Settlements induced by jet-grouting execution in tunnel

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ABSTRACT: During the construction of a tunnel of small cross-section for the new High Voltage cable 380 kV AC property of Terna between Sicily and Calabria (in the Southern of Italy), an embankment of the National Railway line was excavated by the tunnel at very shallow depth, with an overburden of only 8 m. between the new tunnel and the existing railway. With the purpose of minimizing the settlements caused on the railway line (in full operation during the excavation of the tunnel), an umbrella of jet-grouting columns was designed to be installed around the overall tunnel profile, while other jet-grouting columns were planned on the tunnel face. Nevertheless, some significant settlements of the embankment and the railway line occurred during construction which were carefully monitored.

The settlements occurred during the very early execution phases of jet-grouting columns and to a lesser degree during tunnel excavation, as it is to be expected from a theoretical point of view. In fact, during excavation, it was observed that the railway embankment had been built with unsuitable soils in some layers, and that these horizontal layers of very large permeability were strongly deformed during the pressure grouting. The presence of these layers had not been observed during the site investigations, because of the peculiar geometry of the embankment and because no permission had been given for executing boreholes from the railway line.

Anyway, there was no trouble during the transition of trains, caused by the settlements, thanks to a special steel structure which was installed in order to stiffen the railway tracks, with the positive result that equalization of the rail deformations was obtained.

1 INTRODUCTION

Terna, owner of the Italian National electricity transmission grid, planned the building of a new High Voltage cable 380 kV AC between Sicily and Calabria (in the Southern of Italy). The new power line is constituted partly of the suspended line, partly of submarine and underground cable.

Within the project power line, LOMBARDI has designed the underground stretch between the landing of submarine cables at Favazzina and the power station of Scilla, in the regions of Calabria.

Underground structures mainly consist of a sub horizontal tunnel, excavated with a double shield TBM (Length = about 2.9 km, Diameter = about 4.1 m), and a vertical shaft excavated with traditional excavation (depth = about 300 m, Diameter = about 7 m).

Figure 1 Chorography of the project location

Figure 2 Longitudinal section of tunnel and shaft

The first stretch of the tunnel, having a length of 100 m. and a diameter of about 6 m., was excavated with the traditional method to go under the adjacent railway line and road and for the initial stretch of weathered and loosened rock.

In order to minimize the settlements induced on the railway line, soil improvement with jet-grouting was adopted.

This paper deals with the deformation induced by soil improvement and tunnel excavation on the railway embankment, focusing on some findings that were difficult to predict in the design stage.
2 UNDERPASS DESCRIPTION

2.1 Geological and geotechnical framework
Referring to the geological profile shown in Figure 4, the soils affected by the underpass are:
- Backfill (railway embankment) – A coarse gravel, with pebbles and blocks, alternating with sandy and silty matrix;
- Detritus – Slope detritus, composed of coarse gravel and slightly silty sand.

2.2 Ground improvement and structural consolidation description and execution phases
The main improvement and consolidation measures were:
1. Consolidation of the existing wall with steel bars and execution of a wall reinforcing the existing one;
2. Installation of the Verona System “Sistema Verona” for rail protection;
3. Ground improvement of the excavation using reinforced jet-grouting columns.

2.2.1 Consolidation of the existing wall
Before the underpass of the railway embankment with the traditionally excavated tunnel, the reinforcement of the existing wall was planned for a length of about 20 m. between the tunnel axis.

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The construction phases were planned as following:
- Cleaning the existing wall with water under pressure;
- Installation of shotcrete and wire mesh on the wall surface;
- Consolidation of the existing wall with sub horizontal anchor rod (Length = about 12 m.), with a quincunx pattern and spacing of about 1.5 m.;
- Installation of vertical micro-piles at the foundation of the wall;
- Execution of the reinforced concrete wall.

The consolidation of the existing wall reduced the horizontal displacements and, as a consequence, the settlements of railway line and road surfaces.

2.2.2 “Verona System”

Before the execution of the underpass, the Verona System (a rail support system patented by the company Petrucco Italia Srl) has been applied. This system reduces the interference with the railway service, during the construction stages of works.

The Verona System is composed of two main beams HEB 550 and secondary beams HEM 180 in order to support the rails.

In the present project, the Verona System was installed in 39.6 m. (two 13.2 m. modules and two 6.6 m. modules), in the simply supported configuration, with metallic plate foundations (see figure 10). The Verona System was installed over the night, when the train frequency was very low, about 4 or 5 trains per night.

