An experimental investigation into the performance of polyurethane grouting in soil

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ABSTRACT
This paper presents an experimental study on the performance of a two component polyurethane grout. The grout is injected into the soil with packers and polymerized with volume expansion. The strong expansion of grout causes compression of the surrounding soil near the injection point. The improvement of the mechanical behaviour of soil through grouting is investigated by an extensive testing program, which includes the penetration resistance by dynamic probing, the measurement of density and water content with a nuclear gauge, the static and dynamic plate loading tests. The large scale tests are carried out under clearly defined and reproducible conditions.

RÉSUMÉ
Cet article présente une étude expérimentale sur la performance d'un coulis de polyuréthane en deux composants. Le coulis est injecté dans le sol á l'aide des emballeurs et polymérisés avec l'expansion du volume. La forte expansion de coulis cause la compression du sol près du point d'injection. L'amélioration du comportement mécanique des sols par injection est étudiée par un vaste programme de tests, qui comprend la résistance à la pénétration dynamique par sondage, la mesure de la densité et de la teneur en eau avec une jauge nucléaire, les essais de chargement statiques et dynamiques á la plaque. Les essais à grande échelle sont réalisées dans des conditions clairement définies et reproductibles.

1 INTRODUCTION

Polyurethane grouting is usually used for providing water control in ground and structures (Kriekemans 1984, Zelanko and Karfakis 1997, Town 2003, Vipulanandan and Liu 2005). It is especially effective for cutting off gushing water of high pressure and speed. The grout material together with an accelerator will react with water and expand fast to form an impermeable foam. Recently polyurethane grouting has also been used as an effective chemical grout for soil stabilization.

Some basic geotechnical investigations on polyurethane grouting had already been performed both by the University of Padua (Ricceri and Favaretti 2004) and by the IFB Gauer in Germany (Institut Dr.-Ing. Gauer Ingenieur-GmbH 2007). New investigations are carried out by means of nuclear gauge (to determine soil density and water content), plate load tests, dynamic penetration tests (DPL), as well as dynamic plate load tests.

The above investigations were performed on three different soils, before and after grouting. Moreover, two different polyurethane resins were tested: GeoPlus and GeoPlus I. Investigations on the second resin had not been carried out and the producer himself still exhibited some uncertainties on its stabilization capacity.

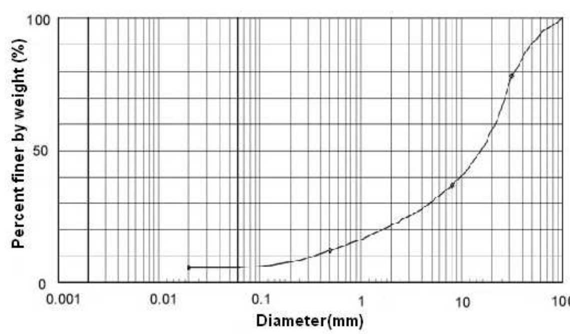

Figure 1. Leitha-gravel, granulometric curve

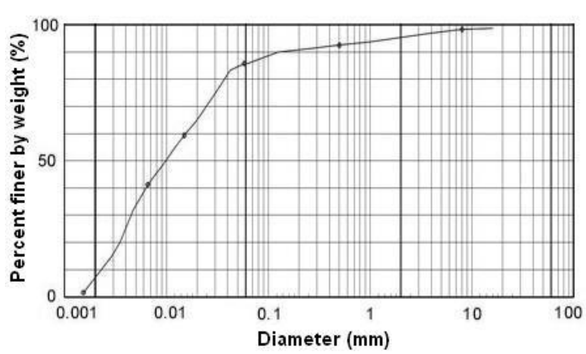

Figure 2. Tegel-marl, granulometric curve

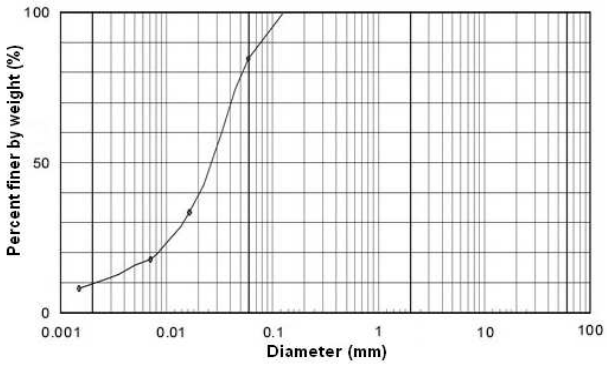

Figure 3. Loess, granulometric curve

2 TEST SET-UP

One cohesionless soil (Leitha-gravel) and two cohesive soils (Tegel-marl and Loess) were tested.

