Ground improving injections underneath historical buildings: five case histories as an overview of a technique

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ABSTRACT: the geotechnical design approach for interventions underneath historic sites and monuments is strongly influenced by the invasiveness of the selected technique. Ground improving interventions with expansion resin injections allow for the compacting of the ground and filling of the voids underneath a foundation in a non-invasive way. In this paper several possibilities offered by this technique will be presented, describing five case histories performed all over Europe. In particular for each of these the most peculiar aspects will be highlighted in order to describe each phase of the intervention design. In terms of the design, different approaches can be used, ranging from a simple statistical approach and going as far as a 3D finite elements modelling. Due to the historical relevance of the buildings, in these cases the continuous monitoring of the job sites also plays a leading role together with comparative on-site tests to measure the effectiveness of the injections.

1 URETEK® TECHNOLOGY APPLIED TO HISTORICAL BUILDINGS RESTORING

1.1 *Introduction*

Often the engineering practice leads engineers to work with the restoring of historical buildings affected by cracks which evolve over the building's lifetime.
Crack generation and evolution are in general due to differential settlements. These are caused by building modification, such as an enlargement, or by a change in the load distribution, or even by a variation in soil properties due, for instance, to a raising or reduction in the water table level or to a chemical soil modification.

Regardless of the reason why settlements have occurred, there are two possible solutions: foundations strengthening or soil improvement by means of a non-invasive technique capable of guaranteeing low impact, especially in the case of historical monuments. Polyuretanic resin injections can be used to this aim, since they improve the foundation soil, causing very low vibrations.

1.2 *Uretek Deep Injections® technology*

Uretek Deep Injections® is already a well- known technology, consisting in local injections into the soil of a high-pressure expansion resin, named Geoplus®, whose properties are widely described in Favaretti et al. 2004, in order to produce a remarkable improvement in the geotechnical properties of the foundation soil.

The operation steps do not require invasive excavations or connection systems to existing and new foundation structures, so it is particularly suitable for historic buildings.

Small quantities of expanding materials are injected with precision underneath the foundation level into the soil volume where the stress state reaches its peak. After, injection resin immediately begins to expand and the high expansion pressure of the injection grout guarantees a proper compaction of the soil. The expansion process first leads to the compaction of the surrounding soil and then, in case of light overstructures, also to a lift.
This expansion process can be theoretically studied as a spherical cavity (or cylindrical, if several injections are performed very close to one, along the same vertical line) expanding in quasi-static conditions.The soil is modelled as a linear elastic-perfectly plastic material with a non-associated Mohr-Coulomb yield criterion and is considered initially subjected to an isotropic state of stress.

During the first part of the expansion process, when the internal pressure of the cavity increases, the soil exhibits elastic behavior. After reaching a specific value of the internal pressure plastic deformation starts, similarly to the elastic phase, until it reaches the pressure limit (σ_{lim}). It is assumed that as soon as pressure limit is reached, the resin solidifies (Dei Svaldi et al. 2005).

The analytical model of the expansion process together with the resin expansion law obtained in the laboratory were used to develop a software, Uretek S.I.M.S. 1.0, capable of predicting the ground improvement index of a soil injected with Geoplus® resin. Its characteristics are well described in Gabassi et al. 2010.

1.3 *The restoring process phases*

The entire design process must include several phases in order to best apply the intervention technique. It is necessary to know the local conditions through preliminary testing: both the soil profile and its mechanical properties by means of a geotechnical investigation (CPTU tests, MAIW system) and the geometry of the foundation system must be determined. Then the injection process must be modelled with the analytical model described above and/or a numerical analysis in order to understand how to best perform it in the field. During the injections the entire procedure must be monitored by electric receivers lit by a laser emitter and anchored to the building whose foundation is to be worked upon in order to measure vertical displacements. During and after the field intervention, a monitoring system called Easy Crack Monitor® is installed to guarantee an automated control of the relative movement of pairs of check points, which can be the two lips of a crack, and verify that they no longer move significantly. However, soil properties are to be investigated after the field intervention in order to verify the soil improvement in terms of strength: CPTU and pressiometer tests are performed at the end of the injection process to compare results with those performed previously.

