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INJECTION CONSOLIDATION UNDER THE PIERS OF THE RAILWAY BRIDGES FOR THE REHABILITATION OF LINE MERANO-MALLES

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ABSTRACT

New design loads on Merano-Malles Railways Line required structural and ground improvement along the whole line and particularly on a couple of XIX century masonry arch bridges near Silandro village, N-E Italy, South Tyrol region.
The need to minimize downward-settlements during ground improvement operation, along with the target to create a controlled upward lift-up of treated footings, brought our design choice toward an extremely delicate and totally monitored Multistage-Multiport Low Pressure Grouting solution, based on Manchettes - pipe technique.
A Successful Design concept, Grouting details, Monitoring results are presented in this paper.

INTRODUCTION

The design is arranged into the Merano-Malles railway line rehabilitation works, commissioned by the STA (South Tyrol Transport Organization) and it is constituted by the structural adjustment of some bridges on the line, in the form of the structural elevation parts (bridge deck extension) and foundations rebuilding and/or strengthening.

The qualification actions, finalized to the V7 and V8 bridges structural functionality restoration and to their settlements reduction, are the subject of this paper. These bridges are located in the Silandro village, South Tyrol (north-east of Italy).
The two bridges of interest for this paper, V7 and V8 are composed as follows:

- V8 three masonry and stone arches, based on two central piers and two lateral abutments;

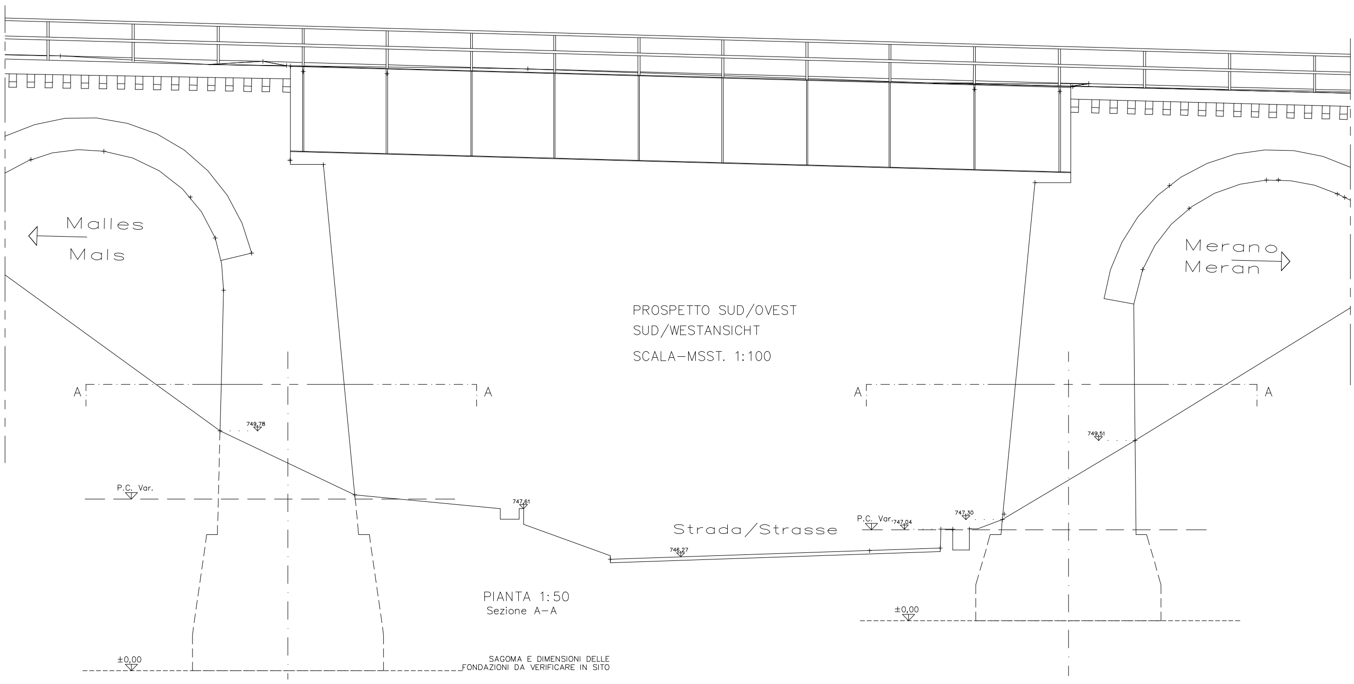

Fig. 1. V7 bridge view: masonry arches and steel reticular plank.

- V7 two masonry and stone arches, each of them equipped with one pier and one abutment, connected by a steel truss bridge deck (Fig. 1).

The original design provided, besides the masonry strengthening, a foundation improvement through steel driven pipes of small diameter. These were located under all supports, the intermediate piers and the abutments, with a function of settlement reducers. To strengthen the piers footing piles were driven from the level ground elevation, with subsequent concrete casting, making the piles connected to the foundation through its enlargement by a concrete crown.
In September, 2001, the foundation ground of the pier on Malles side (V8 bridge) was involved with the pile work in project, which would have had to improve the structure-ground interaction behavior under the new design loads.
The work was stopped on September, 27th, when a crack into the bridge arch showed a major pier settlement (Fig. 2).
The observed settlement was directly related to the piles holes collapse, in the portion in which the walls were not supported by steel casing during its extraction or filled by mortar, and so they tend to converge in order to reach new equilibrium. This fact can produce a disturbance on the surrounding ground portion, with consequent surface settlement.