The rail support system was designed with the methods of permanent bridges, considering a maximum speed of the transiting trains of 80 km/h. This performance capability was amply sufficient, as the maximum speed of the trains had been decrease in 10 km/h for safety reasons taking into account also the past landslide events (2003 and 2005).

2.2.3 Excavation in embankment soils – Cross Section type SG1

After the installation of the Verona System, the underpass was carried out with the cross section type SG1, having a double jet-grouting umbrella reinforced with metallic micro-piles. This measures allowed the safe progress of the excavation, protected by the previously constructed jet-grouting umbrella.

Referring to the figure 11, the cross section type SG1, was applied in 5 excavation steps (6 m. long), for a final length of 30 m, overcoming the railway site. A further 6 m. excavation step was carried out, protected with a metallic umbrella of micro-piles, cemented in the rock.
The aforementioned measures allowed the safe underpass of the railway line SA-RC end of the national road SS 18, both the infrastructure remained in service during the underpass works period.

2.2.3.1 Ground improvement at the excavation contour

Sub horizontal jet-grouting columns, reinforced with metallic micro piles were realized before the tunnel excavation. The columns layout was arranged in order to obtain a conic protective umbrella at the excavation contour.

The single fluid jet-grouting column have diameter of about 500 mm, length of 12 m., overlapping 6 m.; each excavation step was 6 m. long. The reinforcements were realized with a steel pipe (S235, external diameter = 70 mm, thickness = 10 mm). Ground improvement geometry is clearly shown in figures 12 and 13.

At the same time, sub horizontal drilling holes were realized in the perimetric zone of the excavation front. These drilling had the scope to absorb the overpressure induced by the jet-grouting in the soil, that could have caused ground uplift. These drilling holes were realized only in the first jet-grouting step, because no ground level uplift were detected.

Single fluid unreinforced jet-grouting column were realized at the excavation front, with diameter of 500 mm, length of 12 m and overlapping of 6 m.

Also invert zone was improved with single fluid unreinforced jet-grouting column (diameter = 500 mm).

The layout of the improvement measures, hallowed to obtain a ring of improved ground that permitted an excavation with high safety level against ground settlement.

2.2.3.2 Tunnel excavation

The full section excavation, was realized using mechanical excavation equipment (hammer, excavator and, in the hardest zones, road header) without using explosive, with maximum excavation step of about 1.0 m., with the immediate installation of the temporary support:

− Couple of metallic ribs IPN200, spacing = 1.0 m.;
− Shotcrete thickness = 0.25 m., 0.20 m. fibre reinforced and 0.05 m. as finishing, with the purpose of preventing the damage of the waterproof membrane.

In order to allow the contact between the metallic ribs and the jet-grouting column previously realized, the ribs were designed with variable dimensions according to the conic shape of the excavation. The steel ribs were designed closed in the invert section, assuring a good structural efficiency and as a consequence limiting the ground deformation.

2.2.3.3 Final lining

The final lining is in reinforced concrete. First it was cast the invert and subsequently the crown. The final lining has a thickness variable between 0.3 m. and 1.1 m., because the shape of the excavation is conic.
3 JET-GROUTING

The first construction step of the tunnel was used also as field test.

Given the improvement measures and their position respect the railway line, the trial columns were realized with a lateral drilling in order to limit eventual ground uplift.

On the left side of the tunnel entrance, the columns 1-3-5 were realized according the following sequence:
- Drilling hole P1;
- Execution of jet-grouting column 1;
- Drilling hole P2;
- Execution of jet-grouting column 3;
- Drilling hole P3;
- Execution of jet-grouting column 5.

On the left side of the tunnel entrance:
- Execution of jet-grouting column 31;
- Execution of jet-grouting column 33;
- Execution of jet-grouting column 35.

The field test continued with the execution of the jet-grouting column at the bottom A2-A6-A10 and the columns at the front F1-F3-F4. Column F5 and F6 were executed subsequently with a different set of parameters.

The jet-grouting umbrella was completed with the alternate execution of all the columns (adjacent column were not executed one after the other).

During the test, the following parameters were recorded: grout adsorbed parameters, lifting speed, grout leak from the drilling hole, grout leak from the embankment (equal to zero) and the displacement at the monitoring positions.

After analysing all the available data, the following parameter has been selected:
- Pressure: 300-400 bar
- Nozzles: n.2, Ø3 mm
- Flow rate: 3.2 l/s
- Lifting step: 6 cm
- Step: 5-6 s
- Water cement ratio: 0.70
- Injected cement per treatment unit length: 248 Kg

4 MONITORING

Considering the small overburden and the importance of the underpass and of the existing infrastructures, a monitoring system has been provided to evaluate the ground level subsidence induced from the excavation.