In the following, each of these important phases will be described by presenting a specific case history in which the Uretek® technology was applied.

2 PRELIMINARY AND POST-INTERVENTION SURVEYS

2.1 *Palatium Vetus in Alessandria*

In this case history it was necessary to understand the shape of the foundations of the building in order to estimate the local stress induced on the soil, together with the soil properties, in order to plan the restoring intervention.

Figure 1. Palatium Vetus in Alessandria

Palatium Vetus (Figure 1) is in fact the oldest building in Alessandria: it was built in 1170 in the heart of the town and has been refurbished and enlarged so many times that the soil stress state has changed under the foundation system. The final configuration is constituted by only one body with two levels, lying on several types of foundations. To investigate the foundation system a series of drillings were performed. A manual boring machine was used (max energy per bump: 12-14 Joule, frequency: 1200-2800 bumps per minute), making holes of 26 mm diameter (Figure 2). Drillings were performed alongside the perimetral wall to identify the base level of the foundations and also at increasing distance from the wall to investigate the presence of enlargements or connecting beams among the plinths.

Fourteen different areas around the entire building were investigated (Figure 2): walls were found to be constituted by bricks and binder with no discontinuities, the foundation base level varies from 0.5 m to 3.2 m depth and a 10-15 cm layer of crushed stones lies under the foundation system.

The load was estimated to increase due to the restoring intervention, up to 50% (the average value is circa 18-20%) so the final soil stress state varies more or less from 0.35 MPa to 1.19 MPa, depending on the foundation type.

A complete geotechnical survey was also performed in order to estimate the bearing capacity of the soil. Two penetrometer tests were carried out together with a borehole with SPT tests and laboratory tests (oedometer and shear tests): under a superficial

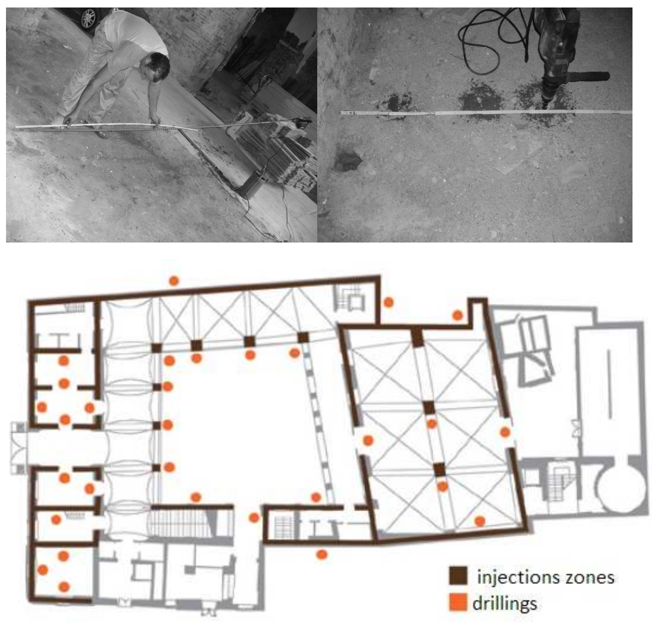

Figure 2. Above: foundation survey at Palatium Vetus. Below: survey and intervention map

replenishment layer, whose thickness varies from 1.5 m to 2.4 m, a 3 m thick clayey layer and a 1 m silty and sandy layer were detected. Under those low resistance soil layers stiffer ones were found: more than 10 m thick of gravelly and sandy layers.

Since the superficial layers had little bearing resistance, soil stabilization was planned by means of the Uretek Deep Injections® technology.

The aim was to increase the mechanical properties of the ground in order to make it able to bear the stress due to the increased load transferred by the foundations. Because of the historical value of the building, the aim was not to interfere with the existing walls, so the Uretek® technology was extremely suitable.

