3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering,
28-30 June 2012, Near East University, Nicosia, North Cyprus

Ground improvement to reduce the liquefaction potential around pile foundations

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KEYWORDS: ground improvement, liquefaction, piles, vibro, stone columns

ABSTRACT: Experience shows that buildings on conventionally designed pile foundations can be substantially damaged by earthquakes. Reason for this is often a liquefaction of the soil around the piles. With modern methods of ground improvement in the surrounding area, like deep vibration or deep soil mixing methods, this liquefaction risk is crucially decreased. Some international examples are presented and recommendations for practice are given.

1 INTRODUCTION

Ground liquefaction can occur due to strong vibrations, which are caused by earthquakes. It arises particularly in loose to medium dense, homogeneous fine sands with low permeability. By the vibrations of the earthquake an excess pore water pressure is created in saturated soils, the ground loses its shear strength and the granular structure breaks down. Apart from the loss of vertical bearing capacity of the piles within the liquefied soil, enormous horizontal forces can be exerted on the pile foundations by the liquefaction. If piles are situated in a loose liquefaction-endangered layer and embedded into a dense bearing layer, they can be over-stressed or buckle due to large bending moments.

The liquefaction risk around the pile foundations can be reduced crucially by modern ground improvement methods. In the context of this publication, after a short review of design processes on projects with liquefaction risk, international projects are presented where the liquefaction risk around the pile foundations was reduced by ground improvement, like vibro replacement, vibro compaction and deep soil mixing.

2 CONSIDERATION OF GROUND IMPROVEMENT DESIGN BY MEANS OF AN EXAMPLE WITH VIBRO REPLACEMENT

By means of the vibro replacement method (Priebe 1998) it is shown how the risk of liquefaction potential can be minimized. Figure 1 yields a ground improvement factor for vibro replacement with simplifying assumptions. This factor depends both on the ratio of the grid area A to the area of the column A_c, and on the friction angle φ_c of the column material.

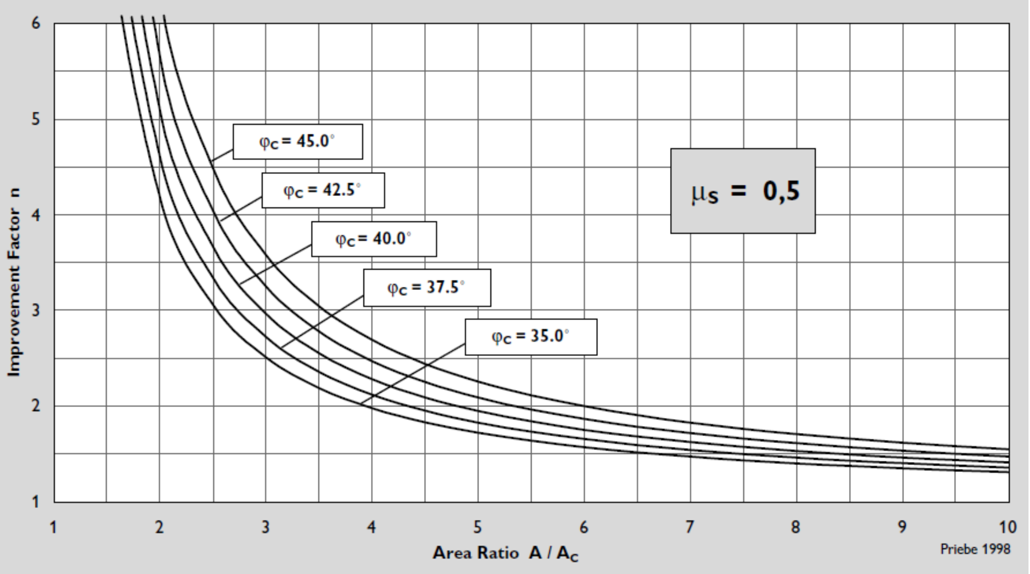

Figure 1: Design chart by Priebe, 1998 to calculate the soil improvement factor for settlements

The reciprocal value of this improvement factor corresponds to the relationship of the remaining stress p_s, which acts on the ground between the vibro replacement columns, and the total stress p without vibro replacement. Thus the presentation of the so-called reduction factor $p_s/p = \alpha$ results in figure 2.

