# **Compensation grouting at Florence HSR tunnel**

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**ABSTRACT:** Florence HSR tunnel underpasses the densely urbanized area of Florence in Italy. TBM/EPB excavation is executed in soft soil and, in particular next to the southern portal, under a shallow cover: 6m to 8m of sand and clay separate the tunnel from the foundations of 2 masonry buildings and a steel bridge. Compensation grouting resulted as the best approach to preserve structures serviceability. The paper describes compensation grouting activities performed, from design to execution. The monitoring and data processing system is also detailed. Together with appropriate real-time post-processing strategies, it allowed a punctual control and guidance of the grouting activities.

## FLORENCE HSR PROJECT

The tunnel to be executed is part of the European high speed train network towards Rome. The underground works consist of: 6.5 km double tunnel excavated with an EPB TBM; a northern portal in Riffredi area; a southern portal at Campo di Marte (which is also the TBM launching pit); and a new underground central station in Belfiore area (Figure 1). Excavations techniques employed comprise mechanized and conventional tunnel excavation, cut and cover and deep excavation (Italferr 2012). Florence soil is characterized by soft clays and sands. The water table lays above the tunnel crown for most of the track. The tunnel under passes more than 150 buildings, many of which can be regarded as historical buildings, with a cover between 6 m to 20 m.



Figure 1. Florence project highlights: a) plan view; b) building 165; c) building 166

Passive and active protection measures have been designed to guard existing buildings, bridges and rails. In particular, compensation grouting has been foreseen in the southern part of the tunnel, area Ponte al Pino, where two buildings are going to be under passed with a cover between 6 m to 8 m (Figure 1), and also at about 3 km in the north of the southern portal to protect the ancient Fortezza Da Basso.

Compensation grouting consists in grouting a controlled amount of mixture at a controlled pressure. The technique allows to consistently reduce or completely avoid settlements induced by excavation on superstructures. Grouting is performed by means of Tube A Manchettes (TAMs) also named Sleeved Port Grout Pipes (SPGP) located at a suitable distance from superstructure and tunnel face. Compensation grouting activities are subdivided in two principal phases: a "pre-treatment" performed prior to tunneling to permeate the area and avoid loss of time and energy during the next phase; "concurrent grouting" performed during excavation advance when relevant settlements are measured. To perform compensation grouting, a suitable monitoring system has to be installed on the superstructure to read structure's settlements (Henn Raymond 1996).

### Compensation grouting activities at Ponte al Pino area

The area is located at the southern end of the tunnel and is the scenario of the compensation grouting activities described in the paper. The area is named after the bridge ("Ponte") crossing the existing railway in proximity of an ancient pine tree (Pino). Two buildings in this area require special mitigation activities, i.e. compensation grouting, hereafter named building 165 and building 166. The buildings are particularly sensitive for two main reasons: excavation cover is particularly small; and excavation volume control is particularly difficult to optimize at such a short distance from the TBM/EPB launching pit. Buildings 165 and 166 are 2 stories masonry buildings with strips and pads footings at -1m and -3 m from ground level, respectively. Building risk assessment assigned risk class 3 and 4 (according to Boscarding and Cording 1989, Table 1) to building 165 and 166, respectively, given an excavation volume loss of 1%.

Compensation grouting is performed from two shafts, shaft 5 and shaft 6 within an active area having less than 50m radius. Grouting is executed in a fluvial clay deposit composed by a lower layer (thickness variable from 3 to 5 m) of clay with silt, sand and gravel with a permeability of  $10^{-4}$  m/s, and an upper level (about 4 m thick) of claily silt with a limited permeability of about  $10^{-8}$  m/s.

Grouting mixes, monitoring system and the overall operability have been tested on a test field located southern of shaft 5 and composed by two concrete plates (plate 1  $6m \times 6m \times 0.5 m$  and plate 2  $8m \times 8m \times 0.5m$ ) realized at ground level. An overall layout of the entire area is shown in Figure 2.



Figure 2. Buildings and compensation grouting shafts in Ponte al Pino area

Table 1. Relevant building risk classes according to Boscarding and Cording 1989		
Class	Description	Cracks width
3 - Moderate	Cutting out and patching might be required, doors and windows sticking, possible	5 to 15 mm
	damage to utility services, water tightness possibly impaired	
4 - Severe	Removal and replacement of sections of wall might be required, doors and windows	15 to 25 mm
	frames distorted, floor slopes, walls lean or bulge noticeably, utility service disrupted	

The monitoring system installed on the buildings and on the test field comprises: 3D targets installed on the facades of the buildings automatically read by a robotic total station; hydrostatic level circuits installed at ground level and in the basement of the buildings. Hydrostatic cells layout is shown in Figure 3.



