Underground works in urban environment

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UNDERGROUND WORKS IN URBAN ENVIRONMENT

TRAVAUX SOUTERRAINS EN SITE URBAIN

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ABSTRACT: During the construction of the new subway under the old part of Lisbon it was necessary to tunnel under several historic buildings. The tunnels were driven using a tunnel boring machine and a station area was excavated by the NATM. Buildings covering an area of 20.000 m² were protected from damage due to excessive settlement by SOILFRAC-Compensation grouting without interruption to their normal use.

RESUMÉ: Pendant la construction du nouveau métropolitain sous le vieux centre de Lisbonne il était nécessaire de passer sous plusieurs bâtiments historiques. Les tunnels de course étaient extraits avec une machine à tunnelier, une station e compli avec NATM. Bâtiments d'une extension de 20.000 m² étaient protegés d'injections de compensation SOILFRAC de dommages à cause de tassements sans interruption de leur usage normal.

1 THE PROJECT

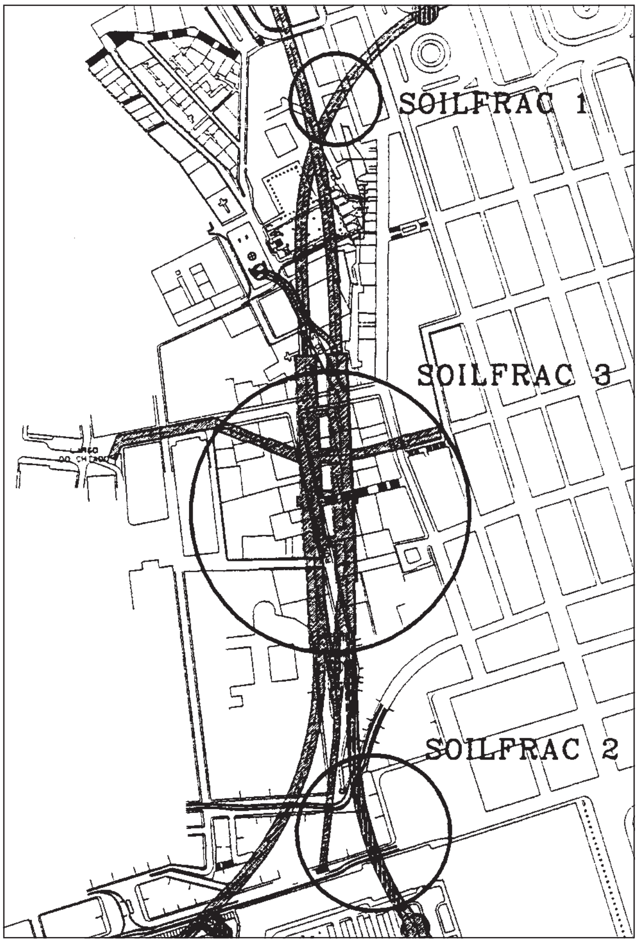

Figure 1. *Two new underground stretches will connect three existing railway stations in city centre of Lisbon. Settlements due to the tunnel excavation are not compatible with the structural behaviour of historic buildings in certain areas. Compensation grouting was used to minimise angular distortions in three areas.*

2 INTRODUCTION

The Soilfrac-technique was used in three different areas (Figure 1) for compensation of settlements. In assessing the effectiveness of the system the following difficulties had to be taken into consideration:
– variation between very soft cohesive layers and compacted sands
– shield tunnels close to foundations (minimum 3,5 m!)
– changing overburden due to the hilly topography
– drilling and grouting below the groundwater level
– twin tunnels for a station with a maximum total face area of more than 500 m²
– historic structures with low rigidity

This report is focusing on the adaptation of the Soilfrac-method to the different situations:
- area 1: EPB-shield crosses buildings attached to the slope of a hill
- area 2: EPB-shield passes under and along a heavily loaded wall close to the foundations - the influence of grouting to the tunnel lining was studied in a full scale trial
- area 3: NATM station tunnels with unusual diameters below sensitive buildings

3 PRINCIPLES OF THE SOILFRAC-TECHNIQUE

The beneficial use of hydraulic fracturing was initially developed to improve the usefulness of oilfields. The needs of stabilisation and controlled relevelling of structures led geotechnical specialists to adapt the method for tasks closer to the surface.