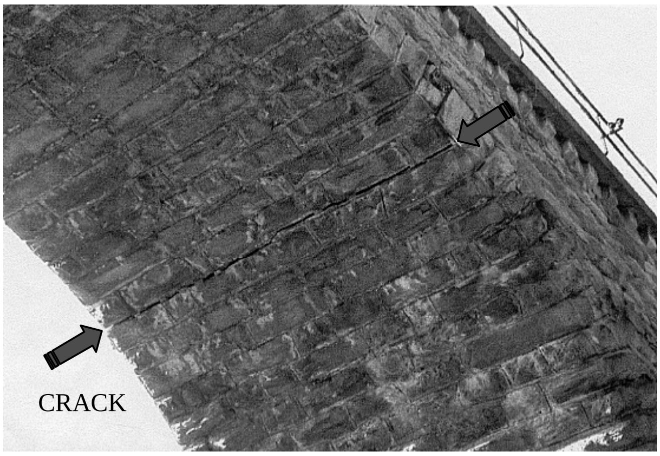

Fig. 2. The crack in the arch caused by settlements.

In fact, nobody can know with precision how large the settlement during the pile work has been, due to the lack of monitoring over the pile driving and no structural analysis would have been justified in relation to the works size. Nevertheless, rough settlement estimation is possible.
In a first evaluation, one can assume that all the holes (Φ=220mm) had collapsed until the diameter reached the external diameter of the steel pile (140mm). In this case, it would be possible to estimate a certain loss in volume, distributed on a potential subsidence basin, that would give a theoretical value for the footing settlement. In the present case, this value is about 50mm and it is interpreted as the superior limit of possible settlements (Fig. 3).

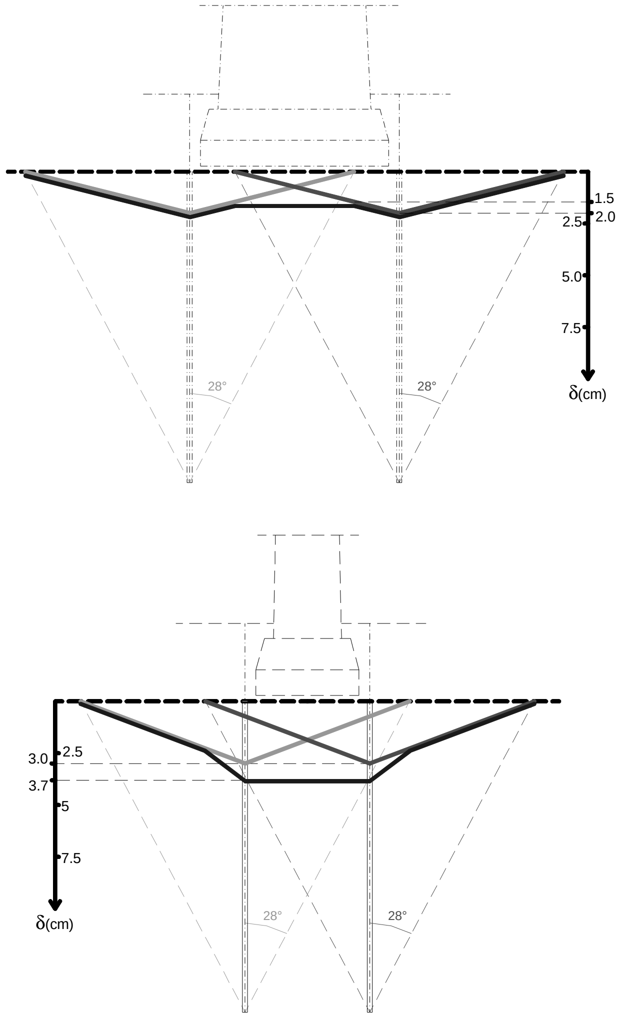

Fig. 3. Rough settlement distribution hypothesis due to volume loss during pile drilling. The first graph shows the holes effect along the longest side of the footing, the second one along the shortest side. The sum of the two effects give the total amount of settlement, theoretically coming to about 52mm.

In a second evaluation, the convergence of a cylindrical hole in an elastic-plastic medium, behaving in accordance to a Mohr-Coulomb plastic criterion, has been estimated, which resulted in a figure greater than 20 mm, instead of 40 mm separating the steel pile from the hole wall.
According to this result and through a simple proportion of the difference in volume loss, a pier settlement of about 30 mm was obtained.
Because of the sensibility of masonry structures to distortion, and with the assumption that a masonry arch can crack at a differential settlement of about 1/500 of its span, it can be obtained that real settlements have been in the order of 1/500 of the span (12 m), and then of more than 25 mm, accordingly to the crack on the arch and to the rough evaluation developed above.

The pile drilling was abandoned and, based on this background, it was necessary to proceed with further additional geotechnical investigations, to support the use of an alternative strengthening method in order to achieve at the same time two results such as settlement recovery and functional adaptation.

ADDITIONAL GEOTECHNICAL INVESTIGATIONS

Before the strengthening work was performed, an additional geotechnical investigation has been carried out, composed of three drillings (with Permeability and SPT tests) and one seismic tomography for each bridge. In particular, a topographical survey was accomplished, in order to record and check further movements. At last, settlement measures were extended during all the period involved by the injection works.

GEOTECHNICAL CHARACTERIZATION OF GROUND INVOLVED INTO THE INJECTIONS WORKS

The V7 piers rest on granular soil composed of locally pebbly sand and gravel, generally weakly silty. In the location of V8 Bridge, the ground is similar, with a succession of sandy levels with silt and gravel. The upper layer consists of a filling material, standing above an alluvial fan debris underlying.

The soil involved in the settlement is the deeper debris, because the footing level lies below the filling materials.

