3D FEM analysis of soil improving resin injections underneath a mediaeval tower in Italy

M. Gabassi, A. Pasquetto & G. Vinco
Uretek, Verona, Italy

F. Mansueto
Studio Montaldo & Associati, Genova, Italy

ABSTRACT: In order to stop the settlement process of a mediaeval tower located in Città di Castello (Italy), polyuretanic resins injections were performed in the foundation soil. The designing of the ground improving intervention was made with a 3D finite elements code and an analytical method based on the finite cavity expansion theory (Yu H.S. e Houlsby G.T., 1991), which allows to predict soil parameters changes due to resin expansion in the ground. During job site activity and for a long period after the works were finished the structure has been accurately monitored; the measured data seem to get on well with the one obtained from model analysis .The model creation, starting from the avilable geological data input, was necessary for the understanding of the causes which trigged to settlements. The Safety Factor improvement experienced during the simulation was about 30%.

1 THE CITTÀ DI CASTELLO CIVIC TOWER

1.1 *Historical overview*

The tower, initially built for military purposes, can be dated around the thirteenth century and is the only slim structure, together with the "Campanile Rotondo", left in the old town Città di Castello.

The building has a rectangular shape, dimensions 6,10 times 6,80 m and has a maximum height in the front of 39,80 m. It is divided into seven different levels, four of which were previously used as a prison.

The tower, like we see it today, is the result of several collapses and reconstructions occurred over time; this can be gathered from the different wall textures, which interchange themselves along the whole tower height.

1.2 *Settlement detection*

In March 2007, following an earthquake registered in the area, with a magnitude of 2.2 of the Richter scale, a separation of 4 cm was detected in the purpose made seismic joint between the tower and the Bishop's Palace. By analyzing the data of the cracks monitoring, a differential settlement caused by the earthquake was clearly identified. This settlement strongly increased the before measured leaning of the tower towards the main square.

In detail, the leaning grew from 72 to 78 cm, making this way even worse a strain state already close to the limit.

2 GEOTECHNICAL INVESTIGATION

2.1 *Real time monitoring*

The real time electronic monitoring was started on October 3rd 2007 and the zero measurement showed a leaning of 74 cm towards the main square and 34 cm towards the contiguous alley.

During the next eleven days, a further settlement of 8 mm was registered in both directions.

2.2 *Geological survey*

During October 2003 a geological survey was performed including four deep soundings, ground penetration radar and laboratory tests.

The foundation depth from the ground level, varies from 2.3 m, on the sides facing the square (front side) and the alley, to 3.6 m on the side jointed to the Bishop's Palace and the backside.

The underground is constituted by a superficial inhomogeneous replenishment layer, which thickness varies from 1.5 to 5.7 m, over a sequence of silty sands and sandy silts layer, followed by a bottom layer of clay and clayey silts at a depth varying from 10.0 to 13.0 m.

These kind of soils, characterized by a strong geometric and granulometric as well as geomechanical variability, determine different responses to static and dynamic stress states, worsen by replenishment layers with strong thickness variability due to the ancient old town urbanization.

The ground water table was detected at a depth of 10 m from the ground level, but is capable of relevant changes depending from the different soils permeability. Also suspended underground water was detected in several spots, coming from water pipes leakages and from the square, following big rainfall events.

2.3 *Geotechnical Parameters*

The Consistency Index (IC), varies from 0.738 to 0.950, revealing a solid to plastic consistency of the analyzed soils. These values are proper of groups of inorganic clays with low to medium plasticity, silty and sandy clay and fine silty sands.

Sandy soils have a medium-high consistency, whereas clayey soils are characterized by high drained cohesion values (c') varying from 25 to 30 kPa and oedometric moduli M included between 6.2 and17.4 MPa meaning a coefficient of volume compressibility m_v ranging from 0.16 e 0.06 m^2/MN.