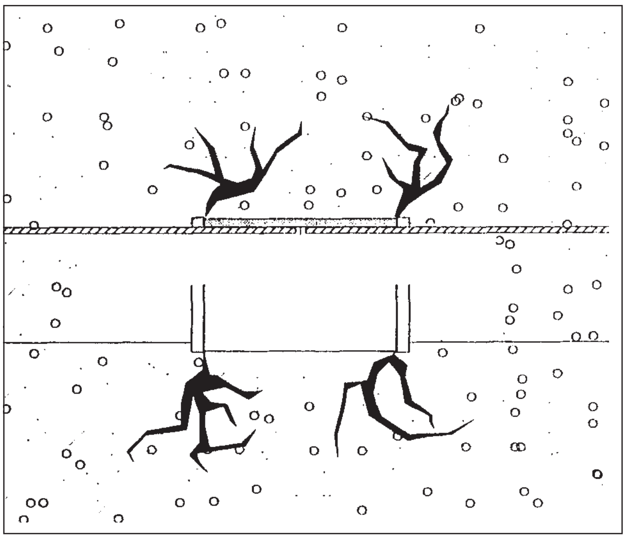

Figure 2a. *Detail tube a manchette: Entrance of grout to the ground from one valve*

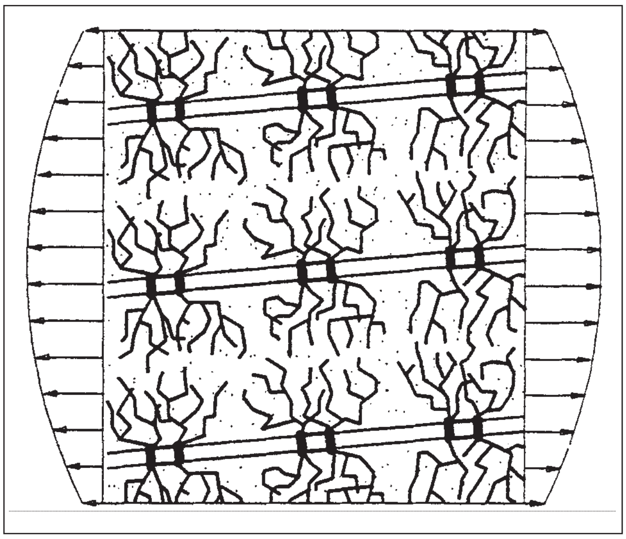

Figure 2b. *Horizontal prestressing*

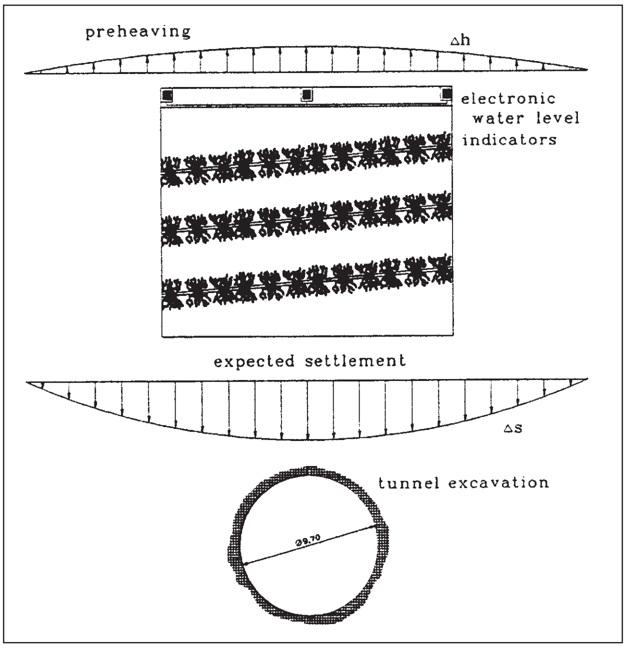

***Figure 2c**. Preheaving of a small amount against the expected settlement trough*

Multiple injections of small volumes of grout can effect an improvement of soil parameters related to deformability. A system of tubes a manchette is installed to allow injections of spatially defined points in the ground (Figure 2a). The travel of the grouting material and its distribution is controllable through parameters such as geometry, flow rate, grouted volume, viscosity, water-solid-ratio with regard to grain size distribution of the ground, ratio of principal stresses and others (Figure 2b).
A modified strength of the treated layer provides the basis for selected preheaving in correlation to the predicted settlement curves. The preheaving phase before the approach of the tunnel excavation front can be very useful to obtain detailed information about the particular behaviour of existing structures above very carefully treated ground and the interaction of both systems (Figure 2c). It is necessary to establish a clear connection between grouting activities and their effects on the surface. Monitoring of all relevant movements enables the site engineer to elaborate a grouting program with the aim of achieving the most effective use of the injected material.

4 AREA 1 - EPB SHIELD TUNNEL

The first application of compensation grouting was characterised by the following:
- 6 storey-buildings with shallow strip-foundations and wooden piles of unknown depth
- backwall of the buildings directly attached to the almost vertical slope of the Carmo-hill
- confinement pressure of the EPB-shield with 9.7 m diameter has to be reduced in a controlled way while passing to take into account the change from more than 30 m overburden to 8 m within a short distance
- soft soil conditions between the bottom of foundations and tunnel crown (angle of friction 28°, E = 4820 kN/m^2,
  c = 2.10 kN/m^2)
- predicted possible settlements of 80 to 90 mm (Figure 3)