Six concrete pipes, with the diameter of about 2 m and the height of about 1 m, were filled with the tested soil. Geomembrane was placed at the bottom of each ring to reduce the interaction between the soils and the concrete pipes. 2000 mm each, were filled with the soils.

Soils were placed into the concrete ring by an excavator from the same height. Leitha-gravel and Loess were spread in two layers of about 80 cm each, whereas Tegel-marl was placed in 40 cm strata and compacted. A frame of steel beams and rods was set up, which serve as a reaction frame for the plate load tests (Figure 4).

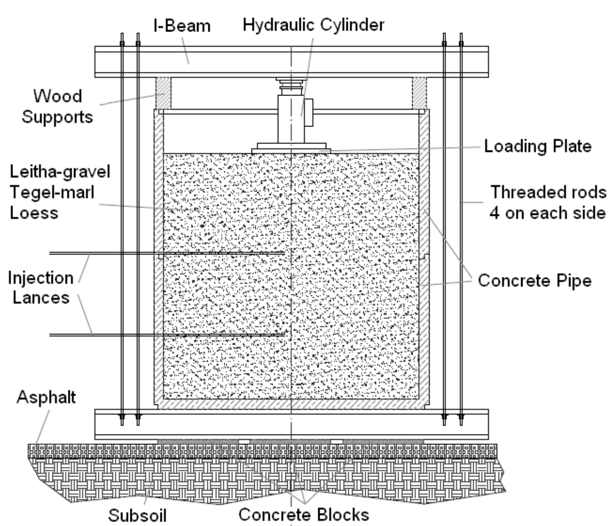

Figure 4. Concrete cylinder and testing set-up

The settlement of the loading plate was measured by four displacement transducers placed around the plate as shown in Figure 5.

To ensure the reproducibility and in order to be able to compare the results obtained with the two different resins, soil properties such as soil density, dry density and soil water content were measured by means of nuclear gauge tests carried out at about 80 cm below the soil surface. These results were compared with the laboratory tests. Some Proctor tests were also performed in the laboratory on Tegel-marl and Loess.

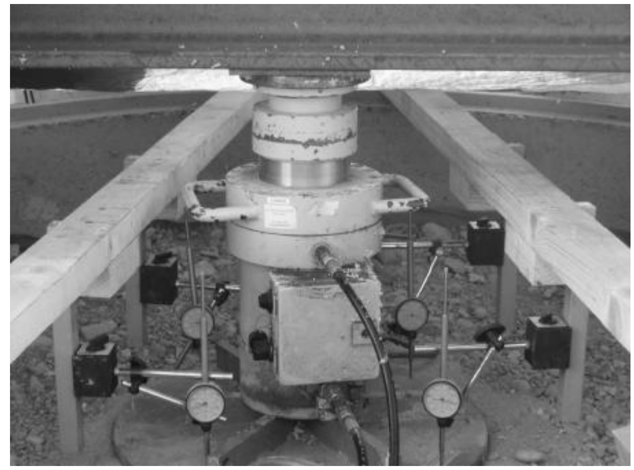

Figure 5. Settlements Measuring System

2.1 Grouting and plate load test

The injections were performed at two levels, i.e. about 1 m and 0.4 m above the cylinder bottom (Figure 6). The grout nozzle was pushed a few centimetres into the soil and little grout was injected. This prevents the outflow of grout along grouting hole. The injection was performed first at the level of 1 m above the bottom and then at the level of 0,4 above bottom. The injection sequence is important for the second injection with higher pressure should not cause burst-out of grout at the soil surface. The spreading of the grout was observed after the tests through excavation. The grout was found to be highly localized in cohesive soil, whereas more homogeneous distribution was observed in cohesionless soil.