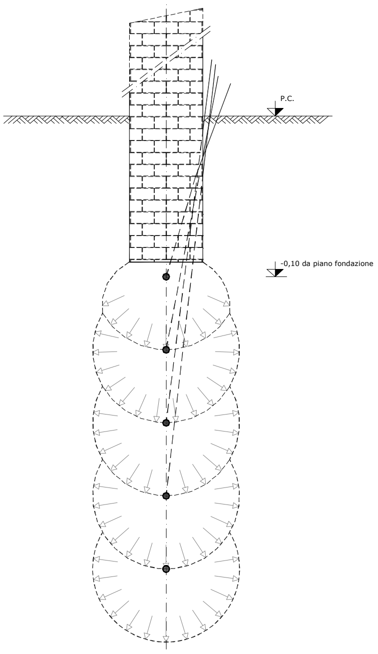

Figure 3. Injection procedure

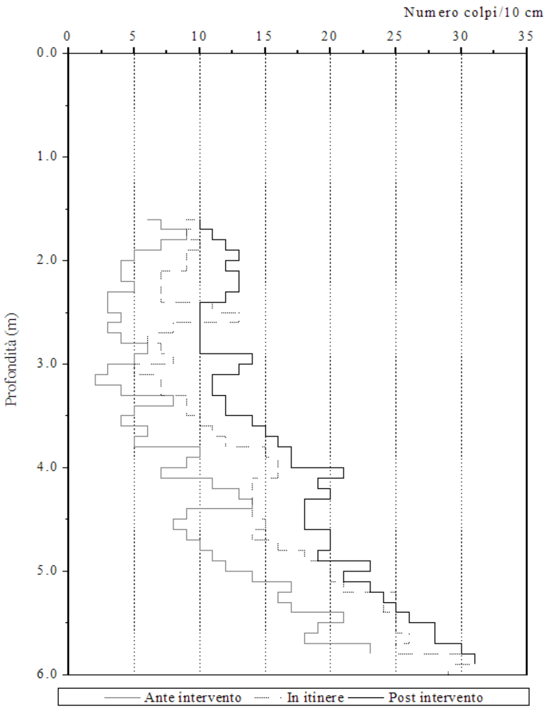

Figure 4. Penetrometer tests before and after intervention at Palatium Vetus

The design was performed by means of Uretek software S.I.M.S. 1.0 described above. For further details the interested reader is referred to Pasquetto et al. (2011). The injections were performed on five different levels from the base level of the foundations until 3.5 m of depth (interaxis distance: 0.6 m) with manual boring machines identical to those used to investigate the foundations, which passed through the final part of the existing foundations themselves, as described in Figure 3. In this way only light vibrations were guaranteed.

To test the improvement of the soil resistance, fourteen comparative penetrometer tests were performed in the treated zones, in accordance with Italian regulation (NTC 2008): Figures 4 shows that mechanical properties increased more than 40% in the critical points, even though the test itself has no more than comparative meaning.

Preliminary survey has thus been found to be very important in order to correctly design the intervention (geometry and soil knowledge) and also to allow the comparison between the initial and final soil characteristics.

3 NUMERICAL DESIGN

3.1 *The Città di Castello tower*

In the case of the Città di Castello tower, it clearly appears how helpful a 3D FEM analysis can be in making important job site decisions.

The tower, dated around the thirteenth century, is a slim structure (rectangular shape: 6.10 m x 6.8 m, maximum height: 39.8 m) leaning towards the main square and also towards the contiguous alley, and the way we see it today is the result of several collapses and reconstructions occurred over time. In particular, after the earthquake occurred in March 2007 a separation of 4 cm was detected in the seismic joint between the tower and the Bishop's Palace, due to a differential settlement. This settlement strongly increased the measured leaning of the tower from 72 cm to 78 cm towards the main square.

In order to model the actual configuration of the tower and to have a reliable prediction of the intervention effects a 3D analysis was performed using the commercial software Plaxix 3D Tunnel.

SOIL TYPE	PARAMETER					
	γ_{sat}	E	c'	φ	ψ	Constitutive law
	kN/m^3	kPa	kPa	°	°	
Replenishment (Silty Clay)	19.5	6250	31	23	-	Mohr-Coulomb
Replenishment (Sandy Silt)	20.0	4000	30	28	-1	Mohr-Coulomb
Replenishment (Sand)	18.5	3000	0	32	-	Mohr-Coulomb
Sandy Silt	20.0	8000	18	30	-3	Mohr-Coulomb
Silty Sand	20.0	9000	18	30	-2	Mohr-Coulomb
Clay and Clayey Silt	21.2	13000	10	27	-	Mohr-Coulomb

Table 1. Soil layers properties for the Città di Castello tower-FEM model

The soil profile and properties were drawn on the basis of four boreholes, ground penetration radar and laboratory tests. Under a superficial inhomogeneous replenishment layer, whose thickness varies from 1.5 m to 5.7 m, a sequence of silty sands and sandy silts layers is found, followed by a bottom layer of clay and clayey silts at depth varying from 10.0 m to 13.0 m. The soil layer parameters are summarized in Table 1 and the OCR is slightly lower than 1.

