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State of the art of compensation grouting in Germany

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ABSTRACT: Since its introduction in 1987 for tunnelling, compensation grouting has developed into a viable geotechnical method which today enjoys a wide range of application in construction work. Basic information is given about efficiency and practice. Case histories are presented where compensation grouting was used for ground improvement, for heaving of building and for protection against settlements during tunnel driving. Special attention is drawn to an advanced measurement system for monitoring movements of soils and foundations.

RÉSUMÉ: Depuis son introduction en 1987 pour des injections de compensation dans le cadre de projets de tunnels, la technique du Soilfrac s'est avérée être une méthode géotechnique sûre qui satisfait un large éventail d'applications dans les domaines de la construction. Nous bénéficions aujourd'hui du retour d'expérience provenant de nombreux chantiers réalisés. Différentes applications sont présentées, où l'injection de compensation a été utilisée pour des renforcements de sol, pour des redressements d'ouvrages et pour des protections contre les tassements pendant les phases de creusement de tunnels. Une attention particulière est apportée aux systèmes d'instrumentation nécessaires pour mesurer le mouvement des sols et des fondations.

1 INTRODUCTION

The Soilfrac®-system (Compensation Grouting) is basing on the hydraulic fractioning of the ground by the injection of water or grout. Originally applied in the mineral oil technology, it was soon used to solve geotechnical problems. Bernatzik (1951) was the first to report on the procedure of soil fractioning with cement grout and to describe experiences when heaving a coke oven in the city of Essen (Germany) (s. Table 1). At that time movements were just controlled by levelling.

Table 1: Selection of early projects of compensation grouting

Project	Year	Reason
Essen, coke oven	1949	mining activities
Hessigheim, lockage	1951	soil loss
Wien, hospital	1967	soft soils
Bochum, church	1977	soft soils
Essen, AEG Kanis	1986	subway tunnelling

Ever since about 1970 the method was improved by the use of injection pipes with groups of peripheral holes which are covered with rubber sleeves to act as valves (TAM = tube-à-manchettes). It now became possible to repeat, at the very place, controlled injections. Since about 1986 modern real-time monitoring systems for the observation of building and subsoil deformations enabled to take direct action on the current course of settlements.

Due to these developments the method could be applied in tunnel driving and was used in 1986 for the first time in Essen (Germany) whilst undercutting of the production buildings of the AEG-Kanis company. Gabener, Raabe, Wilms (1989) reported on this. Because of the good results obtained, further complex projects could be carried out, like in Bielefeld (Germany) in 1989 where a tunnel of 25 m of width subcrosses a block of houses at a depth of some 4.3 m only below the foundations (Fig. 1).

In the course of time the monitoring systems had to meet increased requirements. Today, in Germany, mostly automatic Water level systems on the basis of pressure cells (e. g. GeTec system) are operating with indicators showing an accuracy of

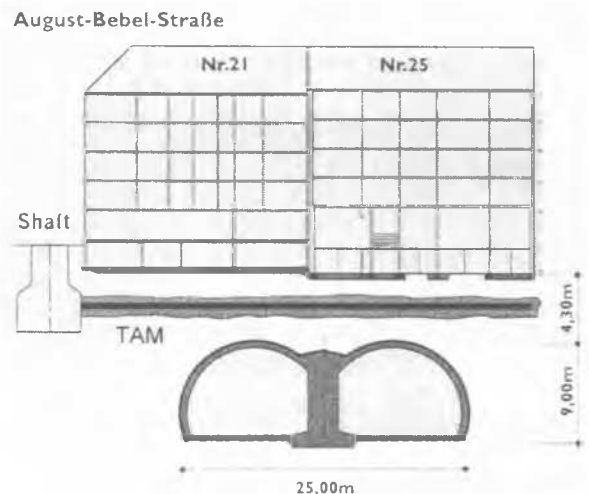


Fig. 1: Tunnel profile beneath Building 21/25

0.02 mm each. Combined with an user-optimized evaluation software, all requirements with regard to reliability, rapidity and graphical display can be met.

2 PERFORMANCE

The Soilfrac®-system is applicable to almost all types of soil. However, the efficiency can decrease considerably at certain boundary conditions. This concerns soils where the state of stresses approaches the state of failure, in particular. According to experiences on record, cohesive soils of soft to very soft consistency can be improved only slightly. In many cases, the execution in these soils requires considerable effort and is therefore uneconomical.