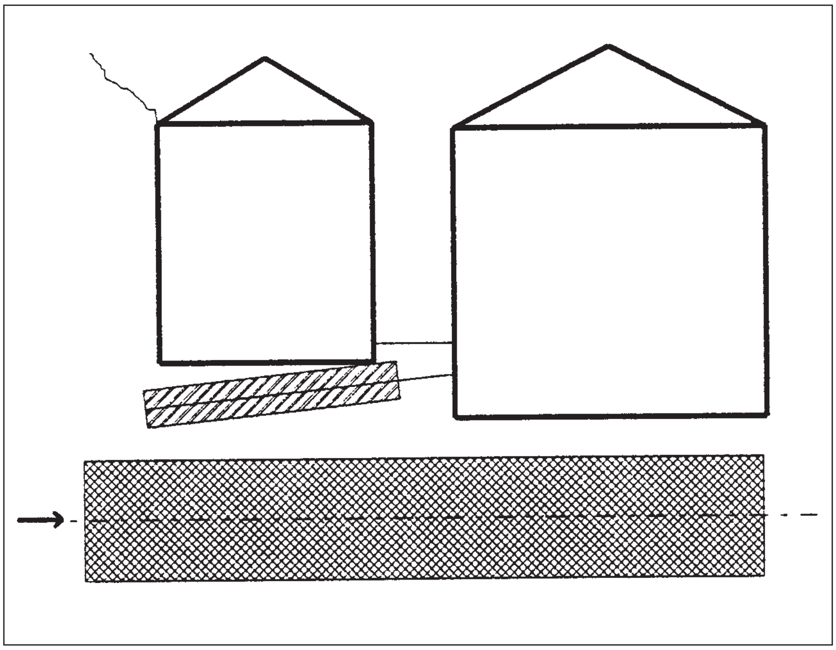

Figure 3. *Compensation grouting in area 1: Distance to foundations less than diameter of the EPB-shield (9.7 m)*

During the preconditioning-phase 357 valves were used to inject a very viscous grout in volumes of 30 to 60 litres. It was necessary to inject an additional 211 manchettes to obtain preheaving rates of 1.1 to maximum 12.6 mm.
The shield passed within 6 days without any unexpected complications. The extensive real-time monitoring results were not only used to control compensation grouting (173 injections with volumes of 20 to 50 litres) but also to minimise heaving in front of the cutting head. Compensation grouting was started when a settlement of 1.0 mm occurred. The observation of existing fissures showed the positive contribution of small steps of relevelling in minimisation the stresses induced to the structure.

5 AREA 2 - SHALLOW RUNNING TUNNEL

The chosen compensation technique proved its flexibility in an area of difficult soil conditions and very sensitive structures. A shallow tunnel was to cross under a government building having high loaded single footings. Heterogeneous soil conditions and a groundwater level 2.0 m below surface with high tidal variation required adaptation to the drilling method and a modification of the grouting equipment to enable the application of high pressures in sandstone.
A sandstone layer of variable thickness was overlaid by lenses of clayey silt and loose sands. The building with massive walls contained sensitive electronic devices necessitating the protection from differential settlement.

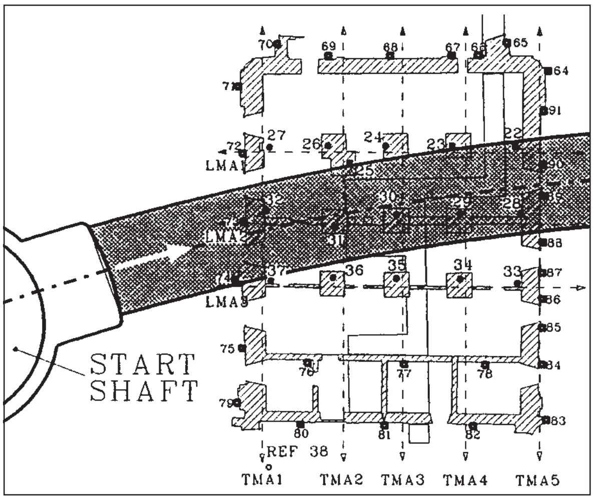

Figure 4. *Area 2: Passage of a historic government building by the 9.7 m Ø-shield machine*

LMAx ... longitudinal profiles equipped with electronic water level gauges
TMAx ... transversal profiles observed by additional water level indicators and ruler scales for precise levelling

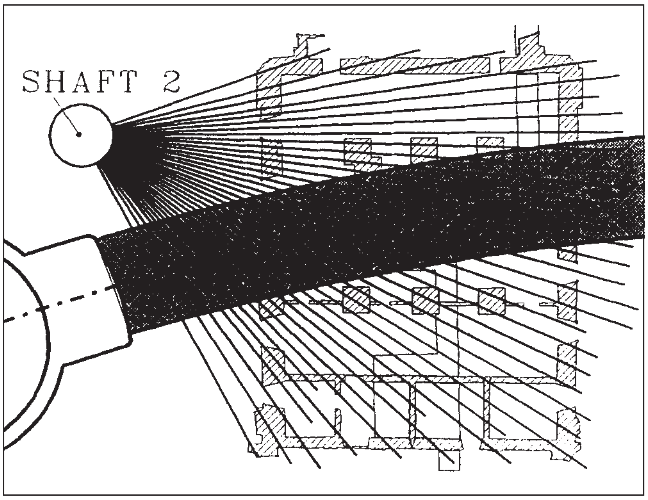

Figure 5. *Area 2: Installation of tubes a manchette, drilled, from a 5.5 m Ø-lined shaft*