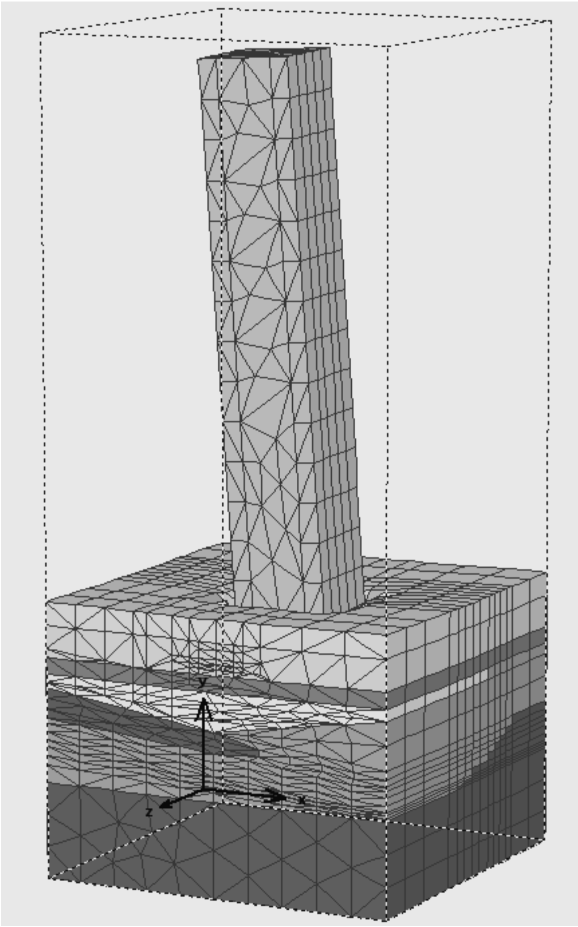

Figure 5. Città di Castello tower mesh for the FEM analysis

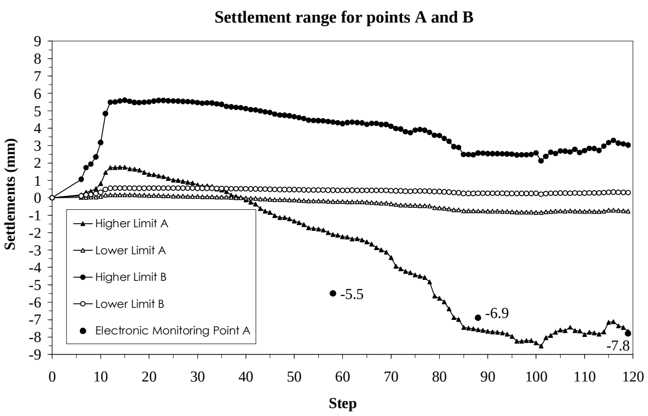

Figure 6. Time-settlement calculated curves and real measurements at Città di Castello tower

The tower was modelled in a vertical position in the input data. Afterwards, the construction phases were simulated using intermediate steps until the final configuration was reached (Figure 5).

The injections were modelled as a volumetric expansion of solid elements by forcing the volumetric strain value of the element according to the volume increase calculated with Uretek S.I.M.S. 1.0. In doing so, an accurate determination of the grout quantities to be injected was possible given the quick reaction time of the resin preventing the material from flowing away from the injection point. A stress-strain analysis of the tower for every scheduled injection phase was thus performed, simulating the injected volume as an expansion of the soil element located exactly in correspondence of the injection point (x, y and z). The stiffness increase of both the surrounding as well as the treated soil was taken from the Uretek S.I.M.S. 1.0 output as well.