All Soilfrac® applications refer to settlements of buildings which arise from two reasons: a) overstressing of the subsoil or b) redistribution of stresses due to loss of soil and/or soil deformation. Case a) is mostly due to non-identified strata with low bearing capacity and demands an utmost caring treatment. Case

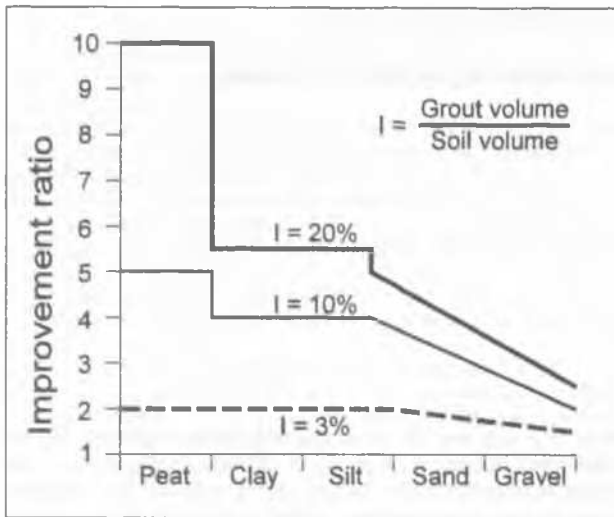


Fig. 2: Improvement ratio for normal consolidated soils

b) can result for example from tunnel driving, mining activities or inadequate sheeting works in excavation pits. In case a) settlements have already occurred and are known, whereas the same are still to be expected at tunnel driving and are estimated from experience or calculations.

On principle, the Soilfrac®-system consists of two phases. In phase I the existing soil is improved, cavities are filled and the horizontal stress is increased. The attainable ground improvement depends on the injected quantity of grout as well as on the type of soil. In case of heave provoked during the grouting process, further improvement is not possible. Falk (1998) suggests several improvement factors dependent on the type of soil and the injection ratio I which could be applied, for instance, to the deformation modulus (Fig. 2). Due to the ground improvement as well as the horizontal stress increase, a considerable reduction of the settlements is obtained which, for example, is produced by tunnel driving. This reduction is in the range of 25 to 50 %. If in normally consolidated soils the horizontal stress approaches the value of vertical stress, which is indicated by a certain contact heave, phase I is terminated and distinctive heaves (phase II) occur.

3 TAM TECHNOLOGY

Today, Soilfrac® is applied by using TAMs only. The TAM is installed almost centrically in the borehole. Attention has to be paid that the rubber sleeves remain in position. The annular space must always be filled with a so-called sleeve grout. If the TAM is properly installed, the pressure diagram shows a distinctive peak. (Fig. 3).

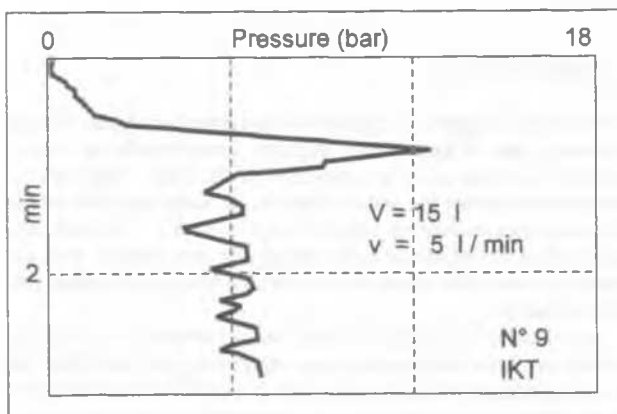


Fig. 3: Diagramm of grouting pressure

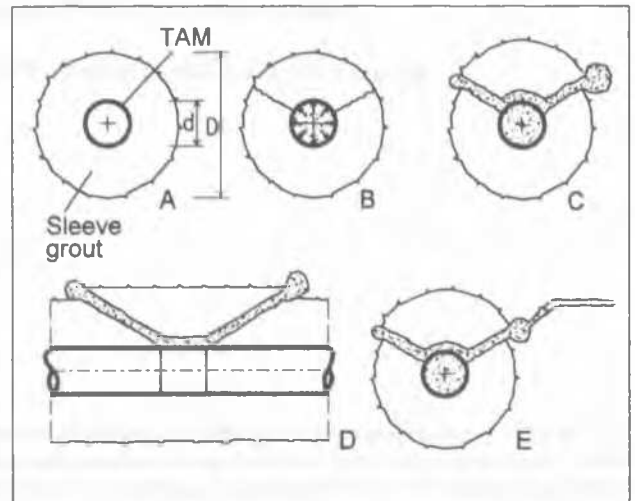


Fig. 4: Crack of sleeve grout

The value of the pressure peak (P_A) depends on the strength of the sleeve grout (β) and the diameter of the borehole only.