The water table is below the level of interest. The debris mean geotechnical parameters are listed in the Table 1 below.

Table 1. Debris geotechnical parameters.

φ'	c'	γ
35°	0	$19 kN/m^3$

The Young's Modulus have been evaluated using the following relation (effective for granular compacted soils):

$E_{ti}=1000*\sigma'_3$ where σ'_3 is the horizontal geostatic effective stress.

The hydraulic permeability coefficients have been obtained from the in situ permeability tests and are different in the two locations of the bridges: more exactly, they vary into the ranges specified below:

V7 bridge: $k=1*10^{-3}m/s\div3,9*10^{-4}m/s$;

V8 bridge: $k=8*10^{-4}m/s\div2*10^{-5}m/s$;

THE INJECTION DESIGN

On the basis of the grain size and the permeability exhibited, the ground was judged to be groutable by cement mix injected under low pressure.

So a new design was conceived including three different work phases:

- supporting frameworks used as safety measures;
- ground improvement, achieved by multi-stage cement grouting, using re-groutable sleeve-port grout pipes under low pressure;
- masonry rehabilitation.

In the present paper the cement mix injections are described. They are stabilized by bentonite and carried out by manchettes (multiport) pipes.

The **treatment targets were**, first of all, to restore the ground compression into its original density conditions and, secondly, to recover the settlement at the location of V8 bridge. Based on this, the injections have been designed and positioned consistently with their purpose. The external ones (A series) were first carried out and lie on the pier contour. They had a special confinement function, other than the core ones, made for tightening purpose, which were implemented after the A injections (named B, C, etc.).

The **holes were drilled** by compressed air rotary. The smallest diameter possible was used depending on the equipment availability and the PVC pipes dimension. The holes were supplied with casings along their total length.

After the PVC multiport pipes were inserted inside the casing, a **primary injection** was performed, through the deepest port, to fill the gap between the hole walls and the pipe itself.

At the same time, the casing was extracted gradually outwards and the hole was filled up with the required mix amount. After each primary injection, the pipe internal surface was washed; the subsequent injection was carried out after minimum of 24 hours from the primary injection.

The primary mix was prepared with a cement/water ratio of 0,35 (35 kg of cement per 100 l of water) and 6kg of colloid additive (bentonite) per 100 l of water.

The effective **injection mix**, on the other hand, was composed of a cement/water ratio of 0,70 (70 kg of cement per 100l of water) and 3kg of colloid additive (bentonite) per 100 l of water. The cement had a high rate of grinding fineness.

About the **injection location and length**, the spacing among the first confining injections (A) on the perimeter has been fixed with respect to the different permeability values; then, the maximum spacing reached 1,7 m around the Merano pier and 1,6 m around the Malles pier (V8 bridge). For the V7 bridge, the maximum spacing was 1,9 m because the permeability was greater. The spacing of the core injections had limitations because of the piers geometry and dimensions, the technical restraints and some localized interferences. The **port pipes** used had 2 different parts. The first part (2 m) was blind, without ports. The second part had ports with spacing of 0,33 m. The injection PVC pipes had a diameter $\phi$of about 1 ¼".

All around and below each footing, **operation sequence** has been splitted in 2 separated phases:

first phase: - "A Series" - Vertical Drill/injection holes along the boundary of the footing, in order to obtain a sort of Confinement retrofit for the second phase injection, to be executed directly beneath footing itself;

second phase: "B Series"- Slanted Drill/injection holes, directly reaching the confined volume beneath the footing - Core Injection- in order to reach the best controlled compaction result.

In all cases, the injections were accomplished in successive groups of four (not adjacent and not contemporary). Within each group of four injections, the pipes set up and the primary injections have been carried out before the drilling of sequent holes group, as well as the effective injections.

For the **injection sequence**, each port, from bottom to top, was injected with the lowest flow rate depending on the equipment, until one of the following events occurred:

1. injected mix volume per port equals to V_{max}=300 l (V8) or 500 l (V7);
2. injection pressure equals to P_{max}=5 bar (P_{max}=3 bar superficially);
3. injection volume increase with an almost constant injection pressure (hydrofracturing);
4. injection pressure increase with an almost constant injection volume (rejection).

The injection was sometimes repeated. Because of that, all the pipes had to be water washed from each port after the injection implementation. In addition, to guarantee the injection good results, a continuous monitoring has been accomplished to check the injection parameters and mix characteristics variations (flow rate, volume per each port and pressure recording).

After a period of 24-36 hours starting after the primary mix had been set, the core injections were implemented, with the pressures and volumes check, as mentioned above.

The injection treatments, carried out from port to port starting from the bottom, were performed by the means of a double packer, connected to the injection circuit. After the opening of the port, the pressurized injection has been continued till it reached the fixed adsorption volume and/or pressure value.

Each injection was performed having the absolute flow rate limitation of 30 l/min, with some exceptions where the injections were implemented with lower limits, in order to avoid hydro fracturing.

The minimum distance between two holes injected simultaneously was estimated in relation to the injection pressures, to eliminate any interference.

In such cases in which the estimated volume injection hasn't allow to reach the prescribed pressure, or vice versa, case by case the necessity to repeat the injection for each single port had to be checked (not before a time of 12-24 hours).

At the end of each phase, and until the treatment completion, the internal sidewall of the injection pipe was washed down.

During all the operations, a **structure settlements** continuous monitoring (checking) has been carried on, through significant bench marks movements record. The pier on Malles side (V8 bridge) has been considered to be subjected to a downward settlement of minimum 30 mm, before it has been treated with injections. In this case, with the aim to maintain the structure safe, a maximum security settlement value of 40 mm has been fixed, consistently with the structure integrity. In relation to this value, a threshold of attention of 10 mm for further settlements was assigned (reached when, more safety measures have been taken).