From the oedometric tests performed, the consolidation pressure and the over consolidation ratio (OCR) were calculated; the tested samples are all in the range of normal consolidated to poorly overconsolidated soils with some peaks in the clays of the deepest part of the soundings:

Table 1. OCR values.

S1 C3	(7.7-8.0 m)	$OCR=\sigma'_p/\sigma'_{v0}$=(179.95/156.91)kPa=1.147
S1 C4	(11.3-11.5 m)	$OCR=\sigma'_p/\sigma'_{v0}$=(229.97/225.55)kPa=1.019
S1 C5	(15.2-15.5 m)	$OCR=\sigma'_p/\sigma'_{v0}$=(499.99/304.00)kPa=1.645

3 GROUND IMPROVEMENT DESIGN

3.1 *Uretek Deep Injections Method®*

Due to the need of a low impact technology, which could guarantee low vibrations and small diameter drillings, a polyuretanic resin injections technique was chosen.

Uretek Deep Injections® is a very particular technology, consisting of local injections into the soil of a high-pressure expansion resin; which produces a remarkable improvement of the geotechnical properties of the foundation soil. The operation steps are relatively simple and do not require invasive excavations or connection systems to existing and new foundation structures.

Small quantities of expanding materials are injected precisely underneath the foundation level into the soil volume were the stress state reaches its peak. In order to avoid the material to flow outside from this volume, the expansion together with the viscosity increase of the resin have to be very quick. Therefore, after having injected the soil to be treated, resin immediately starts to expand.

A high expansion pressure of the injection grout is also needed to guarantee a proper compaction of the soil. It has to be way higher than the stress state induced by the overlaying structures both to allow a certain expansion rate and to avoid higher material consumption.

The expansion process, first leads to the compaction of the surrounding soil and then, in case of light overstructures, also to the lift. All the procedure is monitored by electric receivers lighted by a laser emitter and anchored to the building whose foundation is treated.

A wide set of laboratory tests have been carried out on the Uretek® resin, named Geoplus®, in order to evaluate its main mechanical properties. Vertical compression with free lateral expansion and vertical expansion in oedometric conditions tests were performed in the geotechnical laboratory of the University of Padova (Favaretti et al. 2004).

3.2 *Theoretical view and simulation of the expanding process*

The expansion process of the resin, locally injected into the soil, can be theoretically studied as a spherical cavity (or cylindrical, if several injections are performed very close each to other, along the same vertical line) expanding in quasi-static conditions.

The soil is modelled as a liner 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, soil shows an elastic behavior, while 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 expansion process is theoretically treated adopting analysis at large and small strains, respectively, on the plastic and elastic region (Yu & Houlsby 1991).

3.3 *Uretek ground improvement calculation software*

The analytical model of the expansion process together with the resin expansion law obtained in laboratory, were recently used to develop a software, Uretek S.I.M.S. 1.0, capable to predict the ground improvement index of a soil injected with Geoplus® resin.

Uretek S.I.M.S. 1.0 computerizes the above explained model and enables designers to get the improved ground parameters rapidly. To perform a stress-strain analysis this parameters can later on be used to perform a FEM analysis.

The quality of the previsions, provided by the analytical model, has been verified on a number of real cases. The reliability of the theoretical previsions increases with the quality of the geotechnical investigation available to designer.

During first phase injections, due to the expansion of the grout, all voids are filled, the ground is compacted and its stiffness increases. In normal consolidated ground conditions, this leads to the rise of the horizontal stress to values close to the vertical one in a limited volume around the injection point.

When the isotropic stress state is reached, the expansion pressure also develops in vertical direction, inducing a surface lifting (Schweiger et al. 2004).

The isotropic volume growth is obviously a simplification, because the expansion pressure first develops on the lowest stress plane in homogeneous soil conditions.

3.4 *3D FEM analysis*

The analysis has been performed using a PLAXIS 3D Tunnel software version 1.2 of the Dutch Plaxis b.v. company.

In order to model the intervention, some simplifications were adopted and the injections were this way modelled as a volumetric expansion of solid elements.