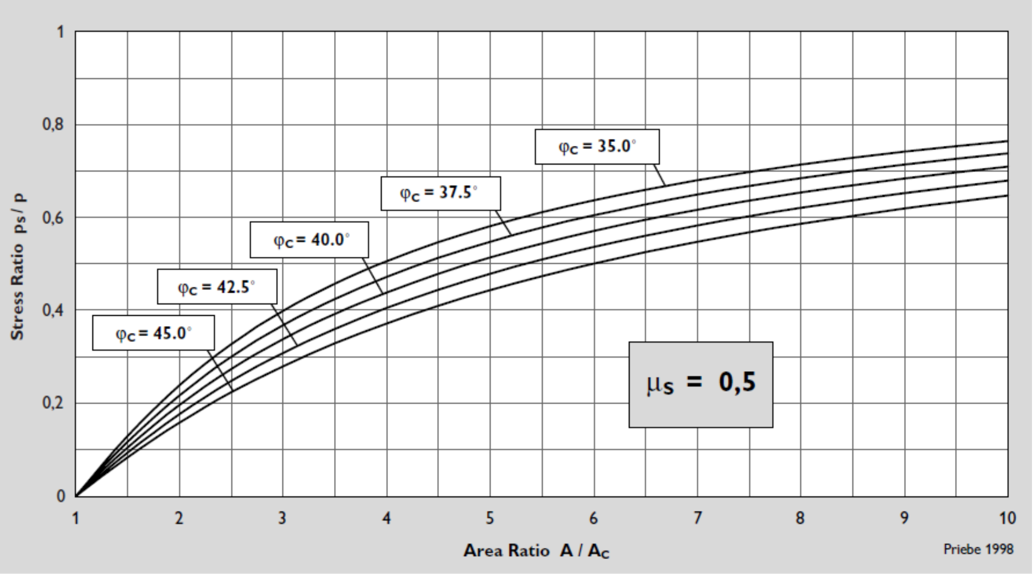

Figure 2. Reduction factor for the seismic stress ratio using vibro replacement (Priebe 1998)

With the plausible assumption that the area of the gravel columns and also the loads taken by it do not contribute to liquefaction, this reduction factor α can equally be used to reduce the seismic stress ratio created during the earthquake. Thus the density requirements of the subsoil exposed to liquefaction are reduced accordingly. Figure 3 shows, how the required cone penetration resistance decreases due to the reduced seismic stress ratio $\alpha \cdot CSR$.

