically optimized solution for the earthquake design has been found for all important and heavy structures of the power plant. In addition - for less heavy structures - soil improvement using stone columns was designed and executed as the best and most environmentally friendly solution.
The given paper shows the simple approach for taking into account the beneficial effects of the stone columns by avoiding liquefaction of the soil in case of an earthquake.
In particular the high quality requirements for the execution of stone columns and bored piles leaded to very strong and successful cooperation between the design and execution.
Finally we would like to thank all participants of the project for the successful and timely finalization of the foundation works.

REFERENCES

Bogazici University (2009), Earthquake hazard and design – Earthquake characteristics for the Egemer power plant site in Erzin, Hatay

Bolton Seed, H., Idriss, I.M., Makdisi, F., Banerjee, N. (1975) Representation of irregular stress time histories by equivalent uniform stress series in liquefaction analyses, Report No. EERC 75-29, College of engineering University of California

Bolton Seed, H. and Booker, J.R. (July 1977) Stabilization of potentially liquefiable sand deposits using gravel drains, Journal of geotechnical engineering division,

Finn, W.D.L., Pickering, D.J.M., Bransby, P.M. (April 1971) Soil liquefaction in triaxial and simple shear tests, Journal of the soil mechanics and foundation division,

Kirsch, K and Kirsch, F (2010) Ground Improvement by Deep Vibratory Methods, CRC Press

Priebe, H. (1995) Die Bemessung von Rüttelstopfverdichtungen, Ernst und Sohn, Bautechnik 72

Saito, A.; Tagawa K., Tamura T., Oishi H., Nagayma H. and Shimaoka H. (1987) A countermeasure for sand liquefaction by gravel drains method, Nippon Kokan Technical report overseas, 1987