The monitoring consists in traditional convergence measures in the tunnel during the excavation and a monitoring system to measure the track twist.

Monitoring the rail geometry was dramatically important in order to assure the train safety during the excavation of the first 50 m. of the tunnel.

The main parameters for the safety of the railway service were individuated in the “longitudinal level” and the “track twist”.

The instrumentation used for the monitoring were electrolevels and topographic targets at ground level.

At the same time, also the state road SS18 was monitored using topographic targets.

Seven cross sections (respect to railway line), were defined (i.e. sections Pk123, Pk139, Pk245, Pk149, Pk154, Pk159, Pk172 in figure 16) with a final total length of about 50 m. referring to the tunnel axis (see figure 16).
The following instrumentation was provided in each instrumented cross section:

- n. 2 electrolevels, one for each rail in transversal direction, set on railroad ties;
- n. 2 electrolevels, one for each rail in longitudinal direction, set on railroad ties;
- n. 4 topographic targets, two on each track set on railroad ties;
- n. 1 reflector prism set on the existing retaining;
- n. 1 topographic targets on state road SS18 in correspondence of the small wall.

Furthermore, cross section instrumented for convergence measure during tunnel excavation have been provided. Each section was provided of 5 optical targets, arranged as shown in figure 20.

5 HISTORY OF INTERVENTIONS AND EXCAVATIONS

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
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<tbody>
<tr>
<td>18.06.2012</td>
<td>VERONA SYSTEM – Start of the system installation</td>
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<tr>
<td>26.06.2012</td>
<td>VERONA SYSTEM – End of the system installation</td>
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<tr>
<td>12.07.2012</td>
<td>MONITORING – Start of data acquisition</td>
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<td>16.07.2012</td>
<td>JET-GROUTING – 1st step, start (field trial)</td>
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<tr>
<td>20.07.2012</td>
<td>JET-GROUTING - 1st step, field trial end</td>
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<tr>
<td>06.08.2012</td>
<td>EXCAVATION – Excavation of the soil at the base of the reinforcing wall</td>
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<tr>
<td>10.08.2012</td>
<td>JET-GROUTING - 1st step, end</td>
</tr>
<tr>
<td>27.08.2012</td>
<td>EXCAVATION – demolition of the existing retaining wall at the base of the</td>
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<td></td>
<td>railway embankment. 1st excavation step, start</td>
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<tr>
<td>30.08.2012</td>
<td>EXCAVATION - 1st excavation step, end</td>
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<tr>
<td>03.09.2012</td>
<td>JET-GROUTING – 2nd step, start</td>
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<tr>
<td>10.09.2012</td>
<td>VERONA SYSTEM – Forced uplift of the downhill railway track (alignment 1 and 2)</td>
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<tr>
<td>14.09.2012</td>
<td>JET-GROUTING - 2nd step, end</td>
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<td>17.09.2012</td>
<td>EXCAVATION - 2nd step, start</td>
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<tr>
<td>19.09.2012</td>
<td>EXCAVATION - 2nd step, end</td>
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<tr>
<td>20.09.2012</td>
<td>JET-GROUTING – 3rd step, start</td>
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<tr>
<td>09.10.2012</td>
<td>JET-GROUTING – 3rd step, end</td>
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</tbody>
</table>

The 3 monitoring stations in the tunnel was provided at stations:

- Pk 0+012 (on the vertical of the downhill railway track);
- Pk 0+021 (on the vertical of the uphill railway track);
- Pk 0+033 (on the vertical of the centreline of the state road SS18).

The optical targets were installed on the steel ribs and the convergence were measured with precision optical instrumentation.
With reference to the sketch in figure 21, the diagram in the figure 22 shows the displacement versus the time of some of the monitoring points, caused by the tunnelling works. The execution time of the main works (jet-grouting / excavation) is shown, with vertical stripes, in the same diagram in figure 22.

The diagram in figure 22 does not take into account the corrections (forced uplift) executed with the Verona System. Consequently, the displacements in the diagrams are theoretical, with the uplift of the Verona System the real settlements were reduced to a maximum of about 35 mm, while the maximum in the diagrams is about 55 mm. The Verona System was very effective mainly in reducing the track twist (the most important parameter for the safety of the train during its transit), which measures were always smaller than the admissible threshold imposed by the railway line owner company.