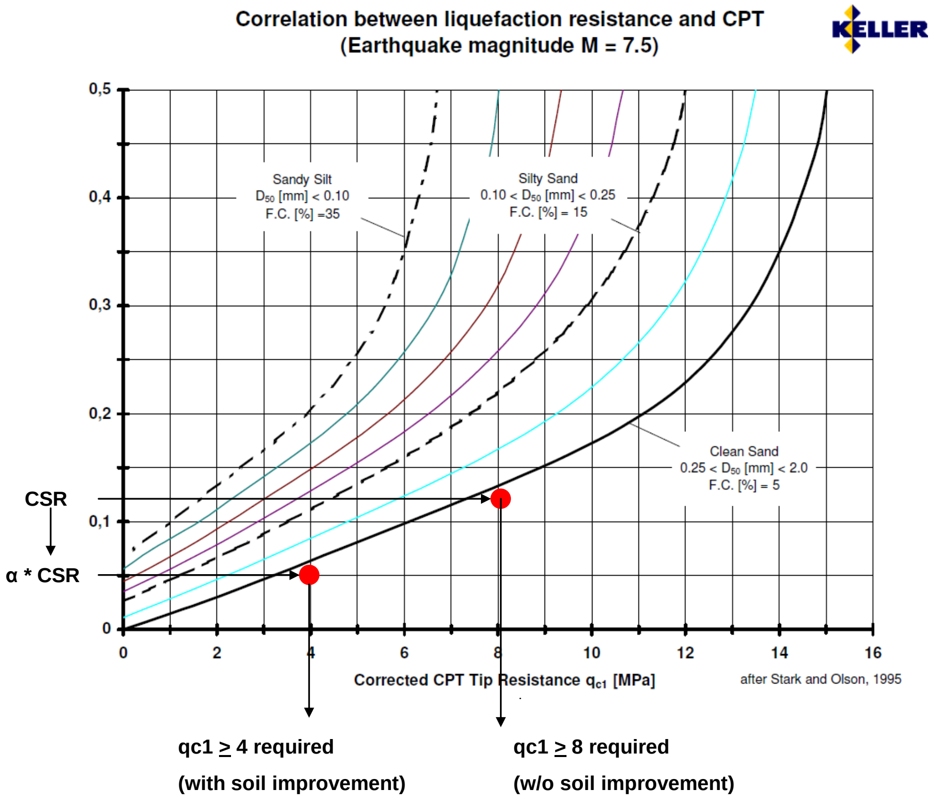

Figure 3. An example of reduction of the required cone penetration resistance q_c due to ground improvement (vibro replacement)

3 GROUND IMPROVEMENT METHODS TO REDUCE THE LIQUEFACTION POTENTIAL AROUND PILE FOUNDATIONS

As already mentioned, ground liquefaction arises due to earthquakes in particular, however not exclusively, in loose to medium dense homogeneous fine sands with low permeability. The range of these soils, which are effected mainly by liquefaction, is represented in figure 4 (hatched area). Further the application ranges of vibro compaction and vibro replacement methods are included. While in clean sands both ground improvement methods are applicable, vibro replacement method is more effective with increasing fines content.

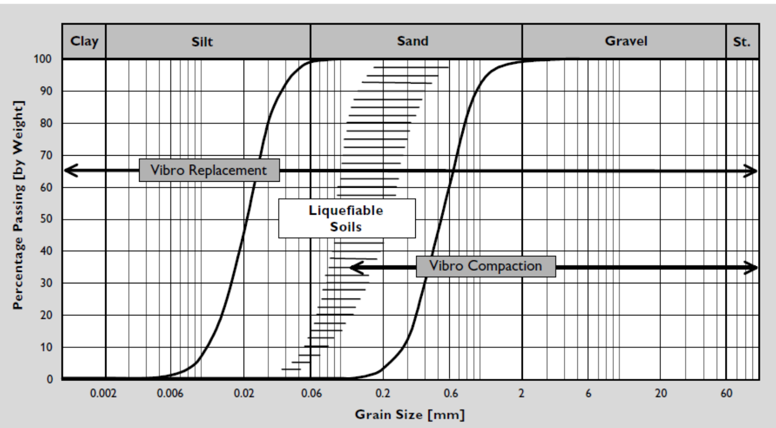

Figure 4. Application range of vibro compaction and vibro replacement methods by Priebe, 1998

Based on recent information in clayey and silty sands the risk of ground liquefaction in such soils must be examined as well. In accordance with Eurocode EC8 part 5 (DIN EN 1998-5) the risk of liquefaction should not be neglected in sands with a clay content of up to 20% (plasticity index PI> 10) or with a silt content of up to 35% (SPT-ratio of N_1 (60) > 20).

Even cohesive soils are endangered of liquefaction. As an example the so-called „Chinese criteria" is shown (see figure 5), which makes a principle classification into potentially liquefiable and non-liquefiable soils depending on the water content and the liquid limit.