All throughout the work a real time electronic monitoring was operating: Figure 6 shows how slight the differences are between the calculated time/settlement curve and the real settlement measurements after every injection phase, thus confirming the reliability of a numerical analysis that reproduces the resin injections.

4 INTERVENTION PHASES

4.1 *The Venice case at "Punta della Dogana"*

The case of "Punta della Dogana" in Venice demonstrates how sometimes the intervention must be scheduled in phases. This can be due to particular local conditions and sometimes the interventions must be changed during the execution itself.

"Punta della Dogana" is a historical place in Venice where trade occurred. The trapezium-shaped buildings were built in 1677 on the basis of the design of the architect Giuseppe Benoni (Figure 7).

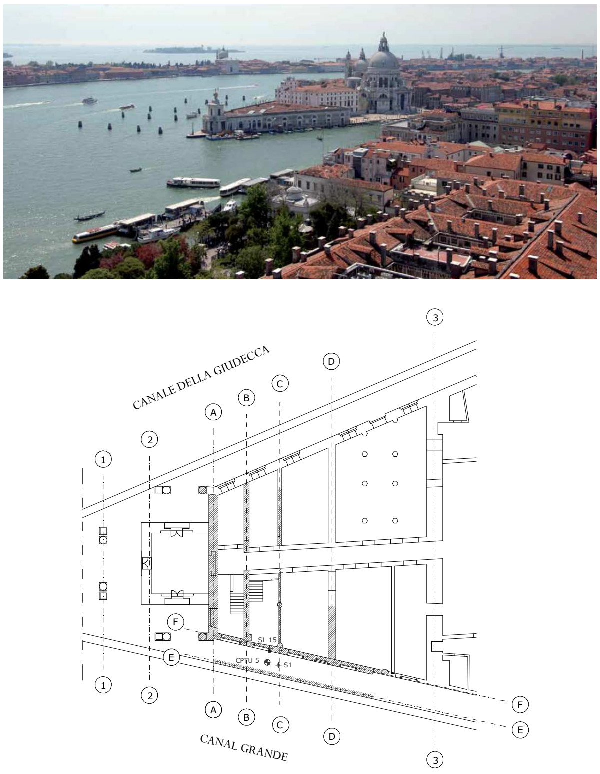

Figure 7. Punta della Dogana view (above), map (below)

The main building has a width that varies from 16 m to 75 m and floors lie on ten brick walls, parallel to one another, as described in Figure 7. Foundations are constituted by bricks and binder walls laying on four different substrates: directly on the soil, on a rigid shelf laid on the ground, on a shelf that lies on wooden piles or on the foundations of an existing tower. The foundation base level varies from 0.69 m to 2.84 m depending on the position.

In May 2003, during the restoring of the "Canal Grande" shore walls (the main channel in Venice) by means of micropiles, settlements of the wall near the "Punta della Dogana" together with settlements of the building itself occurred. These caused old cracks to open again, and new ones to be created. Three mechanisms were responsible for this: vertical differential settlements, elongation in the direction of the internal walls, and rotation of the facades, especially the one towards the "Canal Grande". At that time the shore walls were already being monitored and the monitoring was continued after the episode, highlighting a settling trend. Assuming the zero corresponding to the measurement of 31.07.2002, the settlement-time curve plotted in Figure 8 shows a sharp increase in terms of settlements between April, the 30th and May, the 15th for all the anchorages, especially SL15 that is in correspondence of the "Canal Grande" and continues settling even the year later whilst the others stop.

The reason was traced to the hydraulic phenomenon of heaving. Along the shore, in fact, the soil profile is made up of a sequence of cohesive layers followed by granular ones: the top of the sandy layer is located at -6.3 m under the mean sea level. The restoring of the shore walls had required the use Larssen sheet piling, confining the channel zone in front of the building, and the pumping of water out and then excavating in order to reach the base of the shore wall. The water pressure in the sandy layers, deeper than the sheet piling, was kept undisturbed while the excess pore pressure due to water flow concentrated in clayey layers, thus making the effective stress decrease, the equilibrium fail and the structures collapse.