The period between preheaving and compensation was used to observe the stability of the preheaved values. To ensure frequent comparable readings a water level system with 44 gauges was installed. The water level system consists of liquid-filled indicators. The level inside the indicators is transferred from floaters onto inductive displacement transducers. The influence of temperature, physical disturbances and evaporation-effects can be evaluated and compensated through the software programs specially developed for the requirements of compensation works.

To select the areas of the buildings in need of compensation grouting a detailed damage assessment of the structure was done prior to carrying out a strain analysis. The soil-structure interaction was investigated to form a basis for protective or preventative measures to be designed.
The spanning effect of the building structures was transformed into an equivalent beam, expressing the capacity to resist bending.
Due to the sensitivity of the structure in area 2, having separate foundations, brick walls and arches, the amount of preheaving was limited to 4.0 mm. The residual settlement observed during 119 days was in a range of 1 % to 2 % of the preheaved amount. The maximum settlement recorded due to the passage of the shield machine was less than 4.0 mm. Most of the areas could be compensated within a tolerance of ± 2.0 mm of total settlement (a conservative pretreatment settlement-prediction was in a range of 50 to 60 mm!).

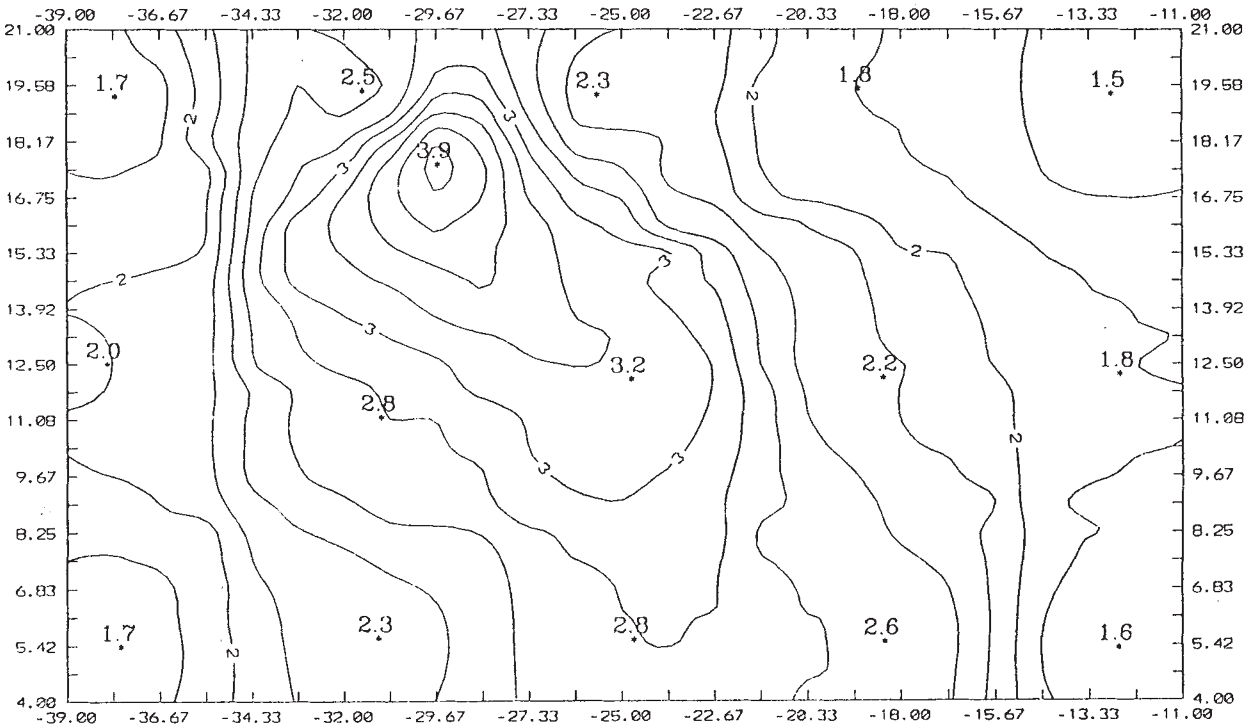

Figure 6. *Area 2:Two-dimensional plot of preheaved rates corresponding to longitudinal profiles LMA 1,2,3 of Figure 4*