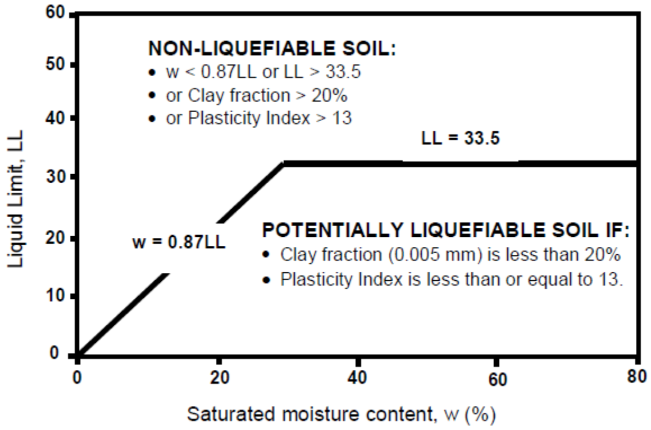

Figure 5. „Chinese Criteria" (modified by ASTM definitions)
for ground liquefaction by Perlea, 2000

Beside the vibro compaction and vibro replacement methods mentioned above a further ground improvement measure is the deep soil stabilization (Deep Mixing Method, briefly DMM), which is applicable in all soil types.

For special applications also earthquake drains can be used for the reduction of the liquefaction potential in soils.

4 REFERENCE PROJECT FOR VIBRO REPLACEMENT

Khalifa Bin Zayed National Stadium, Abu Dhabi: Vibro stone columns around bored piles (2009)

The Khalifa Bin Zayed National Stadium in Abu Dhabi was built on cast in-situ concrete piles with diameters 900mm and 1200mm and a pile spacing of 2.7m. At the time of the construction work the ground consists of a 2.4m thick fill (sand and gravel) placed as working platform, followed by 6-7m loose to medium dense silty, partly clayey sands, beneath gypsum-, sand- and claystone. In accordance with the official regulations the stadium was to be designed for an earthquake of magnitude 6.8 with a peak earthquake acceleration (PGA) of 0.22g. In order to avoid ground liquefaction of the top soil layers in such case, ground improvement became necessary around the piles (extent of the ground improvement, see figure 6).

Since the subsoil predominantly consists of silty/clayey sands (the fines content well over 10%), the vibro replacement method (vibro stone columns) was used. Apart from the increase of shear resistance, increased load-bearing capacity and increase in soil density, a high permeability of the stone columns was recognized as large advantage as well. In case of an earthquake with accompanying excess pore water pressures it could be assumed that a significantly faster reduction of the water pressure and thus avoidance of ground liquefaction takes place.

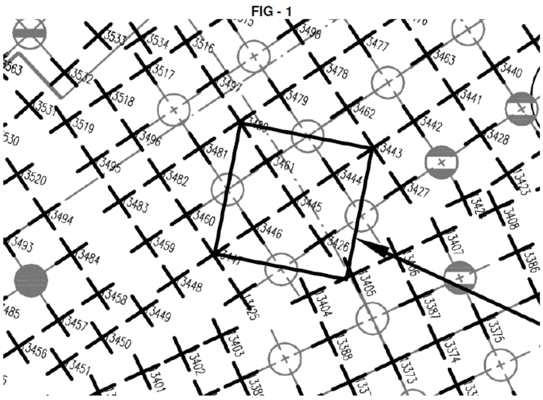

Figure 6. Typical arrangement of the vibro stone columns (crosses) around the bored piles (circles), with marked test field for load test

The assessment of the ground liquefaction risk and the design of vibro replacement were based on 74 cone penetration.

In figure 7 the cone penetration resistance of the unimproved soil ($q_{c,actual}$) and the calculated penetration resistance required for the safety against ground liquefaction are presented both with (q_{c2}) and also without stone columns (q_{c0}). As shown, the risk of ground liquefaction in the depth between 1.0m and 2.7m can be avoided by the installation of stone columns.