A stiffness increase of both the surrounding as well as the treated soil has been adopted; the isotropic expansion implemented in Uretek S.I.M.S. 1.0 was modelled in the 3D FEM analysis, by forcing the volumetric strain value of the element according to the volume increase calculated with Uretek S.I.M.S. 1.0 (Mansueto et al. 2007).

Doing so, an accurate determination of the grout quantities to be injected has been possible. The quick reaction time, as a matter of fact, prevent the material to flow away from the injection point, making this way easier the determination of the injected volumes in a certain soil volume. Considering that the material flows for one meter at the most, the added volume in a sphere of one meter radius around the injection point is equal to the injected quantity times the expansion factor calculated with Uretek S.I.M.S. 1.0 (Pasquetto et al. 2008). Also the soil stiffness increase was taken from the Uretek S.I.M.S. 1.0 output.

Figure 2 shows the different foundation levels of the tower: they are higher towards the square ($x < 0$) and towards the alley ($z > 0$) as verified in the tests.

A stress-strain analysis of the tower for every scheduled injection phase has been performed, simulating the injected volume as an expansion of the soil element located exactly in correspondence of the injection point (x, y and z).

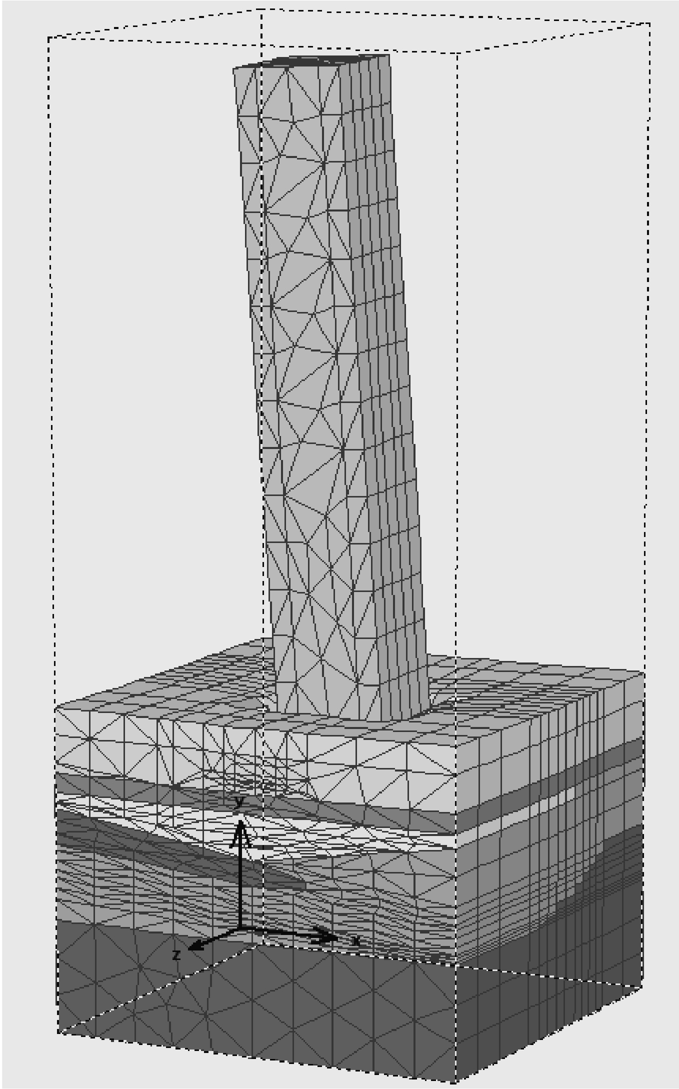

Figure 2. 3D FEM model of the tower.

The volumetric expansion rate has been assigned to every element, according to the volume of resin to be injected in every injection point and the calculated expansion factor of the resin.

The construction of the 3D model, interested 14.310 m^3 of soil and required the generation of 8.708 elements, 25.053 nodes and 52.248 stress points internal to the elements.