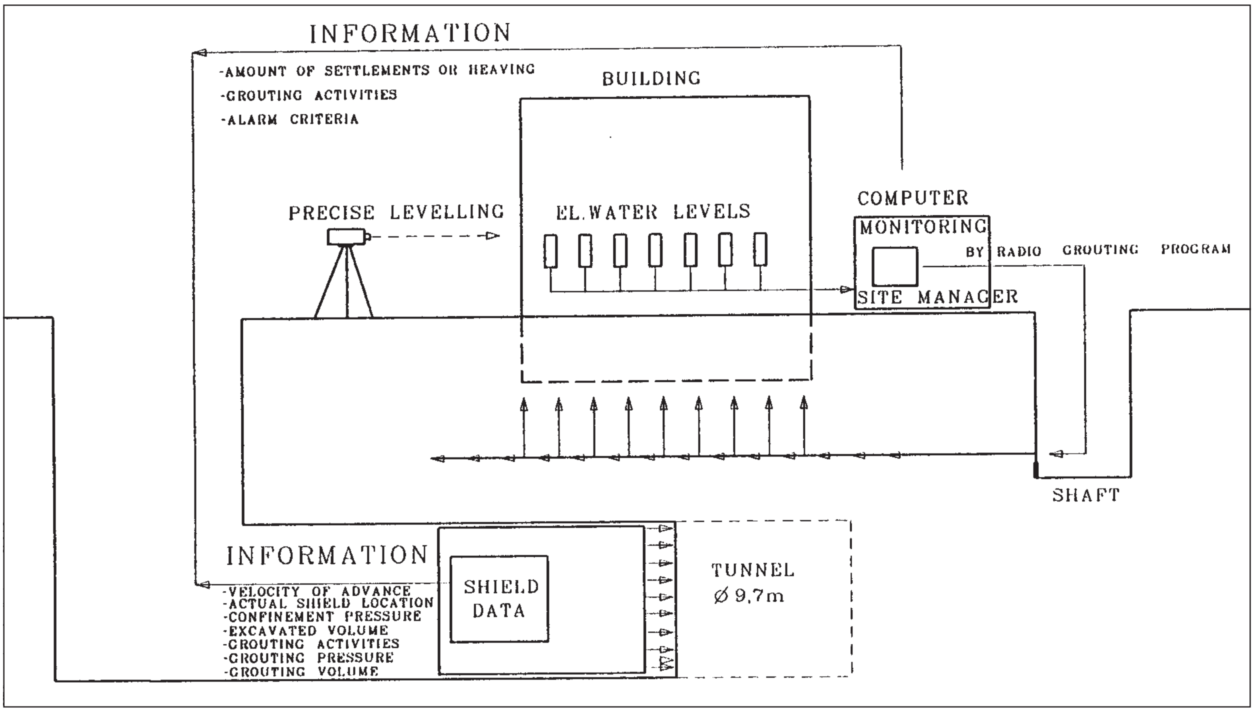

Figure 7. *Communication during the compensation phase:The combination of technical data acquired from the shield machine and all the available grouting parameters combine to serve as the basis for the determination of the grouting program and variations in the tunnel excavation.*

A detailed communication and alarm system was implemented to ensure the highest effectiveness of the process during the passage of the shield. The frequent data acquisition helped to recognise tendencies of movements and to react immediately (Figure 7).
The monitoring system in combination with precise levelling, extensometers and deformation measurement in the tunnel allowed for the definition of two alarm levels. Level 1 (prealarm) was related to individually fixed amounts of settlement within 5 minutes and 30 minutes and an angular distortion of 1:1000. Reaching the alarm level meant shortening the reading intervals of the monitoring system and to intensify the contact with the operator of the shield machine. Alarm level 2 was defined as more than 3.0 mm settlement within 5 minutes and 5.0 mm within 30 minutes or an angular distortion below 1:800, this however was never reached.

Compensation grouting was done with four grouting units working simultaneous-ly, both in day and night shifts.
The effectiveness of the Soilfrac- compensation grouting technique in the classical way depends on the data acquired during installation and preparation. In order to be able to create a basis upon which the tunnel could cross under foundations at a distance of only 3.2 m and to use the small layer between foundations and a tunnel crown for effective grouting a field trial was executed.

The purpose of the full scale trial was to obtain answers to the following questions:
- What is the influence of grouting in the vicinity of the tunnel?
- Can selected heaving of isolated high loaded foundations be achieved?
- Is a 3 m vertical space sufficient to perform effective compensation grouting?
- What are the spatial displacements in the ground during hydraulic fracturing?