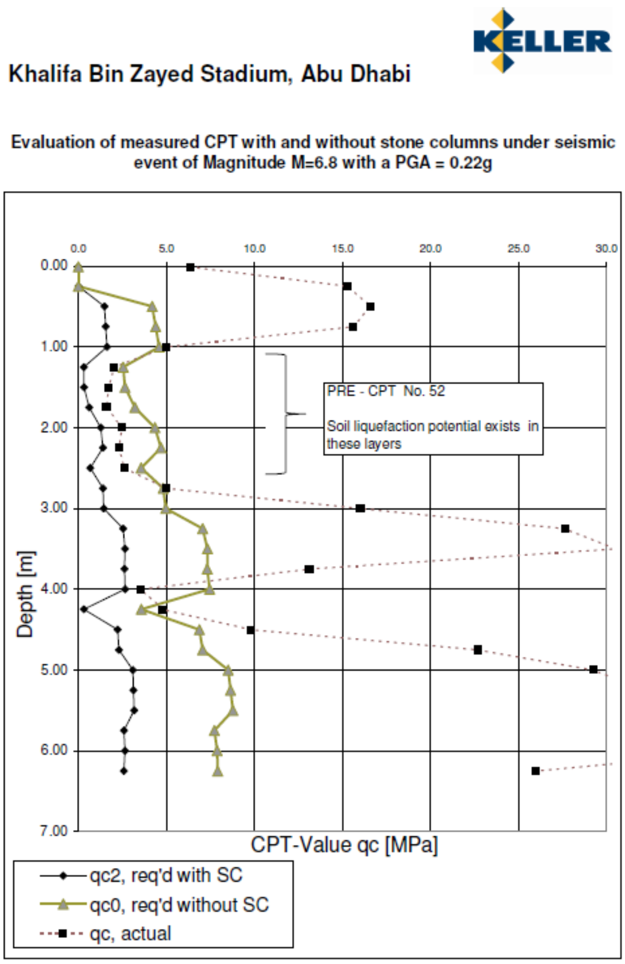

Figure 7. Cone penetration test including required tip resistance with and without vibro stone columns

Based on the site investigations the diameter of the vibro stone columns was set to 0.80m, the spacing to 1.35m and the depth to 6-7m.

The work sequence performed by Keller / UAE was as follows:

- Vibro stone columns had to be installed after the pile installation
- Level measurement of the working platform for the installation unit (vibrocat)
- Execution of pre-treatment CPT's (1 per 1000m²)
- Setting out installation points of the vibro stone columns in a square grid with spacing of 1.35m
- Due to the partially very dense top layer the upper 2m of the installation points had to be predrilled and further 2m of soil had to be loosened
- Installation of vibro stone columns by means of vibrocat, including electronic recording of depth, time, energy consumption, etc.
- Execution of post-treatment CPTs, plate load tests and large-scale load tests in order to confirm the design requirements

In only 2.5 months 50,000 m³ gravel were installed in 13,000 nos. vibro stone columns.

5 REFERENCE PROJECT FOR VIBRO COMPACTION

The Guggenheim Abu Dhabi/ Saadiyat Island: Vibro compaction prior to pile installation (2010)

The Guggenheim Foundation will construct their biggest museum of modern and contemporary art in Abu Dhabi. The over 30,000 square-foot large museum will be built on the Saadiyat Island according to the design by the American architect Frank Gehry. The subsoil at the construction site consists of loose to medium dense sands to a depth of about 4m with embedded thin silt and clay layers (0.10-0.30 m thick) beginning at 1.50m depth. Below the depth of 4m the in-situ density of the sands increases from dense to very dense. The exploration depth of cone penetration tests was approximately 5 to 7m.