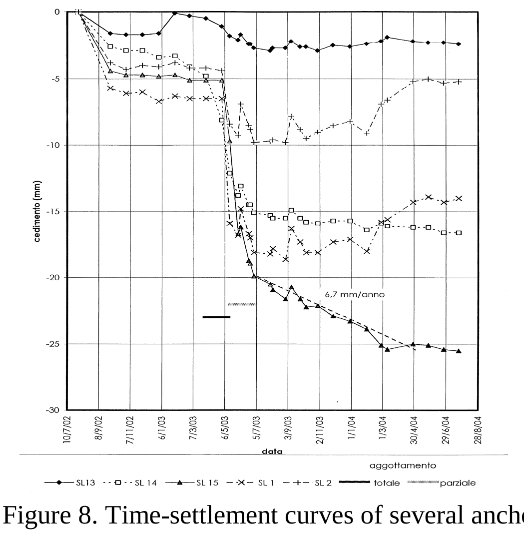

Figure 8. Time-settlement curves of several anchorages

To restore the building a complex series of interventions were scheduled whose aim was to arrest settlement and, in cases where the settlement had been too significant, to raise the building to its previous level. Since settlements were due to changes in soil stress state, the Uretek Deep Injections® was considered suitable to the purpose. It is in fact flexible enough to change schedule in-progress depending on the field results (foundations drillings, comparative penetrometer tests, continuous monitoring). Further, resin injections can induce swelling quite easily.

Injections were performed in three phases in order to allow excess pore pressure to dissipate. At the same time the disturbance caused by pore pressure increase could be limited by diminishing the grout quantities to be injected and by programming the injection sequence so that the same soil volume would be involved only once in the same moment.

The first phase intervention happened in November 2004. Injections were performed from the foundations base level until -8.5 m under the mean sea level in correspondence with the façade and until -5.0 m on the opposite side. Together with local injections a series of "column injections" were performed alongside the shore wall in order to create a sort of retaining structure for the following injections. The second and the third phases were performed the following year and were less invasive. The detailed description is given in Gabassi et al. (2011).

The structure response was monitored twice a day from the end of the first phase, during the injections phase, and every 15 days between the two phases. What occurred was a temporary rise in the pressured water inside the injection pipes as a consequence of the resin expansion, especially during the first phase. The pore pressure increase and the consequent dissipation caused settlements to occur but in the following phases the phenomenon decreased and this trend inverted, showing also a small settlement recovery.

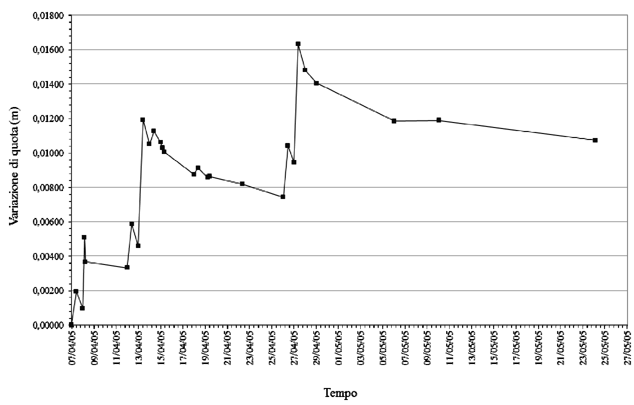

Figure 9. Time-displacement measured curve for "point 17"

Figure 9 shows the time-displacement curve of the check point “17”, close to the SL15 anchorage, on the “Canal Grande” side: the recovery is evident for each intervention phase.

5 DOUBLE INJECTIONS TECHNOLOGY

5.1 *Chapelle Saint Nicodème in France*

There are cases in which the soil improvement must be accompanied by a wall restoring because the structure is heavily damaged. This was the case of Chapelle Saint Nicodème in France (Figure 10).

Figure 10. Chapelle Saint Nicodème in France

It is located in Canton of Baud, in Brittany and its origins date back to the French Renaissance: it was built between 1520 and 1539 by the architect J. Le Layec.

From an architectural point of view the chapel forms a Latin cross: the nave is 31 m long and 7 m wide and belongs to a period of stylistic transition, since the shape is inspired by medieval architectures whilst decorations are closer to the Renaissance repertoire. The main tower reaches a height of 50 m and its rectangular base is 11 m wide and 20 m long.