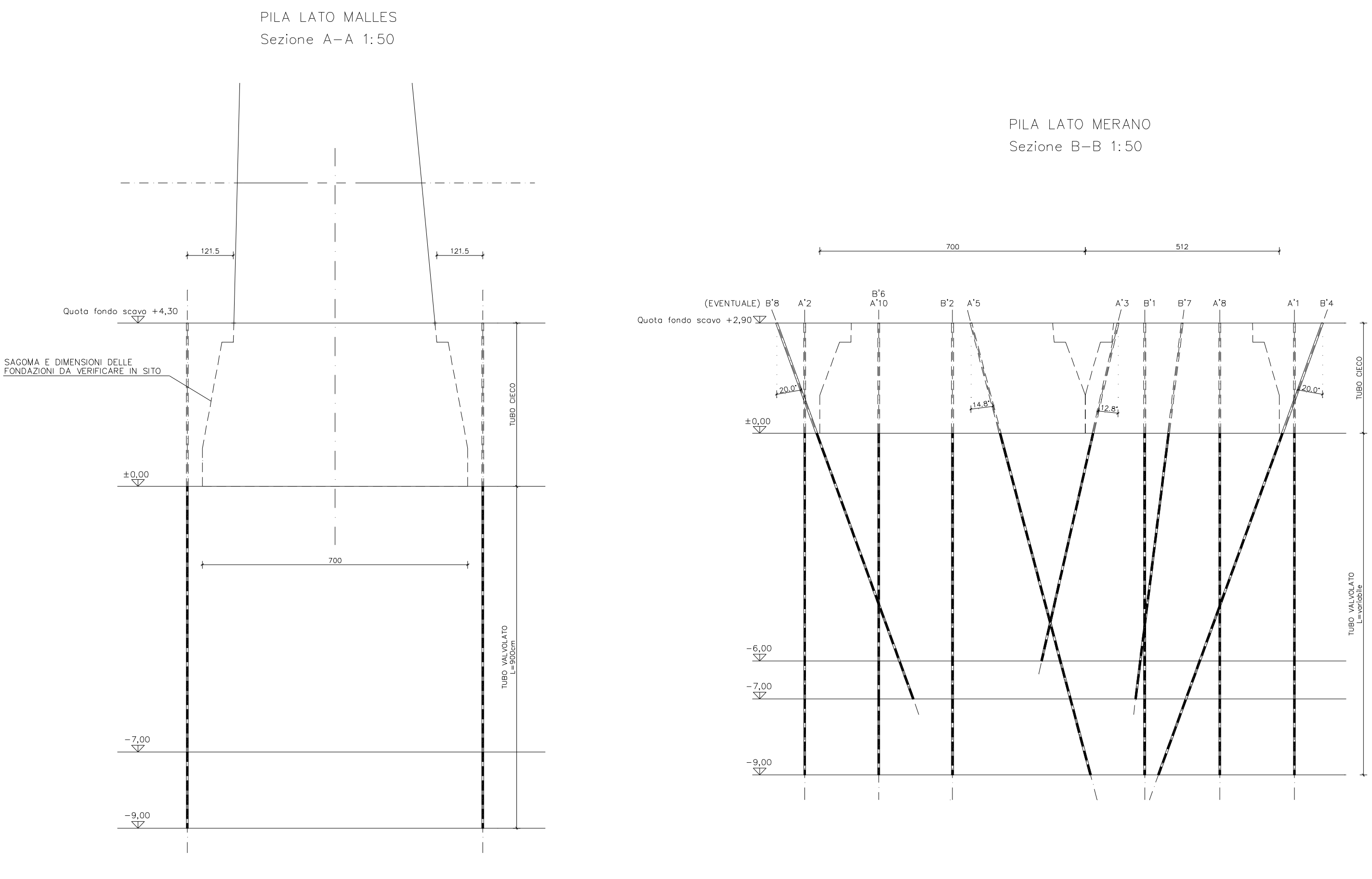

Fig. 4. V8 bridge, Malles pier treatment.

TREATMENT QUANTITY, GEOMETRY, DEPTH

The design provided the strengthening of V8 and V7 bridges piers in details as mentioned in the procedures below.
For the V8 bridge treatment, the Malles side Pier showed great difficulties when directly connected to the already executed piles and its related disturbance. This preexistence has required the guaranty of a major tightening action. For this reason, the injections have been organized into three subsequent series, progressively slanting towards the inner part of the pier. The first A series included a number of 20 vertical confinement injections, and the B series a number of 12 injections inclined towards the inner part, all showing a drilling length of 12 m and an injection length of 9 m. For the internal treatment, above the central core below the pier, 8 injections belonging to the C series were made, with a drilling length varying from 8 m to 12 m and an injection length varying from 6 m to 9 m.
The Merano side pier (V8) had exhibited an interference problem because of the presence of a municipality street, laying near it, to be closed during the development of work. For this reason, it was necessary to operate the injections on the two opposite sides of the pier in an independent manner.
In order to reduce the time, in which the street had to be closed, the pier was initially treated completely along the slope side, through 14 injections (both vertical and inclined), located around the pier without obstructing the street. These injections were characterized by a drilling length of 13 m and an injection length of 9 m. The job was completed by a second series, on the municipal street side, with a drilling length varying from 10 m to 12 m and an injection length varying from 7 m to 9 m.
At the V7 bridge, Malles side pier, an interference with the city drainage system was avoided by means of 14 A series injections (verticals with confined function), with a drilling length of 13 m and an injection length of 9 m. Also 6 B series injections were used inclined towards the inner part of the pier, to treat the core, having a drilling length varying from 12 m to 14 m and an injection length varying from 7 m to 9 m.
The Merano side pier had the major treatment geometrical problems, because of the nearness of the city drainage system, the public illumination line and one duct containing 6 electrical lines (10.000 V). This suggested to operate the injections only on the three sides free from the interfering lines, but this solution would have opposed operative restrictions later that could influence the final result. At the end, the treatment was accomplished through 12 A type injections (both vertical and inclined, positioned in a way to dodge round the service lines, but, at the same time, to guarantee an adequate overlaps), having a drilling length varying from 9 m to 12 m and an injection length varying from 6 m to 9 m, and 7 B type injections, Figure 4 (both vertical and inclined too, with an appropriate location), having a drilling length varying from 11 m to 14 m and an injection length varying from 6 m to 9 m.