6 TRIAL PRAÇA DO MUNICIPIO

A part of area 2 was chosen to perform a full scale trial. 15 tubes a manchette were installed from a shaft outside the building below the groundwater level. The minimum distance to the planned location of the tunnel lining was measured at 1.1 m. The grouting trial was executed in a period of 12 days.
The monitoring system installed on surface and in the ground consisted of:
- electronic water level cells
- optical water levels
- ruler scales for precise levelling
- electrolevels
- earth pressure cells
- vertical inclinometers
- horizontal inclinometers
- multiple extensometers

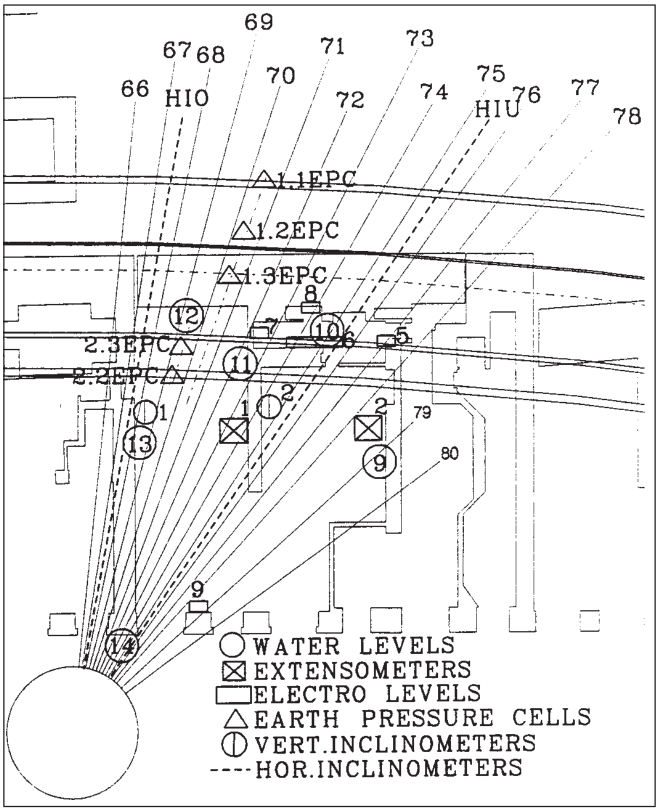

Figure 8. *Test field area 2: Installation of tubes a manchette from a 5.5 m Ø-shaft and geotechnical and geometrical monitoring*

Grouting was done in two phases. 9.5 days of preconditioning were followed by 2.5 days of preheaving. Only 54 of 726 single injections belong to the preheaving phase. 95.4 % of the injected volume was necessary to reach the "point of effectiveness" which is related to the equalisation of existing vertical stresses by induced horizontal stresses (Figure 9).
The passage of the test area by the shield machine was ample proof that a positive result can be achieved by a combination and interpretation of all registered data both from the shield operation and the grouting process.

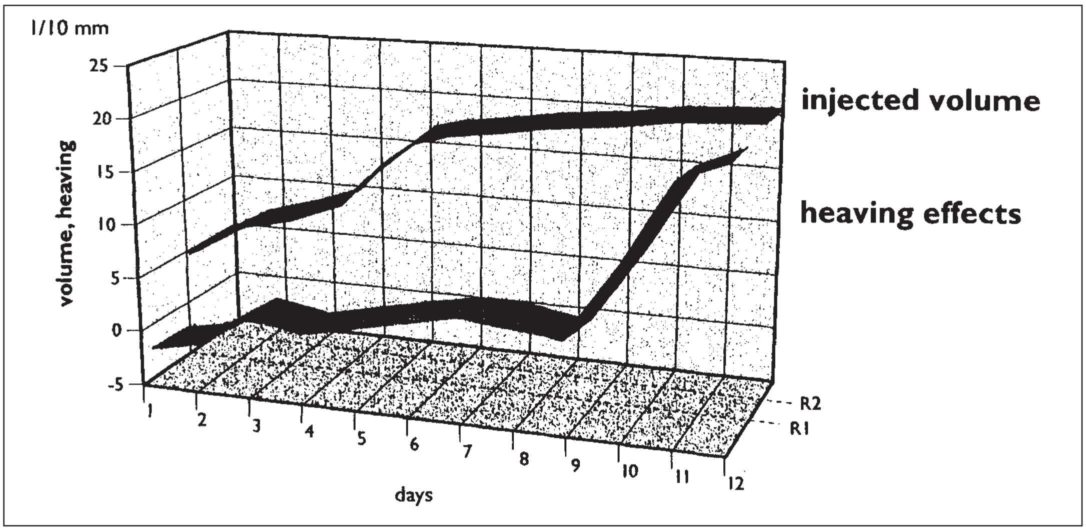

Figure 9. *Test field area 2:A preconditioning phase with continual increase of horizontal stresses in the ground was followed by a short preheaving phase with high sensitivity related to controlled heaving effects*