In 1914 cracks due to problems in the tower foundations were detected. A geotechnical survey carried out in 1926 revealed that the ground was constituted mainly by shale which was loose and sensitive to moisture and this is probably the reason for the instability of the tower. Between 1927 and 1930 low-pressure concrete injections were performed in order to consolidate the subsoil. In 1972, however, an inclination of the chapel towards the south was detected (Figure 11). Moreover, during the latest survey, cracks due to water vapor and to an incorrect water canalisation were also detected.

Because of the critical situation of the building, two types of intervention were planned: soil improvement and wall restoring, both by means of resin injections. The first type is the previously described Uretek Deep Injections® whilst the latter is called

Figure 11. The Chapelle Saint Nicodème leaning tower

Uretek Walls Restoring® and consists in injections whose aim is to fill voids in joints between wall blocks with bender.
The procedure consists in drilling the damaged wall, inserting injection pipes and injecting the IDRO CP 200 resin, which expands thus filling every cavity in the wall. Its mechanical properties are quite similar to mortar once solidified: when injected it is liquid, then in 60 seconds it solidifies, expands and reaches its final consistency.

The intervention was performed in two phases: in April and May 2009 and in October 2009. At the beginning and at the end, pressiometer tests were performed to compare soil resistance before and after the intervention and verify the injections performance. Results are given in Table 2 and show a significant improvement in soil properties.

Before (2003)	After (2009)
17.8<EM<88.2 MPa	21.8<EM<136 MPa
1.96<PI*<4.01 MPa	2.96<PI*<5.94 MPa

Table 2. Pressiometer values at Chapelle Saint Nicodème before and after intervention

6 LONG TERM MONITORING

6.1 *A 19th century building in Genève*

The following case shows the importance of continuous monitoring of crack width with time in order to ensure crack stabilization.

The building subject to intervention in Genève (Figure 12) was affected by very long and deep cracks worsening over time. It is a residential complex constituted by nine independent parts, whose or igins date back to 1828. It was built on the foundations of the city’s old fortification walls. Only one

Figure 12. The building subject to intervention in Genève

side of the building, however, lays on the foundation walls, while the other side, instead, lays on an old replenishment layer: this is the cause for the cracks.

Visible differential settlements had already occurred at the time of construction, since the side laying directly on the soil started settling immediately; the first measurements go back to 1976 and now the maximum differential settlement between the two sides reaches 20 cm, while the rate of settlement is eight times faster than the initial one. The subsoil was also found to be constituted by several cavities, as detected during geotechnical preliminary surveys (Figure 13).

Figure 13. Cavities in Genève subsoil

All this evidence, together with the strict restriction on entering the building's basement, led to the decision of using the Uretek Deep Injections® technology. The injections were performed at different levels for an extension of 280 m long in order to fill the voids and, as it is usual, to improve the soil mechanical properties.

In Figure 14 the settlement trend is plotted over time in correspondence to fixed control points. It is clear that the settlement stabilized after the injection procedure. The injections cause a slight localized settlement due to the procedure itself, but the graph shows that the settlements which were increasing over time prior to the intervention have almost stopped.

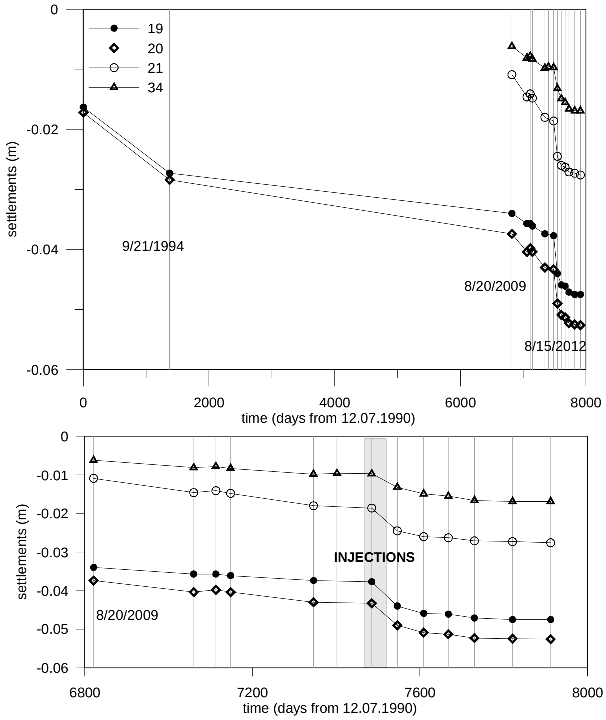

Figure 14. Above: Time-settlement curves of several anchorages. Below: enlargement of the measurements just before and after intervention