THE WORK

The improvement treatment through the mix injection described in this paper was carried on starting in November, 2001, until April of the following year.
The constant monitoring, performed to check all the work steps, has been able to record a downward settlement of about 7-8 mm in the V8 Malles side location, after the injections drillings; this value is close to the prefixed attention threshold (10 mm). For this reason, an additional safety measure has been implemented, represented by the V8 bridge propping. Again for this bridge, the maximum flow rate of 30 l/min has been reduced in some cases, to ensure the respect of the imposed pressure limit.
In the V7 bridge location, an operative phases strict sequence has been applied. In particular, about the Malles side pier, the injection have been implemented four at a time in the two first sets (A1-A4 and A5-A8). The last six (A9-A14) were completed together. The drilling of these was simultaneous to the previous set (A5-A8) primary injection as also to the group A1-A4 injection. About the B series, the longest injections were performed before the shortest ones, to maximize the clamping effect.
The V7 Merano side pier 12 injections were executed four at a time, with the caution to implement the drillings of each "n+1" group after the "n" group pipes placing and primary forming, and during the "n-1" group injection.
In both cases the maximum volumes injected were of about 500 l/port.

QUALITY CONTROLS

The injection mixes prepared in the site location have been normally subjected to quality controls, having the aim to measure the parameters listed below:

specific weight;
Marsh viscosity;
decantation or volumetric yield;
apparent viscosity (Rheometer);
cement segregation;
time setting;
permeability;
compressive strength.

The specific weight always resulted equal to at least 95% of its theoretical value, assuming the cement specific weight to be 3 t/m^3.
In the segregation tests carried out on the stable mixes, the separated water in a time of 24 hours has never exceeded the 5% in volume.
For each drilling the contractor has provided the design team a schedule containing the following information:

- drilling identifying number and execution date;
- drilling length;
- drilling operative system;
- drilling tool;
- casing;
- injection pipe characteristics (ports number, spacing, position);
- primary injection volume;
- tables for each proper injection to show for each port and phase, the following entities:
    - date;

- opening pressures;
- adsorption volumes;
- reached pressures;
- flow rate;
- mix characteristics;
- composition;
- specific weight;
- Marsh viscosity;
- segregation;
- samples identifying data for the successive laboratory tests.

INJECTION PARAMETERS MONITORING RESULTS

The injection parameters monitoring has supplied with useful information to continue the treatment, especially for the V8 bridge, Malles side pier. For this pier, the first A series injections have showed pressures close to a zero value, with flow rates near to 30 l/min; after that, the pressures have progressively approached the limit value of 5 bar, with injected volumes of about 300 l/port and flow rates of about 7 l/min. With respect for the C series, the first ports (from the bottom) of the injections C4, C5, C6, C7 and C8 have reached the volume limit value during the second injection. For this reason, further clamping injection were provided into the first five ports of the mentioned injections, until rejection.

This operation has been carefully executed, to avoid irregular ground raisings. This was possible because of washing the manchette pipes. The washing also made it possible to resume some injections, when necessary.

CORRELATION BETWEEN SETTLEMENT MONITORING AND TREATMENT OPERATIONS

A summary of the working events and related measures of settlements for each pier is scheduled below (Table 2).
As anticipated, after the V8 Malles side pier settlements, caused by the pile execution work, the monitoring of the same bridge began on September 27, 2001. The injection operation near the Malles side pier began on November 9, 2001. During the first phases of injection, the settlements increased, with a minute influence on the Merano side pier; because of that, on November 31, 2001 the attention limit value of 10 mm was reached and the bridge was supported to guarantee the safety of work conditions.