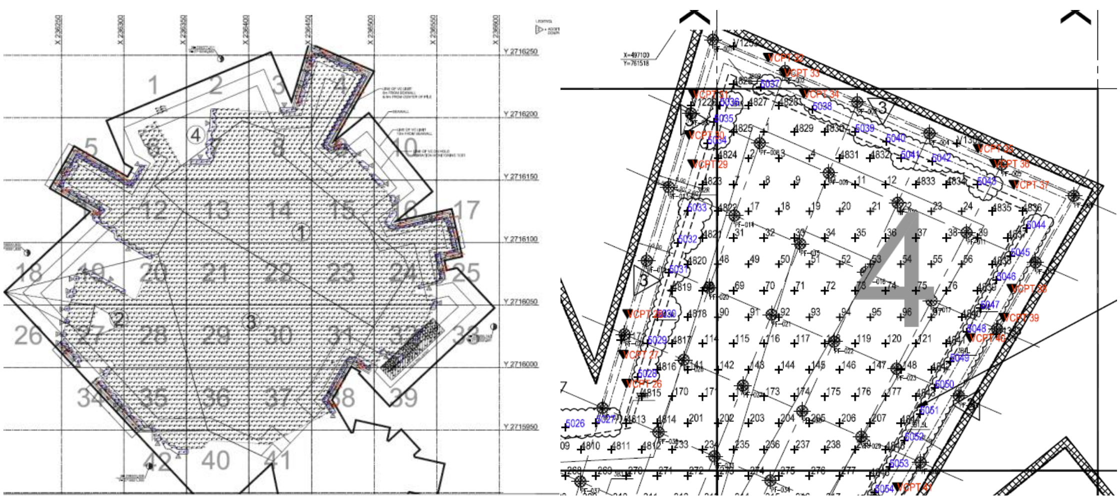

Figure 8. Layout of building with densification points (left),
detail of densification grid with pile locations (right)

In order to eliminate the risk of ground liquefaction during an earthquake event of magnitude 6 with a peak earthquake acceleration of 0.20g, the reclaimed sand masses had to be densified by means of vibro compaction up to a depth of 5m. According to the recommendations by the Geotechnical Consultant the subsoil improvement had to be executed prior to the installation of the pile foundation. Figure 8 shows the layout of the building (left) and a detail of the densification grid with the planned pile locations (right).

In order to determine the required spacing between the densification points field trials with 3 different spacings (triangular grid), 3.5m, 4m & 4.5m, were performed. The trials included as well the execution of 33 "Pre-compaction" cone penetration tests (CPT's) and 57 "Post-compaction" CPT's.

The interpretation of the field trials, including liquefaction analyses, led to the following conclusions:

- With a grid spacing of 3.5m and 4.0m the required cone resistance could be achieved up to a depth of 5m in all compactable layers
- Although the required cone resistance could not be achieved in the non-compactable layers (layers with a high fines content), even there the risk of liquefaction could be reduced successfully

Based on the above mentioned conclusions the densification was performed with a grid spacing of 4m. The densification success was proofed by means of pre-treatment and post-treatment CPT's.

The results of two exemplary liquefaction analyses (before and after execution of the densification) are compared in figure 9 and 10. It can be seen that the liquefaction risk in the depth from 2.5m to 3.6m (horizontally hatched) was eliminated successfully.

