The influence of dynamic loads on postglacial lacustrine fine-grained deposits

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ABSTRACT

In earthquake engineering it is well known that different types of soil, especially sand, have the tendency to liquefy due to dynamic loading. In this research, the dynamic loads are caused by construction methods like jet grouting, vibro compaction or vibro replacement and vibrated sheet pile walls and the soil types investigated are postglacial lacustrine fine-grained deposits, in general silt with different amounts of clay and/or fine sand. The most common liquefaction criteria the "Chinese criteria", Wang et al. (1979) does not fit for this type of soil. It shows in some cases similar liquefying or softening behaviour. Results using the liquefaction susceptibility criteria, Boulanger and Idriss (2006), are presented in this paper. Furthermore a case study to determine dynamic loads like acceleration and changes of pore water pressure during jet grouting is presented.

Keywords: dynamic loads, jet grouting, softening

1. INTRODUCTION

Bringing dynamic loads due to construction methods like vibro replacement, vibrated sheet pile walls or jet grouting into saturated soft to very soft fine grained soils often result in settlement effects without additional loads. In this paper the influence of dynamic loads - in particular jet grouting - on postglacial lacustrine fine-grained deposits is discussed. Jet grouting is a ground modification system whereby the soil gets eroded by a high speed water and/or a cement slurry jet (depending on whether single, double or triple tube jet grouting takes place). The range of pressure required to cut and mix the soil is between 100 and 400 bars. It can be applied in soils with a grain size from gravel to clay for improving soil strength and reducing soil permeability. While this has worked successfully in numerous cases, it has to be considered that jet grouting can induce settlements and ground movement as well (Wong et al. 1997). In several regions of Austria, jet grouting also caused ground surface deformation. Especially in relatively young (10.000 to 5.000 years old) soft to very soft fine-grained lacustrine deposits, great care seems to be required while using methods such as jet grouting. The change of pore water pressure and/or the vibrations have a significant influence

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on certain particle arrangements. Possible rearrangements of particles can lead either to the liquefaction of soils with a sand-like behaviour, or to a cyclic softening failure. Both terms describe similar phenomena in fine grained soils exhibiting clay-like behaviour (Boulanger & Idriss 2006). Another known term, cyclic mobility, which was introduced by Robertson & Fear (1995) is, in this case, not suitable because no settlements should occur after the pore water pressure decreases to its initial value. In two cases researched here, settlements were measured even months after using jet grouting.

Regarding the effects during earthquakes, a great deal of research has been conducted into the liquefaction of sandy soils and there is an increasing research focus on silty and clayey soils. The influence of construction methods on soils, which are susceptible to liquefaction, however, has hardly been studied. Questions that must still be addressed here are how large the dynamic loads (vibrations and changes in pore water pressure) induced by e.g. jet grouting are and whether they are big enough to cause liquefaction, cyclic softening, or even trigger further consolidation.

2. SOIL PARAMETERS FOR LIQUEFACTION CRITERIA

To produce a comparison of the two different liquefaction criteria, soil samples from five different locations in Austria were tested in the laboratory and necessary parameters like grain size distribution, liquid limit (LL) and the plasticity index (PI) were determined. The main similarity of these samples is that they are all postglacial lacustrine still water sediments. Due to the process of sedimentation, this type of soil is laminated (Figure 1). The thickness of these layers varies between millimetres and centimetres, and the grain size of the composition can be between fine sand and clay. The main grain-size fraction, however, is usually silt (Figure 2).

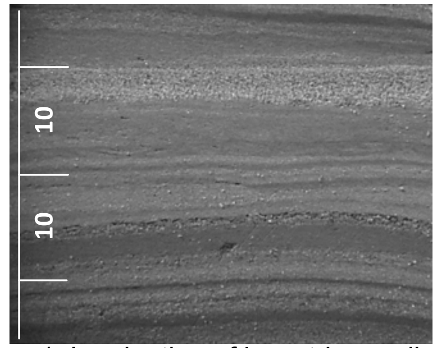

Figure 1. Lamination of lacustrine sediment

The entry values for the “Chinese criteria” (Wang et al. 1979) are the mass percentage of grains finer than 0,005 mm and the liquid limit (LL). For this research, the grain size distribution was determined by sieving and hydrometer analysis and, for the liquid limit as well as for the plastic limit (PL), the fall cone test (cone penetrometer test) and the linear shrinkage test according to ÖN B 4411:2009 were performed.