The deformation behaviour of grouted and ungrouted soil was investigated by plate load tests. Plate load tests enable to obtain the stress-settlement curves. The deformation moduli $E_{v,0.1}$ and $E_{v,0.2}$ can be determined. The two moduli are determined at σ = 0,1÷0,2 MPa and σ = 0,2÷0,4 MPa respectively. The test plate is circular with a diameter of 60 cm. As the diameter of the load plate is quite small in comparison with that of the container, boundary conditions are not expected to influence the results.

Following the Austrian Standard (ÖNORM B4417), the formula for E_v is:

$$E_v = 0{,}75 d \frac{\Delta\sigma}{\Delta S} \qquad [1]$$

where d = 0,6 m is the plate diameter, ΔS is the settlement and $\Delta\sigma$ is one of the two above stress increments.

The loading program is shown in Figure 7. Loading took place at constant rate until 300 kPa, after which unloading took place until 20 kPa was reached. The load was then increased until a settlement greater than 0.02 mm per minute was measured. In general, Tegel-marl and Loess showed larger settlements, whereas Leitha-gravel showed stiffer behaviour.

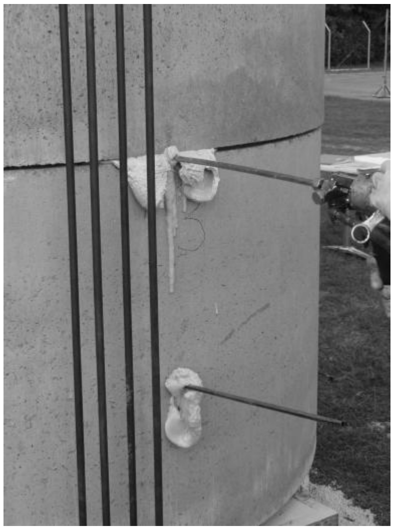

Figure 6. Injection sequence

GeoPlus I settlement reduction proved to be greater than the on enhanced by GeoPlus for both Leitha-gravel and Loess, it is however impossible to compare results obtained for Tegel-marl as the concrete pipe cracked at the bottom during the plate load test.

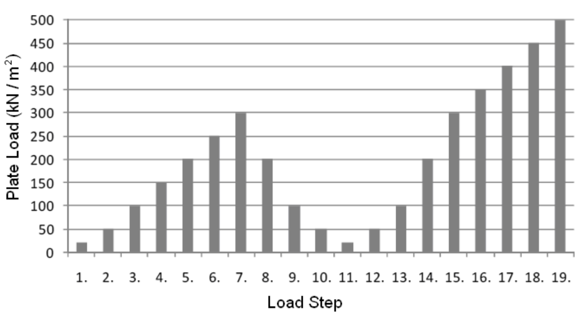

Figure 7. Loading sequence

2.2 DPL and dynamic plate load test

The dynamic penetrometer consists of a steel rod with slightly enlarged cone tip. The dynamic penetration test is carried out similar to the SPT. The steel rod is rammed by a hammer of 10 kg dropped from the height of 50 cm. The cone diameter is 35.7 mm with an area of cross section of 10 cm^2. The number of hammer blows for a penetration depth of 10 cm is registered, which provides some indication to the soil resistance. The dynamic penetration test is widely used in the German speaking countries.

The dynamic load plate test is similar to the plate load test with the difference that an impact load is applied by dropping a hammer at given height. A circular steel plate with a diameter of 30 cm was used. The load set consists of a falling weight along a guide rod. After release, the falling weight slides down along the guide rod and hits a spring-damper element. The maximum plate displacement of three consecutive tests leads to an approximation of the dynamic deformation modulus of the tested soil layer.

3 TESTS RESULTS

The tests results are shown for Leitha-gravel, Tegel-marl and Loess separately. As expected, polyurethane grout improves both soil stiffness and bearing capacity.

3.1 Tests on gravel

The plate load test was carried out to a stress of σ = 500 kPa. The test on natural soil (ungrouted) was stopped at σ = 400 kPa for too large settlement.