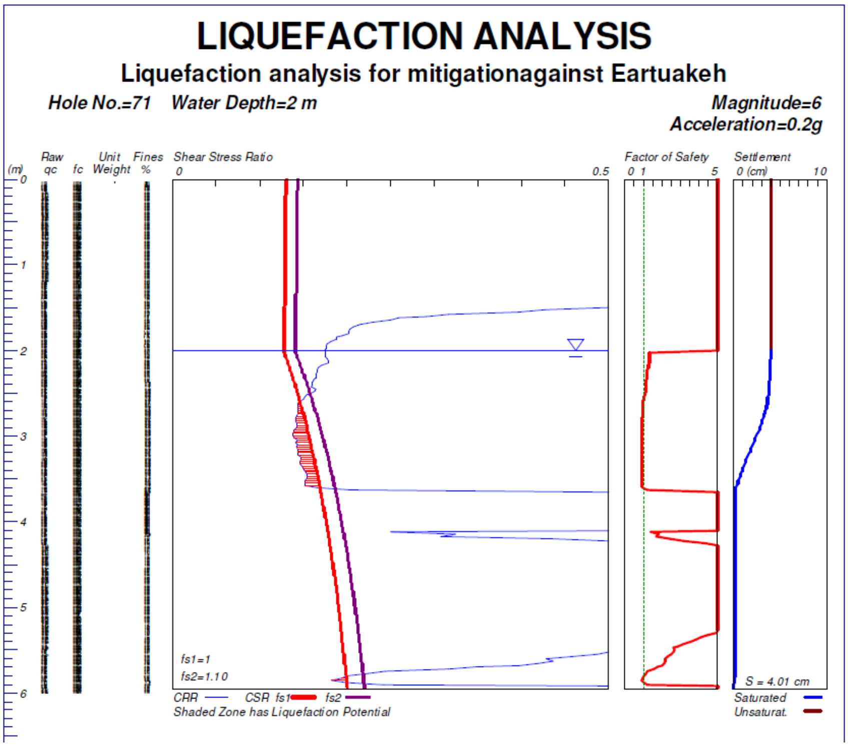

Figure 9. Liquefaction analysis (before densification)

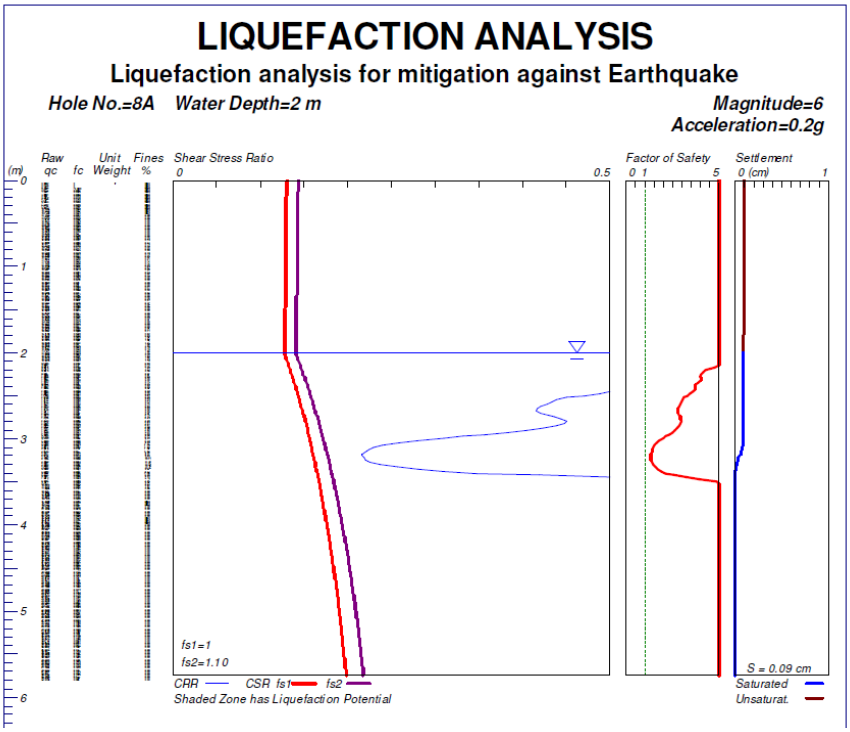

Figure 10. Liquefaction analysis (after densification)

6 CONCLUSIONS

- By means of the presented ground improvement methods the risk of ground liquefaction around pile foundations can be reduced. Thus a more economical design of pile foundations is possible.
- With the help of the diagrams of Priebe (1998), the planner has an instrument at hand to consider ground improvement quantitatively, particularly to reduce the seismic resistance ratio due to the application of vibro replacement and vibro compaction around pile foundations.
- While vibro compaction is suitable in coarse-grained soils, vibro replacement is applicable in both fine-grained and mixed soils.
- In some cases the presented ground improvement methods can be performed even subsequently (seismic retrofit).

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