Figure 3. Monitoring system: hydrostatic levels on building 165 and 166 and typical test field layout

## DESIGN

The local settlements induced by excavation and the effects of compensation grouting have been indepth studied by means of 3D FEM software (MIDAS GTS 2008). The numerical study aimed at showing the effects which some key features have on compensation procedures. The study reproduced excavation advance simulating the EPB shield, surface settlement and ground reaction to compensation grouting. The results obtained from the numeric model represented a valid reference to esteem, for the simulated boundary condition, the influence of grouting on superficial subsidence field. Furthermore, the study defined an analytic procedure to design compensation grouting with regard to mixture quantity and quality, procedures and sequences to be applied for execution and defined a meaningful performance parameter to be used for design.

The analyses investigated the behavior with and without compensation grouting and considering different grouting strategies.

In the analyses without compensation grouting, settlement domain has been studied analytically using Peck formula (Peck 1969). 2D and 3D fem models have been tuned on those results varying soil constitutive models to assess numerical models reliability. Furthermore, 3D analyses modeled in detail excavation advance, simulating each advance step (1.5m) and the overpressure on the cutter-head to be able to capture the dynamicity of the process. An example of 2D and 3D models and settlements comparison is shown in Figure 4.



Figure 4. Numerical models geometries and 2D settlement curves comparison

Compensation grouting effect has been afterwards analyzed considering the case with pre-treatment of the area and the case without pre-treatment. In case of pre-treatment, the analysis has been performed assuming different Young modulus of the pre-treated area in order to verify the effect on the final settlement of the quality of the pre-treatment material (expressed in terms of stiffness of the pre-treated area). The simulation also considered several cases with a different grouting strategy, varying the number and the order of grouting ports simultaneously activated. A comparison of deformed shape with and without compensation grouting is shown in Figure 5.



Figure 5. Comparison of settlements with and without compensation grouting

Numerical simulations pointed out that pre-treatment material shall not require relevant stiffness characteristics. Grouting execution strategy effect proved that the larger the number of simultaneous injections, the higher the compensation grouting performance. Figure 6 compares the results obtained for building 166 injecting all grouting ports at a time, 1 injection at a time from central grouting port outwards and 2 simultaneous injections from central grouting ports outwards. Finally, 3D modeling allowed to verify the influence of the compensation strategy in the longitudinal direction, taking into consideration the effect of the non-injection area located at the rear of the TBM shield (not to damage concrete lining). Compensation grouting efficiency resulted slightly higher in the 3D model (Figure 6).



Figure 6. Influence of grouting strategy and 3D effects in compensation grouting

### SOFTWARE TOOLS

Compensation grouting activities have been performed taking advantage of dedicated software based on the latest web technologies. In Florence the software architecture is composed by a monitoring platform dealing with monitoring instruments, a software controlling grouting equipment and a compensation grouting suite mastering the data flow and assessing the grouting volume and location.

### Monitoring platform

- Monitoring platform principal tasks are:
- Gather data from monitoring equipment
- Provide a convenient representation of structure settlements/heave and distortions
- Store monitoring data

A peculiarity of the monitoring platform developed by the authors for Florence project is its ability to calculate in real time important parameters derived from monitoring readings. Parameters like distortions and maximum deflection ratio are of vital importance for buildings' structural health (Burland et all 2001). They provide a direct measure of the potential shear and bending effects acting on relevant portions of the structure. These parameters are not point-wise information but derive from a set of settlements read along a building structural alignment and, therefore, cannot directly be read with a monitoring instrument.

The monitoring platform gathers settlements data along structural alignments as soon as they are forwarded by the instruments and calculates distortions and maximum deflection ratio making them available in real time to the compensation grouting suite allowing for a direct supervision of both settlements and distortions.

#### **Compensation grouting suite**

Compensation grouting suite is the hearth of compensation grouting activities. The writers developed the suite to provide the required support for the activities on site. Its principal tasks are:

- Real time data retrieval from the monitoring platform
- Real time evaluation of structural health (check on settlements and distortions)
- Definition of which grouting port has to be activated and grouting volumes for each port (Grouting strategy)
- · Automatic communication of the grouting strategy to grouting control system
- · Retrieval of actual grouting volumes, pressures and grouting ports as executed on site

- · Compensation grouting efficiency update
- · Relevant parameters storage

The peculiarity of the compensation grouting suite developed by the authors lays in its ability to provide a real time support for defining the compensation grouting strategy when the team requires it. When threshold values are exceeded, a series of non-uniform grouting injections have to be performed on a precise number of grouting ports to restore building's structural health (in principle restoring building original layout). Which grouting ports have to be activated and the amount of grout for each port has to be defined very quickly for an effective compensation grouting. The compensation grouting suite does it automatically, communicating the strategy directly to the grouting station (the strategy is checked and approved by engineers supervising the activities).