Figure 8 shows large reduction in settlement for grouted soil compared to natural soil of the same initial density. A perusal of the settlement at the stress level of 200 kPa shows that the settlements in natural soil is about ten times as large as in grouted soil.

The best results were achieved with GeoPlus I resin, which reduced the settlement of GeoPlus by further 60%. It seems that both soil type and grout type have influence on the performance of grouting.

The unloading curve shows much stiffer behaviour in all cases, leading to the conclusion that the plastic deformation of the soils tested is a major fraction of total soil deformation.

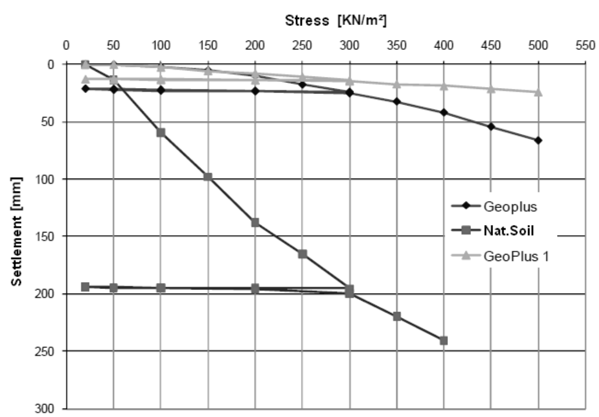

Figure 8. Plate load tests on Leitha-gravel

The deformation moduli $E_{V,0.1}$ and $E_{V,0.2}$ are shown in Figure 10. The highest value is observed for GeoPlus I resin followed by GeoPlus and natural soil. The difference between the two resins is more pronounced for $E_{V,0.2}$ modulus (Figure 10).

Figure 9 shows the number of blow count in grouted and ungrouted gravel. The DPL test was carried out after the plate load test. There is no significant difference for the first 30 cm, which is probably due to the compaction of the plate loading test. Significant increase of the number of blows can be observed at larger depth. The test was terminated at a depth of about 0.90 m, where the penetrometer was stopped by large gravel.

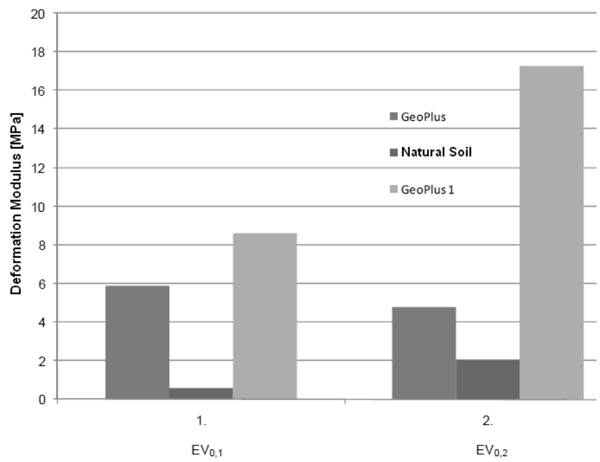

Figure 10. Deformation moduli for Leitha-gravel

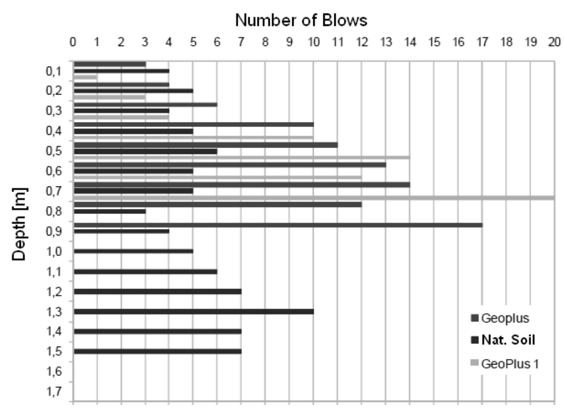

Figure 11. Penetration tests on Leitha-gravel

The following table shows the results of the dynamic plate load test. As can be seen from Table 1, grouted soils show higher deformation modulus. The grout GeoPlus I shows better performance than GeoPlus.