After the intervention a monitoring system called Easy Crack Monitor System® was installed in order to check the crack stabilization. The system allows for the automated and continuous reading of any relative displacement between two lips of a lesion and/or two buildings and/or two structural elements, along two orthogonal directions. It is composed of one or more reading devices in correspondence of the lesions to be monitored and by a central acquisition and transmission of data (Figure 15). The reading device, rigidly connected to the masonry, detects the relative displacement between two stiff portions along two orthogonal directions at regular time intervals. The reading of the movements is made at the same point for both directions, with a precision not greater than 0.5 mm. Each system is also equipped with a temperature sensor. The control unit has the function of collecting data from several reading devices and to transmit them by means of GPRS protocol, at regular intervals, to a server for storage and display.

Figure 15. Easy Crack Monitor System®

The monitoring results are shown in Figure 16: the cracks stabilized since no more displacements occur along the X or Y directions, even when the temperature varied. Two goals were thus reached by performing the injections technique.

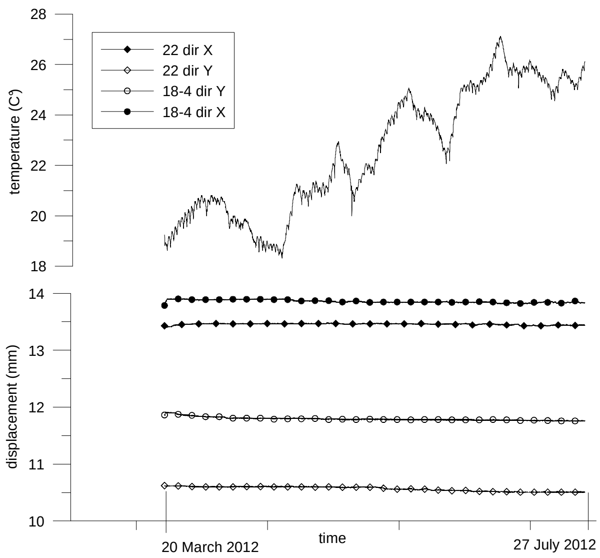

Figure 16. Time- displacement-temperature curves for two cracks (in X and Y directions)

7 CONCLUSIONS

The overall description of five case histories has allowed for the description of the main intervention phases which have to be performed when dealing with the restoring of historic buildings or monuments.

Cracks are often due to factors: differential settlements caused by excessive applied loads or by low mechanical soil properties.

Ground improving interventions with expansion resin injections, such as the Uretek Deep Injections® technology, allow for the compacting of the ground and filling of the voids underneath a foundation in a non-invasive manner.

Preliminary survey is thus fundamental in order to trace the soil profile and its mechanical properties as well as to know foundation geometry in detail, as described in Palatium Vetus case.

The design must be as accurate as possible, therefore, in particular cases, a FEM analysis must be performed to best model the soil and structure response before on-field intervention. This strategy was applied in the case of the Città di Castello tower.

In the case of the Punta della Dogana building, in Venice, an accurate intervention schedule was planned both in advance as well as during the intervention itself to allow pore pressure to dissipate between one injection phase and the next.

If the building is seriously damaged, the walls, too, have to be restored, as described in the case of the Chapelle Saint Nicodème in France.

After each intervention a further geotechnical survey must be performed to ensure the effective performance of the injections, as was done in each of the case histories presented.

It is also beneficial to regularly monitor crack width after the intervention in order to verify that they do not move any more, as described in the case of the old building in Genève in which the Easy Crack Monitor System® was used.

Accurately performing all these phases ensures the best performance of the restoring intervention, as the case histories presented here have proven.

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