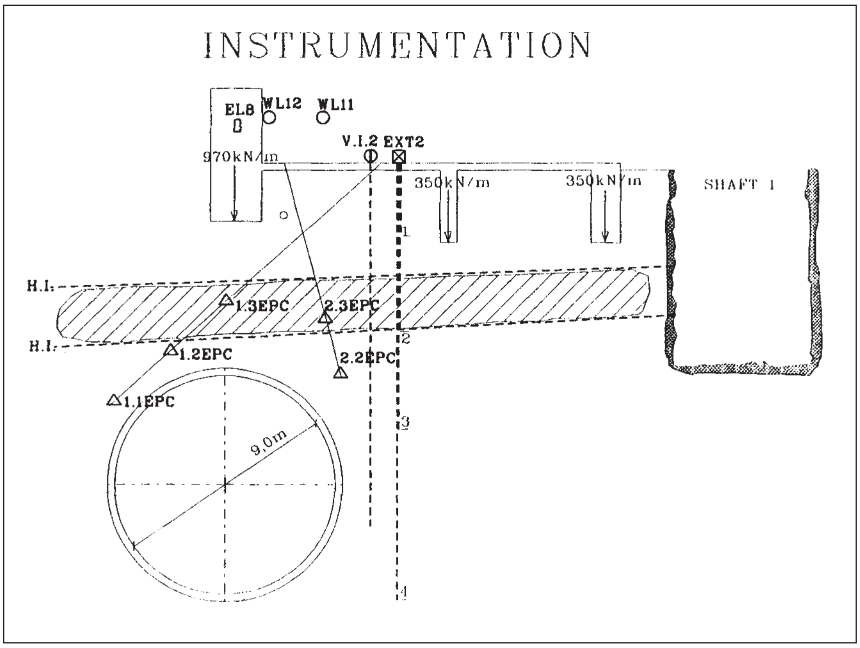

***Figure 10a**. Cross section of test field area 2: Installed monitoring system (legend Figure 8)*

The results of the field trial were used as the basis for the definition of sequences of the work and grouting parameters.

a) Spatial displacements in fine grained soils are directly related to the injected grout volume or more precisely its solid content. Regarding the treated layer as a block of 364 m² extension with approximately 2.0 m thickness the injection of 7610 l solid mass (cement, filler, bentonite) combined with absorbed water caused a total displacement of approx. 7800 l.
b) The maximum increase of pressure registered by an earth pressure cell was 10.5 bar. The influence to pressure cells close to the planned tunnel lining was 0.1 bar. However a significant unfavourable impact to the tunnel lining could not be found (according to other experiences) grouting close to a hollow space should always aim to fulfill the priority of a symmetrical arrangement.
c) Despite the fact that compensation grouting can be considered as a very helpful tool to diminish differential and total settlements, the controlled operation of a EPB shield machine becomes more important as the vertical distance becomes less.

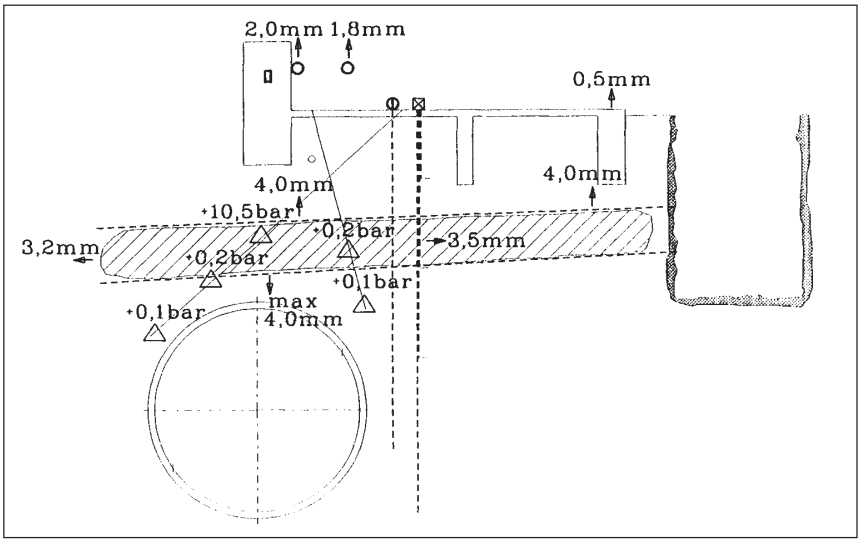

***Figure 10b**. Cross section of test field area 2: Results in terms of average deformations and pressure increases.*

7 AREA 3 - STATION TUNNELS

Two large station tunnels were to be excavated by NATM in several separated phases. Due to differential settlements occurring during the construction of the first tunnel compensation grouting was used as a complementary technique to minimise damages on buildings and public services. Almost the full length of the station was protected by Soilfrac covering an area of approx. 15000 m² from 3 shafts.
The installed system consisting of tubes a manchettes and full computerised grouting modules as well as an automatic monitoring system with more than 80 gauges maintained for a period of 18 months in full operation. In some areas the superficial settlements were reduced to a fifth of the expected amount. In most of the treated zones it was possible to maintain the original level within a very small variation.