Table 1. Dynamic plate load tests on Leitha-gravel

Soil	GP	NS	GP1	GP	NS	GP1
	S_m	S_m	S_m	$E_{v,d}$	$E_{v,d}$	$E_{v,d}$
	(mm)	(mm)	(mm)	(MPa)	(MPa)	(MPa)
Gauge 1	1,79	2,59	1,43	12,59	8,67	15,70
Gauge 2	1,50	1,73	1,62	14,97	12,80	13,86
Gauge 3	2,06	1,96	1,94	10,94	11,58	11,58
Average	1,30	1,44	1,01	17,36	15,62	22,36

GP: GeoPlus; NS: natural soil (ungrouted); GP1: GeoPlus I
S_m: settlement; $E_{v,d}$: deformation modulus

3.2 Tests on marl

As with Leitha-gravel, also for Tegel-marl, the plate load test on the natural soil had to be suspended (this time at σ = 200 kPa) due to excessively large settlement. For grouted soil, however, the test could be continued till the pressure σ = 400 kPa (
Figure **12**).
It can be seen from
Figure **12** that natural soil shows large settlement and the test was terminated at σ = 200 kPa. The effect of grouting can be clearly observed by the reduced settlement. A perusal of
Figure **12** shows that GeoPlus shows better performance than GeoPlus I. This is different from the tests on gravel.

During the test with GeoPlus I the problem reported in Section 2.1 arose and hence the results are not representative. The unloading diagram is again very flat due to the plastic behaviour of the grouted soil.

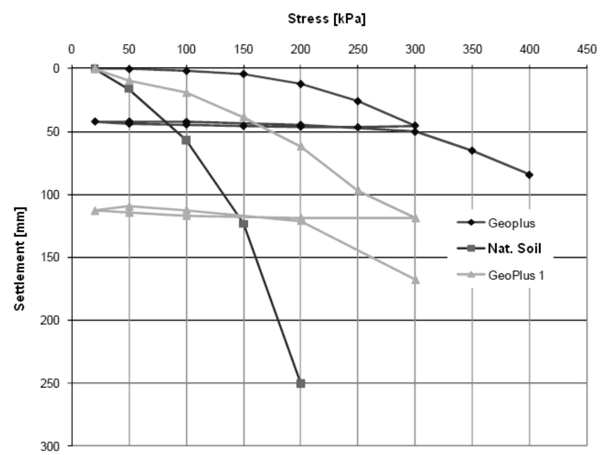

Figure 12. Plate load tests on Tegel-marl

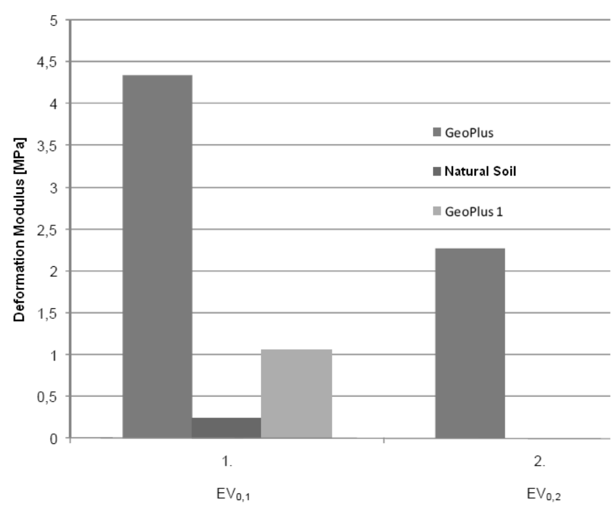

Figure 13. Deformation moduli for Tegel-marl

The deformation moduli are shown in Figure 14. Only the deformation modulus $E_{v,0.1}$ is calculated. The modulus $E_{v,0.2}$ was not calculated for ungrouted soil and GeoPlus I. However, the difference in modulus between GeoPlus-grouted and natural soil is about eight times.