The tower has been modeled in vertical position in the input data. Afterwards, the construction phases have been simulated using intermediate steps, until the final configuration has been reached. The error between the modeled tilting and the measured one, lower than 4%, has been evaluated acceptable. The model has been based on the soil stratigraphy, on the precise geometry of the tower and on the scheduled injection phases.

The initial condition analysis pointed out that, apart from the rather complex local stratigraphy characterized by the presence of overconsolidated material lenses into much more deformable soils, the different foundation levels determined the tower rotation.

Table 1. OCR values.

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

As a matter of fact, to a higher foundation level, corresponds a thicker layer of deformable soil, which origins, therefore, a differential settlement and the rotation of the tower. The leaning direction towards the less deeper foundation can be read as a confirmation of this.

The FEM analysis clearly evidenced this point.

The stress state, in correspondence to the foundation/soil interface, reaches the highest level (700 kPa) underneath the foundation facing the square, exactly were the settlement is the highest. These are the effects of the stress redistribution caused by the tower eccentricity.

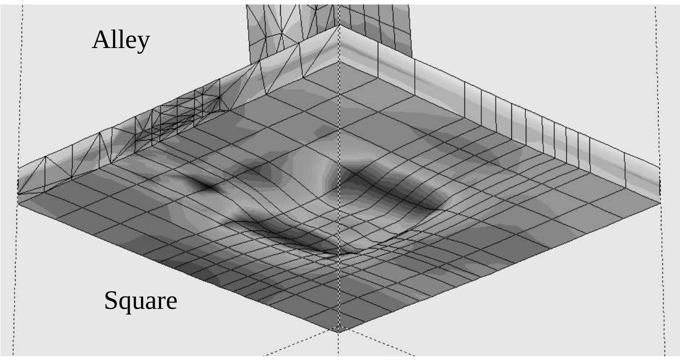

Figure 3. Relative shear stresses distribution.

Figure 3 shows the distribution of the relative shear stresses (meant as the ratio of the existing shear stresses and the resisting ones calculated with a Mohr-Coulomb failure criterion) just underneath the foundations.

It has been observed, that where the settlements are the highest, the existing stresses are equal to the resisting ones, meaning that the soil reached a plastic equilibrium condition.

This obvious result is important, because proves the correspondence of the analysis performed; the foundation ground reached the full mobilization of the end-bearing capacity.

Figure 4 shows an interesting double failure mechanism mobilization. The first one, more superficial, lays just underneath the foundation level and is limited to the first sandy silt soil layer; on the other hand, the second and deeper one, also interests other soil layers under the first one.

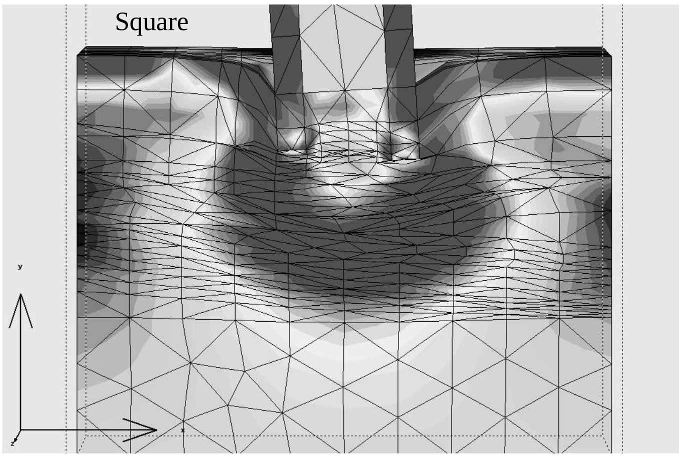

Figure 4. Relative shear stress in the center cut of the tower before the injections.

Therefore, if the first one is a typical superficial punching failure mechanism, the second one depends from the stress state transferring to deeper soil layers; the two effects are certainly related, depending the second from the first one.