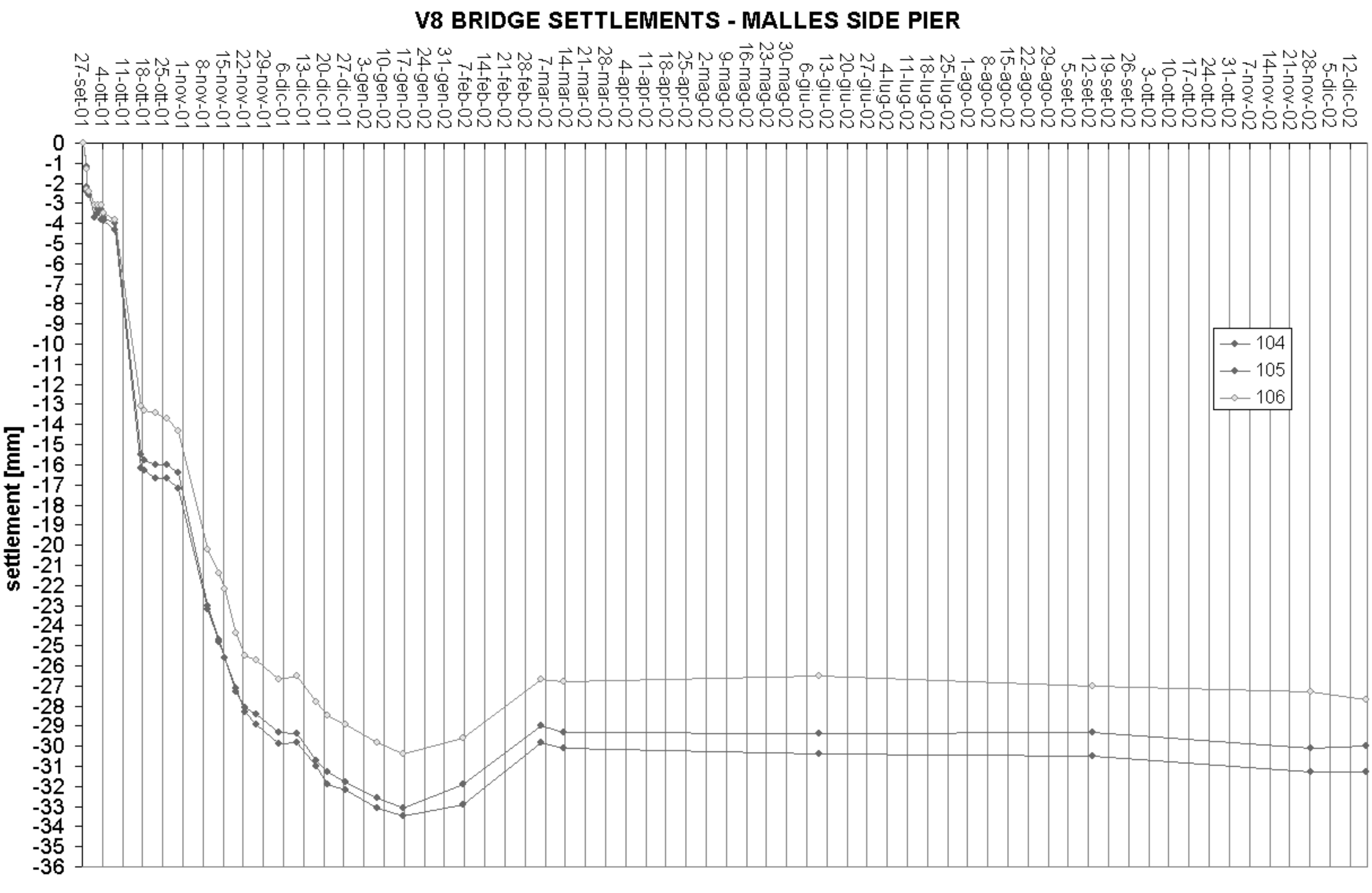

Fig. 5. V8 bridge, Malles side pier settlements.

Table 2. Correlation between settlement monitoring and treatment operations

Pier	Injection period		Maximum downward/upward settlement (mm)	Measure date
V8 Malles side	From Nov. 9, 2001	To Febr. 23, 2002	-33,5	January 17, 2002
V8 Merano side	From March 4, 2002	To June 3, 2002	-3	January 17, 2002
V7 Malles side	From Febr. 23, 2002	To April 4, 2002	+3,2	March 20, 2002
V7 Merano side	From April 4, 2002	To May 18, 2002	+3,7	April 8, 2002

The injection improvement effect began to reveal itself on the Malles side pier on about November 20, when the A series had been completed: in fact, around this date, the settlement curve slope decreased. The injections executed in the Malles side location had a weak influence on the Merano side location, yet limited to few millimeters.

On the date of January 17, 2002, when the propping devices were all operative under the V8 bridge, the maximum settlement values recorded were of about 30÷33,5 mm on the Malles side location and just of about 3 mm on the Merano side location.
At that time, only the confining A series had been completed.
The injections under the V8 bridge, Malles side pier, stopped on February 23, 2002. Observing the settlement curve (Fig. 5), it is obvious that during the period from January 17, 2002 till injections completion, the pier showed a recuperation of about 3,5 mm. In the final equilibrium state, this value became stable with a value of 2,5 mm (last reading: December 12, 2002).
The Merano side pier, not involved in the piles execution, showed as a whole a more stable behavior (figure 6): its critical settlement value was of about 3 mm on January 17, 2002, at a time in which the injection operations under that pier had not started yet.
After that, during the whole injections treatment, the observed behavior was related to a raising. Under this pier, the injection operations ended on June 3, 2002, with a maximum upward settlement of 3,5 mm. At the equilibrium condition, the pier total absolute upward settlement has been recorded around a 1,5-2,5 mm value.
The V7 bridge, Malles side pier began to be treated on February 23, 2002 and showed from the beginning upward settlements till a maximum value of 3,2 mm (March 20, 2002), at the end of B series injections. From that moment on, the settlement state