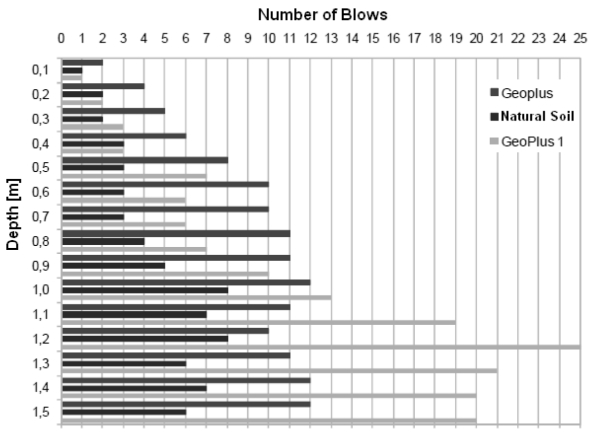

Figure 15. Penetration tests on Tegel-marl

The penetration tests are shown in

Figure **15**. In general, grouting gave rise to higher resistance, which is manifested by increasing blow counts. In fact, the blow count in grouted soil is about twice as high as that in ungrouted soil till the depth of about 1 m. The blow count was lower for GeoPlus I compared to GeoPlus until 1 m. Below this depth, however, GeoPlus I shows larger increase of blow count with depth.

Table 2 shows the results of the dynamic plate load tests. As can be seen from Table 3, grouted soils show higher deformation modulus. The grout GeoPlus shows better performance than GeoPlus I.

Table 4. Tegel-marl, Dynamic Load Plate Test, Settlement Average and Dynamic Deformation Modulus

Soil	GP	NS	GP1	GP	NS	GP1
Measured quantity	S_m	S_m	S_m	$E_{v,d}$	$E_{v,d}$	$E_{v,d}$
Unity of measurement	(mm)	(mm)	(mm)	(MPa)	(MPa)	(MPa)
Average	1,53	4,73	3,87	14,67	4,75	5,81
1	2,02	6,24	5,23	11,13	3,60	4,30
2	2,16	6,07	4,51	9,98	3,70	4,98
3	1,98	6,06	4,40	11,50	3,50	5,11

3.3 Tests on loess

As expected loess shows larger settlement compared to gravel and marl. Due to excessive settlement, the tests in grouted soils had to be stopped at the pressure of 200 kPa (Figure 16). The settlement in ungrouted soil is even larger and the test was terminated at the pressure of 100 kPa. The effect of grouting was however evident as settlement in the pressure till 100 kPa is reduced by about ten times. The performance of GeoPlus 1 is slightly better than that of GeoPlus with the settlements measured in GeoPlus I about 22% smaller than those in GeoPlus.

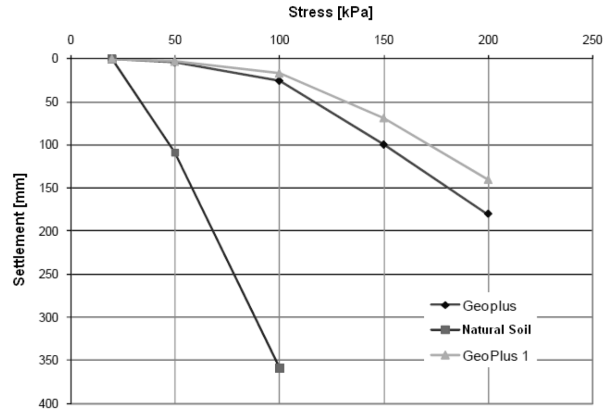

Figure 16. Plate load tests on loess

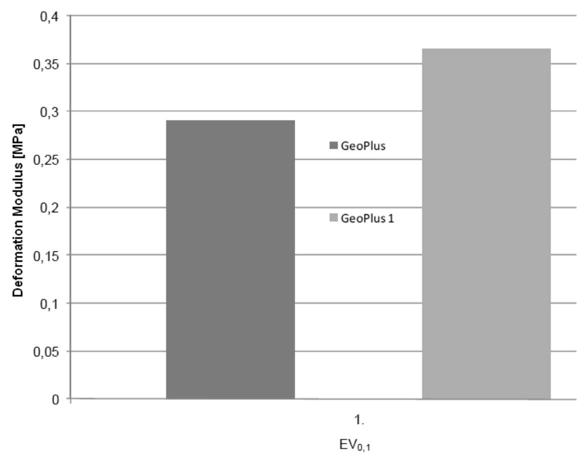

Figure 17. Plate load tests on loess

The deformation moduli from the plate load tests are shown in Figure 18. Due to excessive settlement only $E_{v,0.1}$ could be evaluated. As in the case of Leitha-gravel, GeoPlus I shows better performance than GeoPlus.