3.5 *Executive project*

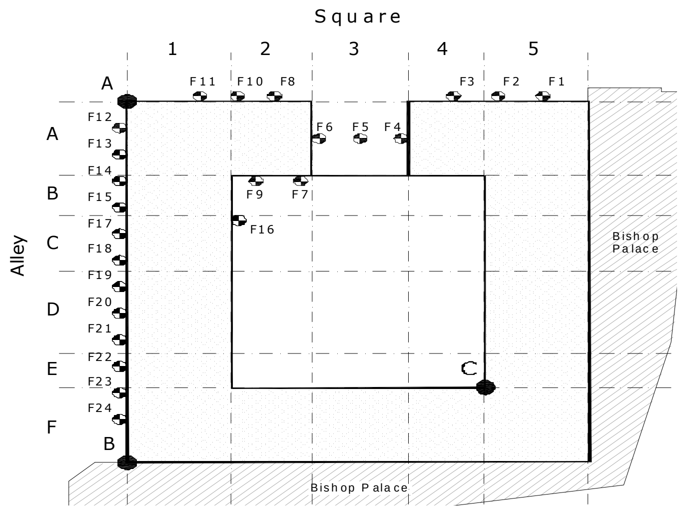

Figure 5. Injections points distribution and monitoring points.

Based on the indications come from the FEM analysis, an executive project has been arranged, which has been changed continuously, depending on the reaction of the tower during the different injection phases.

During a total of 14 working days, 2.475,5 kg of resin were injected. The amount of injected grout per day has been very different, depending on the real time monitoring data analysis.

4 FIELD AND DESIGN DATA COMPARISON

As mentioned before, during the whole work a real time electronic monitoring was operating. These data have been, afterwards, compared with the settlements calculated with the FEM analysis.

4.1 *Expected settlements*

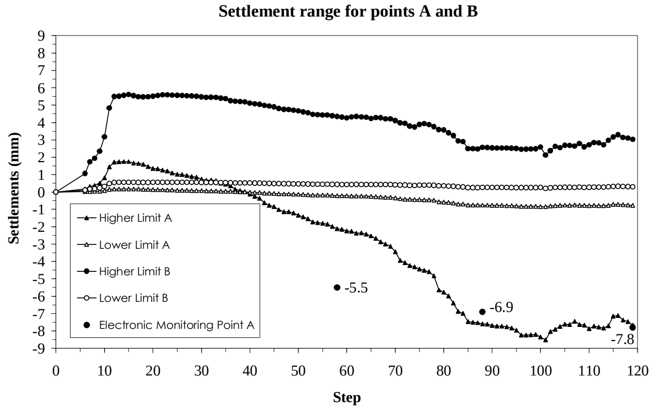

Figure 6. Calculated settlements and monitoring data graph.

Figure 6 shows the expected settlements shells for monitoring points A and B, representing two limit scenarios with zero and full expansion of the resin. The graph also withholds the settlements data, measured on field after each one of the three injection phases.

It can be observed that, according to the modeling, little settlements had to be expected, due to a double effect: a lateral soil flow due to the resin injection and expansion first and a ground strain due to the increase of the effective soil stress, also caused by the resin volume expansion, second.

Figure 6 shows how little are the differences between the calculated time/settlement curve and the real settlements measured on field after every injection phase.

4.2 *Final stress state distribution*

Referring to relative shear stress (Fig. 3), the FEM analysis clearly shows how the injections strongly reduced this value within the improved ground volume.