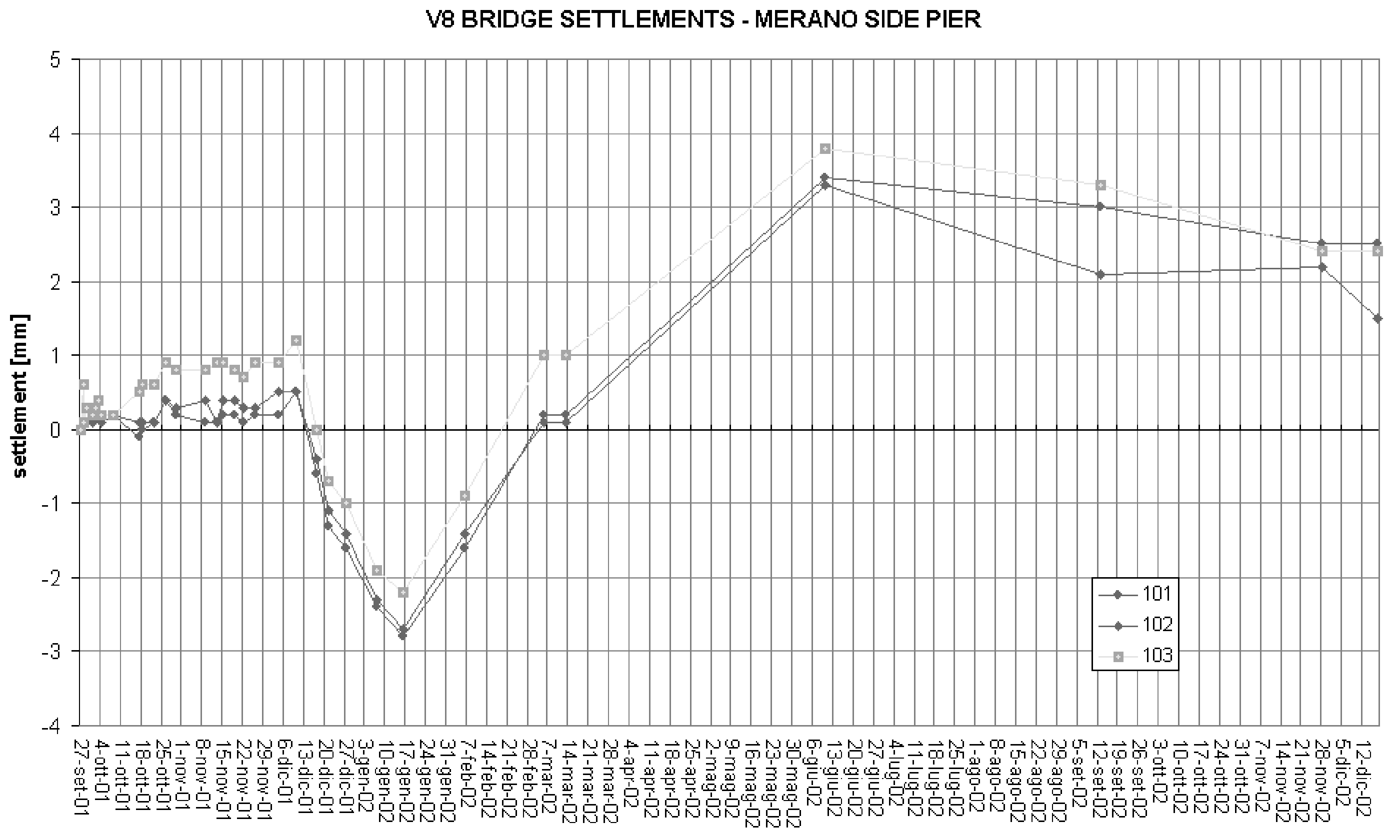

Fig. 6. The Merano side pier settlements (V8 bridge).

remained almost unchanged, recording raising of the same order of magnitude even in the last reading.

The V7 bridge, Merano side pier exhibited a very similar behavior. Its maximum upward settlement was of 3,7 mm on April 8, 2002, at Malles side injection completion and at the beginning of treatment on Merano side. The last readings confirmed the substantial stability, after the injections completion.

In December, 2002 the work and the supports removing under the V8 bridge were completed. Even in this event, no settlements increase was observed.

In general, for all the piers treated, the state reached immediately after the injection completion was confirmed as stable: no subsequent settlements evolution was appreciated.

The substantial difference between the two bridges behavior consists in the different amount of ground disturbance before the treatment: only the Malles side of V8 bridge showed relevant settlements, even during the injections operations. All the remaining piers showed upward settlements, even if moderate, permanent also after the treatment completion.

INJECTION EFFECTS

The final quantities, in their total amount, for each pier, are summarized into the table 3 below.

It is observable that the treatments showed different results and effects with respect to downward/upward settlements and in relation to the initial local disturbance.

According to that, it can be observed that in the location of the Malles side pier, V8 bridge (where the pile disturbance was the highest), the total injected mix was almost twice the volume amount of the one recorded in the other piers location.

Table 3. Final representative quantities for each pier.

	V8 Malles	V8 Merano	V7 Malles	V7 Merano
Injected mix total amount (m^3)	559	260	273	242
Total injection length (m)	339	216	165	167
Injected ports total amount (n)	1127	648	522	483
Injected volume per linear meter (l/m)	1650	1202	1656	1453
Mean injected volume per port (l/port)	496	401	524	501

Looking towards the strength and deformation parameters variation of the treated ground, it is possible to estimate improvement yielded by the injections. For this purpose, it is