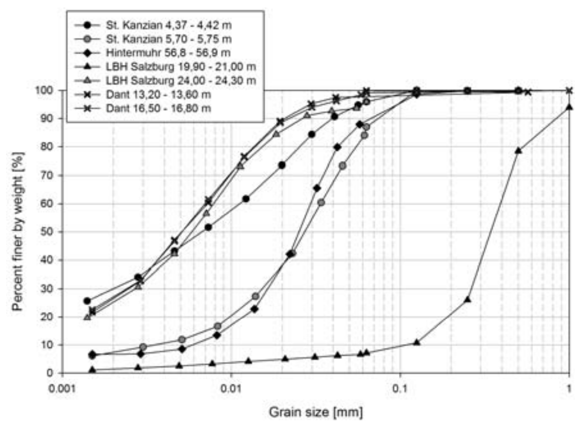

Figure 2. Grain size distribution

3. DETERMINING ACCELERATION AND PORE WATER PRESSURE DURING JET GROUTING

To determine the acceleration and the change in pore water pressure during jet grouting, two tests were conducted. The first test was performed in a 2.70 x 2.70 m chamber in the laboratory concurrently to a different research project dealing with jet grouting. The second series was a field test in St. Kanzian/Carinthia.

3.1. Measurement instrumentation

The measurement of the vibration was performed by two 3D 2g acceleration sensors (ACS) for high frequencies of up to 400 Hz. They are highly shock resistant and the casing (32 x 32 x 25 mm) is nitrogen dampened and hermetically sealed.The measurement of the changes of the pore water pressure was performed with two Glötzl push-in pore water pressure sensors (PWS). The measurement range of the sensors is between 0 and 10 bars.For data logging, a universal data logger and a laptop were used. The sampling rate was set to 400 Hz.

3.2. Laboratory test jet grouting

The laboratory test was performed by Keller Grundbau GmbH in an approx. 2.70 x 2.70 x 2.45m chamber (Figure 3). As filling, material sand was used and the jet parameters were 150 bar, 16 rpm with a pull speed of z = 3.5 cm/sec. The double tube system was used. The diameter of the jet grout column was projected with 1.0 m. After the installation of the sand including the sensors on two levels, the chamber was flooded and the sand saturated. The sensors had a distance to the centre of the jet grout column of 0.75 m and 0.25 m to the outline.

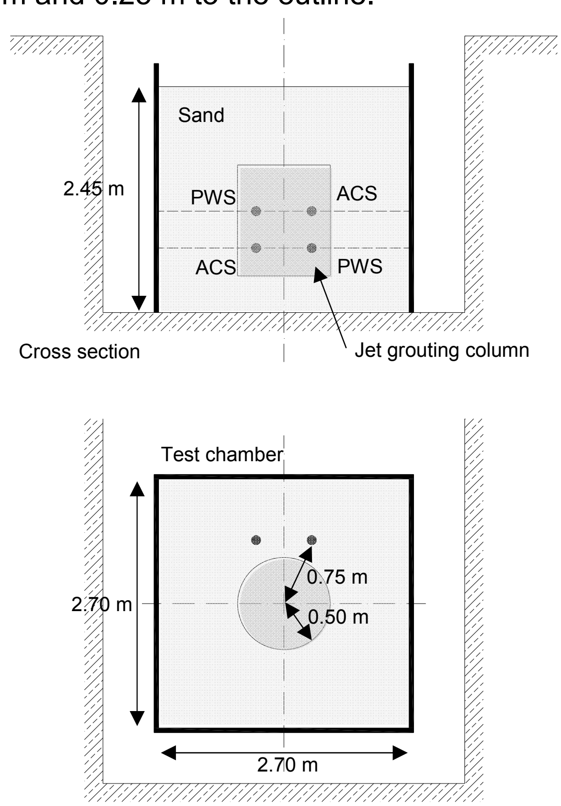

Figure 3. Sketch test chamber

3.3. Field test

The field test was located in St. Kanzian in the southern part of Austria. In addition to some jet parameter tests for a huge infrastructure project, it was possible to perform some in situ vibration and pore water pressure measurements. Therefore, the equipment used in the laboratory test was transferred to the testing field with the exception that only one PWS was used. The sensors were placed between the drilling points as shown in the following graphic at a depth of approx. 3.0 m by pre-drilling and using push-in rods that were withdrawn after the installation of the sensors. A double tube system was used with a maximum pressure of 400 bars, 48 rpm and a variation of pull speed z. The starting point for jet grouting was -8.5 m and the end point -2.5 m below ground level. All columns were pre-cut so the whole process included drilling, pre-cutting and jet grouting.