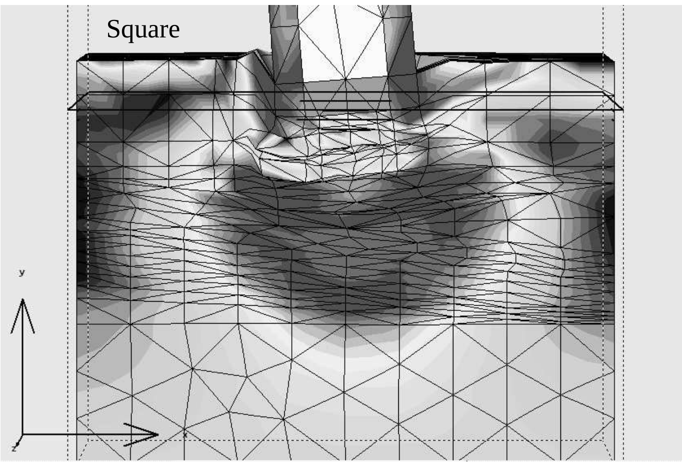

Figure 7. Relative shear stress in the center cut of the tower after the injections.

This reduction is the effect of the soil compaction induced by the resin expansion.

4.3 *Safety factor increase*

The determination of the safety factor, was done using a “c-φ reduction” procedure, which foresees a progressive reduction of the ground parameter values until the soil body collapse is reached.

The final result is a movement/reduction factor graph, which represent the safety factor of the structure.

Figure 8 shows a comparison of the safety factor before and after the intervention; it can be observed that the injections effect was the raising of the safety factor of about 30%.

Figure 8. Safety factor graph.

4.4 *Post intervention monitoring*

The precision monitoring of three datum points, started on March 25th 2007 and has been necessary for measuring the settlements of the structure before during and after the job site.

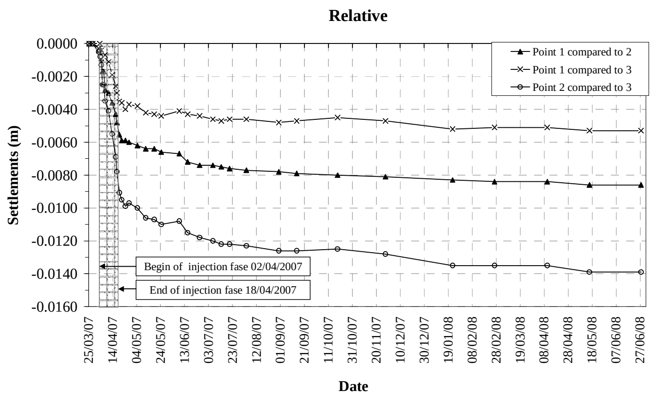

Figure 9. Settlement/Time graph.

Figure 9 shows the settlement/time graph, from which clearly appears how the settlement speed rapidly decreases after the injections. Also other electronic devices have been installed on the tower before the intervention, such as three electronic inclinometers with a 10^{-3} degrees precision and two electronic crack monitors with a 10^{-2} mm precision.

In this case the monitoring had to register eventual settlement trends in the short such as in the long period. In order to obtain a significant measurement, also a thermometer has been installed to neglect movements only due to thermal shocks.

Analysing the data, it has been observed that during the drilling phase no significant settlement were registered, meaning that the small diameter drills made with hand augers didn't influence the tower stability.

On the other hand, during the injection phase, a variation of the cracks opening, such as a tower leaning progress have been observed, confirming this way the results of the FEM analysis.

The monitoring is still working and the tower didn't register any further settlements in the last two years.

5 CONCLUSIONS

In this interesting case history, clearly appears how helpful a 3D FEM analysis can be, to take important job site decisions. In this delicate compensation grouting with polyuretanic resin injections, underneath a mediaeval tower, key choices like the injections sequence such as the grout quantities, were taken according to the modeling outputs.

At the end of the work a good correspondence between settlements data measured on field and the ones forecasted with the analysis was found, confirming the good quality of the model; also in terms of bearing capacity increase, a significant rise of the safety factor was observed.

The aim of this designing approach was the evaluation of the strain behavior of the tower during the different injection phases, in order to analyze the critical points of the work.

To cover the stability problem at hand, also the increasing action of gravity, because of the increasing tilting should be taken into account in a leaning instability problem, which wasn't, however, the purpose of this modeling.

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