$$P_A = \alpha \cdot \beta \text{ [N/mm}^2\text{]} \quad (1)$$

The sleeve is cracking in conchiform clods at an aperture angle of 120° , radially as well as axially. In the ideal case clods of some 20 x 30 cm come off. If the crack is triggered by pure tensile forces the coefficient is approximately as follows:

$$\alpha = 17,8 \left(\frac{D^2 - d^2}{d^2} \right) \cdot \frac{\beta_z}{\beta} \quad (2)$$

This formula shows D [m] as diameter of the borehole, d (m) as diameter of the TAM which is similar to the length of the rubber sleeve, and β_z/β as ratio of the tensile and the compressive strength. For example, with $D = 0,2$ m, $d = 0,06$ m, $\beta_z/\beta = 0,075$ and $\beta = 3$ N/mm² follows a fraction pressure of 40 bar.

The cracking results in fissures in the sleeve grout the width of which depends on the stiffness/density of the soil (Fig. 4). On the soilside of the fissures bulbs and bulges of injected material develop. These bulbs signify the beginning of the actual soil fracturing. With several injections at the same spot, the thickness of the sleeve can be more than doubled. Accordingly, the cracking pressure P_A rises considerably with the number of individual injections. In total the relatively rigid sleeves are partly responsible for the passive reduction in settlements achieved by Soilfrac®.

4 INJECTION PRESSURE

Generally, on application of Compensation Grouting (phase II) the injection quantity as well as the pumping rate are predetermined so that the injection pressure builds up automatically. The pressure (P_p) is measured at the pumping station and recorded accordingly. After termination of the injection procedures the final pressure is used as performance criterion. It always amounts to a multiple of the pressure to crack the soil (P_C) since it comprises additionally pipe losses (P_L), friction losses in the cracked sleeve (P_R) as well as pressure increase due to flow resistance of the grout in the fracs amplified by rising viscosity and decreasing flowability during the injection process (P_v).

$$P_p = P_L + P_C + P_R + P_v \quad (3)$$

All individual shares depend on numerous boundary conditions which vary erratically during the injection process and are difficult to be determined. Kudella (1994) reported in detail on mathematic solutions. An evaluation of final pressures revealed that

that they differ considerably even on apparently same conditons. Therefore, only a qualitative analysis based on simplified derivations is suggested.

The pressure to crack the soil is a function of the minimum principle stress. In overconsolidated soils as well as in cohesionless soils for phase II, the following formula is valid for frictional soils.

$$P_C [\text{bar}] = \frac{1}{100} (\gamma \cdot h + p_0) \cdot \alpha \quad (4)$$

Literature gives values of $\alpha_1 = 1,6 - 2,0$ and p_0 is the additional stress at the TAM-level from the foundation pressure.

The friction loss in the cracked sleeve grout (P_R) is determined as function of the injected quantity V .

$$P_R [\text{bar}] = 0,08 \left[\frac{\text{bar}}{1} \right] \cdot V [1] \quad (5)$$

Accordingly, the increase in pressure due to flow resistance in the fracs amplified by rising viscosity because of the filtration of water, is also determined as function of the injected quantity.

$$P_V [\text{bar}] = 0,12 \left[\frac{\text{bar}}{1} \right] \cdot V [1] \quad (6)$$

The pipe losses (P_L) depend on the diameters and lengths of the pipes and the pumping rate (v). For standard grout the pipe losses at $v = 5 - 25$ l/min are in the range of 1 to 25 bar.

At the Central Station of Antwerp, for example, with $h = 4$ m, $\alpha = 1,6$, $\gamma = 19$ kN/m³, $V = 60$ l, $p_0 = 300$ kN/m², $P_L = 6$ bar (measurement) the following value was obtained:

$$P_p = 6 + 6,0 + 4,8 + 7,2 = 24 \text{ bar} \quad (7)$$

If a cavity is encountered during injection processes, the share of P_C vanishes and in addition the share of P_V diminishes. With $P_V = 0$ in above mentioned case, the value of the final pressure amounts to $P_p \approx 11$ bar.