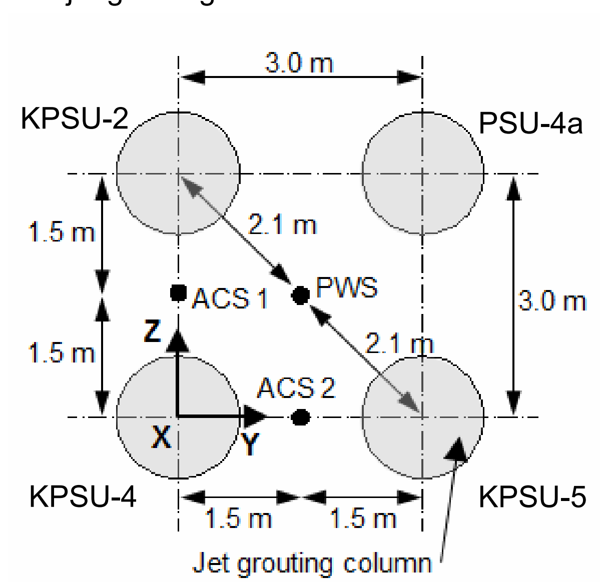

Figure 4. Layout field test St. Kanzian

4. RESULTS

4.1. Comparison of liquefaction susceptibility criteria

The results of the laboratory tests compared against the “Chinese criteria” chart show that only a few soils are susceptible to liquefaction. The range of the liquid limits values is between 26 % and 43.5 %. In detail, several samples from the two locations (Schüttdorf and St.

Kanzian) using this criterion have the potential to liquefy. Some results are close, but most of the soil specimens (Dant and LBH Salzburg) are in the "not susceptible" range. Based on the results of St. Kanzian, the influence of the grain size distribution can be shown. The difference in the grain size distribution (Figure 2) leads to a significant shift to the right, the not susceptible part of the Chinese criteria chart.

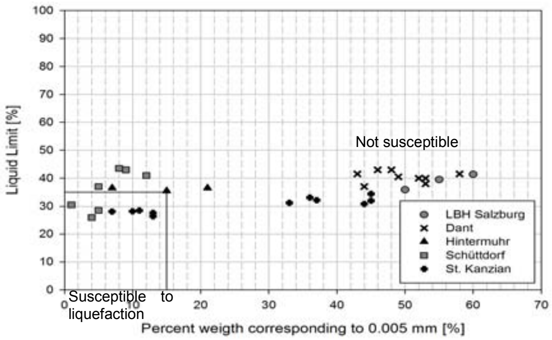

Figure 5. Graph Chinese criteria (Wang, 1979)

The same specimens are presented in the following chart using the liquefaction screening criteria (Figure 6). Most of the specimens are in the region of clay-like behaviour. Only two samples are in the transition zone. The samples that would potentially liquefy according to the previous criteria are in the sand-like behaviour area. The graph, extended with Zones A and B (shaded part) taken from the liquefaction screening criteria of Seed et al. (2003), shows that 40 % of the investigated specimens are potentially liquefiable and 60 % should undergo further testing if the water content $w_c \geq 0.85$ of the liquid limit.

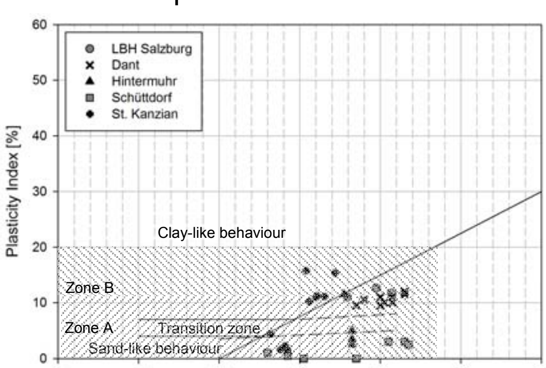

Figure 6. Graph liquefaction susceptibility criteria (Boulanger & Idriss, 2006)

4.2. Laboratory test jet grouting

The experiment in the chamber showed a change in the pore water pressure Δp of up to 0.044 bars (Figure 7). The drilling process caused this increase from a starting level (0.0 bars) to 0.01 bars. At the 2300 second mark, the jet grouting began and induced an increase of the pore water pressure. PWS 1 has a sharper increase and reaches the highest value of 0.043 bars after 2370 seconds, and decreases slightly until the end of the jet grouting procedure after 2425 seconds. The graph of PWS 2 shows a slightly more moderate but steady increase to a maximum of 0.044 bars. Both graphs decrease after the jet grouting has stopped. They also show a wave-like course during jet grouting. The waves have a frequency of 0.27 Hz and show the passing of the nozzle exactly (as seen in Figure 7 below).