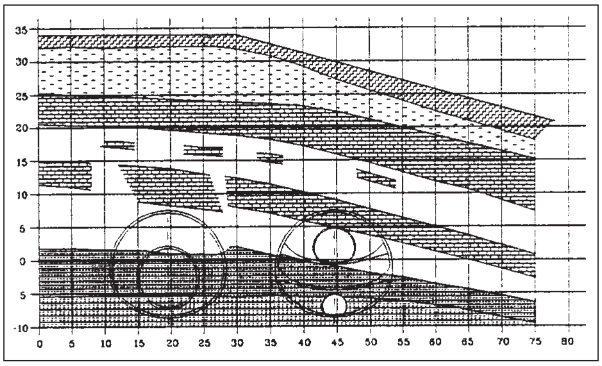

***Figure 11**. Cross section area 3, geological situation: Sandstone layers, sands, slight clayey silts*

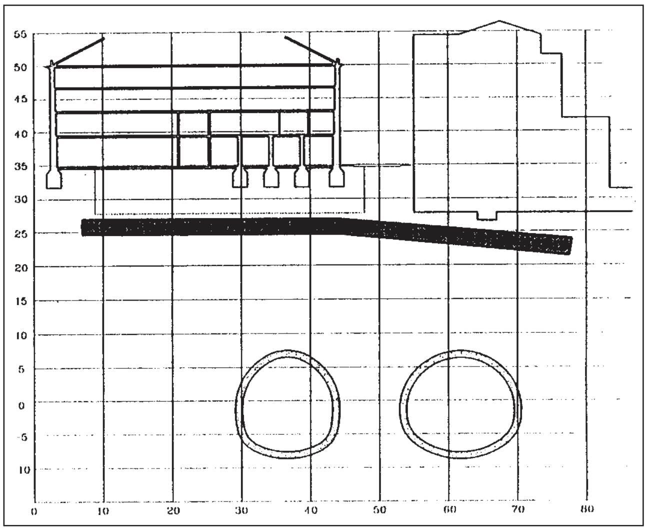

***Figure 12.** Due to the geological situation with softer layers in the upper part the level of treatment was chosen relatively close to the foundations*

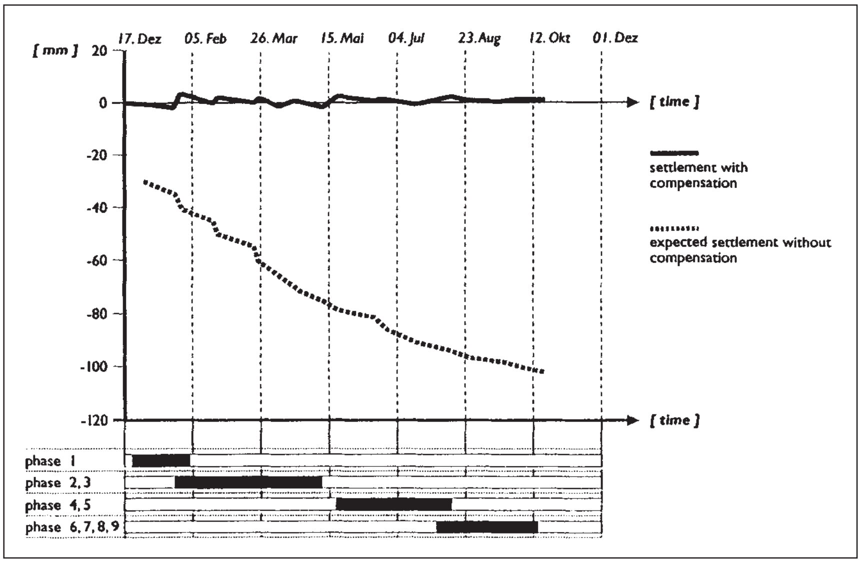

***Figure 13**. Compensation in very small steps related to excavation phases shown in Figure 14*

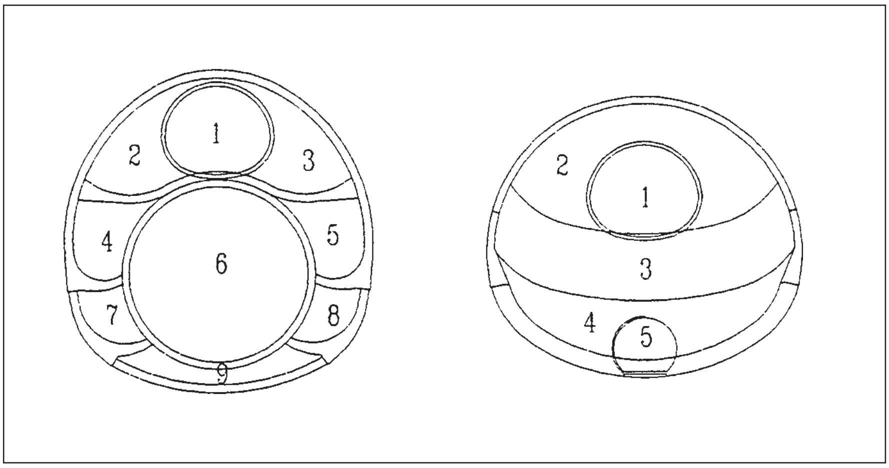

***Figure 14**. Excavation phases area 3*

8 CONCLUSIONS

Soilfrac-compensation grouting was used successfully to minimise differential settlements and to reduce total settlements in various geotechnical and geometrical situations.
The achieved effects showed how a full scale trial can be used to improve details of the application to the benefit of the affected structures.

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