Introduction

In recent years, compensation-grouting techniques in foundation engineering have advanced making it possible to reduce settlement from construction activities to a safe level for the buildings concerned.

Each time the ground is interfered with, whether through tunneling, anchor drilling, pile construction or excavation, the stress condition of the soil is changed. Usually this manifests itself as a surface or building settlement.

Whether these ratios are problematic depends less on the magnitude of the settlement, rather more on the steepness of the settlement depression and the position of the building relative to the settlement depression. Furthermore, the nature of the construction and the building structure play an important role.

In most cases, consistent settlements on the ground area are irrelevant. In this case, problems arise solely due to damage of supply and disposal lines.

If the building is on the edge of the settlement depression or protruding into it, right angles might become tilted or twisted. The damage that can result from this ranges from harmless but expensive tile or stucco damage through to ruptured water or gas lines as well as end-to-end wall cracks. It can even result in flights of stairs collapsing.

The compensation grouting, which we added to our repertoire in 2005 and have since constantly been evolving, offers the possibility to largely avoid this damage.
Basic principles of compensation grouting

In conventional soil injection, the granular structure of the soil should remain unchanged and only be penetrated by the grout, which then hardens in the pore spaces. Occasionally the soil fabric may become unintentionally fractured which consequently leads to the ground surface lifting.

This effect is used for the compensation grouting.

Before the compensation grouting takes place the buildings that are to be secured are equipped with an automated height measurement system that continuously monitors their height to an accuracy of 0.2 mm.

Furthermore horizontal layers of sleeve pipes from excavation pits or grouting shafts that are to be constructed are installed in advance under the buildings that are to be secured. The sleeve pipes have valves at 0.5 m intervals through which the soil can be injected with precision when needed.

Two major advantages of the compensation grouting are immediately visible:

1. The noise and dirt-intensive work takes place in the injection shaft away from the buildings that are to be protected. In contrast for example to conventional jet grouting underpinning there are no usage restrictions while the work is being carried out.

2. The compensation grouting allows a flexible response to any building settlements that actually occur. It is especially easy to respond quickly and accurately where filigree or pre-damaged buildings are concerned.
Elements of the procedure

Grouting shaft

In the first step, one or more compensation shafts or the construction pit are created. In inner city areas it is most common to build circular shafts with as small an outer diameter as possible. Depending on the local space conditions the light shaft diameter suitable for the drill rig is 5.5 m to 8.5 m.

The depth of the floor of the shaft is based on the depth of the injection screen that is to be carried out. Often a part of the shaft and the floor of the shaft are under groundwater – the support must then be waterproof (secant bored pile wall, diaphragm wall) and there must be a sealing sole (sole injection or underwater concrete base).

Bored holes

To drill the up to 50 m long holes out of the compensation shaft, we have developed our own shaft-suited drill rigs. They can be flexibly adapted to shaft diameters of 8.5 m to 5.5 m and can reach the entire shaft wall in several meters of height.

The holes are drilled using a rotary / rotary-percussive double head system with lost releasable bits. A special preventer technique allows drilling against pressing water and prevents unwanted soil loss. High accuracy drilling is required; all boreholes are surveyed by an inertial downholr probe.
Secondary lining of the boreholes

Specially reinforced sleeve pipes are inserted into the holes, making it possible to accurately carry out multiple soil injections. The drilling pipe is then pulled out gradually and the resulting annular gap between the sleeve pipe and soil is injected with a special binder.

Injection facilities for pipe sleeve injections

The core of the system, which is used after completion of the drilling, is a fully computer-controlled pump container with built-in automatic mixer. All functions can be monitored and controlled by a single operator using a console with a touch screen and clear process diagrams. The control computer is connected to the measuring station through a network. The grouting instructions come from here and the actual data from the injections is returned. From the mixer, the grout passes through the injection pump and through the injection line to the packer and finally through the sleeves (check valves) into the ground. Each injection hose is connected with an expansion pipe and a steel cable to be bound into a so called ‘packer bundle’ and is wound onto a drum. The drums are electrically powered and equipped with a high-pressure water pump for the packer expansion. The injection personnel in the shaft can remotely control the winding and unwinding of the packer bundles and eventually expand the packer at the site transmitted by radio from the injections container.
The process of compensation grouting

The contact injection is divided into several sub-steps. In a first step called "contact grouting" the entire sleeve pipe layer is uniformly injected. The goal of this lifting-free injection is to fill the existing pores and gaps to increase the efficiency during the actual compensation.

Depending on the local conditions of the soil and the load, the contact grouting finally blends in with the pre-heave grouting. During the pre-heave the settlements that have incurred during drilling are re-set and specific heave is induced, which accounts for up to 60% of the pre-calculated settlements.

The actual compensation grouting takes place during and after the ground interference that caused the settlement. The injection is made precisely where the measuring system reported settlements exceeding the predetermined limits in the building. In this way, settlements are reduced or reset.

Control software

In order to plan and carry out the injections quickly and effectively, there needs to be a way to quickly gain an overview of the injections made so far and how successful they are for ground lifting. Allocation to the building structure and the resulting pressure on the soil is very important. Therefore, all information collected in the course of the proceedings is imported into a CAD-based data management program that illustrates the corresponding evaluations in a quick and meaningful way.
We use the software "GroutControl" by Getec that we have supplemented with important modules. The program is used for the following tasks:

- Preparation of injections (preparation of target data)
- Visualization of measurement and injection data (evaluation of the actual data)
- Reporting and performance records (documentation)
- Archiving the measurement and injection data in the internal database

**Reference projects**

**North-South city-rail in Cologne, South section** (2005 - 2008):

- 48 buildings to be secured,
- approx. 14.5 km of sleeve pipes,
- Overall grout quantity of around 3,200 m³.

The focus of the work was in the old town, marked by very changeable soil conditions with strong anthropogenic factors and very mixed building fabric from Roman times to the present.

**Wehrhahn urban rail line in Düsseldorf, lot 1** (2007 - 2013)

- 4 shafts and 2 excavation pits,
- 28 buildings to be secured,
- around 17.5 km of sleeve pipes,
- around 800 m³ of grout.
During the Düsseldorf Wehrhahn line construction project there were also other types of compensation grouting:

Compensation bottom plates, equipped with 782 piece valves, were created under 4 components together making up approximately 780 m² of floor area that had to be made before the shield passage. Because sleeve pipes could not be used due to geometrical reasons, single injection lances for multiple injections were used instead. Targeted lifting injections could also be carried out dependent on the measured structural movements. This method, which was first used on the Wehrhahn line, was also completed successfully.