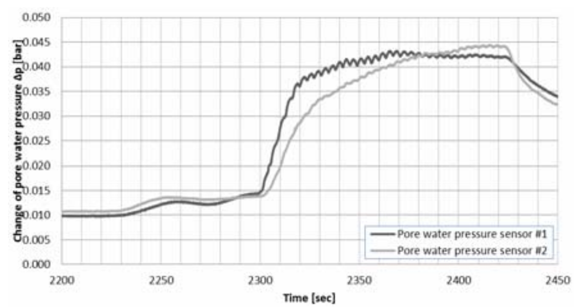

Figure 7. Lab test Pore water pressure [bar]

The following graph (Figure 8) presents a section (2325 to 2405 sec.) of the PWS 1 values. The difference between maximum and minimum of each wave is approx. 0.0015 bars and gets smaller towards the end.

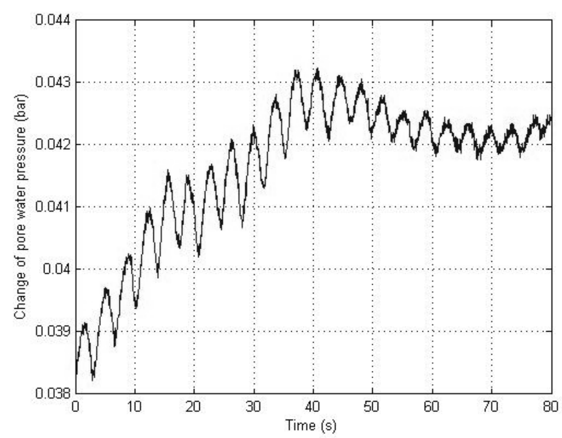

Figure 8. Pore water pressure PWS 1, detail

The measurement of the acceleration also showed the passing of the nozzle, but the background noise was high and the values (± 0.008 g) very low.

4.3. Field test jet grouting

In this paper, the results of acceleration and pore water pressure measurements of two jet grouting columns (KPSU-5 and KPSU-2) are presented. The results of the jet grouting column KPSU-5 show the two process steps, the pre-cutting approx. 990 to 1350 seconds and the jet grouting from approx. 1520 to 1860 seconds. The pore water pressure increases in the first step from 0.232 to 0.244 bars and only increases slightly until the next step. The maximum was 0.250 bars. The final difference of pore water pressure is 0.018 bars as seen in Figure 9.

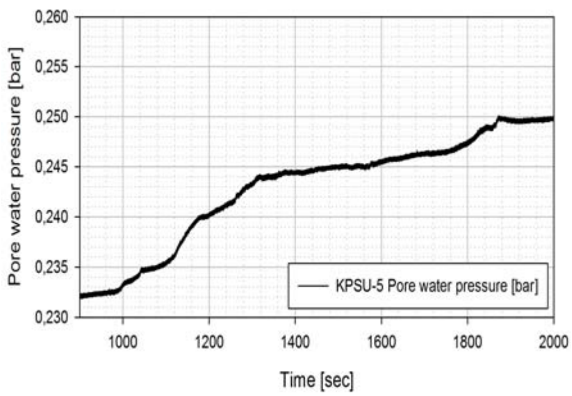

Figure 9. Pore water pressure KPSU-5

In the following charts (Figure 10), the accelerations of ACS 1 and 2 in all three axes are presented. The maximum values of ACS 1 are 0.020, 0.011 and 0.017 g (X-, Y- and Z-direction). The values are slightly higher during jet grouting compared to the pre-cutting phase. The smaller distance of ACS 2 to the column results in higher accelerations. The maximum values of ACS 2 are 0.200, 0.211 and 0.080 g. It is obvious that the maximum acceleration during jet grouting was reached when the nozzle was at the level of the senor. The vertical acceleration (X-direction) is almost as high as the acceleration parallel to the jet. The acceleration orthogonal (Z-direction) had the lowest value.