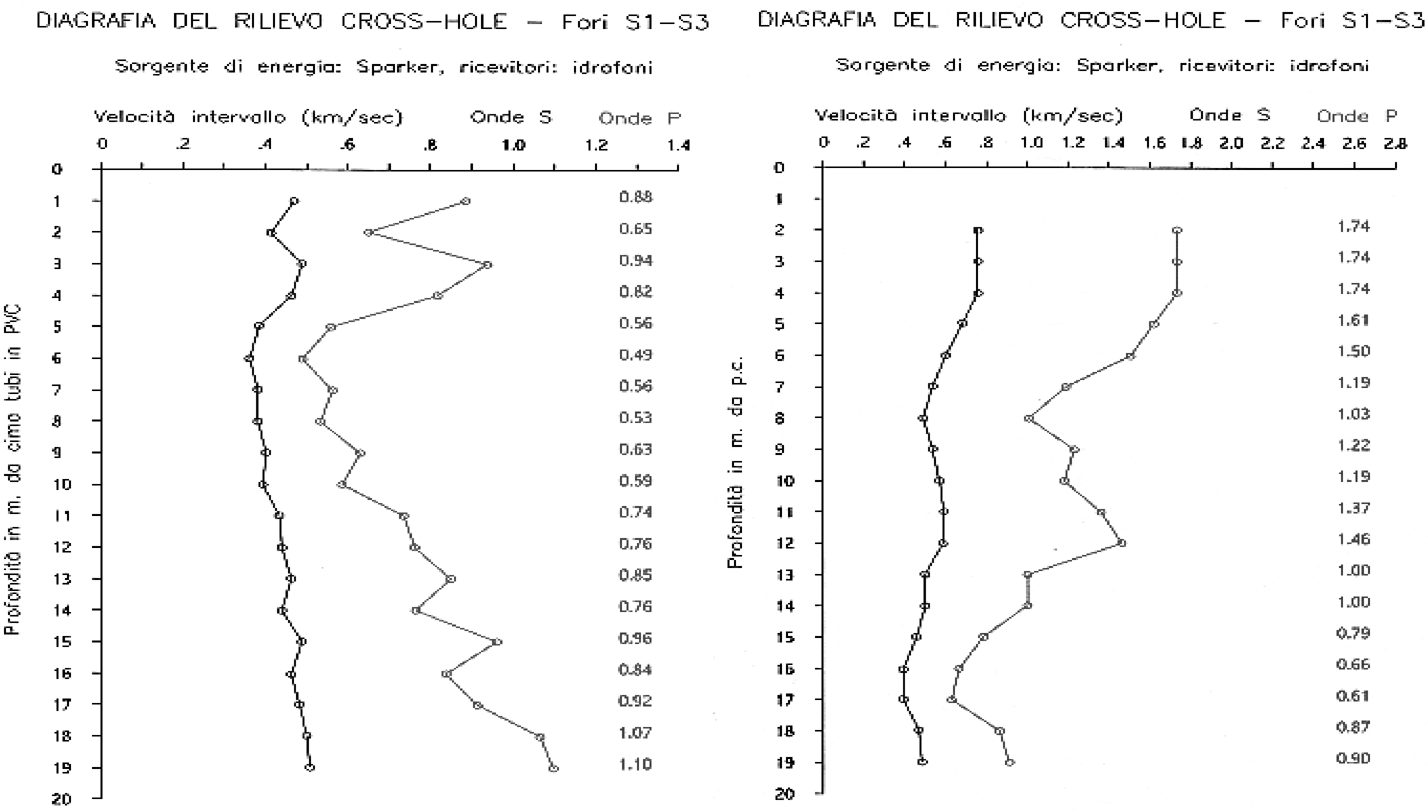

Fig. 7. Comparison between two seismic velocity profiles performed before (left side) and after (right side) the injections.

useful to compare two seismic tomographies performed before and after the injections (figure 7).
From this point of view, the ground deformation modulus variation resulting from the treatment has been assumed to be proportional to the variation of the one evaluated through the seismic tests. As a consequence, starting from the untreated ground modulus value, the one pertaining to the treated ground has been derived. According to this procedure, the improved ground modulus was estimated to be about 2,5 times as large as the original one.

SETTLEMENT REDUCTION

In the cases of V7 and V8 bridges, the net spans are of 8m and 12m respectively; the expected settlement under the new design loads are of about 15 mm and 18 mm.
The settlement/net span ratio is about 1/530 for the V7 bridge and 1/665 for the V8 bridge: these two values are considered critical for the reasons mentioned above.
In the case of arches like the case described in this paper, the greatest strain tend to concentrate in the central portion of the bridge deck, so that structural damages can be even caused by smaller settlements.
The improvement injections, finalized to the settlements reduction, were driven into the ground to a depth of about 9 m under the footing level. This depth has been considered adequate because the treatment reached the whole volume (pressure bulb) affected by the greatest settlement development (depth under footing level of about 2 times the footing dimension).
The expected settlements after the treatment have been estimated: they are supposed to be limited in inverse relation to the modulus increase (precautionary assumed twice the original value).
For the V8 bridge the expected new settlement is:
$\delta' = \delta/2 = 15/2 = 7,5$ mm
and, for the V7 bridge:
$\delta' = \delta/2 = 18/2 = 9$ mm.
Thanks to the improvement treatment, the settlements under the new load will be limited and absolutely acceptable.

CONCLUSION

The size of the work presented in this paper is of course minute in relation to its technical significance. Thus, the aim is to underline the aspects listed below, considered worth mentioning in relation to the success of ground improvement technique of consolidation grouting.
First of all, the accent is posed on the consideration that the technical value, the complexity and the attention to the injection design are absolutely independent from the work size and the result is remarkable for any design extent.
More over, a well-established experience is considerable to reach a good result, particularly in relation to the injection parameters choice.
Further the synergy between a theoretical and an empirical approach, together with the continuous monitoring during the construction, allows to fit in the best way a versatile execution of the low pressure injections.
In the present case, many determinant factors have been combined, to reach an appreciable result, giving perhaps a possible track to future similar projects: the engineering approach, the construction and the measured performance met the quality objectives of improving the arch foundations.