Especially in phase I (Preconditioning) the pressure evaluation is used to determine both loose zones and cavities. It was the aim to obtain a final pressure of $P_p > 20$ bar. At the first run this could not be ascertained at 22 % of the total number of treated sleeves. It was only after the fifth that the pressure level was acceptable. Fig. 5 shows the decreasing number at each run.

This example reveals the importance of a qualitative evaluation of the final pressure already in phase I in order to recognize before-hand loose zones and disturbances in the subsoil. In any case, it is difficult to determine the injection efforts in phase I in advance.

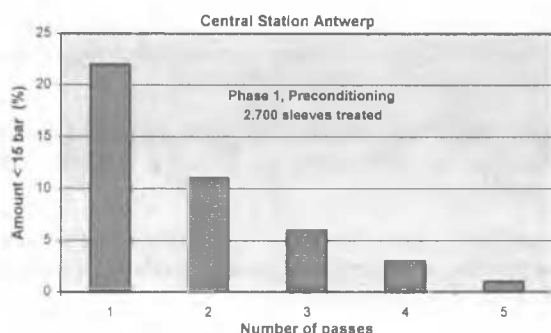


Fig. 5: Number of injections with low grouting pressure

Project	Soil	average Heave [mm]	intensity Grout [l/m ²]	Load [kN/m ²]	ER %	Remark
1a Dinslaken Rheingau 41	G,s	6	148	-50	4	Phase I
1b Dinslaken Rheingau 41	G,s	65	290	-50	22	Re-Levelling
2 Berlin Kochstr.	S	0-54	534	250	5	Phase I + Re-Levelling
3 Hamm [7] Kraftwerk	U,h	30	360	400	8	Phase I + Re-Levelling
4 Lissabon [5] Metro	S/U	2	21	400	10	Phase I Preheave, Test
5 Bielefeld Tunnel B61n	C	7	88	200	8	Phase I Preheave
6 Hamburg [4] Tunnel Övelgönne	S/U	4	44	-50	10	Phase I Preheave
7 Limburg [8] Tetra Pak Tunnel NBS	C,*	4	33	250	12	Phase I Preheave
8 Limburg Tetra Pak	C,*	9	56	250	16	Tunnelling Phase II
9 Niederpleis Tunnel NBS	S	12	81	-50	7	Tunnelling Phase II
10 Antwerpen Central Station, Tunnel	S	23	80	50-800	11	Tunnelling Phase II

* = overconsolidated

Fig. 6: Efficiency of compensation grouting

5 EFFICIENCY

The degree of efficiency E_R describes the ratio between the volume of heave and the volume of injected grout, i. e. the average heave S divided by the injection intensity I , respectively. Here, I is the average volume of the injected grout per m².

$$E_R [\%] = 100 \frac{S [\text{mm}]}{I [\text{l/m}^2]} \quad (8)$$

It is known that at excess pressures normal grout suffers from water filtration. For instance, at an excess pressure of 4 bar grout looses in permeable soils during an injection period of 6 minutes approximately 10 - 15 % water (W_b). Within the fracs the remaining volume causes soil deformation at the top as well as at the bottom, the first of which (α) is relevant for heave. However, the percentile of plastic deformations (S_{PL}) reduces the efficiency furthermore. In addition it has to be considered that a certain number only (δ) of the fracs contribute to heave. Accordingly the following approximation applies:

$$E_{Rmax} \approx [\alpha_2 (1 - S_{PL}) - W_b] \cdot \delta \quad (9)$$

With $\alpha_2 = 70$ %, $S_{PL} = 50$ % of total deformation, $W_b = 12$ % and $\delta = 70$ % the efficiency at maximum is $E_{Rmax} \approx 16$ %. At increased injection pressures and therefore higher values of W_b (e.g. 20 %) the maximum efficiency decreases to $E_{Rmax} \approx 11$ %. If water only is injected, $W_b \leq 1$ and $E_{Rmax} \geq -46$ %. In impermeable soils W_b becomes very little (e.g. $W_b = 5$ %) and therefore a higher maximum efficiency of $E_{Rmax} \approx 21$ % is obtained. Tests in clay carried out by Jafari et al. (2001) have delivered values of between 20 % and -40 % (water), respectively.

Fig. 6 shows the efficiency of several projects. The average value of all sites comes up to of 11 %.