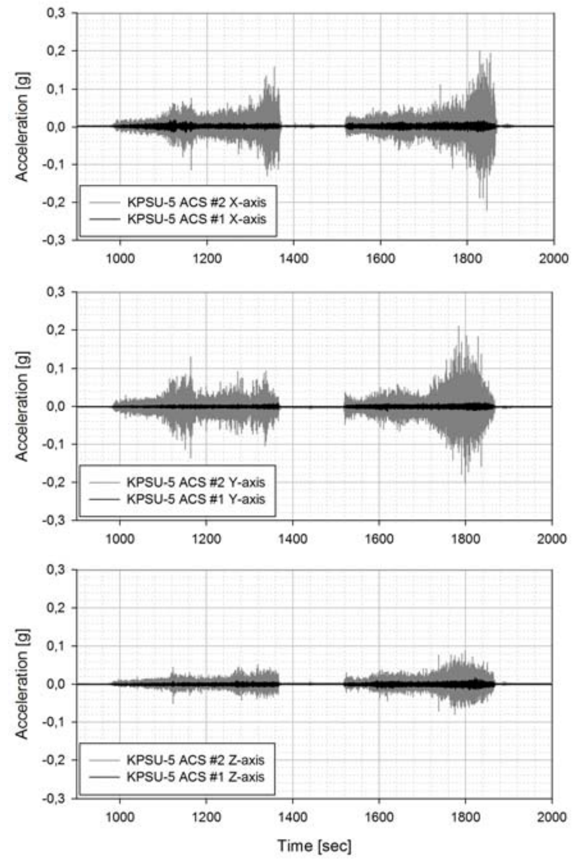

Figure 10. Acceleration KPSU-5, X-, Y- and Z-axes

The pore water pressure increases during the production of the column KPSU-2. This is partially significant as it coincides with the start of pre-cutting at the 1200 sec. mark. The pore water pressure rises from approx. 0.224 to 0.248 bars. After a decrease to a constant level of 0.242 bars, the jet grouting phase increases the pore water pressure to a maximum value of 0.251 bars. The final difference of pore water pressure is 0.027 bars (Figure 11).

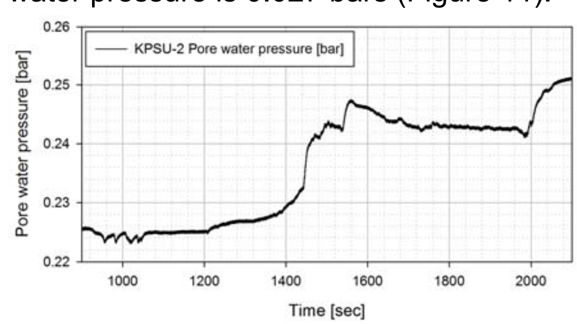

Figure 11. Pore water pressure KPSU-2

The accelerations in all directions were lower than those measured for KPSU-5. There is only a slight difference in the X- and the Z-axis of ACS 1 and ACS 2. The maximum values for ACS 1 are 0.090, 0.030 and 0.049 g and for ACS 2 0.041, 0.019 and 0.020 g.

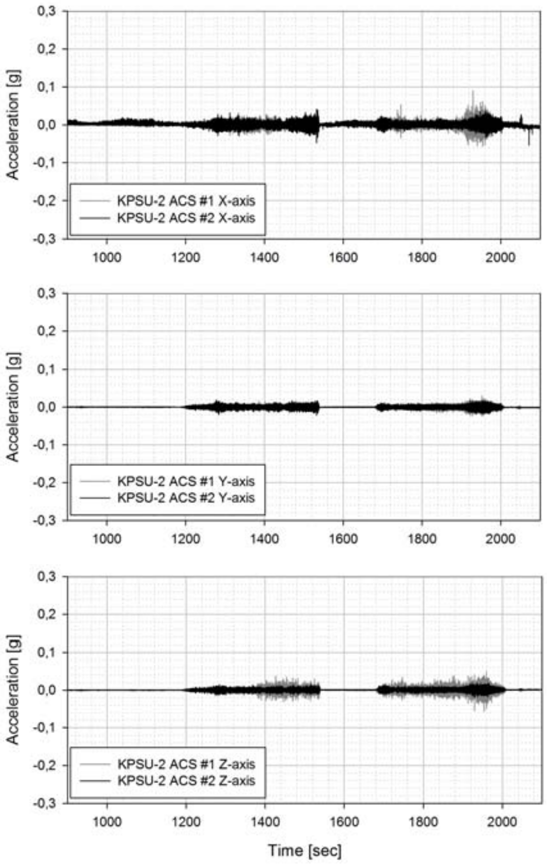

Figure 12. Acceleration KPSU-2, X-, Y- and Z-axes

5. CONCLUSION

All of the soils tested here have shown their potential to liquefy or undergo cyclic softening. Due to the lamination of these soils, it is also possible that only certain layers liquefy or particles rearrange. The input of vibrations and/or excess pore water pressure during jet grouting is not significant, as is shown in the presented results. In some cases, it was still enough to induce settlements not only in an area next to the jet grouting column, but also up to more than 10 meters away. The trigger for these settlements still has to be identified, especially when high clay contents (up to 30 %) contradict the theses of liquefaction. It also has to be considered that the mineralogical composition may have a major influence on the soil behaviour.

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