The diagrams in figure 23 and 24 show the displacements induced during the main working phases.
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Figure 24 Incremental displacement during the main working phases

It can be deduced by the presented diagrams that most of the displacement has been recorded during jet-grouting operations, while during the excavation phases (in the ground improved zone) only small displacement (almost negligible) has been developed.

Most of the displacements of the reinforcing wall developed during the 1st jet-grouting phase, probably caused by the pressure increasing behind the wall. No appreciable displacements were measured during the subsequent works.

The railway tracks (points V_149.2 e V_149.3) present displacements increasing near the front of treatment.

The uplift of the railway tracks, caused by jet grouting, was found locally only during the second part of the 1st and 3rd steps of jet grouting.

The settlements are developed also in the road wall. These settlements were smaller (about the half) compared to the ones measured in correspondence of the railway line, this can be due to the better geological condition underneath the wall (see figure 4).

The smallness of the displacements during the excavation phases confirms the effectiveness of the designed ground treatment.

The small value of the final differential displacements and of the track twist, confirms the effectiveness of the Verrona System in protecting the railway tracks and granting the railway service.

Particularly interesting were the settlements developed during the jet-grouting phases. A priori, considering the small overburden and the treatment pressures, uplift of the railway tracks was expected. The measured displacements were in the opposite direction than the expected ones, this fact can probably be related to the specific geological condition (widely explained in chapter 6).

6 MEASURES INTERPRETATION

The interpretation of the causes of the unexpected settlement is not an easy task. Some interpretations have been carried out taking into account the position of the treatment zones respect to the monitoring points, and of the geological survey on the excavation front during the excavation of each treatment zone.

In the following figures are presented the geological condition at the excavation face in correspondence of each treatment step.
The first 4 excavation phases were in backfill, while the 5th was in rock (transition zone).

In correspondence of the first 3 steps, it can be noted that part of the grout flowed into horizontal layers of coarse material. These coarse material layers were not detected by the surveys in the design stage (boreholes S0 and S2), having a limited horizontal extent.

Although the interpretation of the settlement causes is not an easy task, having only displacement measures and missing some important information (as for example a characterization of the coarse soil layer as it was before the treatment, or stress measures), settlement development is supposed to be mostly due to the presence of these coarse soil layers. In the pictures it can be seen that the grout flowed into and filled the space between gravels and blocks of the coarse layer (this layer probably was the ballast of the old railway line, before the subsequent backfilling and increasing of the railway line level to the actual position).

It can be supposed that the settlement at the ground level can be attributed to the compression of the horizontal layer, caused by the displacement of part of the finer material and replacement with the grout which, in the fluid state, has been deformed under the lithostatic load. The vibrations due to the passage of trains could have been able to intensify the process.

The diagram in figure 22 shows the settlements induced by the treatment in correspondence of the stripes 1_Ja, 2_J and 3_Ja. While in correspondence of stripes 1_Jb and 3_Jb it can be seen an uplift, caused by the grouting pressure (after that the settlement due to the coarse soil has already developed in the correspondent zone).

7 CONCLUSIONS

The present paper describes the displacement induced during jet-grouting treatment in the surrounding soil, referring to the history case of the new High Voltage cable between Sicily and Calabria (in Southern Italy), of whom LOMBARDI has developed the design of the underground structures.

In the first stretch of the tunnel, the soil improvement with jet-grouting was provided in order to achieve the safe excavation of the railway and road embankment, having a maximum overburden of about 8 m.

The analysis of monitoring measures has highlighted as following:
- An increasing of settlements during the jet-grouting execution;
- The almost negligible development of settlement during the excavation phases, index of the effectiveness of the ground improvement.

During jet grouting treatment, the uplift of the railway tracks was expected, because of the small ground coverage and the treatment pressures. The measured displacements were greater than expected, and in the opposite direction. Anyway, there was no trouble for the trains transit while the settlements occurred, thanks to a special steel structure which was installed in order to stiffen the railway tracks, with the positive result that equalization of the rail deformations was obtained.

Monitoring data analysis, together with the survey of the front excavation (during the excavation phases) gave the possibility to suggest a cause of that unexpected settlements.

Settlements development can be attributed to horizontal coarse soil layers. Pictures of the excavation front show that the grout flowed into and filled the void of the coarse layer. It seems likely that the settlement at the ground level can be attributed to the compression of the horizontal layer, caused by the displacement of part of the finer material and replacement with the grout which, in the fluid state, deformed under the lithostatic load.

The vibrations due to the passage of trains could have been able to increase the process.

8 REFERENCES