Figure 19 shows the penetration tests on grouted and ungrouted loess. In general, grouted soils show higher blow count than ungrouted soil. The effect of compaction from the plate load test can be observed till the depth of about 0.50 m. Below this depth the blow count in grouted soils is about four times higher than the blow count in ungrouted soil. Loess grouted with GeoPlus I shows less blow count than loess grouted with GeoPlus. This is to be ascribed to the poor spreading of grout in loess. The spreading of grout was observed by excavating the grouted soil after tests. The spreading of grout in loess was in form of thin laminates. Better spreading of grout was observed in gravel.

Finally, the dynamic plate load tests are shown in Table 5. The better performace of GeoPlus corresponds well with the higher deformation modulus, which is about twice as high as that of GeoPlus I.

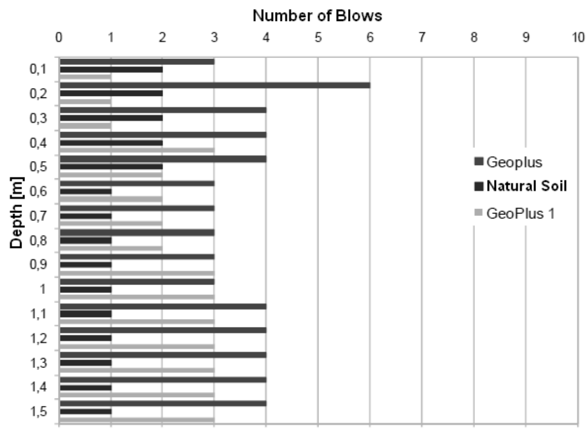

Figure 20. Penetration tests on loess

Table 6. Dynamic plate load tests on loess

Soil	GP	NS	GP1	GP	NS	GP1
Measured quantity	S_m	S_m	S_m	$E_{v,d}$	$E_{v,d}$	$E_{v,d}$
Unity of measurement	(mm)	(mm)	(mm)	(MPa)	(MPa)	(MPa)
Average	1,73	1,78	3,50	13,35	13,31	6,44
1	3,48	4,97	5,67	6,45	4,52	3,96
2	3,89	4,46	5,42	5,77	5,04	4,15
3	3,75	4,43	5,66	6,10	5,08	3,97

4 CONCLUSIONS

- Positive effect of the grout GeoPlus and GeoPlus I on the deformability and bearing capacity can be clearly observed in the plate load tests;
- Settlement in Leitha-gravel was greatly reduced by grouting. GeoPlus I showed better performance than GeoPlus;
- Settlements in cohesive soils (Tegel-marl, Loess) were also greatly reduced. The spreading of grout in the cohesive soils was less homogeneous than in gravel;
- Both $E_{v,0.1}$ and $E_{v,0.2}$ could be obtained for Leitha-gravel. The differences in $E_{v,0.2}$ between GeoPlus and GeoPlus I is even greater than those in $E_{v,0.1}$. The deformation modulus $E_{v,0.1}$ in GeoPlus-grouted Tegel-marl is about eight times higher than in natural soil. GeoPlus I provided better improvement in E_v in the case of Loess;
- The penetration tests show large increase of the blow count in grouted soil compared with ungrouted soils below certain depth. Above this depth, the soil was compacted by the plate load testes conducted before the penetration tests;
- The deformation moduli from the dynamic plate loading tests on Leitha-gravel and loess were only slightly higher than that of the natural soil. The improvement in the E_{vd}-modulus is more evident with Tegel-marl;
- There is only little difference in the performance of the two grouts GeoPlus and GeoPlus I. The performance of the grouts seems to depend on the soil type. GeoPlus I is slightly better than GeoPlus in gravel. In Tegel-marl, however, GeoPlus shows better performance than GeoPlus I.

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