6 REAL-TIME-MONITORING

The first Soilfrac®-projects were controlled simply by levelling. Particularly at tunnel driving this manual procedure requires too much time between measurement and evaluation. Therefore, it became necessary to use advanced measuring systems like automatic levelling or water level systems. Although water level systems are more expensive, the advantage to optical equipment is that they can measure at places visually not accessible. At early tunnel projects in Germany (Essen, AEG Kanis) water level systems were used on the basis of level measuring. De-

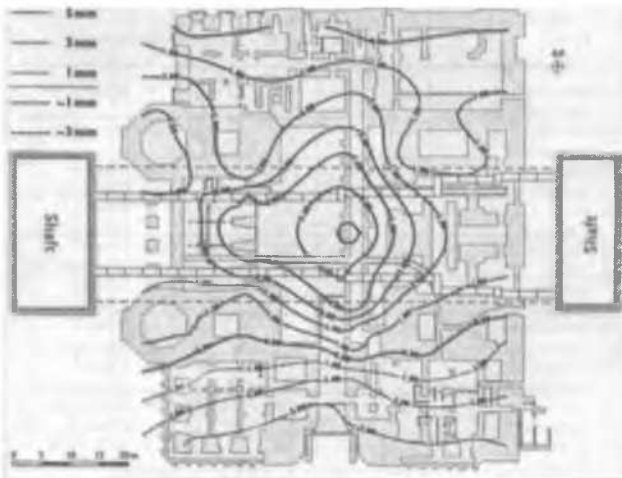


Fig. 7: Central Station Antwerpen, contour line of heave

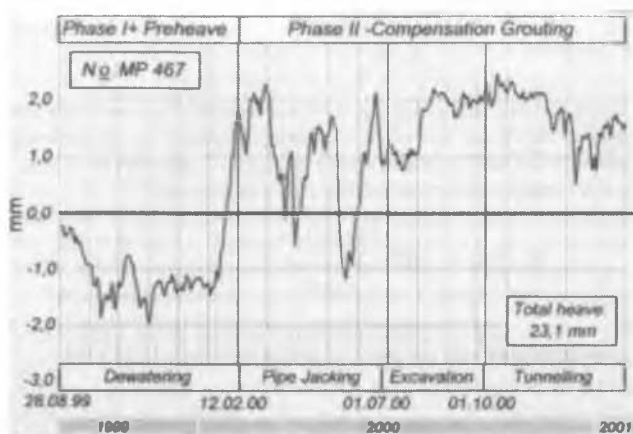


Fig. 8: Central Station Antwerp, settlement and heave

pending on the instrumental range, the individual water cells are of large size. Furthermore, the whole system is temperature-dependent.

In the meantime extremely accurate pressure cells have been developed which enable the construction of water level systems basing on pressure measurement (e.g. GeTec-System). Here, the alterations of the gravitational force at each individual indicator are compared with a reference magnitude and converted into level alterations. The measuring range amounts to approximately 200 mm and the accuracy of the individual sensor to approximately 0,02 mm. The system works at temperatures between - 25° C and 80° C. The temperature influence is compensated by automatic and calibrated adjustments. Also, the systems can be installed at various storeys with interlinks. A high capacity system dynamics updates measuring results within 30 seconds. For example, at the Central Station of Antwerp where approximately 100 indicators had been installed over 3 storeys, an accuracy of the system of 0,3 mm could be guaranteed. So far, at 7 projects the GeTec-System has proved extremely reliable.

The huge quantity of data requires a large-scale software. To control the measuring results, an immediate visualization is necessary. Of special interest is the illustration of settlement/heave in contour lines (Fig. 7) as well as the time-settlement curve at individual measuring points (Fig. 8).

7 CASE HISTORY

The church of St. Martinus in the village of Niederpleis (Germany) was at parts influenced by tunnel works for a new rail-



Fig. 9: Project Niederpleis, grout intensity [l/m²]

wayline Cologne-Frankfurt. The driven tunnel has a diameter of approximately 14 m and a capping of some 12 m. Approximately 370 m of horizontal TAMs were installed radially at a depth of 2.5 m below the foundations of the church. Particularly the high loads on the tower foundations required considerable injection efforts. The illustration of Fig. 9 shows the concentration of injected quantities below the foundations.

Because of the historical structure, settlements resulting from driving works did not have to exceed 1,5 mm. The pipe scale system GeTec with 14 indicators in total was installed for performance control and proved reliable.

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