The suite localizes the settlements retrieved from the monitoring system and activates the grouting ports belonging to that particular area. Monitoring points and grouting ports layout do not coincide on a one-to-one basis as monitoring points are significantly fewer than grouting ports. Therefore, the suite extrapolates the reference settlement value for each grouting port determining the grouting volume required to heave its effective area back to its original level. The grout volume is then calculated considering the Ground Efficiency Factor (GEF) applicable in that area. The GEF is the ratio between the grouted volume and the soil volume increased measured by the monitoring system in a particular area. GEF values for the entire area are continuously updated by the suite at each loop to provide the engineering supervising and confirming the suggested GEF values with the latest information available.



Figure 7. Settlement and distortion representation and compensation grouting suite workflow

#### APPLICATIONS

Compensation grouting activities performed so far in Florence HSR project comprise test field pretreatment and concurrent grouting simulation, and buildings 165 and 166 pre-treatment.

## Test field

Pre-treatment goal was to uniformly heave the test field plates within a range of 3 to 5 mm. Furthermore, a concurrent grouting step has been simulated to check the capacity of the system to actuate a non-uniform displacement field within the largest plate. The non-uniform displacement field was calculated on the basis of the Peck curve for a 1.5 m excavation advance (Figure 10 left).

Pre-treatment strategy was to firstly grout external grouting ports in order to create a confinement perimeter, and then to grout inner grouting ports. Pre-treatment was executed injecting one port at a time. Pre-treatment successful execution is shown in Figure 8 where practically all monitored points present an heave within the

target (The hatched area represent the goal-heave). Only control point 3, in the eastern corner of the plate presents an heave slightly less than 3 mm.



Figure 8. Pre-treatment results for plate 2 on test field

The results of concurrent grouting simulation is shown in Figure 9 and Figure 10. Goal-heave is given for each control point in the legend and represented in the graph with the hatched area. Grouting strategy was to inject outer TAMs first, proceeding inwards and injecting 4 ports at a time. The resulting deformed shape obtained is flatter than the goal-shape. In particular northern corners present a higher heave than desired, while peak heave at control point 6 has been practically reached. This is due to the high relative stiffness of the plate (50 cm thick, 8m x 8m), which resulted in a flatter deformed shape. Nevertheless, the results obtained can be regarded as successful in reproducing a Peck curve for the simulated advance.



Figure 9. Concurrent grouting simulation: heave measured at control points



Figure 10. Concurrent grouting simulation: 3D view of the heave measured on plate 2

### **Building 165**

Considering the position of building 165 with regard to the tunnel axis, pre-treatment target was a nonuniform heave varying from 7 mm to less than 1 mm. Excavation effects are expected to be larger on the western areas of the building and the pre-treatment strategy has therefore been adjusted to recreate on a smaller, positive scale excavation settlement domain. Pre-treatment strategy employed 4 grouting ports at a time, injecting first the outer area to create a confinement perimeter and proceeding inwards. Control point layout on building 165 are shown in Figure 11. Measured heave is shown in Figure 12 where desired values are hatched in green. An larger heave has been achieved on control point 1, nevertheless pre-treatment activities has been considered successful.



Figure 11. Building 165: control points layout



Figure 12. Building 165: pre-treatment results at control points

## **Building 166**

As per the test field, pre-treatment target was to achieve a uniform heave within 3 to 5mm. Pre-treatment strategy employed 4 grouting ports at a time, injecting first the outer area to create a confinement perimeter and proceeding inwards. Control points layout is shown in Figure 13. Measurements are shown in Figure 14. Slightly smaller heave (2.5 mm) is measured on control point 4 and 13. Nevertheless, the results have been considered sufficient to prove the good efficiency of compensation grouting system in that area.



Figure 13. Building 166: control points layout



Figure 14. Building 166: pre-treatment results at control points

#### CONCLUSIONS

The paper described compensation grouting activities performed so far in Florence HSR project. Compensation grouting resulted as the best solution to ensure structural health of two masonry building laying at short distance from TBM launching pit and having a net cover varying from 6 to 12 m. The paper described the in-depth numerical simulations performed to assess compensation grouting efficiency and to define the influence of compensation grouting key factors. The paper described the results of compensation grouting activities performed in a test field area where the monitoring system, the compensation grouting suite, the grouting mixtures and the overall efficiency of the system have been intensively proven. After pre-treatment, a settlement field was reproduced, corresponding to the Peck formula displacement field obtained for a 1.5 m excavation advance. Results obtained were successful and the paper described the results of the following pre-treatment activities performed for the two masonry buildings.

The success of the compensation grouting activities performed could not be obtained without the support of particular software tools developed by the authors which enabled a real time access to monitoring data, simultaneous building risk assessment and direct calculations of grouting volumes and locations which were directly transferred to the grouting control system and injection team.

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